HES-UIE-26

Book of abstracts

International Conference on Heating by Electromagnetic Sources

Induction, Dielectric and Microwaves, Conduction & Electromagnetic Processing

Edited by Michele Forzan and Paolo Di Barba

PADOVA UP

Prima edizione 2026, Padova University Press

Titolo originale: HES-UIE-26. Book of Abstracts.
International Conference on Heating by Electromagnetic Sources.

ISBN 9788869385438

Università degli Studi di Padova
Via 8 Febbraio 2, Padova
www.padovauniversitypress.it

https://www.padovauniversitypress.it/en/publications/9788869385438

UNIVERSITÀ DEGLI STUDI DI PADOVA

UIE - International Union for Electricity Applications
SIG-E&R Education and Research
AMPERE - Association for Microwave Power in Europe
for Research and Education
A.E.I.T. - Sezione Veneta

International Conference on Heating by Electromagnetic Sources

Induction, Dielectric and Microwaves, Conduction & Electromagnetic Processing

Padua, 15 - 18 September 2026

Auditorium, Centro Culturale Altinate San Gaetano - via Altinate 71, Padua

Organized by
LEP - Laboratory for Electroheat - Padua
Department of Industrial Engineering
University of Padua (Italy)

Conference Chair: Fabrizio Dughiero

Book of Abstracts

Edited by Michele Forzan and Paolo Di Barba

The organisers gratefully acknowledge the sponsorship and financial support received from the following Institutions and Organisations:

SPONSORS

Università degli Studi di Padova
Department of Industrial Engineering - Padova University
UIE - International Union for Electricity Applications
AMPERE - Association for Microwave Power in Europe
A.E.I.T. - Sezione Veneta

CONTRIBUTORS

ATE Applicazioni Termo Elettroniche S.r.l. - Brendola (VI), Italy
FLUXTROL Inc. - Auburn Hills (MI), USA
INOVA LAB - Padova, Italy
UNOX S.p.A. - Cadoneghe (PD), Italy

SCIENTIFIC COMMITTEE

F. Dughiero - Chairman of the Conference
E. Baake - Hannover University, Germany - S.C. Chairman
M. Forzan - University of Padova, Italy - S.C. Chairman
K. Van Reusel - Katholieke Universiteit Leuven, Belgium - S.C. Chairman
J. Barglik - Silesian University of Technology, Poland
F. Bay - Mines ParisTech, France
P. Bocher - ETS, Canada
V. Bojarevics - University of Greenwich, United Kingdom
A. Datta - Cornell University, USA
P. Di Barba - University of Pavia, Italy
S. Eckert - Helmholtz-Zentrum Dresden-Rossendorf, Germany
A. Jakovics - University of Latvia, Latvia
V. Kotlan - University of West Bohemia, Czech Republic
C. Leonelli - University of Modena and Reggio Emilia, Italy
O. Lucia - University of Zaragoza, Spain
G. Marconi - Danieli S.p.A., Italy
F. Marquis - GH, Spain
Z. Ren - Shanghai University, China
R. Ruffini - Fluxtrol Inc., Auburn Hills, Michigan, USA
A. Smalcerz - Silesian University of Technology, Poland
P. Veronesi - University of Modena and Reggio Emilia, Italy
E. Wang - Northeastern University, China
X. Luo - ICARE Institute, HUST University Wuhan, China

CONFERENCE PROGRAMME

The Conference runs as a single track, with no parallel sessions. Each oral contribution is allotted 15 minutes: 12 for the presentation and 3 for discussion. The author shown in **bold** gives the presentation.

In this book the abstracts follow the order of the programme below. The number in square brackets is the contribution number and identifies the abstract throughout the volume.

Programme as of 31 August 2026. The final programme is distributed at registration and published on the Conference website.

Time schedule

September 15	September 16	September 17	September 18
	08.30 - 09.15 **Late registration**		
		09.00 - 10.15 **Session S4** **Electrified Reactors & Power Supplies**	*09.00 - 10.30* **Session S7** **Microwave & RF Processing**
	09.15 - 09.30 **Opening Ceremony**		
	09.30 - 10.10 **Keynote Lecture** **DANIELI - Ing. C. Fabbro**		
	10.10 - 10.30 **Discussion**		
		10.15 - 11.00 **Coffee Break**	
	10.30 - 11.00 **Coffee Break - Posters on display**		*10.30 - 11.00* **Coffee Break**
	11.00 - 12.30 **Session S1** **EM Processing, Electrification & Green Steel**	*11.00 - 12.30* **Session S5** **AI & Numerical Modelling**	*11.00 - 12.15* **Session S8** **EM Melting & Metallurgical Processes**
			12.15 - 12.45 **Closing Session & Awards**
	12.30 - 13.30 **Lunch**	*12.30 - 13.30* **Lunch**	
			12.45 - 13.15 **Farewell Lunch - End of the Conference**
	13.30 - 15.15 **Session S2** **Materials Processing & Innovative Products**	*13.30 - 15.00* **PANEL SESSION** **AI & Electrification of Thermal Processes**	
14.00 - 18.00 **PhD School / Summer School (separate programme)**			
		15.00 - 15.45 **Session S6** **Optimization, Measurement & Safety**	
	15.15 - 16.00 **Coffee Break** **Poster Session**		
		15.45 - 16.15 **Coffee Break**	
	16.00 - 17.30 **Session S3** **Induction Heating: Coil Design**		
		16.15 - 17.30 **Session S6 (cont.)** **Optimization, Measurement & Safety**	
17.00 - 19.30 **Registration**			
19.30 - 21.00 **Welcome Reception**		*19.30 - 22.30* **Gala Dinner**	

FIRST DAY

Wednesday 16 September 2026

08.30 - 09.15 - Late registration

09.15 - 09.30 OPENING CEREMONY

Institutional addresses and opening of the Conference

09.30 - 10.10 INVITED KEYNOTE LECTURE

"Green Steel: Sustainability Challenges of the Ecological Transition and Danieli's Innovative Technologies for the Decarbonisation of the Steel Industry"

Ing. Claudio Fabbro - Executive Vice President R&D, DANIELI & C. Officine Meccaniche S.p.A.

10.10 - 10.30 - Discussion

10.30 - 11.00 - Coffee Break - Posters on display

11.00 - 12.30 SESSION S1 Electromagnetic Processing, Electrification and Green Steel

11.00 - 11.15 [27] Mamdouh Omran, Hao Yao and Timo Fabritius
Microwave processing steel making side streams
Univ. of Oulu (FI)

11.15 - 11.30 [23] Sven Eckert
Electrification of high-temperature industrial processes: the European CITADEL project
HZDR (DE)

11.30 - 11.45 [9] Martins Sarma, Lars Skaarup Jensen and Sven Eckert
Calcination of Limestone via Induction Heating
HZDR (DE)

11.45 - 12.00 [21] Michael Dumont, Ahmed Essyed, Van-Hieu Ngo, Jean Mario Nhut, Cuong Pham-Huu and Arnaud Brazier
Electrification of Chemical processes: methane pyrolysis via induction heating for H2 production
EMDPI (FR)

12.00 - 12.15 [43] Igor Niedzwiecki and **Egbert Baake**
Sustainable electrification of fossil fueled thermoprocessing applications
Leibniz Univ. Hannover (DE)

12.15 - 12.30 [2] Thorsten Ott
Ceramic Induction Air Heater Based on Cellular Structures for High-Temperature Process Heat
DLR (DE)

12.30 - 13.30 - Lunch

13.30 - 15.15 SESSION S2 Materials Processing and Innovative Products

13.30 - 13.45 [3] Jan Hrbek
Indirect Induction Heating for Tungsten Detritiation
Research Centre Rez (CZ)

13.45 - 14.00 [4] Jan Hrbek, David Rot, **Adrian Villalba Weinberg**, Dmitrii Komissarenko and Andreas Börger
Electrical conductivity of white fused alumina in the liquid state
Imerys Villach (AT)

14.00 - 14.15 [5] Dmitrii Komissarenko, Adrian Villaba Weinberg, Jasmin Koller, Veronika Müller, Bruno Korner and Andreas Börger
Scandia-stabilized Zirconia for electrochemical cells: Synthesis in Cold Crucible
Imerys Villach (AT)

14.15 - 14.30 [24] Baseer Ahmed, Vaclav Kotlan and Poznyak I. V.

Estimation of the Electrical Resistivity of Gadolinium Oxide inside the Cold Crucible using the Inverse Problem Technique via ANSYS
Univ. West Bohemia, Pilsen (CZ)

14.30 - 14.45 [34] Karel Slobodník and Václav Kotlan
3D Printed Metal-Doped Ceramics for Induction Heating Susceptors
Univ. West Bohemia, Pilsen (CZ)

14.45 - 15.00 [8] Zhi Yi, Alexander Köppen and Baake Egbert
Reliable High-Temperature Electrical Contacting for Structurally Integrated Thermally Sprayed Heating Elements
Leibniz Univ. Hannover (DE)

15.00 - 15.15 [63] G. Gardan[1], **G. Poggiana[1]**, F. Lucchini[1], M. Forzan[1], F. Dughiero[1], and R. Torchio[1,2]
Electrothermal Processes for Rare Earth Element Recycling from Energy-Transition E-Waste: A Review
Univ. Padova (IT)

15.15 - 16.00 COFFEE BREAK & POSTER SESSION *(listed at the end)*

16.00 - 17.30 SESSION S3 Induction Heating: Coil Design and Applications

16.00 - 16.15 [42] Krzysztof Konopka and Jerzy Barglik
Induction Surface Hardening of Steel Workpieces Examples of Applications
Silesian Univ. of Technology (PL)

16.15 - 16.30 [15] Dmitry Ivanov, John Inge Asperheim, Bjørnar Grande and Prerana Das
Numerical Investigation of AISI304 Steel Induction Tube Welding
ENRX (NO)

16.30 - 16.45 [FLX] R. Goldstein
Changing Goal Functions for Induction Heat Treating Coil Design
Fluxtrol Inc. (US) - invited review

16.45 - 17.00 [30] Philippe Bocher, Luc Amar, Tom Jaulin, Raynald Guilbault and Louis Berger
Design Considerations and Challenges for Optimizing Rolling Fatigue Performance in Induction-Hardened Components
ETS University of Quebec (CA)

17.00 - 17.15 [25] Johannes Lohn
Additively Manufactured Copper Inductors for Induction Heating Applications
J. Lohn (DE)

17.15 - 17.30 [28] Andrea Trovo, Maria Evelina Mognaschi, Fabrizio Dughiero and Paolo Di Barba
Welding techniques for Flow Battery stack manufacturing: a comparative analysis
Univ. Padova / Univ. Pavia (IT)

SECOND DAY

Thursday 17 September 2026

09.00 - 10.15 SESSION S4 Electrified Reactors, Power Supplies and Equipment

09.00 - 09.15 [62] Marius Weiser, Siegfried Bajohr and Frederik Scheiff
Ohmic Heated Catalytic Reactor Structures: Design and Operational Stability Analysis
KIT (DE)

09.15 - 09.30 [14] Alejandro Pazvantov, Hector Sarnago and Oscar Lucia
Multi-Load Power Electronic Converter for Induction Heating Domestic Applications
Univ. Zaragoza (ES)

09.30 - 09.45 [13] Maxwell Rodriguez, Hector Sarnago, Jesus Acero and Oscar Lucia
Advanced electronic control architecture for electronic power converters applied to induction heating
Univ. Zaragoza (ES)

09.45 - 10.00 [59] Tianfeng Liu and Xiaobing Luo
An ultra-thin plate-level micropump for liquid cooling systems
Huazhong UST (CN)

10.00 - 10.15 [66] A. Doni, M. Lazzarin, N. Sinigaglia and M. Zerbetto
Thermographic Risk Assessment and Electromagnetic Optimization of an Induction Sealing Process
INOVA LAB (IT)

10.15 - 11.00 - Coffee Break

11.00 - 12.30 SESSION S5 Artificial Intelligence and Numerical Modelling for Electroheat

11.00 - 11.15 [1] Antons Cvečkovskis
Physics-Informed Graph Neural Network for Fast Thermal Prediction in Induction Heating
CENOS (LV)

11.15 - 11.30 [7] Jesús Acero, Óscar Laherta, Denis Navarro, **Claudio Carretero**, Ignacio Lope and José-Miguel Burdío
Electromagnetic Property Identification of Domestic Induction Heating Loads using Neural Networks
Univ. Zaragoza (ES)

11.30 - 11.45 [37] Yuki Shimizu, Arata Takahashi, **Kengo Sugahara** and Keiko Sugahara
AI Agent-Based Automatic Mesh Generation for Induction Heating Simulation with Automatic Boundary Layer Control
Kindai Univ. (JP)

11.45 - 12.00 [41] Jakub Wyciślik and Sławomir Golak
Comparison of methods based on surrogate models on the example of induction heating process optimization
Silesian Univ. of Technology (PL)

12.00 - 12.15 [64] M. Zorzetto[1], R. Torchio[1,2] , F. Lucchini[1], M. Forzan[1], and F. Dughiero[1]
Discrepancy Correction in Surrogate Models for Nonlinear Thermal Problems
Univ. Padova (IT)

12.15 - 12.30 [46] Andrii Chepurnyi and **Andris Jakovičs**
Acceleration of numerical modeling of methane combustion using a plasma-chemical element in a gas turbine
Univ. of Latvia (LV)

12.30 - 13.30 - Lunch

13.30 - 15.00 PANEL SESSION AI and Electrification of Thermal Processes

Introduction by the moderator, sixty minutes of moderated discussion among the panellists and twenty-five minutes of questions from the floor. Topics: the role of AI in the control and optimisation of electrothermal processes; digital twins and surrogate models; high-temperature electrification and green steel; industrial barriers to adoption. The panellists will be announced in the final programme.

15.00 - 15.45 <u>SESSION S6</u> **Optimization, Measurement and Safety**

15.00 - 15.15 [19] Borja Lopez-Alonso, Jesus Acero, Eric Agudo, Enrrique Gómez-Barrena, Héctor Sarnago and Oscar Lucía
Optimization of an Induction Heating Applicator for Implanted Prosthesis Disinfection
Univ. Zaragoza (ES)

15.15 - 15.30 [67] F. Dughiero, **F. Lucchini**, P. Di Barba, N. Sinigaglia and M. Lazzarin
ARTE: Contactless Temperature Estimation and Energy-Aware Power Optimization for Domestic Induction Hobs
Univ. Padova / Univ. Pavia (IT) - in collaboration with INOVA LAB

15.30 - 15.45 [40] Claudio Carretero, Oscar Lahuerta, Ignacio Lope and Jesus Acero
Self-Heating-Induced Offset Drift in NTC Thermistor for Domestic Induction Heating Systems
Univ. Zaragoza (ES)

15.45 - 16.15 - Coffee Break

16.15 - 17.30 <u>SESSION S6 (continued)</u> **Optimization, Measurement and Safety**

16.15 - 16.30 [22] Adrian Smagór, Paweł Gradoń, Grzegorz Moskal and Agnieszka Tomaszewska
The influence of heating power on the sinters microstructure of new cobalt superalloys from the Co-Al-W and Co-Ni-Al-W systems
Silesian Univ. of Technology (PL)

16.30 - 16.45 [11] Thomas Wondrak, **Max Sieger**, Lukas Krause and Sven Eckert
Current tomography for electroheat process monitoring
HZDR (DE)

16.45 - 17.00 [12] Thomas Wondrak, Max Sieger, Lukas Krause and Sven Eckert
Innovative industrial process monitoring by inductive measurements
HZDR (DE)

17.00 - 17.15 [48] Albert Smalcerz, Roman Przylucki and Jerzy Barglik
Some Aspects of Temperature Measurements in Induction Heating Systems
Silesian Univ. of Technology (PL)

17.15 - 17.30 [20] Koen Van Reusel
Safety Assessment According to the European Legislation and IEC Standards Regarding the Industrial Use of Microwave Technology
Laborelec / KU Leuven (BE)

19.30 - 22.30 - Gala Dinner

THIRD DAY

Friday 18 September 2026

09.00 - 10.30 SESSION S7 Microwave and RF Processing

09.00 - 09.15 [17] **Muralimohan Juttu Vidyasagar**, Ralph Behrend, Hartmut Krause, Mareen Zöllner, Thomas Krampitz and Holger Lieberwirth
Microwave Assisted Recycling of CFRP Composites in a Continuously Operated Conveyor Belt Furnace - Process Parameters and Results
TU Freiberg (DE)

09.15 - 09.30 [47] **Matteo Pola**, Irene Mellone and Matteo Albani
Scaling up Microwave-Assisted Pyrolysis for Plastic Valorization: Design and Ongoing Challenges
Univ. of Siena (IT)

09.30 - 09.45 [36] **Ruth De Los Reyes**, Vicente Sanz, Eduard Palomares and Elias De Los Reyes
Laboratory-Scale adaptation of microwave air heating technology for very low gas flow rates
UPV Valencia (ES)

09.45 - 10.00 [44] Elena Colombini, Magdalena Lassinantti Gualtieri, Isabella Lancellotti, Cristina Leonelli and Paolo Veronesi
Predictive models for copper slag based microwave susceptors
Univ. Modena e Reggio Emilia (IT)

10.00 - 10.15 [45] Paolo Veronesi, Elena Colombini and Cristina Leonelli
Microwave and induction heating of green carbon anodes for aluminium production
Univ. Modena e Reggio Emilia (IT)

10.15 - 10.30 [49] Carmen Alfaro, Ismael Viejo, Javier Sagües, Alberto Pascual, Joaquin Javier Perez Aparicio, Begoña García, Ivan Echeverria, Jose Ignacio Tolosa, Ainhoa Bilbao, Paolo Veronesi, Elena Colombini, Marcel Mallah, Panagiotis Davris, Efthymios Balomenos and Marria Herrando
Microwave-Driven Electrification Strategies for High-Temperature Industrial Processes in Ceramic, Asphalt, and Aluminium Production
CIRCE + consortium (ES)

10.30 - 11.00 - Coffee Break

11.00 - 12.15 SESSION S8 Electromagnetic Melting, Metallurgical Processes and Modelling

11.00 - 11.15 [52] Maksimilians Pīrs, Aleksandrs Jegorovs, **Andris Jakovics** and Mihails Birjukovs
Simultaneous 2D Phase & Velocity Field Measurements for Hele-Shaw Bubble Flow in Liquid Metal
Univ. of Latvia (LV)

11.15 - 11.30 [53] Ansis Emīls Zīvers, Ansis Ziemelis, Kristofers Rolands Kangīzers, Pēteris Zvejnieks and **Mihails Birjukovs**
Shape & Collective Dynamics in Geometrically Confined MHD Bubble Flow
Univ. of Latvia (LV)

11.30 - 11.45 [31] **Vaclav Kotlan**, Iveta Petrasova, Radek Holota and Vjaceslav Georgiev
Numerical Shape Optimization for Uniform Direct Electrical Heating of Test Samples
Univ. West Bohemia, Pilsen (CZ)

11.45 - 12.00 [54] Ansis Emīls Zīvers, Kristofers Rolands Kangīzers and **Mihails Birjukovs**
2WCF-SVD: 2-way consistent Farneback with SVD-based artifact filtering for multiphase optical flow velocimetry
Univ. of Latvia (LV)

12.00 - 12.15 [6] Mirco Fuchs and Egbert Baake

Identification of anisotropic material properties and heat losses in soft magnetic composites
Leibniz Univ. Hannover (DE) - presented by K. Dadzis

12.45 - 13.15 - Farewell Lunch - End of the Conference

POSTER SESSION

Wednesday 16 September, 15.15 - 16.00

[16] Pablo Burgos, Héctor Sarnago and Oscar Lucia
Load detection strategy in new non-resonant inverters applied to domestic induction heating applications
Univ. Zaragoza (ES)

[32] Pablo Guillen, Héctor Sarnago, Jose M. Burdio and Oscar Lucia
A Coupled Inductors Non-Resonant Inverter Topology for Domestic Induction Heating
Univ. Zaragoza (ES)

[29] Ignacio Alvarez-Gariburo, Héctor Sarnago, Gabriel Costa, Fausto Rene Viteri, Tomás García-Martínez, Ramón Murillo Murillo and Óscar Lucía
Design and Implementation of a Power Electronic Generator for Induction-Heated Electrified Biomass Pyrolisis Reactors
Univ. Zaragoza (ES)

[10] Oscar Lahuerta Sediles, Claudio Carretero Chamarro, Denis Navarro Tabernero and Jesus Acero Acero
Physics-Informed Neural Networks for characterizing thermistors immersed in a magnetic field
Univ. Zaragoza (ES)

[18] Borja Lopez-Alonso, Ismael Perisé-Badía, Nicolás Dulanto, Héctor Sarnago, Óscar Lucía and Ignacio Ochoa
Electrical Characterization System for 3D Tumor Spheroid Models in In Vitro Electroporation Studies
Univ. Zaragoza (ES)

[35] Tim Irlweck, Claudius Stockinger and Ulrich Nieken
Inductive Heating of Chemical Reactors: Experimental and Numerical Investigations
Univ. Stuttgart (DE)

[57] Victor Demidovich, Yuriy Perevalov and Fedor Chmilenko
Digital Twins of Induction Heaters in the Metallurgical Industry

[58] Robert Goldstein
Understanding What's Not on the Screen When Modeling Electromagnetic Processing
Fluxtrol Inc. (US)

[60] Guoqing Sun and Xiaobing Luo
A High-performance miniature synthetic jet pump for cooling applications
Huazhong UST (CN)

[65] M. Bullo, C. De Massari and C. Santoloce
RF Heating for an Energy Storage System Developed in the Horizon Europe Project HYSTORE
INOVA LAB (IT)

CONTENTS

The contributions are listed in the order of the Conference programme.

Session S7 - Microwave and RF Processing

Session S8 - Electromagnetic Melting, Metallurgical Processes and Modelling

Poster Session

Microwave processing steel making side streams

A. Omran[1], H. Yao[1], W. Danuka[1], T. Fabritius[1]

Oulun Yliopisto, Process Metallurgy Research Group, Oulu, Finland

Corresponding author: M. Omran (mamdouh.omran@oulu.fi)

ABSTRACT.

Steel and metals industries generate large streams of by-products wastes annually. These wastes are considered to be hazardous material in many European countries due to their high contents of leachable heavy metals. Environmental regulations force the metal industry to take major steps towards efficient recycling of by-products wastes and prohibiting the wastes landfilling.
In this work, we propose a method, based on microwave heating, for recycling steelmaking wastes. This will lead to increase electrification of metallurgical processes and reduce greenhouse gas according to EU Green Deal vision. In this study, microwave energy was applied for the recovery valuable metals from different fine solid materials generated from iron and steelmaking industries, including electric arc furnace (EAF) dust, CRC dust and basic oxygen furnace (BOF) slag and Sludge.
The results indicated that microwave energy improves the selective recovery of zinc from EAF dust and enhance the reduction rate of zinc oxide and ferrite. Furthermore, it is observed, that the microwave pre-treatment improves the liberation and grindability of BOF slag, increase magnetic susceptibility and enhancing magnetic separation efficiency.

***Keywords*—** Microwave energy, Steelmaking side stream, dielectric properties.

INTRODUCTION

The steel industry is critical to the worldwide economy, providing the backbone for construction, transportation, and manufacturing. There are different types of by-products generated from steel industries [1, 2]. These wastes are considered to be hazardous material in many European countries due to their high contents of leachable heavy metals [3]. It is estimated that steelmaking industries in Europe generate about 80 million tonnes of by-products per year [4]. European environmental regulations are now forcing the metal industry to take major steps towards efficient recycling of by-products and prohibiting landfilling of steel waste. However, more and more waste continues to be generated, and a large amount of valuable metals in these waste resources cannot be selectively recycled because of the high recovery costs.
This work aims to improve recycling of steelmaking wastes and overcome the disadvantages of traditional recycling methods by developing a new technique based on microwaves. Thus, the project aims to increase electrification of metallurgical processes and reduce greenhouse gas emissions according to EU Green Deal vision.

REFERENCES

[1] M. Omran, T. Fabritius (2017) Powder Techn., 308: 47–60.
[2] Z. Huaiwei, H. Xin (2011) Resour. Conserv. Recycl. 55: 745-754.
[3] B. Das, S. Prakash, P.S.R. Reddy, V.N. Misra (2007) Resour. Conserv. Recycl. 50: 40-57.
[4] Environmental Protection Agency (2002) European Waste Catalogue and Hazardous Waste List

Electrification of high-temperature industrial processes: the European CITADEL project

S. Eckert[1], et al.

[1] Helmholtz-Zentrum Dresden – Rossendorf, Bautzner Landstraße 400, 01328 Dresden, Germany
Corresponding author: S. Eckert (s.eckert@hzdr.de)

ABSTRACT. The Horizon Europe project CITADEL develops and demonstrates advanced electrical heating technologies to substitute fossil combustion in energy-intensive industrial high-temperature processes. Five industrial demo cases—refractory firebrick production, glass melting, steel ladle and tundish preheating, concrete waste recycling, and copper wire annealing—are investigated. The project combines electromagnetic and resistive heating concepts with multiphysics modelling, grid-aware control strategies, and techno-economic assessment. This overview highlights the applied heating technologies, modelling approaches, and first insights into dynamic process control under volatile electricity market conditions.

Keywords— Industrial electrification, electromagnetic heating, multiphysics modelling, process control, demand response.

INTRODUCTION

Industrial high-temperature processes (800–1600 °C) are predominantly driven by natural gas combustion. Electrification offers a direct pathway to deep decarbonisation but fundamentally alters heat transfer characteristics, reactor dynamics, and process controllability.

Unlike combustion-based systems, electrical heating methods—such as resistance heating, plasma heating, microwave or induction-based approaches—enable localized and potentially volumetric energy deposition. However, they introduce new challenges regarding temperature uniformity, refractory stresses, electromagnetic–thermal coupling, and economic exposure to electricity price volatility. CITADEL addresses these challenges through coordinated demonstration and modelling activities across five industrial sectors.

PROBLEM DESCRIPTION

Industrial high-temperature processes typically operate in the megawatt range and rely on combustion-based heating. Electrification introduces three major challenges: (i) Changed heat transfer physics (radiative combustion vs. Joule, plasma, induction or resistance heating), (ii) Economic exposure to volatile electricity markets, and (iii) Grid stability and flexibility requirements. Experimental validation at industrial scale is costly and risky. Therefore, CITADEL combines pilot and industrial demonstrations with advanced modelling tools to reduce technical and financial uncertainty

ELECTRIFICATION OF FIVE INDUSTRIAL DEMO CASES

Refractory Firebrick Production: Conventional tunnel kilns are partially substituted by microwave plasma burners. Plasma heating provides high power density and rapid temperature ramping. Numerical heat transfer simulations support optimisation of hybrid burner configurations to ensure thermal homogeneity and controlled substitution of natural gas.

Glass Production: A hybrid end-port regenerative furnace equipped with electrodes is analysed. First-principles (FP) models and CFD simulations evaluate electro-boosting strategies and transient furnace dynamics. The models allow investigation of thermal load shifts and their impact on glass quality and furnace stability

Steel Making – Ladle and Tundish Preheating: Gas-fired preheating of ladles and tundishes is replaced by oxy-fuel and resistance-based electric heating concepts. Numerical simulations (COMSOL, ANSYS Fluent) assess temperature uniformity, refractory stress, and heating efficiency. Radiation-dominated and combustion-based approaches are compared to quantify emission reduction potential.

Concrete Waste Recycling: Electrified heating air separator (eHAS) concepts are investigated for high-temperature thermal cracking of cement-rich fractions. Particle-scale thermal models are developed to predict heat penetration and reaction kinetics in heterogeneous granular materials.

Copper Wire Production: A gas-fired batch annealing process is replaced by continuous DC plasma annealing. Power demand modelling enables integration into flexibility markets and adaptive process control.

MULTIPHYSICS MODELLING AND DIGITAL PROCESS TWINS

A central technical pillar of CITADEL is the development of physics-based modelling tools for electrified processes The modelling framework includes: Finite Volume and Finite Element CFD simulations, reactor-network first-principles models, radiative heat transfer modelling in participating media, coupled electromagnetic–thermal simulations, transient energy balance and emission modelling.

These models serve as digital twins to: predict process response to electric heating, analyse thermal load shifts, evaluate residence time distributions, support advanced control design. Model reduction techniques are applied to bridge the gap between high-fidelity simulation and real-time control implementation.

GRID-AWARE OPERATION AND ADVANCED CONTROL

Electrification increases sensitivity to electricity price volatility and grid stability constraints. CITADEL therefore integrates: flexibility metrics, market-coupled energy procurement models, demand Response participation strategies, model-based Predictive Control (MPC) and PID-based approaches.

Dynamic boosting experiments in the glass furnace demonstrate the impact of short-term power modulation on temperature stability and residence time distribution. By coupling process models with electricity market models, techno-economic feasibility of load shifting is quantified under day-ahead and intraday price volatility

CONCLUSIONS

CITADEL demonstrates that large-scale electrification of high-temperature processes requires:

- Adaptation of heating technology to process physics,
- Multiphysics modelling to reduce scale-up risk,
- Grid-aware control strategies to ensure economic viability.

The project establishes a technically validated and transferable framework for replacing fossil combustion by advanced electrical heating in heavy industry. The integration of electromagnetic heating technologies with digital twins and flexibility-driven control represents a key enabling pathway toward climate-neutral industrial heat.

Calcination of Limestone via Induction Heating

M. Sarma[1], L.S. Jensen[2], and S. Eckert[1]

[1] Helmholtz-Zentrum Dresden – Rossendorf, Bautzner Landstraße 400, Dresden, Germany
[2] Fuller Technologies, Valby, Copenhagen, Denmark
Corresponding author: M.Sarma (m.sarma@hzdr.de)

ABSTRACT. This work investigates the feasibility of calcining limestone using induction heating as a pathway toward combustion-free cement production. Metallic susceptors are employed to transfer electromagnetic energy to non-conductive $CaCO_3$, enabling temperatures above 1000 °C. Initial experiments confirm CO_2 release but reveal strong thermal gradients and limited conversion under static conditions, highlighting the need for feedstock mobility to achieve efficient volumetric heating.

Keywords — Inductive decarbonization, thermo-electromagnetic coupling, electrified calcination.

INTRODUCTION

Adopting induction heating provides a robust solution for reducing carbon emissions in hard-to-abate industries. Although its effectiveness in large-scale processing is well-established, applying it to non-conductive materials requires advanced electromagnetic-thermal coupling strategies to ensure efficient energy transfer to the feedstock.

Cement production, specifically the calcination of limestone ($CaCO_3 \rightarrow CaO + CO_2$), is a primary candidate for industrial electrification [1]. Traditionally, the endothermic reaction, which typically occurs at around 900–1000 °C, has been driven by directly combusting fossil fuels. Our research investigates the feasibility of decarbonizing this process by using induction heating, with conversion of electromagnetic energy into heat and subsequent transfer to the *meal* (homogeneous blend of raw materials used as the kiln feed) via metallic susceptors.

PROBLEM DESCRIPTION

To drive the calcination of the non-conductive limestone, we have developed a versatile experimental model system that can incorporate various types of susceptors. Figure 1a shows a schematic illustration of the experimental assembly. A coaxial susceptor made of molybdenum, steel or iron, attached to one of the supporting plates, allows a controlled thermal gradient to be established. Another configuration uses multiple discrete iron or steel spheres dispersed throughout the medium to maximize the interfacial surface area for heat transfer (example of different susceptors presented in Figure 1b).

RESULTS

Figure 1c presents the CO_2 evolution (experiment conducted in Ar environment) during the induction-heated calcination of a 4.3 g $CaCO_3$ sample using steel coaxial susceptor. The core temperature of it was kept at 1050 °C throughout the duration of the experiment. While experimental results verify the occurrence of thermal decomposition, LOI testing revealed a conservative conversion rate of 8%. The reaction effectively terminates at 4000 seconds. The extended 'tail' observed in the concentration profile most likely represents a limited diffusion of the produced CO_2 towards the detector (Wi.Tec INFRA.sens AK5), rather than a continuation of the calcination reaction.

The modest conversion efficiency stems from the low thermal conductivity of limestone, which establishes a sharp temperature drop-off away from the central susceptor. In contrast, while dispersed susceptors provide a larger heating surface, the skin effect inherent in induction processing limits energy absorption to the outer boundary of the susceptor grid, hindering uniform volumetric heating of the sample.

Based on these results, it is clear that feedstock mobility is a prerequisite for efficient, high-volume calcination. Our investigation moves forward with optimizing the interaction between moving particles and the induction-heated susceptors by utilizing three different approaches to facilitate continuous particle flow – fluidizing the limestone, creating a particulate-gas flow and constructing a rotary calciner setup.

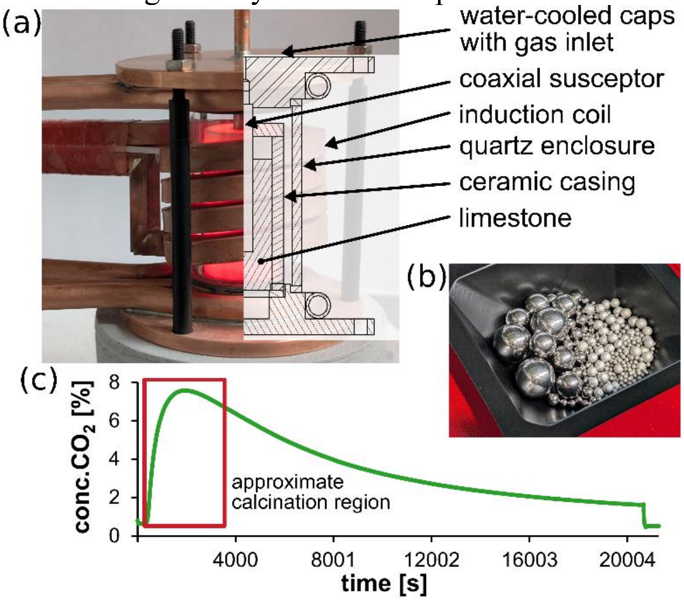


Figure 1: (a) Experimental setup of induction heating, (b) different sized susceptors in form of steel/iron spheres, (c) calcination curve.

CONCLUSIONS

Preliminary calcination trials utilizing induction heating demonstrate a viable pathway for industrial decarbonization. Although initial experiments yield a low conversion rate, this is not disqualifying; they primarily highlight the limitations of static batch processing in media with poor thermal conductivity. In contrast, industrial-scale kilns utilize continuous flow of the meal, while significant improvements can further be achieved with a fluidized system [2]. Employing a dynamic processing environment in the model experiments will likely yield a significant conversion rate improvement.

Acknowledgements

The ECem project receives funding from the Innovation Fund Denmark under grant agreement No. 3148-00027B.

REFERENCES

1. Varnier L, d'Amore F, Clausen K, Melitos G, De Groot B, Bezzo F. Combined electrification and carbon capture for low-carbon cement: Techno-economic assessment of different designs. J Clean Prod. 2025;498:145029.

2. Mirzaei M, Pedersen M, Jensen LS, Varunkumar S, Wu H. An experimental and CFD investigation of pulsed fluidization of cohesive particles. Chem Eng Sci. 2026; 321:122976.

Electrification of Chemical processes: methane pyrolysis via induction heating for H_2 production

M. Dumont[1], A. Essyed[2], V-H. Ngo[2], J.-M. Nhut[2], C. Pham-Huu[2], A. Brazier[3]

[1] EMDPI, Jam Consulting, Grenoble, France.
[2] ICPEES, UMR 7515 CNRS-University of Strasbourg, Strasbourg, France.
[3] TotalEnergies, One Tech R&D, Pau, France.
Corresponding authors: M. Dumont (michael.dumont@emdpisolutions.com)
C. Pham-Huu (cuong.pham-huu@unistra.fr)

ABSTRACT. Catalytic methane decomposition (CMD) under direct induction heating (IH) provides a CO_2-free route to turquoise hydrogen. Methane is pyrolyzed over a porous carbon catalyst ($C_{po\text{-}s}$), yielding H_2 and solid carbon (Cs). Acting simultaneously as susceptor and catalyst, $C_{po\text{-}s}$ enables operation at 600–900 °C with improved energy efficiency. This work assesses the energy performance of a lab-scale CMD reactor to quantify the influence of $C_{po\text{-}s}$ properties and operating conditions and to guide process optimization and scale-up. Efficient heating (up to 70% of electrical efficiency at 300 Hz) is achieved through rapid formation of a conductive Cs network enabling a global induced current loop. A simplified homogenized model supports optimization and facilitates scale-up design.

***Keywords*—**Catalytic methane decomposition, turquoise hydrogen, induction heating.

INTRODUCTION

In the framework of the European Green Deal with net-zero GHG objectives by 2050, interest in electrifying the chemical industry has grown significantly, particularly in catalytic processes by using induction heating for H_2 production, hydrogenation reactions, plastic conversion, and CO_2 methanation [1]. Hydrogen can be produced through several pathways, commonly classified by colour - from grey to green - depending on the production method and associated emissions: Steam Methane Reforming (SMR), dry reforming of methane, methane partial oxidation, methane pyrolysis (CMD) and water electrolysis. Thus, CMD is especially attractive because it avoids the costly CO_2 capture and storage steps required for SMR (which emits approximately 9 kg of CO_2 per kg of H_2 produced) and it requires roughly seven times less energy than water electrolysis. During the endothermic dissociation of methane, only solid carbon and hydrogen is formed: $CH_{4(g)} \rightarrow C_{(s)+}\ 2H_{2\ (g)}$ (ΔH =37.5 kJ/mol H_2).

In catalysis, induction heating (IH) directly heats the catalyst bed, enabling rapid, precise temperature control while limiting gas-phase heating and suppressing secondary reactions. Integrating IH with carbon-based catalysts offers an efficient and sustainable approach to enhance catalytic performance.

PROBLEM DESCRIPTION

Beyond the chemical and catalytic considerations [2], the efficiency of the CMD process is assessed experimentally and extrapolated to larger scales. The induction system consists of a coil placed around the quartz reactor, positioned in front of the $C_{po\text{-}s}$ substrate, insulated with thermal felt, and connected to a power supply operating at 300 kHz. The coil current is regulated to maintain a setpoint temperature around 800°C. From the experimental data, the time evolution of the induction efficiency (ratio of Joule power dissipated in the $C_{po\text{-}s}$ to the total electrical power supplied) and the global efficiency (ratio of the power required by the reaction to the total power) is extracted and compared with modelling results (Table 1). A simplified 2D axisymmetric model is developed to reflect the experimental configuration (Figure 1b), incorporating electromagnetic and thermal descriptions while omitting detailed chemical and kinetic aspects. The $C_{po\text{-}s}$ substrate is assumed to be electrically connected and is represented using a homogenized approach: the C-bed is treated as an equivalent dense medium with apparent thermal and electrical conductivity determined by correlating parametric electromagnetic simulations with experimental process data and electrical measurements.

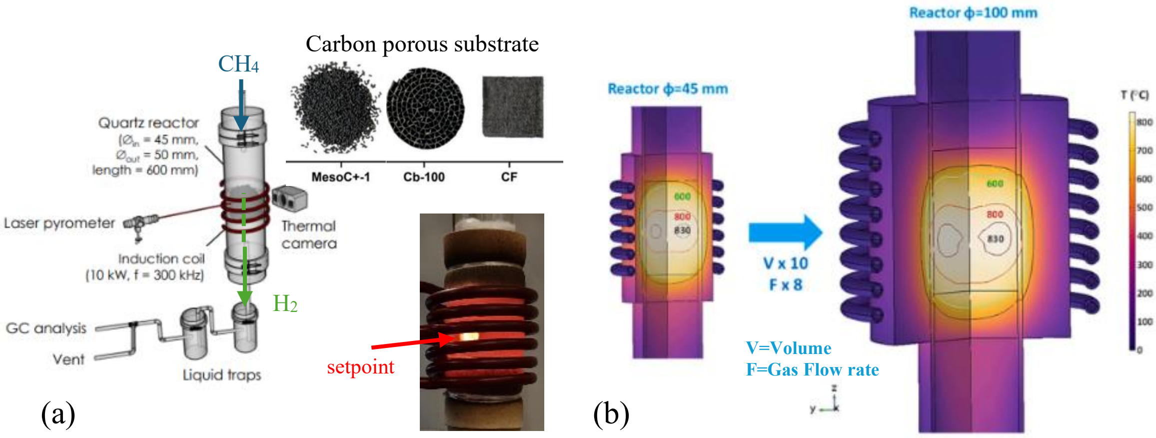


Figure 1. Methane pyrolysis by induction heating. (a) Experimental setup with insulated reactors and porous carbon catalyst, (b) EM+Thermal modelling at 800°C and upscaling

Table 1: Comparison between optimized lab-scale and R&D reactor at the final stationary state T=800°C via modelling approach

Reactor diameter (mm)	frequency [kHz]	Power [W]	Induction efficiency [%]	Global efficiency [%]	Energy consumption (kWh/kg H_2)	H_2 productivity (g H_2/h)
45	300	201	81	3.8	137	1.5
100	145	432	87	14.2	37	11.8

CONCLUSIONS

Induction-heated methane pyrolysis achieves high electrical efficiency (>70%) when reactor geometry, operating frequency, and $C_{po\text{-}s}$ substrate properties are optimized. The process generates a highly ordered pyrolytic carbon layer that enhances induction heating and temperature uniformity by increasing electrical and thermal conductivity, without catalyst deactivation. For an upscaled R&D reactor (Ø100 mm), global efficiency is expected to quadruple, with an energy demand of ~40 kWh kg^{-1} H_2. With IH, the reactor is easily scalable to Ø300 mm by sizing frequency and lower energy consumption is expected ~15 kWh kg^{-1} H_2 due to lower relative heat losses. Additional studies are required to determine the optimal reactor length and assess thermal-gradient effects within the C-bed.

REFERENCES

1. Truong-Phuoc L., Duong-Viet C., Nhut J.M., Pappa A., Zafeiratos S., Pham-Huu C., Induction heating for the electrification of catalytic processes, ChemSusChem. 2024 Dec 23.
2. Ngo V.-H., Essyed A., Romero T., Nhut J.-M., Dumont M., Grishin A., Bétremieux I., Brazier A., Zafeiratos S., Pham-Huu C., Breaking methane without metals: induction- heated carbon catalyst at low temperature process, Carbon Energy.2025 (submitted).

Sustainable electrification of fossil fueled thermoprocessing applications

I. Niedzwiecki, E. Baake

Corresponding author: I. Niedzwiecki (niedzwiecki@etp.uni-hannover.de)

ABSTRACT.
In Germany, the industrial sector is a major consumer of energy, using nearly one third of the country's net energy supply, with 70% dedicated to generating process heat. Currently, 80 % of the energy used to generate process heat is sourced from fossil fuels, mostly natural gas. This heavy dependency on imported fossil fuel imposes a severe impact on the competitiveness of the energy intensive industry sector, especially during a time of sudden change of legislation or natural gas supply. To achieve a higher resilience towards the change of operational conditions, it is central to develop a strategy for a comprehensive electrification of the process heat generation.

Keywords— electrification, practical example, method development.

INTRODUCTION

Over the past five decades, the abundance and affordability of natural gas, coupled with its ease of use as a heat source, has led to the widespread adoption of natural gas burners across most thermal processes while the use of alternative (electric) heating methods has been widely disregarded. For the past 30 years, relying on natural gas has been economically advantageous, thanks to stable supply conditions [1]. The generation of process heat consumes nearly 70 % of the total primary energy. However, with Germany's lack of domestic natural gas resources, this strategy has resulted in a significant dependency on natural gas imports, while simultaneously limiting the industry's ability to adapt swiftly to sudden changes in operational conditions or fuel supply disruptions. As the result of the dependence, the disruption of the natural gas supply in 2022, starting with the Russian invasion of Ukraine has critically undermined the competitiveness of Germany’s energy-intensive industrial sector, contributing to a recent economic recession [3].

PROBLEM DESCRIPTION

To increase the general resilience of the energy intensive industry sector and to ensure its long-term profitability, these evaluations must provide tailored solutions responsive to varying energy market conditions, resource availability, and changing legislature. Given the varying temperature ranges and process requirements of industrial heating applications, substitution potential must be assessed on a case-by-case basis. As illustrated in Figure 1, electric heating has traditionally occupied a niche. Particularly in high-power applications, the industry now faces a critical challenge, that – since it was not necessary before – no reliable evaluation concepts, or general guidelines for the electrification are available yet. The aim of the paper is the investigation of a universal strategy which includes the development of different electrification concepts for an existing high-power thermoprocessing application, and the estimation and evaluation of operational costs based on varying operational conditions.

When designing new installations, a fully electric solution can usually be implemented. In the thermal processing of metals, the two main technologies are inductive heating and indirect resistance heating with conductive heating as an additional niche technology. When electrifying

an existing application, the installed power or the use of the preferred technology itself can be limited by mounting space. In addition, not only does every process has its own electric, thermal or installation boundaries, but they also tend to change significantly the more invasive the electrification concept is planned. Therefore, in many cases, the primary challenge will be developing technical solutions for the electrification of specific thermal installations.
Typical energy intensive electrothermal installations have a lifetime of around 20-30 years. This way, the operational (energy) costs account for the majority of the overall expenditure. Therefore, in the evaluation of economic viability of a given electrification concept, the conversion cost and the loss of production during the conversion time can be disregarded.
This paper will summarize the general design of substitution methods and conclude into the development of electrification strategies for high temperature thermoprocessing applications taking the economic impact of renewable energy generation on the energy price into account.

REFERENCES

[1] Monatliche Importmenge an Erdgas in Deutschland von Januar 2018 bis März 2025 (in Terajoule) [Graph], BAFA, 20. Mai, 2025. [Online]. Verfügbar: https://de.statista.com/statistik/daten/studie/1341326/umfrage/importmenge-von-erdgas-nach-deutschland/

[2] C. Rohde, S. Arnold-Keifer: "Erstellung von Anwendungsbilanzen für die Jahre 2021 bis 2023 für die Sektoren Industrie und GHD" Frauenhofer ISI, 2022.

[3] Veränderung des realen Bruttoinlandsprodukts (BIP) in Deutschland gegenüber dem Vorjahr von 1971 bis 2024 [Graph], Statistisches Bundesamt, 7. März, 2025. [Online]. Verfügbar: https://de.statista.com/statistik/daten/studie/14537/umfrage/jaehrliches-wachstum-des-bruttoinlandsprodukts-in-deutschland/

[3] H. Pfeifer, B. Nacke, F. Beneke: „Praxishandbuch Thermoprozesstechnik - Band 2: Anlagen, Komponenten,
Sicherheit", 2. Auflage, Vulkan-Verlag, Essen 2011

Ceramic Induction Air Heater Based on Cellular Structures for High-Temperature Process Heat

T. Ott[1]

[1] German Aerospace Center, Institute of Engineering Thermodynamics, Stuttgart, Germany
Corresponding author e-mail: thorsten.ott@dlr.de

ABSTRACT. Decarbonizing industrial high-temperature processes requires renewable electricity-based alternatives, as resistance-based heaters are limited above 900 °C, particularly at industrial scale and in corrosive environments. Inductive air heater concepts with electrically conductive ceramics can achieve higher gas outlet temperatures and power densities, with the potential to supplant natural gas burners. In this work, a novel concept utilizing cellular structures based on TPMS (triply periodic minimal surfaces) is presented. However, a comprehensive understanding of the coupled electromagnetic, thermal, and mechanical phenomena required for the reliable design of this power-to-heat concept is still lacking. This paper focuses on modeling the spatial distribution of the electromagnetic field and the resulting current density, as well as the associated temperature field within TPMS structures. For this purpose, a 3D finite-element model is introduced. This allows the interaction between the electromagnetic fields and the resulting heat generation and distribution to be evaluated with respect to material and geometric parameters. The results form the basis for further model development and the implementation of a multiphysics model.

Keywords— power-to-heat, induction air heater, high-temperature heat, cellular structures.

INTRODUCTION

The decarbonization of industrial high-temperature processes requires alternative technologies capable of supplying high-temperature process heat from renewable electricity. State-of-the-art systems typically rely on resistance-based heaters with metallic heating wires that are convectively exposed to a gaseous heat transfer medium. However, their applicability and operational lifetime are significantly limited at elevated temperatures (> 900 °C), particularly at industrial scale and in corrosive environments. A novel approach involves the inductive heating of electrically conductive ceramic geometries with a high specific surface area that enable direct flow-through of the heat transfer medium. By means of contactless heating and high-temperature-resistant materials, this concept enables high operating temperatures, long service life, and high power densities, thereby offering the potential to replace natural gas burners. Current research work focuses on concepts based on packed beds and honeycomb structures [1].

This work investigates a novel concept utilizing cellular structures based on TPMS (triply periodic minimal surfaces) structures, which are complex three-dimensional geometries that repeat periodically in three spatial directions and are typically described using trigonometric functions. Such geometries enable high strength and geometrically porous configurations comparable to biological structures, whereby high heat transfer efficiencies and mechanical durability can be achieved when transferred to technical applications. Combined with their geometric flexibility, they offer significant potential to improve power density, efficiency, and durability [2,3]. However, a comprehensive understanding of the coupled electromagnetic, thermal, and mechanical phenomena required for the reliable design of this power-to-heat concept is still lacking.

PROBLEM DESCRIPTION

The fundamental challenge lies in accurately modeling the spatial distribution of the electromagnetic field and the resulting current density within the complex TPMS geometry, as well as the associated temperature field, including the formation of local hotspots. Due to the large number of possible TPMS geometries (see Figure 1), a preliminary selection is made based on a literature review of different TPMS classes and simplified thermal models accounting for heat transfer and pressure drop.

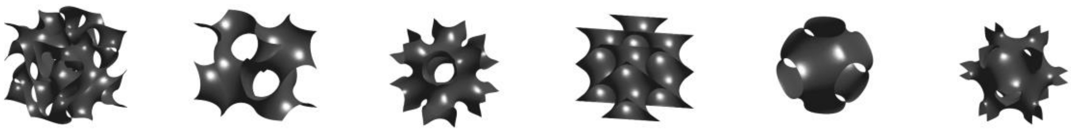


Figure 1. Unit cells of several exemplary TPMS structures.

To numerically model the spatial distribution of the electromagnetic field, current density, and the resulting heat source density (Joule heat), FEM models are developed. For this purpose, solid bodies are first generated from the TPMS surfaces, imported into ANSYS Maxwell, meshed, and assigned the relevant electrical boundary conditions and material properties. The resulting modeling tool serves as the foundation for simulation studies investigating the spatial distribution of current density and heat source density depending on material and geometric parameters.

CONCLUSIONS

Using these FEM models, the interaction between electromagnetic fields and the resulting heat generation and distribution can be characterized as a function of material and geometric parameters. The spatial distribution of fields, current densities, and heat sources, as well as the resulting temperature fields within the TPMS structures, are determined. Furthermore, the induced heat source term is parameterized based on geometry, allowing for initial conclusions on structural designs with high electrical and thermal power densities. The results provide the foundation for further modeling efforts and are incorporated into the development of a multiphysics model that accounts for electrical, thermal, and fluid-dynamic aspects.

REFERENCES

1. Belik S. High-temperature induction air heater for Brayton Carnot battery application [dissertation]. Stuttgart: Universität Stuttgart; 2023. doi:10.18419/opus-14153.

2. Wang J, Chen K, Zeng M, Ma T, Wang Q, Cheng Z. Investigation on flow and heat transfer in various channels based on triply periodic minimal surfaces (TPMS). Energy Conversion and Management. 2023;283:116955. doi:10.1016/j.enconman.2023.116955.

3. Peng C, Marzocca P, Tran P. Triply periodic minimal surfaces based honeycomb structures with tuneable mechanical responses. Virtual and Physical Prototyping. 2022;18(1):e2125879. doi:10.1080/17452759.2022.2125879.

Indirect Induction Heating for Tungsten Detritiation

J. Hrbek[1]

[1] Research Centre Rez, Hlavní 130, Rez, 250 68 Husinec, Czech Republic
Corresponding author: J. Hrbek (jan.hrbek@cvrez.cz)

ABSTRACT. Tungsten detritiation is one of challenges for future fusion energy production, requiring rapid thermal treatment. Due to the extreme variability in the electrical conductivity of tungsten powder, this study proposes an indirect induction heating approach using a graphite crucible. A 3D coupled electromagnetic-thermal model was created in Ansys Electronics Desktop (AEDT) to optimize the process. Experimental validation confirms that the proposed geometry and heating parameters effectively achieve the required thermal conditions.

***Keywords*—** induction heating, tungsten powder, mathematical modelling.

INTRODUCTION

Nuclear fusion has the potential to transform energy production in the coming decades. However, it also presents new technological challenges. The detritiation of tungsten is one such obstacle.

Tritium can be released from tungsten by heating the metal. This process should be conducted as quickly as possible. Therefore, induction heating has been proposed as a solution. However, the load is intended to be tungsten powder with particle sizes ranging from tens of micrometres to several millimetres [1]. The size of the tungsten particles and their pre-heating treatment impact the load conductivity by three orders of magnitude, making it technically challenging to design direct induction heating for this application. Consequently, indirect induction heating in a graphite crucible is being considered.

Mathematical modelling was employed to design the heating process, as presented in the following sections.

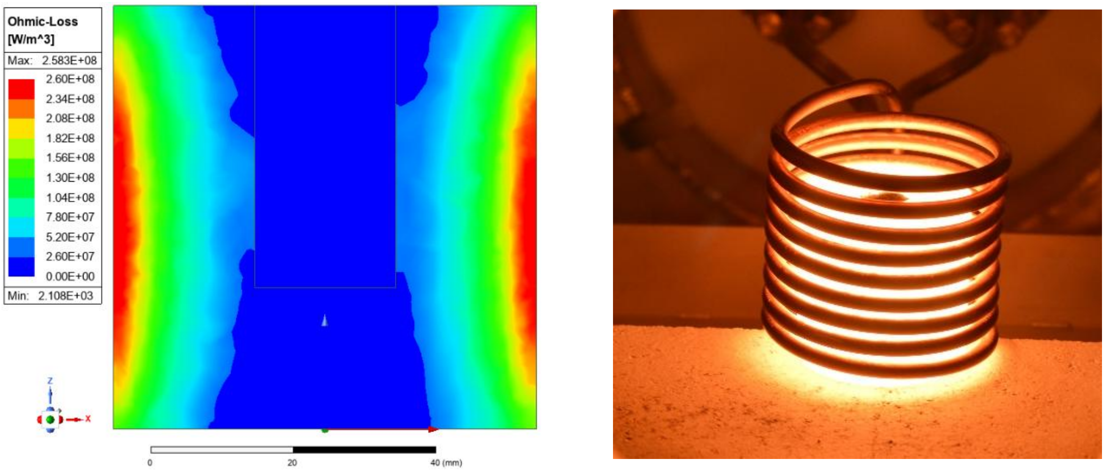
PROBLEM DESCRIPTION

The simulation involved solving a coupled electromagnetic and thermal field problem in full 3D geometry using AEDT 2025 R1 with Ansys Mechanical.

The indirect heating assembly uses a cylindrical graphite crucible with an outer diameter of 60 mm and a total height of 60 mm. With a wall thickness of 20 mm, it has a central cavity with a diameter of 20 mm, which is designed to contain the tungsten powder load. The induction system comprises a 9-turn helical inductor excited by a current I_{RMS} = 487 A at an operating frequency of 11 kHz.

For the purposes of the thermal model and the simulation of heat transfer within the tungsten powder, an effective thermal conductivity was established, accounting for the material porous nature and the heat transfer through it via both conduction and radiation [2].

Figure 1a shows the distribution of Joule losses in the cross-section of the graphite crucible containing tungsten powder, as obtained from the electromagnetic calculation. The results suggest that the proposed geometry and heating parameters are appropriately selected. Consequently, several experiments were conducted. Figure 1b illustrates a photograph of the graphite crucible containing tungsten powder during one of the experiments.



(a) (b)

Figure 1. The graphite crucible with tungsten powder – Joule losses distribution (a) and an experiment (b).

CONCLUSIONS

The experimental results demonstrate the suitability of the proposed geometric configuration and heating parameters for the indirect induction heating of tungsten powder in a graphite crucible. Furthermore, the created mathematical model provides a reliable framework for further optimisation of the process. The next stage of the research will involve using the experimental data obtained to refine the model and gradually increase the load temperature by tuning the process.

ACKNOWLEDGEMENT

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.
Implementation of activities described in the Roadmap to Fusion during Horizon Europe through a joint programme of the members of the EUROfusion consortium has been also supported by the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic project number 9D22001.

REFERENCES

1. Stoklasa J, Hrbek J, Karásková Nenadálová L, Mészáros B, Paukov M. Possibilities of Reprocessing Solid Waste with Tritium from Fusion Using High-Temperature Heating. Fusion Science and Technology. 2024; 80(3–4):311–320.
doi: https://doi.org/10.1080/15361055.2023.2259227

2. Kaviany M. Principles of heat transfer in porous media. 2nd ed. New York: Springer-Verlag; 1995.

Electrical conductivity of white fused alumina in the liquid state

J. Hrbek[1], D. Rot[1], A. Villalba Weinberg[2], D. Komissarenko[2], A. Börger[2]

[1] Department of Electrical Power Engineering, Faculty of Electrical Engineering, University of West Bohemia, Univerzitni 8, Pilsen, Czech Republic
[2] Imerys Technology Center Austria, Seebacher Allee 64, 9524 Villach, Austria
Corresponding author: A. Villalba Weinberg (adrian.weinberg@imerys.com)

ABSTRACT. White Fused Alumina (WFA), a high-purity aluminum oxide material with global production of approximately 1 million metric tons annually, is traditionally produced using electric arc furnaces. While energy-efficient, this method lacks process flexibility and melt stream control. Cold crucible induction technology offers solutions to these limitations but requires precise knowledge of the melt's electrical conductivity for optimal furnace design. This paper investigates the electrical conductivity of liquid white fused alumina using experimental data and inverse problem-solving techniques based on Pozniak et al.'s methodology to optimize cold crucible induction furnace design for WFA production.

Keywords— cold crucible, alumina, induction melting, fused minerals

INTRODUCTION

White Fused Alumina (WFA) has been produced via electric arc furnaces for over a century. Despite mature technology and good energy efficiency, arc furnaces present operational challenges including production inflexibility and difficult melt control.
Cold crucible induction furnaces offer a promising alternative, but require comprehensive understanding of alumina's electrical conductivity in liquid state to optimize electromagnetic field distribution and power coupling efficiency.
Measuring electrical conductivity in high-temperature oxide melts (>2050°C) is technically challenging. Traditional graphite crucibles cause chemical reduction of alumina to metallic aluminum, while refractory-lined vessels lead to melt contamination through dissolution. Non-polluting measurement techniques, such as inverse problem approaches, provide viable alternatives for determining conductivity from induction system operational parameters.

PROBLEM DESCRIPTION

Without accurate electrical conductivity values accounting for impurity effects, engineers cannot optimize furnace dimensions and power system specifications. The electromagnetic field distribution is directly dependent on the melt's electrical properties, which are significantly affected by impurities such as Na_2O (0.18 wt% in smelter grade alumina, Table 1).

Table 1: Chemical composition [wt%] of smelter grade alumina.

Al_2O_3	Fe_2O_3	SiO_2	TiO_2	CaO	Na_2O	SUM
99.78	0.01	0.01	0.01	0.01	0.18	100.00

The experimental part of the here discussed method consists of melting the alumina in a cold crucible induction furnace and hold the melt at two temperatures above the melting point:

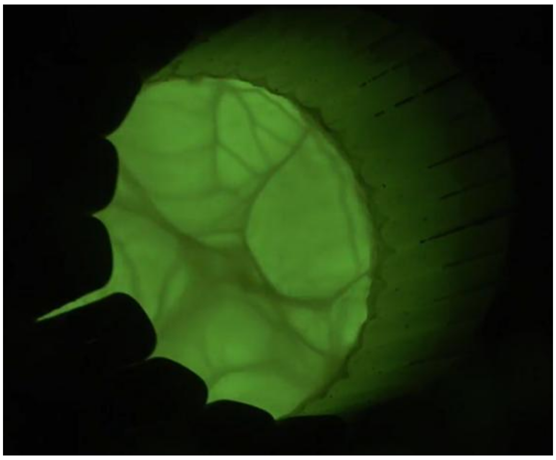


Fig. 1. WFA melt at 2200°C.

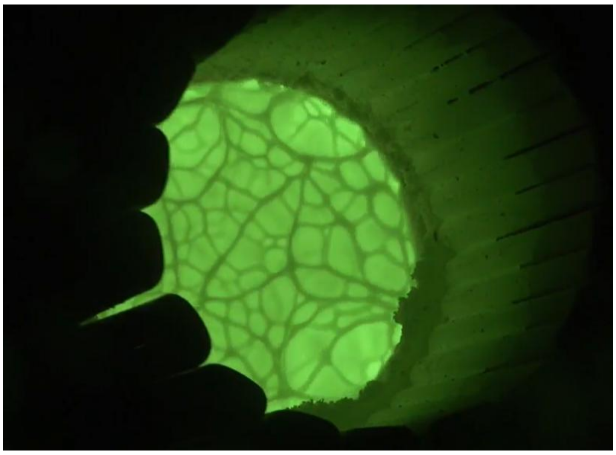


Fig. 2. WFA melt at 2400°C.

From the recorded process data (power, impedance), the electrical conductivity of the melt is mathematically deduced. The resulting conductivity was 295 $S \cdot m^{-1}$, which is significantly higher than reported values of "pure" alumina by the same method.

CONCLUSIONS

This research successfully applied inverse problem-solving techniques to measure molten alumina's electrical conductivity with <8% systematic error. The non-contact method overcame traditional measurement limitations at extreme temperatures (>2050°C), providing crucial data for cold crucible induction furnace optimization.

The conductivity data enables improved furnace design, potentially enhancing energy efficiency and reducing costs. With global production at ~1 million metric tons annually, even small improvements could deliver significant economic and environmental benefits.

REFERENCES

1. Pozniak I V, Pechenkov A Yu, and Shatunov AN. Induction furnace with cold crucible as a tool for investigation of high temperature melts. Proceedings. The 9th Russian-Korean International Symposium on Science and Technology, 2005. KORUS 2005. IEEE, 2005. P. 372–76.

2. Gross C, Assmus W, Muiznieks A, Raming, G, Mühlbauer A, & Stenzel C. Power consumption of skull melting, part I: Analytical aspects and experiments. Crystal Research and Technology: Journal of Experimental and Industrial Crystallography, 34(3). 1999. p. 319–28.

Scandia-stabilized Zirconia for electrochemical cells: Synthesis in Cold Crucible

D. Komissarenko[1], A. Villalba Weinberg[1], J. Koller[1], V. Müller[1], B. Korner[1] and A. Börger[1]

[1] Imerys Technology Center Austria, Seebacher Allee 64, 9524 Villach, Austria
Corresponding author: D. Komissarenko (dmitrii.komissarenko@imerys.com)

ABSTRACT. Induction heating has emerged as a promising alternative to the traditional arc melting process in the production of a variety of materials. Although the method has already been verified in the metal-casting industry, there is less evidence on the feasibility of the production of oxide-ceramic materials via induction heating. In the present work, cold crucible technology was used for the synthesis of scandia stabilized zirconia in an induction kiln operated at medium frequency of 180 kHz. Optimization of fusion parameters, including power input and exposure time under the electromagnetic field, enabled the production of high-purity, single-phase ScSZ ingots, which were subsequently used as feedstock for electrolytes in solid oxide fuel cells and electrolysis cells (SOFC/SOEC).

***Keywords*—** Stabilized zirconia, cold crucible, ionic conductivity, SOFC/EC

INTRODUCTION

In contrast to the metal industry, where induction heating has already been implemented, the arc-melting is still dominating in the ceramic sector for the production of the fused materials. Compared to conventional electrical arc furnace fusion, cold crucible technology offers an advantage in reducing carbon emissions, primarily due to the absence of graphite electrodes and rapid heating capabilities. Furthermore, it is particularly advantageous for producing materials requiring high purity [1].

One promising application of this technology is in the production of zirconia ceramics for solid oxide fuel cells and electrolysis cells (SOFC/SOEC), which demand high-purity feedstock materials. Additionally, compared to wet-chemical synthesis methods, direct melt crystallization enables the production of materials with larger grain sizes, thereby enhancing the ionic conductivity of these materials [2]. In the current work, zirconium dioxide stabilized with 6 mol.% Sc_2O_3 (6ScSZ) was selected as the material for synthesis using cold crucible technology.

PROBLEM DESCRIPTION

Limited information on the growth of single crystals of ScSZ using cold crucible technology has been reported in the literature. Borik et al. [3] employed a 5.28 MHz generator to produce scandium oxide-stabilized zirconia crystals. However, no literature describes the influence of process parameters on the properties of these materials when using medium-frequency generators and rapid cooling techniques. In this study, 6ScSZ ingots were produced using a furnace operated at 180 kHz.

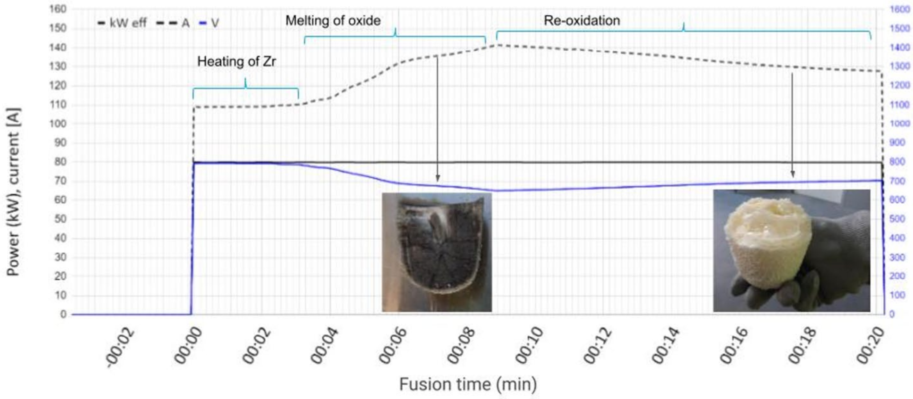


Fig. 1 Power input and current vs fusion time of 6ScSZ.

It was observed that fully re-oxidized ScSZ ingots can be produced within 20 minutes of fusion with a power input of 80 kW (Fig.1). The produced zirconia materials were single phase according to XRD. The milled powders obtained from the 6ScSZ ingots were used as a raw material for fabrication of electrochemical cells. The materials demonstrated a high ionic conductivity of 0.07 Sm/cm at 800°C.

CONCLUSIONS

Scandia-stabilized zirconia ingots were successfully produced via induction heating using a furnace operated at frequency at 180 kHZ. Fully re-oxidized material can be obtained within 20 minutes after the process initiation when the current returns to the initial values. The materials revealed a pure phase composition with high ionic conductivity values of 0.07 Sm/cm.

REFERENCES

1. Kuzmino YS, Lomonova EE, Osiko VV. Cubic Zirconia and Skull Melting. Cambridge International Science Publishing Ltd. Cambridge UK. 2008.
2. Mahato N, Gupta A, Balani K. Doped zirconia and ceria-based electrolytes for solid oxide fuel cells: a review. Nanomaterials and Energy. 2011. Vol.1. 27-45.
3. Borik MA, Bredikhin SI, Kulebyakin AV, Kuritsyna IE, Lomonova EE, Milovich FO, Myzina VA, Osiko VV, Panov VA, Ryabochkina PA, Seryakov SV, Tabachkova NYu. Melt growth, structure and properties of $(ZrO_2)_{1-x}(Sc_2O_3)_x$ solid solution crystals (x=0.035−0.11). J Cryst Growth. 2016. 3. 54–61.

Estimation of the Electrical Resistivity of Gadolinium Oxide inside the Cold Crucible using the Inverse Problem Technique via ANSYS

Baseer Ahmed[1], I. V. Poznyak [2], and Vaclav Kotlan [1]

[1] Faculty of Electrical and Computational Engineering, University of West Bohemia, Pilsen, Czech Republic
[2]Faculty of Industrial Automation and Electrical Engineering, "LETI", ETU University, Saint-Petersburg, Russia
Baseer Ahmed (basrahmd@fel.zcu.cz)

ABSTRACT. The study investigates the electrical and electromagnetic parameters involved in the induction heating and melting of gadolinium oxide inside the cold crucible. The methodology includes the study of the melt process in the cold crucible and its various stages, calculation of load radius, assessment of power distribution across the load, as well as calculation of the physical geometry of the ingot and electrical parameters of the melt process.

***Keywords*—** induction melting, electrical resistivity, cold crucible, ANSYS.

INTRODUCTION

The study uses the Inverse Problem technique in ANSYS to investigate the induction melting of gadolinium oxide inside a cold crucible. The research focuses on understanding the electromagnetic and thermal behavior of the cold crucible system and identifying key process parameters that govern melting efficiency and material properties [1][3]. The geometry of the resulting ingot is calculated along with the depth of penetration. The electrical resistivity of molten gadolinium oxide was estimated using the Inverse Problem technique through ANSYS. A comparative mathematical model for the Inverse Problem technique is developed, incorporating electromagnetic field equations and power balance equations.

PROBLEM DESCRIPTION

Gadolinium oxide is a highly valuable material for applications in optics, nuclear technology, and theragnostic systems. Still, its high melting point and low conductivity make it difficult to process using traditional methods [2]. While cold crucible melting is an effective solution for maintaining purity and reaching extreme temperatures, there is a lack of detailed research on electromagnetic behavior and electrical resistivity estimation of gadolinium oxide. This gap prevents the reliable process modeling and optimization needed for its production, motivating the present work.

Methodology and data preparation for the inverse problem technique

During the melt process, the electrical readings were observed, and boundary conditions were set, e.g., transient temperature and non-magnetic space. These observed readings were used to calculate the power balance equations. The geometry of the ingot was calculated and mass of the ingot was measured, and the depth of penetration inside the melt pool was calculated. Then, using the inverse problem technique [3] to rearrange the data in ANSYS, the final results were obtained, and the graph was observed. During the estimation, to determine the electrical resistivity of gadolinium oxide within the melt pool, all physical, electrical, and magnetic conditions were considered. The resulting graph and table of results are given below. Power balance equations, depth of penetration and preparation of data for the Inverse Problem technique are mentioned in the full paper.

These equations are used for the inverse problem technique, i-e magnetic potential vector [3] and the power balance equation

$$curl\left(\frac{1}{\mu}curl\ A\right)+\gamma\frac{\partial A}{\partial t}=Jext, \tag{1}$$

$$P^2=\eta_{ele}U_aI_a. \tag{2}$$

Figure 1, shows how the electrical resistivity is estimated using both measured and calculated power along with input impedence.

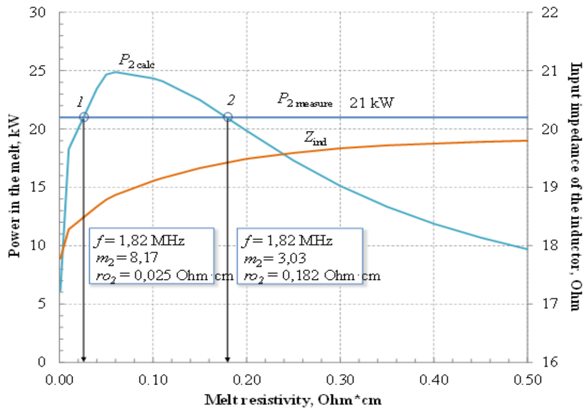


Figure 1. Estimated electrical resistivity graph

The table shows the calculated values necessary for estimating the electrical resistivity of gadolinium oxide using ANSYS.

Table 1: Results of the calculation of the inverse problem technique

U_a, kV	I_a, **A**	I_g, **A**	P_2, **kW**	η_{ele}	f, **MHz**	T, **°C**	r_0, **Ω.cm**	U_a, **kV**	I_a, **A**
7.5	4	1.7	21	0.70	1.8	2500	1.82	7.5	4

CONCLUSIONS

The combination of electromagnetic modelling and test data analysis allowed us to characterize the electrical properties of the gadolinium melt pool inside the cold crucible.

REFERENCES

1. Alferd Muhlbauer, History of induction heating and melting, Deutsche National-bibliografie, 2008, pp.23–26.

2. N. N. Greenwood, A. Earnshaw, “Chemistry of the Elements”, Butterworth-Heinemann, 2nd Edition - November 25, 1997.

3. I. Poznayek, Yu Udalove, A. Shantunov, “Induction furnace with cold crucible as a tool for investigation of high temperature melts, “KOROUS. 9th Russian-Korean International Symposium on Electric Power Engineering, pp. 372–376, January 2005.

3D Printed Metal-Doped Ceramics for Induction Heating Susceptors

K. Slobodnik[1], and V. Kotlan[1]

[1] University of West Bohemia in Pilsen, Univerzitní 8, Pilsen, Czech Republic
Corresponding author: K. Slobodnik (karelsl@fel.zcu.cz)

ABSTRACT. This paper presents 3D-printed ceramic susceptors doped with steel particles for induction heating. Experimental testing and numerical modelling confirm their functionality and highlight the influence of material composition on heating performance.

***Keywords*—** Induction heating, susceptor, additive manufacturing, microparticles.

INTRODUCTION

Additive manufacturing of ceramics enables the production of complex geometries with a wide range of material properties. In addition, conductive additives, such as steel powder, can be added to produce ceramic-based susceptors. In this work, we present a custom extrusion-based 3D printer designed for printing ceramic pastes. Using this printer, steel-doped ceramic structures are fabricated and evaluated for inductive heating performance. The study explores the relationship between composition and heating behaviour, demonstrating the feasibility of additively manufactured ceramic susceptors.

PROBLEM DESCRIPTION

Thermal susceptors are components of devices that absorb energy and convert it into heat. They are currently the subject of frequent discussion regarding innovations in hot-air generation technology and energy savings. In a previous study [1], a Si-C system with graphene fibers was tested. This principle proved functional, but complicated to manufacture and prepare the susceptor. The main idea behind a hot air generation system is to heat the filler using induction heating; therefore, the filler must be electrically conductive. For the air to be sufficiently and evenly heated, the susceptor must be of sufficient length or be porous.

We combined our experience from developing our own 3D printer [2] for ceramic material with the concept of conductive additives in a heat-resistant substrate.

The first part of the work involved verifying whether adding steel microparticles to the ceramic material would result in a conductive structure capable of being heated by electromagnetic induction after the ceramic was fired.

The second and main part involves analyzing the dopant distribution in the ceramic. Since this marks the beginning of work on this topic, it is necessary to determine the required amount of steel particles. This is determined by the mass ratio. Samples were prepared with varying concentrations, and time-dependent profiles were measured in the experimental setup using integrated contact measurement. These curves are then used to calibrate the numerical model. The model can then be used for further analysis of the system's behavior.

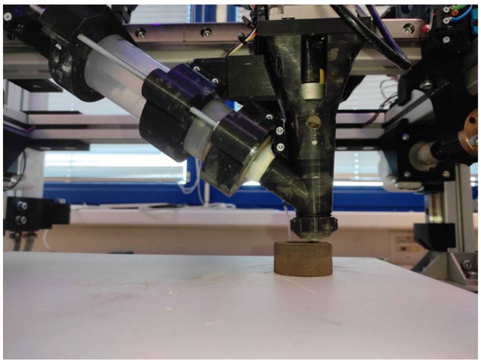


Figure 1. Demonstration of an additive manufacturing of a metal-doped ceramic susceptor

In figure 1, you can see the extruder of 3D printer designed for ceramic printing. After printing, the mixture of ceramic and steel microparticles is dried and fired. One of our next tasks is also to prepare a microstructure image of the sample before and after baking. In figure 2, you can see the laboratory testing of the possibility of induction heating and the temperature distribution in the IR image. The next results will be mentioned and discussed in the full paper.

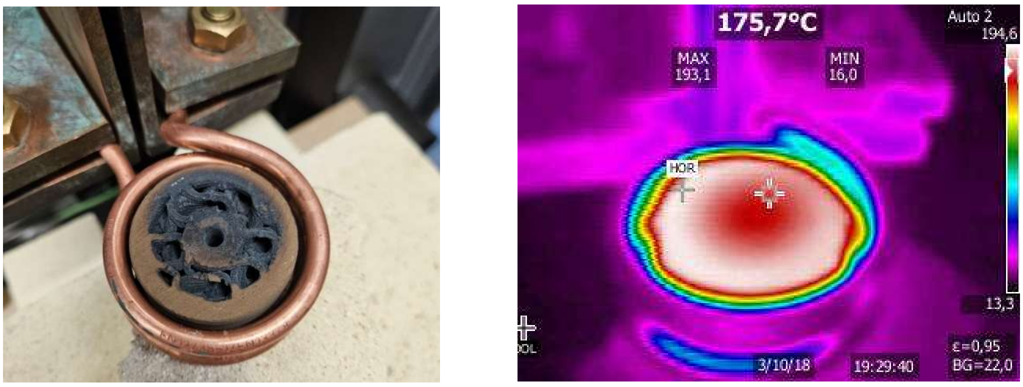


Figure 2. Laboratory testing of the function of the susceptor. The temperature distribution is after 120 seconds.

CONCLUSIONS

The proposed 3D-printed susceptor manufacturing system offers greater design flexibility and is more responsive. According to initial tests, the resulting susceptor is capable of heating up, but more slowly than a Si-C-based susceptor with graphene fibers. Tests and calibration optimizations are being conducted using a digital twin, and the next step will be to test the suitability of using steel chips or flakes instead of spherical particles.

REFERENCES

1. Hackert A, Stiller J, Winhard J, Kotlan V, Nestler D. Inductive Heating of Ceramic Matrix Composites (CMC) for High-Temperature Applications. MATERIALS, 2024, Vol. 17, Nr. 10, DOI 10.3390/ma17102175.

2. Slobodník K, Spurný R, Šroubová L, Šebele J. Design and control of ceramic 3D printer. Proceedings of the 15th International Conference ELEKTRO 2024. Piscataway (NJ): IEEE; 2024. ISBN: 979-8-3503-7235-9.

Reliable High-Temperature Electrical Contacting for Structurally Integrated Thermally Sprayed Heating Elements

Z. Yi[1], A. Köppen[1], and E. Baake[1]

[1] Institute of Electrotechnology, Leibniz University Hannover, Wilhelm-Busch-Str. 4, 30167, Hannover, Germany
Corresponding author: Z. Yi (Yi@etp.uni-hannover.de)

***Keywords*—** Thermally sprayed heating elements, Electrical contacting, High-temperature reliability.

INTRODUCTION

Industrial heat treatment is still largely based on natural gas, resulting in significant carbon emissions and fossil energy dependence. With tightening emission targets and rising energy costs, electrification of process heat is becoming increasingly important [1]. However, conventional resistive heating elements exhibit significantly lower power densities than gas burners. Moreover, their mechanical vulnerability precludes installation beneath the workpiece, where falling material would lead to severe damage. As a result, they are not well suited to replace gas burners, particularly in continuous high-load furnace applications. To address these limitations, a structurally integrated heating layer produced by thermal spraying is investigated as an alternative concept. By integrating the heating function directly into the load-bearing surface, this approach eliminates mechanically vulnerable free-standing elements.

PROBLEM DESCRIPTION

Electrification of industrial heat treatment is a key approach to reduce CO_2 emissions and enable sustainable operation. However, current electrical heating technologies still exhibit limitations. Conventional resistance heating elements are mainly restricted to small and medium-scale furnaces due to limited power density, pronounced high-temperature creep, and insufficient mechanical stability [2]. In continuous production systems such as roller hearth furnaces or strip heat treatment lines, heating elements cannot be installed beneath the workpiece, since a typical material drop would result in severe mechanical damage to the elements. This structural constraint explains why these areas are still predominantly heated by gas burners. Consequently, a heating concept is required that enables electrification while simultaneously tolerating mechanical loading.

To overcome these limitations, this study investigates a heating element based on a thermally sprayed multilayer structure consisting of a substrate, an insulating layer, a conductive heating layer, and a protective top layer. Although thermally sprayed heating systems have been applied in low-temperature applications, their performance under high temperature conditions above 1000 °C has not yet been systematically investigated. Key challenges include achievable heat flux density, temperature homogeneity influenced by electrical contacting, and thermo-chemical stability in furnace atmospheres up to 1200 °C. Among these, electrical contacting represents a critical issue. The heating structure is realized as a thermally sprayed planar coating on a substrate, which requires a reliable electrical interface to the surface layer. Since the heating element is installed inside the furnace, the contacting region is likewise exposed to

operating temperatures of up to 1200 °C and must withstand simultaneous electrical loading and thermal stresses.
The concept offers significant potential advantages. By utilizing previously unheated furnace areas, it may increase the overall furnace power density and enable more compact designs.
Nevertheless, its practical feasibility critically depends on stable electrical contacting at elevated temperatures. To address this issue, a dedicated contacting structure was developed (Fig. 1).

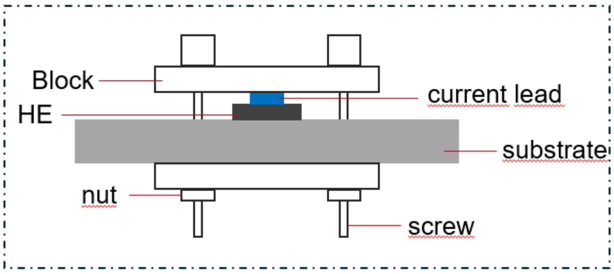


Figure 1. Schematic of the electrical contacting configuration for the thermal spray sample.

To evaluate its performance under realistic operating conditions, an experimental setup providing controlled power supply and temperature monitoring was constructed (Fig. 2), enabling investigation of the thermo-electrical behavior of the heating layer.

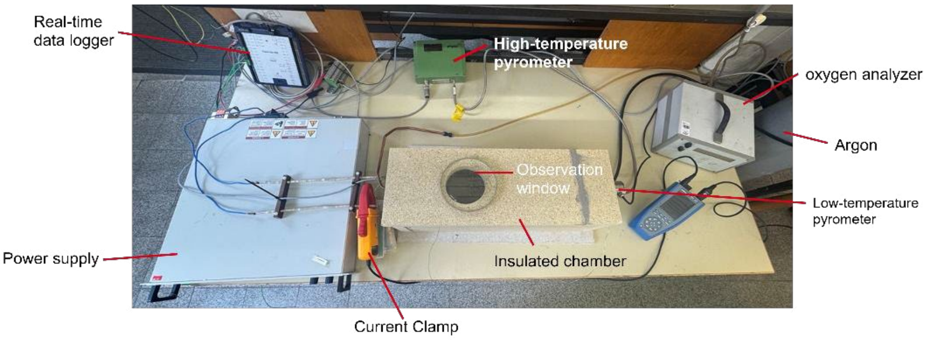


Figure 2. Experimental setup for thermo-electrical testing of the heating layer in an argon atmosphere.

CONCLUSIONS

Reliable electrical contacting of structurally integrated thermal spray heating elements under high-temperature furnace conditions was achieved using a mechanically clamped concept and a dedicated experimental setup. The experiments demonstrated stable current transfer and reproducible heat generation under process-relevant conditions, providing a basis for further assessment of lifetime and attainable heat flux.

REFERENCES

1. Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit: „Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung“, Berlin, 2016.

2. S. Lupi: „Fundamentals of Electroheat: Electrical Technologies for Process Heating“, Springer International Publishing, 2017.

Electrothermal Processes for Rare Earth Element Recycling from Energy-Transition E-Waste: A Review

G. Gardan[1], G. Poggiana[1], F. Lucchini[1], M. Forzan[1], F. Dughiero[1], and R. Torchio[1,2]

[1] Department of Industrial Engineering - University of Padova, Via Gradenigo 6/a, Padova, 35131, Italy
[2] Department of Information Engineering - University of Padova, Via Gradenigo 6/b, Padova, 35131, Italy
Corresponding author: R. Torchio (Riccardo.torchio@unipd.it)

ABSTRACT. Rare-earth elements (REEs) play a key role in the manufacture of electrical and electronic devices. However, concerns regarding their availability and the vulnerability of global supply chains have steadily increased. Consequently, considerable attention has been devoted over the past decade to recovering and reusing REEs from waste electrical and electronic equipment, commonly referred to as e-waste.
Conventional thermal recovery processes offer substantial potential for industrial-scale implementation. Nevertheless, they also present significant challenges, including high energy consumption, elevated operating costs, variable recovery efficiencies, and adverse environmental impacts. In this context, electrothermal technologies represent alternative heating solutions that may improve process efficiency while reducing emissions and the overall carbon footprint, particularly when powered by low-carbon electricity.
This work investigates the role of electrothermal technologies in thermal processes for REE recovery from selected e-waste streams associated with energy-transition technologies. Several electrothermal technologies are reviewed and compared, with particular emphasis on their suitability for industrial-scale REE recovery. Among the technologies considered, induction and microwave heating emerge as promising solutions for future sustainable industrial recycling systems.
Keywords— Rare earth element recovery, E-waste recycling, Electrothermal technologies, Circular economy.

INTRODUCTION

Owing to their distinctive chemical and physical properties, rare-earth elements (REEs) play a key role in the electrical and electronic industries and are widely used in electrification and renewable-energy technologies [1], [2]. However, ensuring a reliable supply of REEs remains a major challenge [3]. To mitigate these supply risks, considerable attention has been devoted over the past decade to recovering REEs from waste electrical and electronic equipment, commonly referred to as e-waste. REE recycling may alleviate both supply risks and the environmental challenges associated with e-waste management, particularly in view of the steadily increasing global generation of electronic waste. Nevertheless, REE recovery from e-waste presents several limitations. Because electrical and electronic components may contain hazardous substances, improper recycling practices can pose risks to human health and the environment. In addition, established REE-recycling routes are often characterized by high costs and energy requirements and may generate harmful gaseous emissions and wastewater streams if not properly controlled.

Thermal processing steps, in which controlled heating induces physical or chemical transformations in the treated materials, are common to a wide range of recycling routes. Moreover, recovery performance may depend strongly on the operating temperature. Accurate thermal control is therefore essential for process optimization. However, thermal treatments are

often costly and energy-intensive and have traditionally relied on combustion-based heating systems. In this context, electrothermal technologies represent a viable alternative because they can substantially improve heating efficiency and, consequently, overall process efficiency, while also providing more accurate and flexible temperature control. Furthermore, the associated carbon dioxide emissions may be reduced when the required electricity is generated from low-carbon or renewable energy sources.
This work therefore presents a comparative assessment of the principal categories of electrothermal furnaces and examines their suitability for the industrial-scale recovery of REEs from selected e-waste streams associated with energy-transition technologies. A more comprehensive comparison is provided in [4].

PROBLEM DESCRIPTION

Electrothermal technologies have been investigated to varying extents for the recovery of REEs from the selected e-waste streams.
Electric arc furnaces, traditionally employed in the steel industry for scrap melting and the production of high-quality steels, are increasingly being considered for recovering valuable materials from end-of-life products and industrial waste streams.
Indirect-resistance furnaces have been investigated more extensively for the thermal treatment of several waste streams, including waste printed circuit boards and permanent magnets recovered from electric motors and generators.
Induction heating has been successfully applied to the recycling of materials obtained from energy-transition technologies, with permanent magnets representing the most extensively investigated application [5].
Finally, microwave-assisted processes have shown considerable potential owing to their rapid and selective heating capabilities.

CONCLUSIONS

This paper reviews the application of electrothermal technologies to rare-earth element (REE) recovery from e-waste streams associated with energy-transition technologies. One of the main findings of this review is that, although several electrothermal technologies are technically compatible with the temperature ranges and operating conditions required for REE recovery, their application remains unevenly distributed across different e-waste streams and process stages. Future research should therefore move beyond laboratory-scale demonstrations and focus on process scalability, energy efficiency, material selectivity, and integration into industrial recycling chains.

REFERENCES

[1] B. Zhou, Z. Li, Y. Zhao, e C. Chen, «Global potential of rare earth resources and rare earth demand from clean technologies», *minerals*, 2017.
[2] C. C. Pavel *et al.*, «Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications», *Sustain. Mater. Technol.*, 2017.
[3] M. M. Nkiawete e R. L. Vander Wal, «Rare earth elements: Sector allocations and supply chain considerations», *J. Rare Earths*, vol. 43, fasc. 1, pp. 1–8, gen. 2025.
[4] G. Gardan, G. Poggiana, F. Lucchini, F. Dughiero, R. Torchio, "Rare Earth Element Recycling from Energy-Transition E-Waste: A Review of Thermal and Electrothermal Processes," Journal of Rare Earths, 2026, DOI: 10.1016/j.jre.2026.07.019.
[5] Y. Bian, S. Guo, L. Jiang, J. Liu, K. Tang, e W. Ding, «Recovery of rare earth elements from NdFeB magnet by VIM-HMS method», *ACS Sustain. Chem. Eng.*, 2016.

Induction Surface Hardening of Steel Workpieces Examples of Applications

K. Konopka[1], J. Barglik[2]

[1] ELKON company, Prosta 3, Rybnik, Poland
[2] Silesian University of Technology, Krasińskiego 8, Katowice, Poland

Corresponding author: J.Barglik (jerzy.barglik@polsl.pl)

ABSTRACT. Induction surface hardening (ISH) technology consists of two consecutive steps: rapid induction heating of treated steel workpieces and practically immediate intensive cooling, Such a technology makes possible to obtain expected thin hardening surface zone and accordingly to requirements to keep soft and unchanged internal zones. The paper presents selected examples of ISH technologies for steel workpieces of complex shapes applied in Polish industry. For some of them research activities were mostly realized in a framework of collaboration between the ELKON company and the Silesian University of Technology.

***Keywords*—**Induction hardening, Electromagnetic processing of materials, Transistor generator

INTRODUCTION

Induction surface hardening (ISH) technologies are often applied in industry but mostly for steel workpieces with regular axisymmetric or flat shapes [1]. However application of ISH technologies for any steel workpieces of complex shapes like gear wheels, mandrels etc. seems to be more complicated and often require additional research activities. Some selected examples of ISH technologies for steel workpieces of complex shapes applied in Polish industry are presented in the paper. The ELKON company has been established in 1990. It has been concentrated on fully automated electromagnetic processing of materials with a special emphasis put on ISH technologies. Research activities have been often realized in a framework of collaboration between the ELKON company and the Silesian University of Technology.

ISH TECHNOLOGIES

The ISH process is characterized by a location of the inductor close, directly opposite to the surface of steel workpiece. Extremely high power density in the thin hardened zone is generated. Thickness of the hardened zone of course depends on many factors like: frequency of field current, power delivered to the treated workpiece, time of heating and cooling. In order to generate high power density in the thin hardened zone it is necessary to apply high frequency transistor sources making possible to realize the heating part of the process rapidly. Fig. 1 presents the arrangement of contour induction surface hardening of small gear wheels realized by means of consecutive dual frequency method [2]. The research project funded by the National Center for Research and Development was successfully realized by the Silesian University of Technology with a close cooperation with the ELKON company in years 2014-2017. Nowadays based upon the agreement between two partners the technology is offered by the ELKON. Fig. 2 presents another kind of the ISH process: tooth-by-tooth hardening of gear wheels by tooth fully automated and practically implemented to industry [3].

Fig. 1 Contour ISH of gear wheels system

Fig. 2 Tooth-by-tooth ISH system

OTHER PROJECTS REALIZED BY ELKON COMPANY

Area of activities of the ELKON company is very wide. It covers not only ISH technologies but also other induction heat treatment and electromagnetic processing technologies like annealing, tempering, welding, soldering, purification, preheating and melting. Examples of advanced fully automated technological systems elaborated by the ELKON company are presented for instance in [4]. Many of them have been elaborated by the ELKON in close collaboration with the Silesian University of Technology. Some of them have been realized for producers of automobile and industry.

CONCLUSIONS

The paper presents selected examples of ISH technologies for steel workpieces of complex shapes applied in Polish industry. Research activities including mathematical modeling, measurements of material properties, critical temperatures and hardness distribution were mostly realized in a framework of collaboration between the ELKON company and the Silesian University of Technology.

REFERENCES

1. Rudnev V., Loveless D., Cook R., L. Handbook of Induction Heating. Second Edition, CRC Press. Taylor and Francis Group, 2017.
2. Barglik J.: Identification of temperature and hardness distribution during dual frequency induction hardening of gear wheels, Archives of Electrical Engineering, 2018, 67, 913–923
3. Konopka K., Konopka Z.: Application of electromagnetic induction in processing and heat machining of metals – implemented automated technological processes. Mechanik, 2012, nr 11, 1009-1011.
4. https://elkon.com.pl/15.03.2026

Numerical Investigation of AISI304 Steel Induction Tube Welding

D. Ivanov[1], J.I. Asperheim[1], B. Grande[1] and P. Das[2]

[1] ENRX Group a.s., Bølevegen 10, Skien, Norway
[2] ENRX a.s., Bølevegen 4b, Skien, Norway
Corresponding author: D. Ivanov (dmitry.ivanov@enrx.com)

The paper discusses a 3D numerical model for induction tube welding based on the T–Ω formulation of Maxwell's equations in the frequency domain, coupled with the advection–diffusion heat transport equation. A numerical finite element method (FEM) formulation based on a mixed finite element approach (Whitney edge elements for conducting regions and Lagrange nodal elements for non-conducting regions) is presented. This approach minimizes the number of degrees of freedom required in the 3D formulation compared to alternative formulations of Maxwell's equations. Global constraints are defined to allow the specification of the coil voltage or current in the system. The advection–diffusion heat transport equation is discretized using Lagrange nodal elements. It is shown that a large advection component requires numerical stabilization, such as the Streamline Upwind/Petrov–Galerkin (SUPG) method. An implementation using the GetDP environment is also discussed.

An approach to geometry and mesh parameterization is presented, allowing the rapid construction of various FEM-ready descriptions of the tube welding system defined by a finite set of parameters. The approach is implemented in the GMSH environment. Criteria for mesh quality and the type of finite elements are discussed in order to achieve numerical stability and accuracy of the simulation results, depending on process parameters such as the induction heating frequency and material properties.

A special focus is given to the challenge of incorporating the magnetic components, such as impeders, into the model based on the formulation of Maxwell equations in frequency domain.

It is shown that the combination of process parameters for tube welding of non-magnetic stainless steels, typical tube sizes, and the material properties involved, allows non-compromising full-scale 3D simulation of the process using available computational power and standard direct linear solvers, such as Intel MKL Pardiso or MUMPS. The approach is validated by comparison of the simulation result to a real tube welding line data demonstrating a high level of relevance.

The implemented model is used to run a series of simulations focusing on the effect of AISI304 tube wall thickness. It is demonstrated that, due to the relatively large penetration depth in non-magnetic steel, the current distribution in the tube body for relatively small wall thicknesses differs from the classical view of induction tube welding of steels. The effect is discussed in detail, and the corresponding regimes are defined depending on the process parameters and the geometry of the tube welding system.

***Keywords*—** Induction tube welding, finite element method, stainless steel.

Changing Goal Functions for Induction Heat Treating Coil Design

R. Goldstein[1]

[1] Fluxtrol, Inc., 1388 Atlantic Blvd., Auburn Hills, MI, USA
Corresponding author: R. Goldstein (rcgoldstein@fluxtrol.com)

ABSTRACT. Traditionally, induction heat treating processing requirements have been defined based upon achieving a proscribed heat pattern with required hardness values at selected locations. Over time, the development of induction heat treating coil design process has shifted from analytical and empirically based to progessively more virtual methods. Induction coil design using virtual methods relied primarily on electromagnetic and thermal models to predict a temperature based upon equilibrium phase diagrams with an offset of temperature to account for the shorter heating times typical for induction heat treating. Over the past 10 – 20 years, manufacturers have found that oftentimes in induction heat treating processing, there is a significant disconnect between hardness and component performance. Newer understanding of the material response to non-equilibrium processing like induction heat treating is evolving and influencing the goal functions for both component designers and induction heat treating coil and process design. This presentation will cover some of these areas while giving some examples of enhanced properties that offer the potential to dramatically improve component performance on a per weight basis.

Keywords— Electromagnetic Processing, Rapid Thermal Processing, Non-Equilibrium Thermal Processing, Residual Stresses, Distortion Engineering, Dimensional movement, Induction Heating, Induction Coil Design, Computer Simulation, Virtual Validation

INTRODUCTION

Modern computer hardware and software capabilities have improved drastically over time and it is now possible to solve multi-physics electromagnetic processing problems in 3D within reasonable amounts of time in many cases. Many papers have been published at previous HES events on multi-physics modeling for technologies including mass heating, heat treating, magneto-hydronamics, welding, crystal growing, inductive coupled plasma and melting. These models provide accurate calculations based upon the input data provided to them.

The challenge arises when the input data provided does not reflect the real-world situation. Common issues encountered include:

- Not considering a multi-physics module in the calculations
- Not considering processes that occur prior to the electromagnetic process
- Use of materials property data that is not based upon the processing conditions
- No good, known physical model exists for a physical phenomena
- Not understanding the power supply operating mode or limits
- Not understanding how the material may impact the power supply operation
- Not understanding the goal function and critical properties for component performance
- Not considering manufacturing tolerances on incoming product

In some cases, if we understand how these practical considerations can impact our process, it is possible to consider them in the modeling process and stress the model for various incoming conditions. In other cases, it can help us to quickly identify whether the condition occurring in the electromagnetic process is a result of the electromagnetic process or something which was present in the incoming material that needs to be addressed in order to have a successful process. Specific to induction heat treated components, incoming residual stress states, composition, incoming material structure, heating time and the quenching process are all key factors that have a large impact on the component performance. A few examples are given below on the importance of understanding more than just the time and temperature to More and more the trend is that major manufacturers are working on modeling the entire manufacturing process chain sequentially with induction heat treatment as one of the steps in the manufacturing chain and are focused on optimizing the sequence to achieve best component performance.

RESIDUAL STRESSES

In the past, component specifications for induction heat treatment used to provide for a surface hardness level(s) over a certain region of the component along with total and effective case depths for the various regions. Manufacturers have learned over the past few decades that the residual stress distribution plays a very large role in the ability of the component to function effectively and reliably in service and have now begun specifying minimum residual stress levels for performance as opposed to just a hardness distribution [1]. Ivanov, et. al, published work on simulating stress and strain during induction hardening and the importance of residual stresses in gear heating during the middle of the 2010's [2, 3]. Goldstein, et. al showed the impact of the residual stresses from the progressive induction heat treating process on a full flow axle have on the resulting stresses to an applied torsional load [4]. The results showed a drastic reduction in the component stress under applied loads, which will result in higher values of ultimate and fatigue strength compared to the models without considering the residual stresses. On the other side of the equation, it is the author's experience that unfavorable distributions of residual stress due to improper induction heat treatment that still met hardness pattern requirements also caused a significant decline in component performance compared to expectations based upon a neutral stress state.

These new standards require the use of not only electromagnetic and thermal models, but also at a minimum metallurgical and residual stress calculations. What can be especially challenging in some of these cases is that the database for these materials is not well developed for induction heat treating conditions, which is essential for the accurate prediction of residual stresses. Compounding the issue is that many of the tools that are commonly used for measuring material properties are not well suited to measuring the conditions present in induction heat treatment and can lead to incorrect property measurement, yielding incorrect results. Some of these factors are described below.

<u>Spray Quenching Process</u>

Practitioners have long known that the quench intensity, concentration, cleanliness, temperature and distribution and can have an impact on the final component dimensions, hardness distribution and can also result in part cracking. Li et. al. demonstrated using computer models that the heat transfer coefficient used for modeling has a large influence on the resulting residual stress levels in induction heat treating as well as play a strong role in the dimensional movement of the component on a progressively hardened axle shaft (Figure 1) [5]. The values used in these models were made using linear heat transfer coefficients developed using standard characterization tools for quenchants. There was some limited information on induction spray quenchants for induction heat treatment available that showed heat transfer coefficients orders of magnitude higher than the values used in this study and Nemkov, et. al published the influence that using a non-linear value for the heat transfer coefficient can have on the time for the component on martensite formation which is the main driver of heat treatment induced residual stresses [6].

Goldstein and Mackenzie showed that the values used were based not upon the spray quenchants themselves, but were actually the limits of the measurement devices that were used to measure the heat transfer coefficients due to thermal lag inherent in the device itself [7]. Proposals for potential improved designs of characterization devices were presented and suggested for use to expand the range of potential measurements possible, but further work is required to make appropriate tools for real component quench spray characterization as real induction quenching systems on real components tend to be much more complicated than a simple non-linear value.

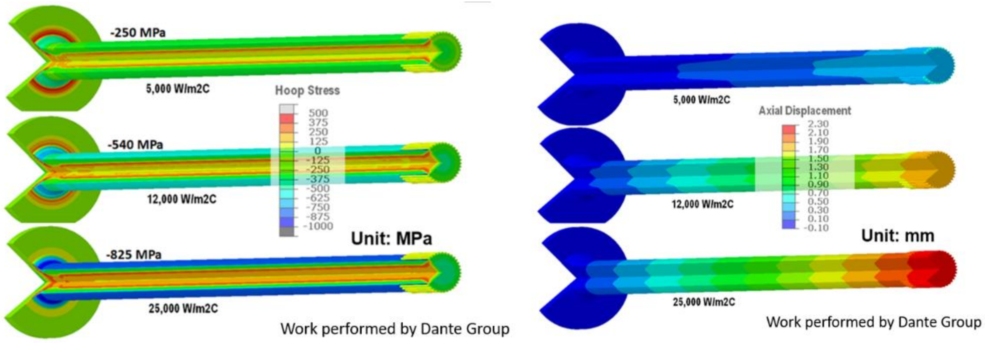


Figure 1. Dimensional movement and residual stresses for induction hardened axle shaft with different applied heat transfer coefficients to simulate quenching

As an alternative to the physical measurement, computation fluid dynamics models show promise, but these are not necessarily well validated for induction spray quenching conditions and are computationally very expensive. There is a significant amount of work required to convert this portion of the technology from a qualitative assessment to a quantitative tool over time.

TIME DEPENDENCY

Past focus on time dependency in coil design was based upon achieving hardness patterns with available equipment. The main industrial/academic practice for computer modeling of induction hardening was to assume a temperature at which the material would transform from the initial structure to austenite. Oftentimes, this value was taken using the AC3 value from the equilibrium phase diagram for a given steel for hypoeutectoid steels or AC1a for hypereutectoid steels. Sometimes, this value was offset by a certain number of degrees (typically 50 - 100 C), to account for the short-time heat treatment based upon experience of practitioners to achieve the desired hardness. Generally, the utility of this method was limited to a narrow window of materials and processing times.

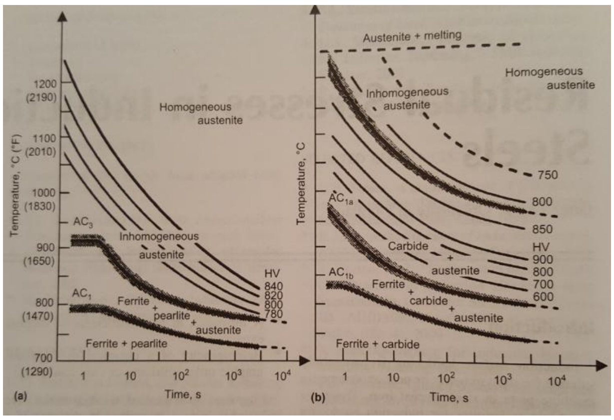


Figure 2. Hypoeutectiod steel CK45 left, hypereutectoid steel 100Cr6 right [8]

Characterization tools are available for the determination of the AC values for times relative to induction heat treatment. The most common tools are dilatometers using induction heating as a source or direct resistance heating. AC values determined using these methods for 2 common European Steels that are induction heat treated were presented by Prof. Liscic in ASM Handbook Volume 4C (Figure 2) [8]. Besides just the AC values being presented, we can also see that even if completely "austentic", the Hv values for the resultant material (assuming adequate quenching) are also time and temperature dependent. For exemplary purposes, if we were to consider a goal of "800 Hv" in the as quenched condition for contour hardening of a fine module gear with heating time of 0.2 s, then the required temperature would be close to 1100 C. If we were to apply that same target to a wheel hub with heating time of 5 seconds, the target temperature would be between 950 and 1000 C.

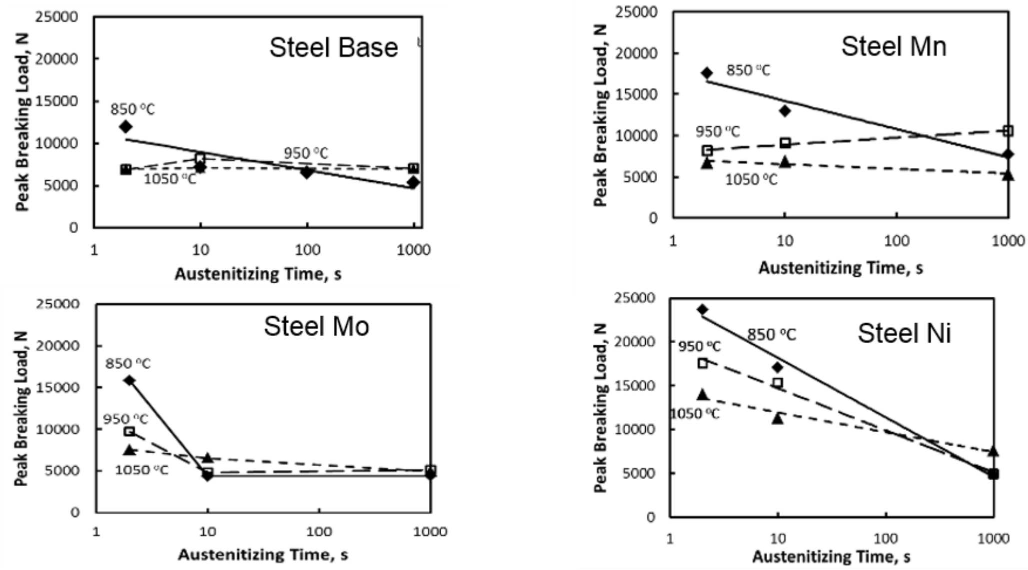


Figure 3. Hypoeutectiod steel CK45 left, hypereutectoid steel 100Cr6 right [7]

Recent data have shown that some of these conditions of inhomogeneous austenite or combinations of austentite and other non-transformed structures are leading to much better component performance. A good example of this is the work of Cryderman and Speer for 0.56wt% carbon steels with various microalloying additions [9]. Their work achieved 3 times higher notch bending fatigue results under some non-equilibrium heating conditions for some of the materials tested at around 2 seconds of hold time. The improvement diminished at varying rates with increasing time (Figure 3).

CONCLUSIONS

Industry is becoming more competitive and it is driving the need for reduced development times while also achieving higher strength to weight and performance to cost ratios. In this environment, virtual methods are required to meet the desired goals for future product development. Traditional virtual methods for simulating the induction heat treating process, considering only the electromagnetic and thermal fields were good qualitative tools for helping to achieve desired heat patterns and hardness specifications.

Recent studies have shown that there can be very large differences in component performance capability (well over 100%) based upon residual stresses or processing time and temperature despite the products having the same or very similar hardness values and heat pattern. These

results highlight the need to develop improved material databases that incorporate the non-equilibrium transformation behavior of materials and to better understand the impact that will have on the resultant component performance. In some cases, such as spray quenching, there is also a need for improved characterization tools and methods to accurately measure heat transfer coefficients.
Future virtual development methods will progressively mature towards simulating the entire manufacturing process chain as well as the performance of that component in the final assembly under real world loading conditions. This will require the integration of many more models into the process and expertise from multi-disciplinary teams to appropriately optimize the induction heat treating process for a given task.

REFERENCES

[1] Persinger, J., Solution Left: The Story of Virtual Heat Treatment Simulation at General Motors, ASM Heat Treating Society Conference, October 22-24th, 2025, Detroit, Mi, USA.
[2] Ivanov, D., et al. "Simulation of stress and strain for induction-hardening applications." *Journal of materials engineering and performance* 22.11 (2013): 3258-3268.
[3] Ivanov, D., John Inge Asperheim, and Leif Markegård. "Residual stress distribution in induction hardened gear." *Heat Treating Conference*. Vol. 84123. ASM International, 2015.
[4] Goldstein, R., et. al., Integrated Computational Development of Induction Heat Treatment Process for Automotive Axle Shafts, *MS&T Conference* October 23–27, 2016, Salt Lake City, UT, USA
[5] Li, Z., et. al., "Effect of Quenching Rate on Distortion and Residual Stresses During Induction Hardening of a Full-Float Truck Axle Shaft," *J. Mat. Eng. Perf.,* vol. 23, pp. 4170-4180, 2014. https://doi.org/10.1007/s11665-014-1196-0
[6] Nemkov, V.S. et al. "Computer Simulation of Induction Heating and Quenching Processes," in *2nd International Conference on Quenching and Control of Distortion, March 1999*, Prague, Czech Republic, 1999.
[7] Goldstein, R., Mackenzie, D. S., Limitations of Standard Probes for the Measurement of Spray Quenchants, *3rd International Conference on Quenching and Distortion Engineering*, May 5-8, 2025, Vancouver, BC, Canada
[8] Rudnev, V., Totten, G., ASM Handbook Volume 4C – Induction Heating and Heat Treatment, ASM International, 2014. https://doi.org/10.31399/asm.hb.v04c.9781627081672
[9] Cryderman, R., Speer, J. Microstructure and Notched Fracture Resistance of Low Alloy 0.56% C Steels after Simulated Induction Hardening. *J. of Materi Eng and Perform* **33**, 4253–4264 (2024). https://doi.org/10.1007/s11665-024-09138-7

Additively Manufactured Copper Inductors for Induction Heating Applications

Dr.-Ing. Johannes Lohn[1]

[1] PROTIQ GmbH, Flachsmarktstraße 54, 32825 Blomberg, Germany
Corresponding author: Dr.-Ing. Johannes Lohn (jlohn@protiq.com)

ABSTRACT.
Induction heating is a widely used industrial process whose performance strongly depends on the design of the copper inductor. Conventional inductors manufactured from bent and joined copper tubes are limited in geometric freedom and cooling integration. Additive manufacturing enables copper inductors with complex geometries, integrated internal cooling channels, and application-specific electromagnetic field distributions. This paper outlines functional principles, advantages, and limitations of additively manufactured copper inductors and compares them with conventional designs. Industrial application examples highlight the suitability of this approach for complex geometries and small to medium batch sizes.

Keywords
Additive manufacturing; Copper; Induction heating; 3D-printed inductors; Metal AM

INTRODUCTION
Induction heating enables efficient and localized heating by inducing eddy currents in electrically conductive workpieces using an alternating magnetic field. The inductor geometry directly influences heating behavior, efficiency, and process stability. Conventional copper inductors are typically manufactured by bending copper tubes and manual assembly, which restricts achievable geometries and cooling concepts. Metal additive manufacturing allows the production of copper inductors with complex three-dimensional shapes and integrated internal structures, enabling application-specific optimization.

PROBLEM DESCRIPTION
Customized inductor geometries are often required for industrial induction heating processes. Conventional manufacturing methods offer limited geometric freedom, restricted cooling integration, and high effort for prototyping and iterative design changes. These constraints can result in non-uniform heating, reduced efficiency, and extended development times.

ADDITIVE MANUFACTURING OF COPPER INDUCTORS
Additive manufacturing enables the layer-wise fabrication of copper inductors directly from digital models. The electromagnetic operating principle is identical to conventional inductors, while the design freedom allows optimized current paths, magnetic field distributions, and cooling channel placement close to current-carrying regions. Manufacturing challenges include copper's high thermal conductivity and reflectivity, as well as post-processing requirements for interfaces and cooling channels.

ADVANTAGES AND LIMITATIONS

Advantages include high design freedom, integrated cooling, reduced assembly steps, and rapid design iteration. Limitations arise from higher manufacturing effort, post-processing needs, and cost efficiency that depends on geometry complexity and production volume.

COST CONSIDERATIONS

While additive manufacturing involves higher material and machine costs, tooling is eliminated. The approach is particularly advantageous for complex geometries and customized inductors in small to medium batch sizes, whereas conventional manufacturing remains cost-effective for simple standard designs and large series.

CONCLUSIONS

Additively manufactured copper inductors provide significant advantages in design flexibility and functional integration. Despite higher manufacturing effort, the technology represents a promising solution for advanced induction heating applications requiring customized and geometrically complex inductors.

Welding techniques for Flow Battery stack manufacturing: a comparative analysis

A. Trovò [1], M. E. Mognaschi[1], F. Dughiero[2], P. Di Barba[1]

[1] Department of Electrical, Computer and Biomedical Engineering, Via A. Ferrata, 5, Pavia - Italy
[2] Department of Industrial Engineering, Via Gradenigo, 6/a, Padova, Italy
Corresponding author: A. Trovò (andrea.trovo@unipv.it)

ABSTRACT. Flow Batteries (FBs) are considered a promising solution for large-scale energy storage especially for Long Duration Energy Storage Services (LDES), due to their safety, long operational lifetime, and flexible scalability. The performance and reliability of these systems strongly depend on the manufacturing quality of the stack, where multiple components must be assembled while ensuring mechanical stability and leak-tight sealing. In this context, welding technologies play a key role in the fabrication process. This paper reviews several welding techniques used for flow battery stack manufacturing, including ultrasonic welding, laser welding and microwave welding, comparing their principles, process parameters, advantages, and potential applications in stack components.

***Keywords*—** Flow Battery, ultrasonic welding, laser welding, microwave welding

INTRODUCTION

A conventional FB system generally consists of electrolyte storage tanks, circulation pumps, piping infrastructure, and a stack where the redox reactions responsible for energy conversion take place. The stack is typically composed of a series of repeating electrochemical cells including bipolar plates, porous electrodes, ion-exchange membranes, sealing elements, and supporting structural frames [1]. Figure 1 shows the scheme of a stack FB single cell.

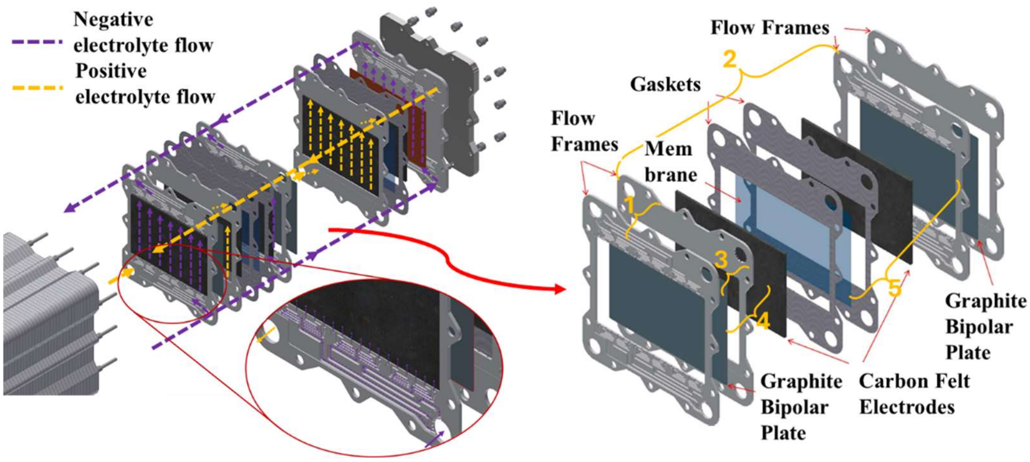


Figure 1. Left: electrolyte distribution in a FB stack. Right: single cell of a FB stack showing the possible joining interfaces achievable through welding techniques: (1–2) between flow frames, (3) between bipolar plate and flow frame, (4) between carbon felt electrode and bipolar plate, and (5) between membrane and flow frame.

PROBLEM DESCRIPTION

The correct assembly of the stack is a critical aspect of system reliability. During operation, the structure must ensure sufficient mechanical stability, adequate electrical conductivity, and chemical compatibility with the circulating electrolyte solutions. At the same time, effective sealing of the fluid channels is required to prevent electrolyte leakage. Even small leaks may lead to performance degradation, contamination of internal components, and potential safety issues. For these reasons, the development of robust and reliable joining techniques represents an important step in the manufacturing of flow battery stacks. The choice of the most suitable joining process is strongly influenced by the materials employed in the stack architecture. These include chemically resistant thermoplastics, graphite-based composite plates, and metallic components used as current collectors. Several welding techniques can be adopted depending on the specific design requirements. Ultrasonic welding, laser welding and very recently microwave welding are possible processes, each characterized by different mechanisms of heat generation, processing conditions, and levels of industrial maturity. Table 1 provides an overview of the main welding techniques discussed in the literature and highlights their typical applications in the various components of FB stacks.

Table 1: Typical process parameters for welding techniques in FB components.

Technique	Principle	Material in FB Stack	Advantages	Limitations	Ref.
Ultrasonic welding	High-frequency (f≈20-40 kHz) mechanical vibrations generate localized heating through friction at the interface between materials.	Polymer frames, thin thermoplastic parts, graphite-polymer composite components	Very short cycle times, low energy consumption, limited distortion	High equipment cost, requires careful joint design; less effective for thick components	[2]
Laser welding	A focused laser beam produces localized heating at the interface of the components (power P ≈ 200-300W, wavelength ≈ 980 nm), enabling precise fusion with minimal thermal impact.	Polymer components, metallic current collectors, sealing structures	High precision, narrow heat-affected zone, suitable for automation	High equipment cost, optical properties of materials must be compatible	[3]
Microwave welding	Electromagnetic microwave radiation (f≈2.45 GHz, P≈170 W) selectively heats materials or conductive fillers at the interface, promoting localized melting and bonding.	Polymer composites with conductive fillers, graphite-polymer bipolar plates, felt electrodes	Rapid heating, lower energy consumption, reduced thermal gradients	Average equipment cost, requires microwave-susceptible materials, promising process	[4]

CONCLUSIONS

This work reviewed several welding approaches applicable to FB stack fabrication, including, ultrasonic, laser, and microwave welding. Each technique presents specific advantages and limitations depending on the materials involved and the design of the stack components. Conventional methods such as ultrasonic welding remain used for polymer-based structures, while laser and microwave welding offer promising opportunities for improved process control and advanced materials. Future research should focus on optimizing process parameters and evaluating long-term durability of welded joints.

REFERENCES

1. Arenas L F, Ponce de León C, Walsh F. C., Engineering aspects of the design, construction and performance of modular redox flow batteries for energy storage. Journal of Energy Storage. 2017; 11: 119-153.
2.Ultrasonic welding Batteries. https://www.sonomax.it/en_gb/sector/batteries/ [Acc 03/2026].
3. Niu Y, Wang Z, Peng T, Li C, Qu F, Qiu W, Guo W, Zhao R, Xu C, Xu Q. Bonding and Adhesion Mechanisms for Laser Transmission Welding of Thermoplastic Polymers in Liquid Flow Batteries. Langmuir 2025; 41 (21):13209-13219.
4. Richtr P, Gerber T, Fischer P, Charvát J, Ress C, Noack J, Hage B, Svoboda M, Gráf D, Beneš J, Mazúr P. Development of high-performance and cost-effective electrode assembly for redox flow batteries. Results in Engineering. 2025; 27: 106285.

Ohmic Heated Catalytic Reactor Structures: Design and Operational Stability Analysis

Engler-Bunte Institut, Karlsruhe Institute for Technology, Karlsruhe/DE;
Marius Weiser, Siegfried Bajohr, Frederik Scheiff

Heating chemical processes using fossil fuels is a major source of greenhouse gas emissions in the chemical industry [1]. One prominent example is methane reforming, which accounts for over 60 % of global hydrogen production and generates approximately 90 million tonnes of CO_2 emissions annually due to the heat demand supplied by fossil fuels [2]. Given the limited availability of sustainable feedstocks or fuels and the fact that they often require energy-intensive conversion processes direct electric heating using CO_2-free electricity offers a promising pathway for decarbonising chemical processes, especially against the backdrop of the rapid expansion of renewable energy sources.

One potential approach is ohmic heating, in which electric current is passed directly through catalytically active or structural components such as honeycombs, foams, lattices, or particle beds thereby releasing process heat in situ within the reaction volume or at the catalyst itself. Laboratory- and pilot-scale studies demonstrate the potential of ceramic semiconductor materials (e.g., SiC) as heating elements; however, a comprehensive understanding of internal heat release, the resulting temperature fields, and the fundamental design principles for high-power-density, operationally safe reactors is currently lacking. NTC (Negative Temperature Coefficient) behaviour of these materials, in particular, poses potential thermal instability, as positive feedback loops can trigger thermal runaway and hazardous operating conditions.

The work presented here systematically develops the physical and mathematical foundations for the design and stability analysis of resistance-heated reactors. It integrates thermodynamic, kinetic, and electrical boundary conditions, formulating the design as an optimization problem that accounts for constraints regarding voltage, current, catalyst requirements, and geometry.

Analysing the time-dependent behaviour of the ohmic heating allows for conclusions regarding the process's steady-state nature and stability, from which fundamental design and operating principles are derived. Figure 1 illustrates exemplarily how the outlet temperature of an axially contacted SiC monolith under axial inert gas (N_2) flow depends on the applied voltage, and highlights the qualitative shift in operating behaviour towards a non-steady thermal runaway behaviour.

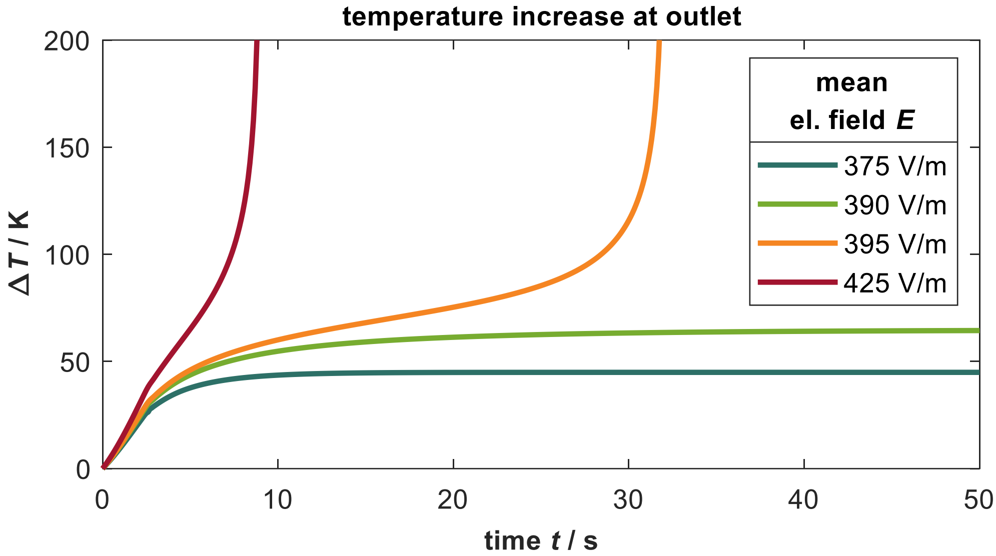


Figure 1 - Development of the outlet temperature of an axially contacted SiC monolith during nitrogen flow (space velocity 1000 h^{-1}) [3]

[1] European Environment Agency, *Total greenhouse gas emissions in the chemical industry (Indicator)* **2024**, https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/total-greenhouse-gas-emissions-in-the-chemical-industry (Accessed on January 28, 2025).

[2] IEA, *World Energy Outlook 2024*, Paris **2024**.

[3] M. Weiser, S. Bajohr, F. Scheiff, *Design and Optimisation of Resistance-Heated Reactors for Catalytic Applications: Methanol Reforming as Case Study*, Jahrestreffen der DECHEMA-Fachsektion Energie, Chemie und Klima (2026), Frankfurt am Main, Deutschland, 24.03.2026 – 25.03.2026, Frankfurt (M) **2026**.

Multi-Load Power Electronic Converter for Induction Heating Domestic Applications

Alejandro Pazvantov[1], Héctor Sarnago[1], and Óscar Lucía[1]

[1]Deparment of Electronic Engineering and Communications, University of Zaragoza.
50018 Zaragoza, Spain.
Corresponding author: Alejandro Pazvantov (alejandropk@unizar.es)

ABSTRACT. This paper presents the analysis, design and implementation of a multi-load electronic converter for domestic induction cooktops, with particular emphasis on its control architecture. The proposed solution consists of a cost-optimized topology with a reduced number of components, capable of delivering up to 3.6 kW and maintaining independent power control of different inductors. The proposal is verified experimentally on a 3.6 kW prototype.

***Keywords*—** Induction heating, microcontroller, converter.

INTRODUCTION

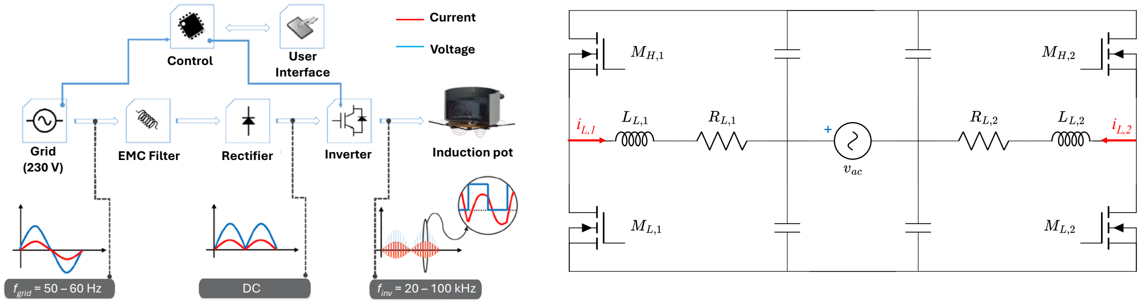
Induction heating has established itself as the chosen technology in numerous industrial [1], domestic [2], [3] and medical applications owing to its advantages in terms of energetic efficiency and operational performance. These features enable a higher-quality and safer heating process, preventing the excessive heating of the vitroceramic glass.

Regardless of the application, induction heating is based on exposing the object to be heated to an alternating magnetic field, which generates heat within the object by electromagnetic phenomena such as eddy currents (in any conductive material) and magnetic hysteresis (mainly in ferromagnetic materials). To generate this magnetic field, an alternating current is driven through a coil referred to as the inductor. The benefits in terms of efficiency, heating speed, safety and precision have led to increasing interest in this technology within the domestic sector.

PROBLEM DESCRIPTION

Current trends in the design of induction cooktops focus on achieving higher efficiency and improved cost-performance ratio, with the aim of increasing market accessibility. To achieve cost-optimized induction cooktops which performance is similar to conventional systems, it is necessary to reduce the hardware in the electronic power stages while preserving the capability of independently controlling each inductor. To date, the simplest way to power the different inductors is to use classic topologies (Figure 1a), typically half-bridges, for each of the inductors. These solutions, however, are costly due to the greater number of components used for the inverter of each inductor.

The main challenge lies in developing a power electronic topology with a reduced component count and optimized cost, while maintaining independent control of each inductor. To overcome this challenge, this paper presents the analysis, design, and implementation of a power electronic converter based on a new low-cost topology (Figure 1b) for domestic induction cooktops, focusing the study on its control architecture. This topology eliminates the need to incorporate a previous rectifier stage, reducing the number of components and the cost, as well as improving the overall efficiency of the system.



(a) (b)

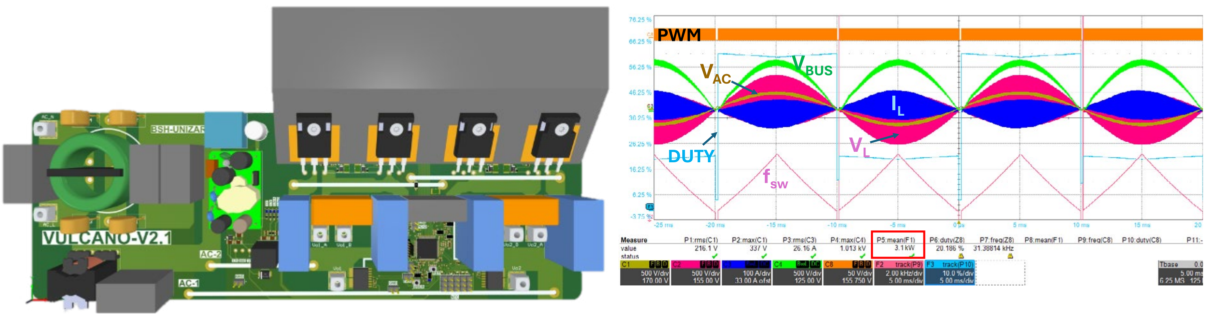
Figure 1. Induction cooktop topologies (a) Classic and (b) New cost-optimized

Control architecture and experimental results

To implement the converter control, a STMicroelectronics microcontroller is used. This approach represents a change from the current paradigm, as an ASIC and microcontroller-based control architecture is typically used. The proposed control architecture integrates synchronised real-time acquisition, DMA-based data transfer, and adaptive modulation.

Experimental results

To validate the proposed converter, a hardware prototype was developed (Figure 2a). The experimental results (Figure 2b) confirm the correct operation of the converter at power levels above 3 kW, demonstrating proper power regulation and robust performance under different load and grid conditions.



(a) (b)

Figure 2. New cost-optimized converter (a) 3D PCB design and (b) Experimental results

CONCLUSIONS

The proposed topology demonstrates the feasibility of designing a cost-optimized power electronic converter for induction cooktops without compromising the independent control capability of each inductor and enabling a significant reduction in the number of components compared to conventional solutions.

REFERENCES

1. V. Esteve, J. Jordan, E. Sanchis-Kilders, E. J. Dede, E. Maset, J. B. Ejea, and A. Ferreres, “Improving the reliability of series resonant inverters for induction heating applications,” IEEE Transactions on Industrial Electronics, vol. 61, pp. 2564–2572, 2014.
2. O. Lucia, J. Acero, C. Carretero, and J. M. Burdio, “Induction heating appliances: Toward more flexible cooking surfaces,” IEEE Industrial Electronics Magazine, vol. 7, pp. 35–47, 2013.
3. P. Guillen, H. Sarnago, J. Acero, J. M. Burdio, S. Llorente, and L. O, “Induction heating appliances: Fifty years of technological success: Paving the path for sustainable homes,” IEEE Industrial Electronics Magazine, vol. 19, no. 3, pp. 51–66, 2025.

Advanced electronic control architecture for electronic power converters applied to induction heating

Maxwell Rodríguez[1], Hector Sarnago[1], Jesus Acero[1], and Oscar Lucía[1]

[1] Department of Electronic Engineering and Communications, University of Zaragoza, 50018 Zaragoza, Spain
Corresponding author: Maxwell Rodríguez (maxwell@unizar.es)

ABSTRACT. Power converters for induction heating increasingly demand higher computing and communications capability to support intelligent control and advanced monitoring. This paper introduces a web-enabled FPGA-SoC that keeps the deterministic acquisition/control pipeline in programmable logic—synchronized sampling, coherent window buffering, autonomous burst transfers to on-chip shared memory —minimizing CPU overhead, while the processing system exposes a lightweight REST service for browser-based monitoring and parameter update. RPU cores execute hard real-time tasks under asymmetric multiprocessing.
Keywords— induction heating, FPGA, inverter.

INTRODUCTION

Induction heating is widely adopted in industrial, domestic, and medical applications thanks to its high efficiency, fast thermal response, and accurate heat regulation[1,2]. It relies on high-frequency excitation to generate an alternating magnetic field that heats the load through eddy currents and hysteresis losses, which demands synchronized real-time sensing. The push toward higher efficiency, power density, and added safety and diagnostic (including predictive) functions is turning induction control into a computing and communications challenge, calling for low latency, time deterministic architectures with robust networked configuration [3].

PROBLEM DESCRIPTION

The objective is to deliver a single platform that merges hard real-time control with remote, browser-based monitoring, without letting communications affect control-loop determinism. The solution therefore targets: (i) synchronous acquisition of key electrical variables and low-latency execution of time-critical functions, (ii) a lightweight communications layer (e.g., REST) that supports smooth visualization and remote parameter updates, and (iii) an efficient low-latency interconnect—based on shared on-chip memory—that guarantees data coherence and scales to higher sampling and monitoring demands.

Proposed hardware architecture

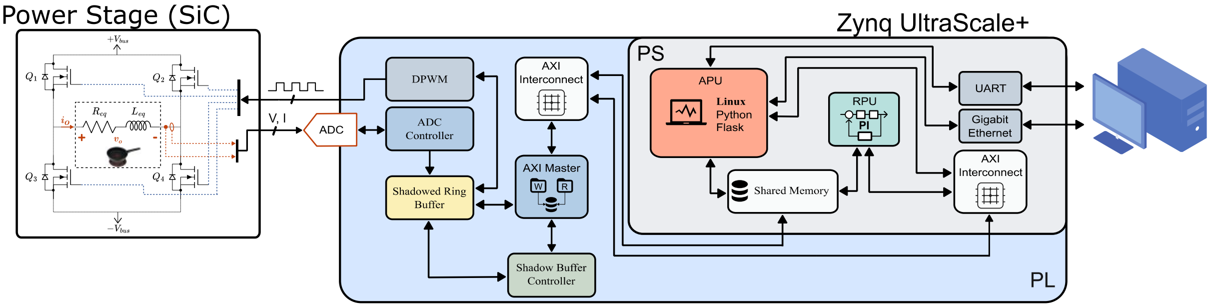
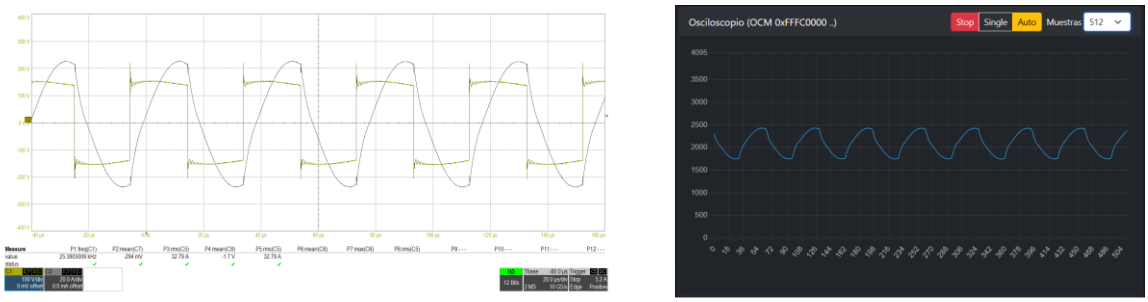


Figure 1. General block diagram of hardware architecture.

Figure 1 provides an overview of the proposed FPGA-SoC architecture, highlighting the PS–PL functional split that isolates the real-time control chain from the communications and monitoring layer accessed from a standard browser.

In the PL, the time-critical path is implemented end-to-end: synchronized acquisition feeds a shadowed ring buffer to extract coherent measurement windows, which are moved to shared memory through high-efficiency AXI burst transfers, while dedicated logic generates the switching/control signals for the power stage. Furthermore, in the PS, a lightweight software stack exposes a REST API for measurement access and parameter adjustment, and the RPU executes coordinated real-time tasks using the same shared-memory map. External connectivity is provided through standard interfaces (e.g., Ethernet/UART), enabling remote supervision without compromising real-time behavior.



(a) (b)

Figure 2. Waveform validation of output current (3.2 kW, 25 kHz): (a) oscilloscope (b) web interface.

CONCLUSIONS

A web-enabled platform has been developed and validated on an FPGA SoC that integrates real-time hardware control and remote monitoring of induction converters into a single SoC, keeping the critical path in PL independent of the services and communications layer. The on-chip link to shared memory reaches 1.506 GB/s in writing (94.1%) and 1.31 GB/s in reading (82.1%) of the AXI4-Full limit, enabling massive acquisition with end-to-end latencies below 45 ms. Validation at 3.2 kW and 25 kHz confirms consistency between oscilloscope and web display. This approach anticipates the direction of next-generation induction cooktops: more connected, observable, and upgradeable, ready for advanced diagnostics and energy optimization without losing robust timing behavior.

REFERENCES

[1] Lucía O, Maussion P, Dede EJ, Burdío JM. Induction Heating Technology and Its Applications: Past Developments, Current Technology, and Future Challenges. IEEE Transactions on Industrial Electronics 2014;61:2509–20.

[2] Guillén P, Sarnago H, Acero J, Burdío JM, Llorente S, Ó L. Induction Heating Appliances: Fifty Years of Technological Success: Paving the Path for Sustainable Homes. IEEE Industrial Electronics Magazine 2025;19:51–66.

[3] Díaz Llerena E, Mateos Gil R, Pavón Luque J, Calvo Guillén D. Versatile SoC architecture for integration of HW accelerators in power electronics applications. 2021 22nd IEEE International Conference on Industrial Technology (ICIT), vol. 1, 2021, p. 817–22.

An ultra-thin plate-level micropump for liquid cooling systems

Tianfeng Liu, and Xiaobing Luo

School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China
Corresponding author: Xiaobing Luo (luoxb@hust.edu.cn)

ABSTRACT. The pursuit of higher performance in portable electronics intensifies the conflict between thermal dissipation and space constraints. To address this, this paper proposes and validates an active liquid cooling solution with an ultra-thin plate-level micropump. The core innovation lies in the co-design framework of the micropump's electromagnetic and hydraulic components, which enables deep physical coupling between the electromagnetic actuator and the heat exchange unit. The fabricated prototype (50 × 50 × 10 mm^3) delivers a maximum flow rate of 950 mL/min and a maximum pressure head of 70 kPa. Thermal performance test demonstrates the effectiveness of the liquid cooling system.

***Keywords*—** thermal management, active liquid cooling, co-design framework

INTRODUCTION

The advancement of artificial intelligence and high-performance computing technologies imposes more stringent demands on thermal management capabilities[1]. However, there is a fundamental trade-off between cooling performance and device compactness. While active liquid cooling offers advantages over air cooling in temperature uniformity and heat dissipation capacity, its implementation depends critically on the size and performance of micropumps[2]. This study adopts a horizontal stacking arrangement of electromagnetic and hydraulic components to realize a slimmer profile. The radial dimensions of the two subsystems become mutually constraining, so it is imperative to pursue an integrated co-design methodology.

DESIGN PROCESS AND RESULTS

Figure 1(a) illustrates the structure of the micropump with horizontally stacked hydraulic and motor components. Under the excitation of the driving signal, the stator generates an alternating magnetic field, which drives the magnet steel (and thereby the impeller) to rotate about the shaft. This rotation draws in low-pressure liquid and discharges high-pressure liquid.

Design methods

Figure 1(b) illustrates the co-design framework for the hydraulic and motor components. The procedure begins with selecting the rotational speed based on requirements. The respective parametric design spaces of the two subsystems are then computed. An iterative optimization is subsequently performed under the given geometric constraints, continuing until a design point is identified that meets the performance requirements while achieving the highest possible overall system efficiency.

Hydraulic performance test

Figure 1(c) illustrates the hydraulic performance test bench. Once powered, the micropump draws low-pressure fluid from the water tank and delivers it through the flow meter before the fluid returns to the tank, with a differential pressure gauge (DPG) monitoring the pressure drop across the pump. The resultant performance curve is plotted in Figure 1(d). Comparison with simulation results shows consistent trends between the simulated and measured data, with an error margin of less than 10%.

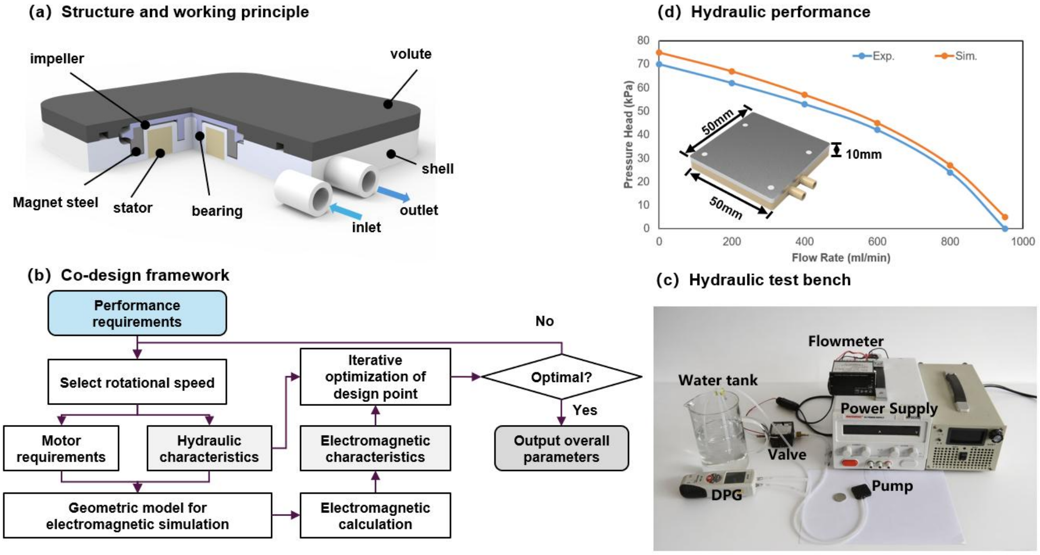


Figure 1. Design process and results of micropump.

Thermal performance test

Figure 2 shows thermal performance test bench and results. Comparative thermal performance tests demonstrate that the advantage of liquid cooling over air cooling becomes more pronounced as the heat source power increases. At an ambient temperature of 24.5°C, for a 190W heat source, the same-sized air-cooling module can only maintain a temperature of 93.5°C, whereas the liquid cooling system incorporating the proposed micropump significantly reduces this temperature to 77.0°C, achieving a temperature drop of 16.5°C.

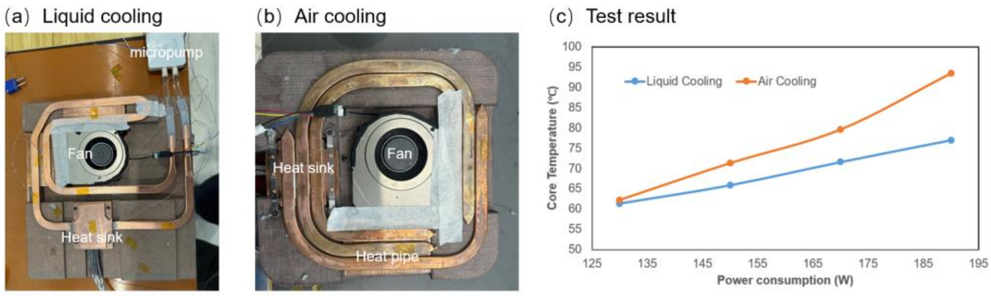


Figure 2. Thermal performance test bench and results.

CONCLUSIONS

This study developed an ultra-thin plate micropump for liquid cooling systems by introducing a hydraulic-electromagnetic co-design methodology. The fabricated prototype measuring 50 × 50 × 10 mm³ delivers a maximum flow rate of 950 mL/min and a maximum head of 70 kPa. At 24.5°C ambient temperature, the micropump-based liquid cooling system kept the 190 W source at 77.0°C, achieving a temperature reduction of 16.5°C compared to the air-cooled solution.

REFERENCES

1. Li Z. Comprehensive review and future prospects on chip-scale thermal management: Core of data center's thermal management. Applied Thermal Engineering. 2024; 251:123612.
2. Mohith S, Karanth PN, Kulkarni SM. Recent trends in mechanical micropumps and their applications: A review. Mechatronics. 2019;60:34-55.

Thermographic Risk Assessment and Electromagnetic Optimization of an Induction Sealing Process

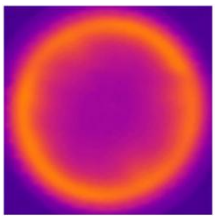
A. Doni[1], M. Lazzarin[1], N. Sinigaglia[1], M. Zerbetto[1]

[1] InovaLab, Vicolo Vincenzo Bellini 10F, Padova, Italy
Corresponding author: N. Sinigaglia[1] (n.sinigaglia@inovalab.eu)

ABSTRACT
Induction sealing of aluminium foils is a critical operation in the packaging of corrosive detergents, since an incomplete seal may cause leakage and compromise a production batch. This work combines thermographic process monitoring with electromagnetic redesign to estimate sealing risk and improve process robustness. Because the aluminium foil is hidden by the plastic cap, its temperature cannot be measured directly during production. The relevant cap pixels are converted into a temperature histogram with 1 °C bins between 16 and 55 °C. A Bayesian Noisy-OR model is trained on a binary dataset of correct and incorrect seals, providing an interpretable risk coefficient for each temperature. Process adjustment based on this result reduced the observed defective-seal rate from 2.8% to 2.1%, a 25% relative reduction. Electromagnetic simulation also showed a 34% peak-to-minimum variation of deposited power density in the original system. A redesigned inductor reduced the simulated variation to 9%.

***Keywords*—** Thermography, Induction, Packaging, Sealing, Risk assessment

INTRODUCTION
Induction heating enables rapid and contactless energy transfer to conductive materials. In induction sealing, a conductive aluminium foil below a plastic cap is heated and bonded to the container. In the investigated production line of corrosive products, the quantity most directly related to sealing quality — the foil temperature — was not optically accessible. Infrared thermography provides non-contact surface-temperature information [1], but in this case it can only observe the external plastic cap. The objective was therefore to extract an interpretable relation between the visible thermal signature and the probability of sealing failure, and to combine this information with electromagnetic simulation to identify both suitable operating conditions and a more uniform inductor design. Figure 1a shows an example of a cap infrared image and Figure 1b shows the external annular region considered in the analysis.



(a)

(b)

Figure 1. (a) A cap thermography. (b) The region of interest selected in the cap analysis.

PROBLEM DESCRIPTION

Production tests were performed to create a binary classification dataset in which each cap was labelled as correctly or incorrectly sealed. The region of interest of each cap is summarized in a vector B containing histogram bins from 16 to 55 °C. A Bayesian Noisy-OR risk model [2] was fitted to the data. The implemented failure probability is evaluated as in eq. (1).

$$P(failure|B) = 1 - e^{-(k_b + \sum_T k_T * \max(0, B_T - d))}, \quad d = 0.002 \qquad (1)$$

where k_T is the risk coefficient associated with the T-th temperature bin and k_b a learned baseline value. Unlike a black-box classifier, the fitted coefficients can be inspected directly and associated with process temperature. Figure 2 shows k_T fitted values, showing three regimes: below 34 °C the values are extremely high as the foil receives insufficient energy; between 34 and 41 °C the risk is minimum; above 41 °C it increases progressively, indicating excessive energy transfer. The identified optimal range was used to adjust the production conditions. The measured defective-seal rate decreased from 2.8% before optimization to 2.1% afterwards. The estimated risk cannot become negligible, however, because the measured temperature belongs to the plastic cap rather than to the aluminium foil. Heat diffusion through the cap smooths local temperature differences and can hide non-uniformities that remain relevant to sealing quality. To quantify this limitation, the original induction system was analyzed through electromagnetic simulation. The deposited power density showed a 34% difference between maximum and minimum values along the relevant sealing region. A new inductor geometry was therefore designed to improve electromagnetic uniformity. In simulation, the redesigned configuration reduced the same peak-to-minimum variation to 9%.

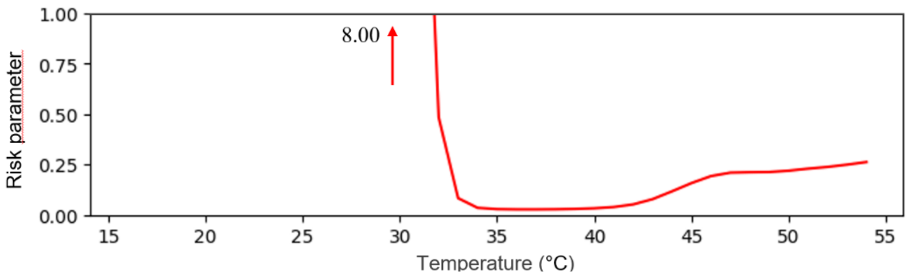


Figure 2. fitted value of each risk parameter k_T. The learned k_b is 0.025.

CONCLUSIONS

An interpretable method for monitoring and optimizing an industrial induction-sealing process has been presented. Thermographic data from the plastic cap was associated with sealing failures through a Bayesian Noisy-OR model. The learned coefficients identified 35–40 °C as the best cap-temperature range and supported a process adjustment that reduced defective seals from 2.8% to 2.1%. The analysis also highlighted the limitation of indirect thermography. A redesigned inductor reduced the simulated deposited-power variation from 34% to 9%. Validation of the new system will determine the additional improvement in sealing reliability.

REFERENCES

1. R. Usamentiaga, P. Venegas, J. Guerediaga, L. Vega, J. Molleda, and F. G. Bulnes, "Infrared Thermography for Temperature Measurement and Non-Destructive Testing," Sensors, vol. 14, no. 7, pp. 12305–12348, 2014, doi: 10.3390/s140712305.

2. J. Pearl, Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference. Morgan Kaufmann, 1988, Pages 381-414, doi: 10.1016/B978-0-08-051489-5.50014-X

Physics-Informed Graph Neural Network for Fast Thermal Prediction in Induction Heating

Antons Cvečkovskis[1, 2]

[1] University of Oslo
[2] CENOS, Lastādijas iela 8 k-1, Rīga, Latvia
Corresponding author: A. Cvečkovskis (antons@cenos-platform.com)

ABSTRACT. Induction heating needs fast EM–thermal simulations for control and optimisation. The Finite Element Method is accurate but costly. In this paper, we propose a physics-informed GNN for transient heat modelling on unstructured meshes and a physics-informed EM surrogate that predicts A and ϕ in the frequency domain. Each model is validated against FEM on representative geometries. The thermal model predicts multi-step rollouts. We target robust physics-informed graph learning for transient thermal fields and a pathway to coupled EM–thermal prediction suitable for industrial induction heating.

Keywords— Induction heating; Physics-informed graph neural networks; Maxwell's equations; Joule heating; Surrogate modelling

INTRODUCTION

Induction heating is commonly used for heat treatment and process heating; however, accurate multi-physics simulations can be computationally intensive, particularly for iterative design, optimisation, and control [1]. The coupled electromagnetic-thermal problem is generally non-linear, especially when electrical conductivity and magnetic permeability vary with temperature.

Recent advancements in graph neural network models, such as MeshGraphNets, offer a framework for learning on unstructured meshes while maintaining locality and geometric inductive bias [2]. Physics-informed MeshGraphNets have demonstrated that using FEM-style residuals can enable data-efficient learning for transient problems on arbitrary meshes [3].

Building on these advancements, this digest presents a PI-GNN approach for induction heating that utilises separate electromagnetic and thermal surrogates, trained with discretisation-consistent residual losses and validated against FEM simulations using NGSolve [4]. It also outlines a roadmap towards developing a coupled, temperature-dependent surrogate.

PROBLEM DESCRIPTION

We consider a 2D axisymmetric domain: a conductive workpiece, a stranded-coil region, and the surrounding air. The thermal model incorporates a convective boundary condition at the interface between the workpiece and the air. A Neumann symmetry condition is applied along the symmetry axis. The $t_{end} = 1s$ and $\Delta t = 0.1$ s. The current rollout predicts the next n = 5 time steps.

The electromagnetic surrogate focuses on a frequency-domain eddy-current formulation represented in an $A - \phi$ framework [5]. From the predicted fields, the complex electric field is calculated as $E = -j\omega A - \nabla\phi$ and $q(x) = 1/2\,\sigma(T)\,|E(x)|^2$.

The thermal surrogate predicts temperatures $T^{n+1}, T^{n+2}, \ldots, T^{n+n_{roll}}$ based on the previous state T^n and the heating source q^n. A discretisation-consistent residual is constructed using FEM assembled mass and stiffness matrices, along with boundary and load contributions. For a single time step, the per-time-step residual $R^{n+1}\left(\tilde{T}^{n+1}, T^n\right)$ is defined as

$$R^{n+1} = (1/\Delta t\,\mathbf{M} + \mathbf{K})\,T^{n+1} - 1/\Delta t\,\mathbf{M}T^n - \mathbf{Q}(T^{n+1}) - g, \quad (1)$$

where $\mathbf{M}$ and $\mathbf{K}$ represent the finite element method mass and conductivity matrices, respectively. The $\mathbf{Q}(\cdot)$ denotes the source term, and g is the boundary flux. Given a prediction from the PI-GNN denoted as $\tilde{T}^{n+1}$, the physics-informed loss is calculated for the free DOFs using $\mathcal{L}_{\text{FEM}}^{n} = ||R^{n+1}(\tilde{T}^{n+1}, T^{n})||_2^2$. This loss is normalised by the number of free DOFs and equals zero when $\tilde{T}^{n+1}$ aligns with the FEM solution.

For the electromagnetic surrogate, an objective is formulated based on the complex residual $r = \mathbf{K}a - f$, similar to equation (1), which is separated into real and complex parts and normalised by a number of DOFs.

The induction heating problem is solved by combining the two models, as can be seen in the Figure 1. At time t^n, the EM surrogate is evaluated using the current temperature-dependent properties, starting with $\sigma(T^n)$, to derive q^n. Following this, the thermal surrogate updates the temperature from T^n to T^{n+1} using the method outlined in equation (1).

Both surrogates use a MeshGraphNet [2] architecture (12 message-passing layers, MLP-128).

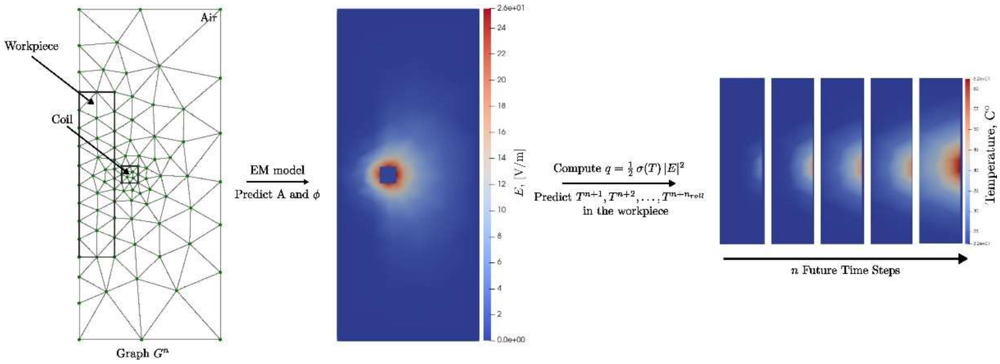


Figure 1. An outlook of the IH surrogate model (EM+Thermal).

CONCLUSIONS

This digest presents a framework for developing induction heating surrogates using physics-informed MeshGraphNets on unstructured meshes.

A harmonic $A - \phi$ electromagnetic Physics-Informed Graph Neural Network is utilised to predict complex potentials and calculate Joule heating. Additionally, a transient thermal PI-GNN performs multi-step rollouts, trained using a FEM—assembled weak residual. The next step is to couple these surrogates via operator splitting, thereby incorporating temperature-dependent properties.

REFERENCES

1. Rudnev V, Loveless D, Cook RL, Black M. Handbook of Induction Heating. First edition. Boca Raton, FL: CRC Press; 2002.

2. Pfaff T, Fortunato M, Sanchez-Gonzalez A, Battaglia PW. Learning Mesh-Based Simulation with Graph Networks. doi.org/10.48550/arXiv.2010.03409

3. Würth T, Freymuth N, Zimmerling C, Neumann G, Kärger L. Physics-informed MeshGraphNets (PI-MGNs): Neural finite element solvers for non-stationary and nonlinear simulations on arbitrary meshes. https://doi.org/10.1016/j.cma.2024.117102

4. Schoberl J. C++11 Implementation of Finite Elements in NGSolve.

5. Jin J-M. The finite element method in electromagnetics. Third edition. Hoboken. New Jersey: John Wiley & Sons Inc; 2014.

Electromagnetic Property Identification of Domestic Induction Heating Loads using Neural Networks

J. Acero[1], Ó. Lahuerta[1], D. Navarro[1], C. Carretero[2], I. Lope[2], J.M. Burdío[1]

[1] Dpt. of Electronic Engineering and Communications, University of Zaragoza, Spain
[2] Dpt. of Applied Physics, University of Zaragoza, Spain
Corresponding author: J. Acero (jacero@unizar.es)

ABSTRACT. This work proposes a method for identifying the electrical conductivity and magnetic permeability of cookware used in domestic induction heating applications through deep learning techniques. Specifically, the method employs Convolutional Neural Networks (CNN) to extract features from time-domain voltage and current waveforms at the inductor. The approach leverages the fact that the electromagnetic properties of the load determine the impedance and, consequently, the response of the system. Validation shows that the proposed CNN architecture can accurately estimate these parameters, providing a robust tool for optimizing induction system performance and safety.

Keywords— Induction heating, electromagnetic properties, neural networks, deep learning.

INTRODUCTION

Domestic induction heating (IH) is a mature technology characterized by its high efficiency, safety, and fast heating rates. The performance of these systems is highly dependent on the coupling between the induction coil and the cookware. To ensure optimal energy transfer and satisfactory user experience, it is crucial to identify the electromagnetic properties of the load—specifically, the electrical conductivity (σ) and the relative magnetic permeability (μ_r).

Traditional identification methods often rely on manufacturer-provided specifications or standardized data sheets. In contrast, this work introduces a data-driven approach using deep learning, specifically CNNs, which have shown high performance in feature extraction from current and voltage waveforms within the field of power electronics.

PROBLEM DESCRIPTION

In IH the coupled inductor-load system's equivalent impedance Z=R+jωL varies significantly depending on the material and geometry of the cookware. This work focuses on identifying σ and μ_r by analyzing the current and voltage waveforms at the inverter output. Rather than identifying σ and μ_r separately, the ratio σ/μ_r (which is related to the impedance boundary condition of the load [1]) is identified. Furthermore, the permeability is treated as a complex quantity $\mu_r=\mu'_r-\mathrm{i}\cdot\mu''_r$, therefore, the CNN is designed to predict both the modulus and phase of σ/μ_r. Figure 1 illustrates the proposed prediction scheme. A dataset of R_{eq} and L_{eq} is is generated through finite element frequency-domain simulations over a specific range of $\sigma/(\mu'_r-\mathrm{i}\cdot\mu''_r)$ values. These parameters are then integrated into a time-domain analytical simulator—based on the state-space equations of a series resonant half-bridge inverter—to obtain the training waveforms. This data feeds the CNN, which outputs the modulus and phase of $\sigma/(\mu'_r-$

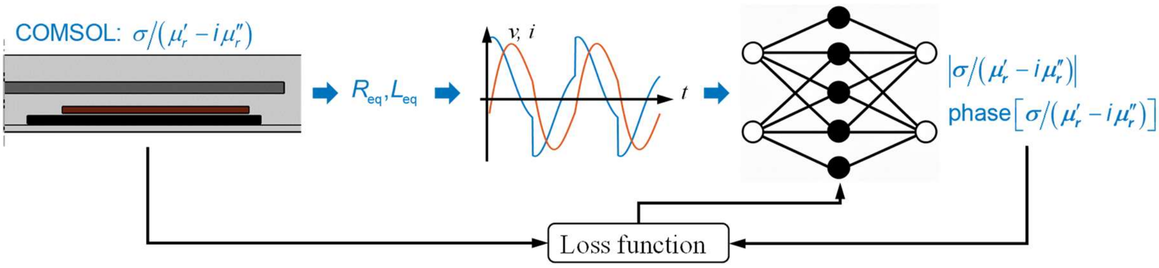


Figure 1. Schematic representation of the proposed estimation method of $\sigma/(\mu_r' - \mathrm{i}\mu_r'')$.

i·μ''_r). This value is compared against the original inputs via a loss function L. Finally, the μ_r complex value can be derived if σ is known.

The proposed method is validated using a ferromagnetic material from the COMSOL library, specifically *Stainless Steel 430 Annealed*, which has a conductivity of σ=1.74 MS/m. The material's average permeability is derived from the COMSOL dataset. Figure 2 compares these values with the real and imaginary parts predicted by the CNN across various inverter DC supply voltage amplitudes. As shown, the real component of the predictions follows a similar trend to the co-simulation results. The imaginary component remains negligible at low excitation levels and stabilizes as the material reaches saturation. These trends are consistent with those reported in the literature [1].

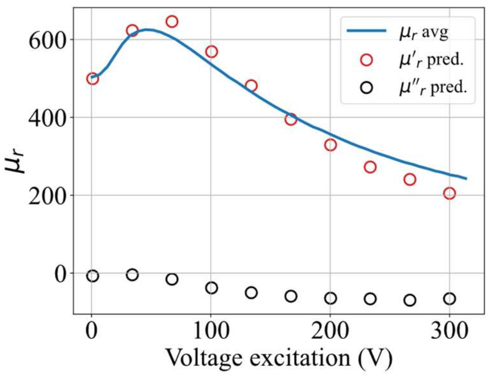


Figure 2. Comparison of ttheoretical and predicted permeability of the *Stainless Steel 430 Annealed*

The information provided by the synthesis tool points that the used CNN is very simple, being an 1D CNN with only three layers.

CONCLUSIONS

This work shows the feasibility of using Convolutional Neural Networks for the identification of electromagnetic properties in induction heating loads. The key of the method is to predict the relationship $\sigma/(\mu'_r$-i·$\mu''_r)$ instead of predicting separately the conductivity and the permeability. By processing raw temporal waveforms, the CNN effectively captures the underlying physical parameters. The obtained results and the simple structure of the CNN paves the path for an on-line non-destructive identification method.

REFERENCES

1. Yuferev S., Ida N. Surface Impedance Boundary Conditions. In: Proceedings of the XII International. A Comprehensive Approach, 1st ed. Boca Raton, FL, USA. CRC Press. 2009.

2. Carretero C., Acero J., Burdío J.M. Normalized nonlinear impedance boundary condition in anhysteretic magnetic material for eddy current problems. IEEE Transactions on Magnetics. 2024.

AI Agent-Based Automatic Mesh Generation for Induction Heating Simulation with Automatic Boundary Layer Control

Y. Shimizu[1,2,3], A. Takahashi[2], Kengo Sugahara[4], and Keiko Sugahara[4]

[1] College of Science and Engineering, Ritsumeikan University, Shiga, 5258577 Japan
[2] MotorAI Inc., Shiga, 5258577 Japan
[3] Faculty of Engineering, Yokohama National University, Yokohama, 2408501 Japan
[4] Faculty of Science and Engineering, Kindai University, Higashiosaka, 5778502 Japan

Corresponding author: Y. Shimizu (yu-shimizu@motorai.jp)

ABSTRACT. This paper presents an AI agent system that performs automatic three-dimensional mesh generation for induction-heating finite-element analysis. Given natural-language instructions, the agent automatically identifies conducting regions in a CAD model and generates skin-depth-aware boundary-layer wedge meshes with appropriate parameters. Evaluation on 10 benchmark models, including industrial geometries, shows that the agent produces meshes with a mean Scaled Jacobian deviation of 0.32% from expert-created meshes, demonstrating that the agent can automatically generate boundary-layer meshes of expert-level quality.

Keywords— Induction heating, mesh generation, AI agent, finite-element method.

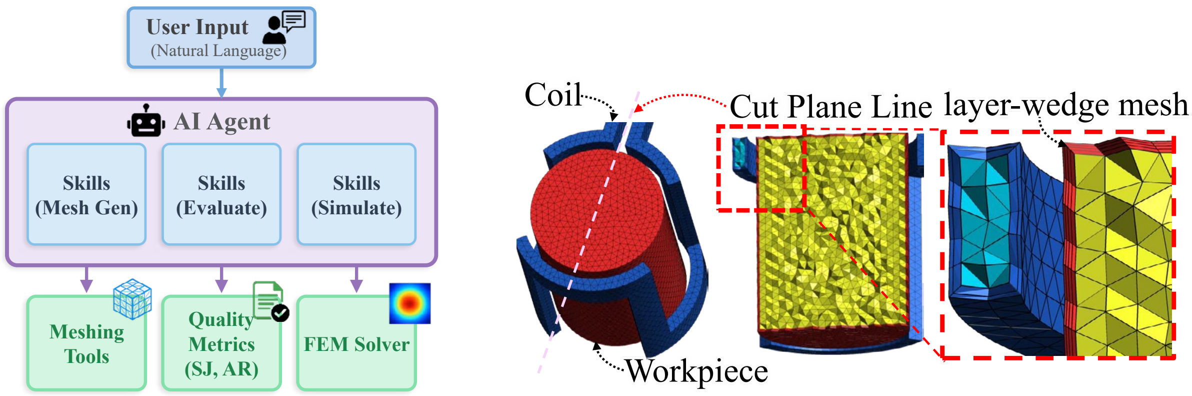
INTRODUCTION

Finite-element analysis of induction heating (IH) requires volume meshes that resolve the electromagnetic skin effect. Accurate modeling demands boundary-layer meshes whose element sizes conform to the skin depth, but configuring these parameters — first-layer height, growth ratio, and number of layers — requires domain expertise and trial-and-error for each geometry. In [1], we demonstrated automatic generation of 2D quadrilateral meshes; however, that approach was limited to simple 2D geometries and lacked adaptive decision-making. While neural-network-based mesh density prediction has been studied [2], no prior work has addressed skin-depth-aware 3D boundary-layer mesh generation for IH problems using an AI agent. This study proposes, to the best of our knowledge, the first AI agent that automatically identifies conducting regions, determines skin-depth-based boundary-layer parameters, and generates 3D wedge meshes through iterative quality optimization.

PROPOSED METHOD

The proposed system combines human oversight with an AI agent built on a large language model (Claude Sonnet 4.5, Anthropic) that operates a commercial meshing engine. Given a CAD model, material properties, and natural-language instructions, the agent identifies conducting surfaces requiring skin-depth resolution, configures boundary-layer wedge meshes, generates volume meshes, and iteratively optimizes quality (Figure 1(a)). Unlike rule-based scripts, the agent performs context-dependent reasoning — interpreting geometry features, relating quality metrics to physical requirements, and adapting its strategy — allowing it to handle diverse IH geometries without geometry-specific programming.

The boundary-layer mesh is configured by three parameters: first-layer height, growth ratio, and number of layers, determined from the electromagnetic skin depth δ. Figure 1(b) shows an example where the agent automatically identified the conducting surfaces of an industrial model and generated a 4-layer wedge boundary-layer mesh for skin-depth resolution, with tetrahedral elements filling the interior. The agent evaluates the Scaled Jacobian (SJ) metric and iteratively adjusts mesh sizes and boundary-layer parameters until all elements satisfy SJ > 0.2, which is generally required for reliable FEA convergence [3].



(a) AI agent system overview

(b) Agent-generated boundary-layer mesh

Figure 1. (a) AI agent system workflow. (b) Agent-generated mesh for an industrial IH model: cross-section showing wedge boundary-layer elements at the conducting surface.

EVALUATION AND RESULTS

Ten 3D IH benchmark models (seven simplified, three industrial) comprising 58 mesh blocks in total were used. To validate the quality of agent-generated meshes, each was compared with a mesh created by a human expert (co-author).

Table 1 summarizes the results. Overall, 91% of blocks (53/58) fell within $\pm 1\%$ SJ Mean deviation and 98% within $\pm 5\%$. Boundary-layer meshes showed particularly close agreement (SJ Mean deviations below 0.2%), confirming that the agent's automatic skin-depth-based parameter selection produces wedge meshes consistent with expert practice.

Table 1: Mean SJ deviation between agent and expert meshes [%]

	All (58)	Simplified (40)	Industrial (18)
SJ Mean	0.32	0.35	0.27
SJ Mean (BL only)	0.14	0.18	0.07

CONCLUSIONS

An AI agent system that automatically generates skin-depth-aware boundary-layer wedge meshes for 3D IH finite-element analysis was proposed. Evaluation on 10 benchmarks, including industrial geometries, confirmed that the agent produces meshes with SJ Mean deviation of 0.32% from expert meshes, with 91% of blocks within $\pm 1\%$. The full paper will present the detailed system architecture, the meshing engine integration, and coupled electromagnetic–thermal simulation results.

REFERENCES

1. Y. Shimizu, K. Sugahara, and K. Sugahara. Automatic quadrilateral mesh generation system using large language model. In *Proc. of COMPUMAG 2025*, 2025.
2. R. Chedid and N. Najjar. Automatic finite-element mesh generation using artificial neural networks — Part I: Prediction of mesh density. *IEEE Trans. Magn.*, 32(5):5173–5178, 1996.
3. P. M. Knupp. Algebraic mesh quality metrics. *SIAM J. Sci. Comput.*, 23(1):193–218, 2001.

Comparison of methods based on surrogate models on the example of induction heating process optimization

J. Wyciślik[1] and S. Golak[1]

[1] Department of Industrial Informatics, Faculty of Materials Engineering and Digitalisation of Industry, Silesian University of Technology, ul. Krasińskiego 8, 40-019 Katowice, Poland
Corresponding author: J. Wyciślik (jakub.wycislik@polsl.pl)

ABSTRACT. Optimization problems in electromagnetic engineering are often limited by the high computational cost of finite element simulations required for evaluating the objective function. Surrogate models offer a promising solution by significantly reducing computation time while maintaining acceptable accuracy. This work presents a conceptual comparison of selected surrogate modeling approaches and their integration within an optimization framework, demonstrated on a 3D induction heating problem. The focus is placed on different model types, including Gaussian processes and neural network ensembles, as well as on acquisition strategies guiding the selection of new evaluation points.

Keywords**—** induction heating, process optimization, surrogate models, finite element analysis.

INTRODUCTION

Optimization of electromagnetic processes, such as induction heating or electromagnetic levitation, involves complex physical phenomena including eddy currents and field distributions. These problems are typically solved using the finite element method, which ensures high accuracy but entails a significant computational burden for each simulation [1, 2]. In parametric optimization, requiring repeated evaluations of the objective function, this cost becomes a major limitation. Surrogate-based optimization methods address this issue by replacing the expensive numerical model with a computationally efficient approximation [3, 4]. Recent studies demonstrate the effectiveness of such approaches in electromagnetic applications [5], yet there remains a need for systematic comparison of different surrogate models and their integration within the optimization process.

PROBLEM DESCRIPTION

The considered problem involves the optimization of a 3D induction heating process, where the objective function is evaluated using finite element simulations. The reference model was implemented using Gmsh and GetDP, enabling accurate electromagnetic field analysis at the cost of high computational effort. To address this limitation, a surrogate-assisted optimization framework was developed in Python, utilizing libraries such as PyTorch, scikit-learn, and GpyTorch, as well as code developed by the authors. Within this framework, the surrogate model approximates the objective function, providing both predictive mean and uncertainty, which are used to guide the selection of new sampling points. Different classes of surrogate models are considered, including Gaussian processes [6], as well as neural network ensemble approaches offering increased modeling flexibility. Various acquisition strategies, such as Expected Improvement, are analyzed to balance exploration and exploitation [7]. The study focuses on illustrating the general optimization workflow, highlighting the role of prediction and uncertainty propagation in the decision-making process. The proposed approach aligns with recent developments in surrogate modeling for electromagnetic systems [5, 8, 9].

CONCLUSIONS

The presented concept demonstrates that surrogate models can significantly reduce the computational cost of optimization in complex electromagnetic problems, enabling more efficient exploration of the design space. The comparison of different model types and acquisition strategies indicates that the choice of surrogate model plays a key role in overall performance. In particular, alternatives to Gaussian processes and more advanced sampling strategies offer promising directions for further improvement. The proposed approach is conceptual in nature and provides a foundation for future research on more efficient surrogate-assisted optimization methods in electromagnetic applications.

REFERENCES

1. Queipo NV, Haftka RT, Shyy W, Goel T, Vaidyanathan R, Kevin Tucker P. Surrogate-based analysis and optimization. Progress in Aerospace Sciences 2005;41:1–28. https://doi.org/10.1016/j.paerosci.2005.02.001.

2. Sacks J, Welch WJ, Mitchell TJ, Wynn HP. Design and Analysis of Computer Experiments. Statist Sci 1989;4. https://doi.org/10.1214/ss/1177012413.

3. Forrester AIJ, Sóbester A, Keane AJ. Engineering Design via Surrogate Modelling 2008. https://doi.org/10.1002/9780470770801.

4. Shahriari B, Swersky K, Wang Z, Adams RP, de Freitas N. Taking the Human Out of the Loop: A Review of Bayesian Optimization. Proc IEEE 2016;104:148–75. https://doi.org/10.1109/jproc.2015.2494218.

5. Zorzetto M, Torchio R, Lucchini F, Forzan M, Dughiero F. Proper Orthogonal Decomposition for Parameterized Macromodeling of a Longitudinal Electromagnetic Levitator. IEEE Trans Magn 2025;61:1–7. https://doi.org/10.1109/tmag.2025.3542131.

6. Rasmussen CE, Williams CKI. Gaussian Processes for Machine Learning 2005. https://doi.org/10.7551/mitpress/3206.001.0001.

7. Snoek J, Larochelle H, Adams RP. Practical Bayesian Optimization of Machine Learning Algorithms 2012. https://doi.org/10.48550/ARXIV.1206.2944.

8. Zybała R, Wyciślik J, Golak S, Ciepliński P, Sak T, Madej P. Fast Numerical Optimization of Electrode Geometry in a Two-Electrode Electric Resistance Furnace Using a Surrogate Criterion Derived Exclusively from an Electromagnetic Submodel. Applied Sciences 2024;14:10957. https://doi.org/10.3390/app142310957.

9. Golak S, Wyciślik J, Zybała R, Hanusek R. Numerical Modeling and Optimization of Large-Scale Molten Titanium Levitation. Materials 2025;18:1268. https://doi.org/10.3390/ma18061268.

Discrepancy Correction in Surrogate Models for Nonlinear Thermal Problems

M. Zorzetto[1], R. Torchio[1,2], F. Lucchini[1], M. Forzan[1] and F. Dughiero[1]

[1] Department of Industrial Engineering, University of Padova, 35131 Padova, Italy
[2] Department of Information Engineering, University of Padova, 35131 Padova, Italy
Corresponding author: M. Zorzetto (matteo.zorzetto@phd.unipd.it)

ABSTRACT. Accurate and computationally efficient models are essential for the real-time monitoring of electrical devices. The finite element method (FEM) is a powerful tool for simulating thermal problems, however, FEM models are often too large and computationally demanding to be executed in real-time on low-cost hardware. Model order reduction (MOR) techniques address this issue by constructing significantly smaller reduced-order models (ROMs) while introducing only a minimal loss of accuracy. Nevertheless, MOR techniques remain challenging to apply to nonlinear problems. In this work, a discrepancy modeling framework is employed to correct, rather than replace, linear reduced-order models, thereby enabling them to capture nonlinear effects while retaining their computational efficiency.

Keywords— Model Order Reduction (MOR), Discrepancy Modeling, Finite Element Method.

INTRODUCTION

The efficient and safe operation of many electrical devices, such as motors and power converters, often depends on knowledge of temperature at locations that are not easily accessible for measurement. Techniques such as Kalman filtering combine available measurements with a model of the device to estimate such temperatures [1].

For this process to be effective, the model must be both accurate and computationally efficient. The computational cost of models obtained via the FEM can be reduced using MOR. Projection-based MOR techniques construct a reduced representation of the problem by projecting the system matrices onto a lower-dimensional subspace [2]. However, while effective for linear problems, projection-based MOR becomes more challenging in the presence of nonlinearities and may require intrusive techniques. Alternatively, black-box machine learning techniques can learn relationships between quantities in the time domain. However, black-box approaches generally do not exploit prior physical knowledge of the system and may require large Neural Network (NN) architectures, making them potentially unsuitable for real-time tasks.

PROBLEM DESCRIPTION

In this work, discrepancy modeling is proposed as a method for surrogate modeling of nonlinear thermal problems. Discrepancy modeling provides a framework to learn the mismatch between an approximate model of a system's dynamics and measured data [3]. This concept is adapted to thermal surrogate modeling through the following pipeline.

First, a high-fidelity model is developed using techniques such as FEM. MOR is then performed by approximating the n-dimensional solution as $x \approx Vz$, where $V \in \mathbb{R}^{n \times r}$ is the reduced basis matrix. The linear part of the high-fidelity model is then projected using the same reduced basis V

$$V^\top E V \dot{z} = V^\top A V z + V^\top B u, \tag{1}$$

yielding a linear Reduced Order Model (ROM) with r ≪ n states

$$E_r \dot{z} = A_r z + B_r u\,, \tag{2}$$

where $E_r = V^\top E V, A_r = V^\top A V, B_r = V^\top B$.
The same reduced basis V is used to project the time-domain solutions of the (nonlinear) high-fidelity model from the full n-dimensional space onto the r-dimensional subspace. A NN is then trained to learn the discrepancy between the linear ROM and the reduced high-fidelity data, with the learning performed entirely in the reduced space. The technique was employed for generating surrogate models of thermal problems including radiative heat transfer [4].

CONCLUSIONS

The proposed approach combines linear MOR with machine learning for non-intrusive surrogate modeling of thermal problems. The method retains the physical interpretability and computational efficiency of projection-based MOR, while compensating for nonlinear effects using a compact neural network. The accuracy and the non-intrusive nature of the approach make it an interesting tool for real-time temperature estimation.

REFERENCES

1. Eleffendi MA, Johnson CM. Application of Kalman Filter to Estimate Junction Temperature in IGBT Power Modules. IEEE Transactions on Power Electronics. 2016 Feb;31(2):1576–87. doi:10.1109/TPEL.2015.2418711

2. Hartmann D, Herz M, Wever U. Model Order Reduction a Key Technology for Digital Twins. In: Keiper W, Milde A, Volkwein S, editors. Reduced-Order Modeling (ROM) for Simulation and Optimization: Powerful Algorithms as Key Enablers for Scientific Computing [Internet]. Cham: Springer International Publishing; 2018. p. 167–79. doi:10.1007/978-3-319-75319-5_8

3. Ebers MR, Steele KM, Kutz JN. Discrepancy Modeling Framework: Learning Missing Physics, Modeling Systematic Residuals, and Disambiguating between Deterministic and Random Effects. SIAM J Appl Dyn Syst. 2024 Mar 31;23(1):440–69. doi:10.1137/22M148375X

4. Zorzetto M, Torchio R, Lucchini F, Dughiero F. Neural Network-Based Discrepancy Modelling of Reduced Order Models With Surface-to-Surface Radiation. IET Power Electronics. 2025;18(1):e70132. doi:10.1049/pel2.70132

Acceleration of numerical modeling of methane combustion using a plasma-chemical element in a ga turbine

A. Chepurnyi[1], A. Jakovičs[2]

Institute of Numerical Modelling, University of Latvia, 3 Jelgavas street, Riga, Latvia

Corresponding author: A. Chepurnyi (andrii.chepurnyi@lu.lv)

ABSTRACT. Plasma-assisted combustion can improve the operability of low-emission gas turbine combustors under lean conditions. In this study, methane combustion in a swirl-stabilized combustor w a plasma-chemical element was investigated using parametric CFD modeling. The results showed low CO emissions, a wider stable combustion region, and only minor changes in NOx. The obtained CFD dataset is being used for the initial development of a neural-network surrogate model for faster predict of combustion and emission parameters.

***Keywords*—** Plasma-chemical systems; activation energy reduction

INTRODUCTION

Gas turbine engines: Figure 1., are widely used in aviation, power generation, and industrial applicatio due to their high power density, compact design, and ability to operate under demanding conditions.

Figure 1. Gas turbine engine. Photo taken from official US Air Force (USAF) resources (https://www.kadena.af.mil/News/Photos/igphoto/2003251498/)

Plasma-assisted combustion is a promising approach for extending the operability of low-emission ga turbine combustors, where ignition reliability and flame stabilization under lean conditions are often critical [1,2]. In particular, direct-current plasma-chemical systems: Figure 2, with vortex and magneti arc stabilization can intensify oxidation processes by generating reactive radicals and by effectively lowering the activation energy of key combustion reactions [3,4].

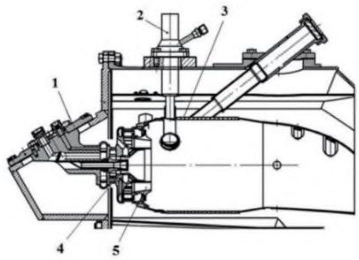


Figure. 2. Location of a plasma–chemical element in the low-emission combustion chamber: 1 – burn device; 2 – plasma–chemical element; 3 – flame tube; 4 – internal radial swirler; 5 – external radial swirler (The figure is taken from source https://doi.org/10.2478/pomr-2023-0022)

PROBLEM DESCRIPTION

The main problem is the high computational cost of parametric CFD modeling of fuel combustion in gas turbine combustor with a plasma-chemical element.In this study, a parametric CFD analysis of methane combustion was performed for a swirl-stabilized gas turbine combustor equipped with a plas

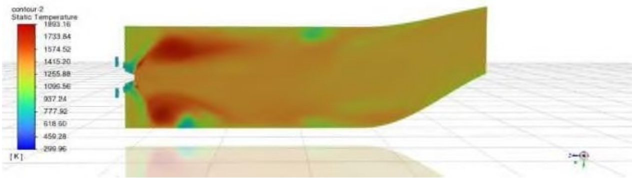


Figure 3. Temperature field in the combustion chamber (using a plasma-chemical system)

chemical element. The plasma-chemical effect was represented in a reduced-order manner by modifyi the activation energy of oxidation reactions as a function of the volume fraction of plasma-chemical products β, according to the methodology reported in earlier studies [5,6]. Numerical calculations wer carried out for β = 0, 0.005, 0.01, 0.015, and 0.02, corresponding to activation energy reductions of 0% 6%, 9%, 11%, and 12%, respectively. For the reference case , stable combustion was obtained, with a peak temperature of about 1900 K: Figure 3, in the recirculation zone and a physically realistic flame structure. As the plasma activation level increased, the results showed a gradual decrease in CO emiss while NOx remained nearly unchanged, together with an enlargement of the stable combustion region the primary zone, in agreement with previously reported trends [6]. In parallel with the CFD study, the resulting dataset is being used for the initial development of a neural-network surrogate model capable rapidly predicting the main combustion and emission parameters as functions of plasma activation and operating conditions [7]. Such a surrogate model can significantly accelerate parametric studies, stabil map generation, and the engineering design of plasma-chemical integration in gas turbine combustors

CONCLUSIONS

Recent advances in scientific machine learning are opening up additional avenues for accelerating combustion simulations. Multilayer perception (MLP) approximation models trained on parametric C datasets have shown promise for rapidly approximating complex reacting flow fields without the need expensive full-scale simulations. In earlier work by the present authors [7], an MLP approximation mo trained on the results of this CFD study demonstrated the ability to predict outlet temperature, CO_2, ar NOx emissions with relative errors of less than 5%, significantly reducing the computational cost of estimating a single operating point. This study utilizes initial numerical experiments that confirm that hybrid CFD-neural network workflows can significantly complement traditional parametric sweeps ar support rapid validation of plasma-chemical operating regimes.

References

1. Starikovskiy A, Aleksandrov N. Plasma-assisted ignition and combustion. Prog Energy Combust Sc 2013;39:61-110.

2. Starikovskaia SM. Plasma assisted ignition and combustion. J Phys D Appl Phys. 2006;39: R265-2

3. Fridman A. Plasma chemistry. Cambridge: Cambridge University Press; 2008.

4. Ju Y, Sun W. Plasma assisted combustion: Dynamics and chemistry. Prog Energy Combust Sci. 201 48:21-83.

5. Serbin SI. Modeling and experimental study of operation process in a gas turbine combustor with a plasma chemical element. Combust Sci Technol. 1998; 139:137-158.

6. Serbin S, Diasamidze B, Dzida M, Chen D. Investigation of the efficiency of a dual-fuel gas turbine combustion chamber with a plasma-chemical element. Polish Maritime Research. 2023;30(2):68-75.

7. Chepurnyi A., Jakovics A. Neural network acceleration of numerical simulation of methane combus in a gas turbine engine. Eurasian Phys Tech J. 2025;22(4):53-62

Optimization of an Induction Heating Applicator for Implanted Prosthesis Disinfection

B. López-Alonso[1] (corresponding), J. Acero[1], E. Agudo[1], Enrique Gómez Barrena[2], H. Sarnago[1] and O. Lucía[1]

[1]Department of Electronic Engineering and Communications. I3A. University of Zaragoza. Zaragoza, Spain.
[2]Hospital La Paz. Universidad Autónoma de Madrid. Madrid, Spain.
Phone : +34876555320 E-mail : blopez@unizar.es

ABSTRACT. Prosthetic implants, such as knee or hip prostheses, have significantly improved the wellbeing of patients suffering from joint disorders. However, prosthetic joint infections remain one of the most challenging complications due to the formation of resistant microbial biofilms. In this context, hyperthermia has been studied as an effective alternative to antibiotics for biofilm eradication. Among the different heating techniques, induction heating arises as a suitable solution due to its contactless nature and the metallic alloys commonly used in prostheses. The effectiveness of this approach depends on the electromagnetic performance of the induction coil. This paper presents the finite-element-based optimization of an induction heating inductor for implanted prosthesis disinfection, analyzing different coil configurations to improve magnetic coupling and heating efficiency under surgical operating conditions.

***Keywords*—** Induction heating, power electronics, biomedical applications, prosthesis disinfection.

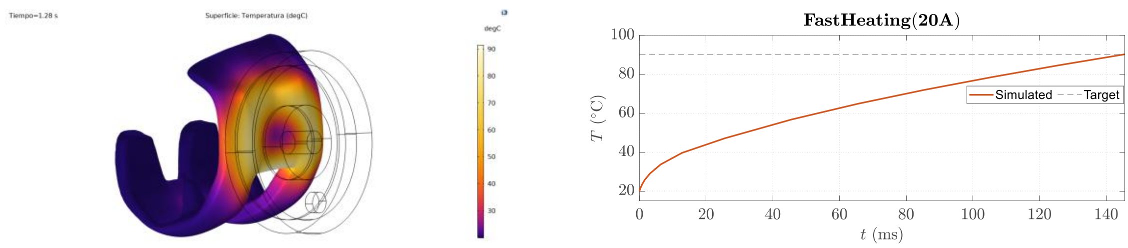
INTRODUCTION

Orthopedic prostheses are particularly susceptible to bacterial colonization and biofilm formation (1), often leading to persistent infections requiring revision surgery. Conventional treatments based on antibiotics and surgical cleaning show limited effectiveness, motivating the investigation of alternative approaches such as localized hyperthermia for biofilm eradication. Among available techniques, induction heating enables contactless and selective heating of metallic implants while minimizing thermal impact on surrounding tissues (2)

Recent studies have demonstrated the feasibility of portable induction heating systems for implanted prosthesis disinfection under surgical conditions (3). However, efficient and localized heating depends on the electromagnetic design of the induction coil under portability and contactless operation constraints. In this context, this paper presents a finite-element-based optimization of an induction heating inductor to improve magnetic coupling and power dissipation in prosthesis disinfection applications.

PROBLEM DESCRIPTION

The heating performance of induction-based prosthesis disinfection systems is governed by the electromagnetic coupling between the induction coil and the metallic implant. Under portable and contactless operating conditions, inadequate magnetic field distribution may lead to non-uniform heating or localized overheating regions. Therefore, the induction coil must be designed to ensure efficient power transfer while promoting homogeneous temperature distribution over the prosthesis surface.



(a) (b)

Figure 1 Finite-element model of the induction heating system for prosthesis disinfection: (a) temperature distribution in the prosthesis obtained from the coupled electromagnetic–thermal simulation, (b) temporal evolution of the prosthesis temperature during induction heating at 20 A.

A coupled electromagnetic–thermal multiphysics model has therefore been developed in COMSOL Multiphysics® to simultaneously evaluate induced losses and the resulting temperature distribution in the prosthesis. This approach enables the optimization of the inductor geometry considering both power transfer capability and thermal uniformity.

Power Dissipation Model

From the electromagnetic model, the power dissipated in the prosthesis is given by

$$P_o = R_{eq} I_{o,rms}^2 = \sum_{h=1}^{\infty} \frac{R_{eq} \hat{V}_{oh}^2 / 2}{R_{eq}^2 + (h\omega_s L_{eq})^2} \quad (1)$$

which links the equivalent electromagnetic parameters obtained from the finite-element model with the thermal energy delivered to the implant.

Geometrical Modeling

The finite-element model incorporates the geometrical representation of a commercial knee prosthesis together with different induction coil configurations designed for portable operation. The analyzed geometries include the induction coil, magnetic flux concentrator, surrounding air domain, and the metallic implant, allowing an accurate representation of the coil–prosthesis interaction at typical operating distances. Figure 1 illustrates the implemented geometrical model, showing an example of the analyzed induction coil together with the prosthesis geometry considered for the optimization study.

CONCLUSIONS

This paper presented the finite-element-based optimization of an induction heating inductor for implanted prosthesis disinfection. A coupled electromagnetic–thermal multiphysics model was developed to evaluate heating performance under equivalent operating conditions. The final version will include the complete model together with a comparative analysis of the evaluated inductor geometries. The obtained results provide design guidelines for improving heating uniformity and efficiency in portable induction hyperthermia systems.

REFERENCES

1. Gbejuade HO, Lovering AM, Webb JC. The role of microbial biofilms in prosthetic joint infections. Acta Orthop. 2015;86(2):147-58.
2. Pijls B, Sanders I, Kuijper E, Nelissen R. Synergy between induction heating, antibiotics, and N-acetylcysteine eradicates Staphylococcus aureus from biofilm. International Journal of Hyperthermia. 2020;37:130-6.
3. Álvarez-Gariburo I, García-Galán EC, Plaza MM, Barrena EG, Esteban J, Sarnago H, et al. A portable induction heating system for implanted prosthesis disinfection. International Journal of Applied Electromagnetics and Mechanics. 2024;75(2):131-43.

ARTE: Contactless Temperature Estimation and Energy-Aware Power Optimization for Domestic Induction Hobs

F. Dughiero[1], F. Lucchini[1], P. Di Barba[2], N. Sinigaglia[3], and M. Lazzarin[3]
1 Department of Industrial Engineering, University of Padova, Padova, Italy
2 Department of Electrical, Computer and Biomedical Engineering, University of Pavia, Pavia, Italy
3 InovaLab S.r.l., Vicolo Vincenzo Bellini 10/F - Padova, Italy
Corresponding author: F. Dughiero (fabrizio.dughiero@unipd.it)

ABSTRACT. This paper presents ARTE, an advanced framework for domestic induction hobs combining cookware recognition, real-time bottom-temperature estimation, and intelligent power control. The system relies on a wireless contactless inductive sensor installed beneath the glass surface, which exploits impedance variations to identify cookware and estimate its thermal state.

On this basis, the power regulation task is formulated as a multi-objective optimization problem, where the goal is to achieve a user-defined target temperature while balancing energy consumptio heating time, overshoot, and smoothness of the power profile. The solution is sought on the Paretc optimal front, providing optimal trade-offs among efficiency, thermal precision, and cooking responsiveness. The proposed framework opens the way to future AI-based cooking systems able adapt power scheduling to cookware, food type, and desired culinary outcome.

Keywords— induction cooking, contactless temperature sensing, impedance measurement, multi objective optimization, Pareto front, intelligent cooking control.

INTRODUCTION

Domestic induction hobs are intrinsically attractive because of their high efficiency, fast trans response, and compatibility with advanced power-electronics control. Nevertheless, user interactio still predominantly based on predefined power levels rather than on the actual thermal state of cookware. This creates a mismatch between the physical control variable handled by the appliance the quantity of real interest for the cooking process, namely the temperature of the pan bottom, wh is strongly related to the thermal state experienced by the food. ARTE was conceived to bridge gap by combining electromagnetic sensing, vessel recognition, and closed-loop thermal control wit a single embedded architecture. Unlike infrared sensors or external probes, the proposed sensor is fu integrated below the glass top, does not interfere with usability or cleanability, and provides feedb directly linked to the electromagnetic properties of the cookware. This makes the approach especi attractive for dynamic cooking processes in which robustness, compactness, and fast thermal estimation are essential.

PROBLEM DESCRIPTION

Optimization problem formulation.

Let $T_k$denote the cookware-bottom temperature estimated at the discrete time instant $k$by the ART wireless electromagnetic sensor and let $P_k$be the power command applied to the induction system. For a user-defined target temperature $T^{\star}$, the control problem is formulated over a finite horizon a the search for admissible power sequences $\{P_k\}_{k=0}^{N-1}$defining the design parameters of the optimization, such that multiple performance criteria are simultaneously optimized. In particular, t optimizer seeks to minimize the total supplied energy

$$J_e = \sum_{k=0}^{N-1} P_k \ \Delta t,$$

and the lack of smoothness of the power profile

$$J_s = \sum_{k=1}^{N-1} (P_k - P_{k-1})^2$$

Subjected to a constraint on the time requested to reach the target temperature $T^{\star}$, and on the admissible thermal overshoot

$$|T_k - T^{\star}| \leq \delta,$$

The thermal dynamics of the cookware–hob system is solved whit a numerical procedure based or the Finite Element Method (FEM).

Since these objectives are inherently conflicting, the problem is formulated as a constrained multi- objective (CMOP) problem. The solutions lie in the Pareto optimal set, formed by the set of non-dominated power trajectories representing the best trade-offs. A future extension of this framewor may consist in the introduction of an AI-based supervisory layer able to select the most suitable Pareto-optimal strategy not only based on cookware characteristics, but also according to the type food and the desired cooking outcome.

CONCLUSIONS

ARTE shows how electromagnetic sensing can be transformed into an enabling technology for next generation of domestic induction hobs. The contactless inductive sensor provides the informat layer required to recognize cookware and estimate pan-bottom temperature in real time, while optimization layer converts this information into an energy-aware power trajectory aligned with user thermal request. The proposed formulation is academically relevant because it frames induct cooking as a coupled estimation-and-control problem involving electromagnetic measureme thermal dynamics, and constrained numerical optimization. At the same time, it opens a c technological path toward intelligent appliances in which model-based control and artifici intelligence cooperate to improve energy efficiency, cooking repeatability, and user experience. Fut work will focus on experimental validation of the optimization loop on different cookware fami and food-related operating conditions, as well as on the development of AI strategies able to adapt heating profile to specific ingredients and recipes.

REFERENCES

Acero J, Burdío JM, Barragán LA, Navarro D, Alonso R, García JR, et al. Domestic induction appliances. IEEE Industry Applications Magazine. 2010;16(2):39–47.
Bono-Nuez A, Martínez-de-Juan JL, Forcadell J, García-Pardo C, Prats-Boluda G, Pons-Linares J. The inductor smart sensor for material identification in domestic induction cooking. IEEE Sensors Journal. 2018;18(12):4982
Mehta P, Bukov M, Wang CH, Day AGR, Richardson C, Fisher CK, et al. A high-bias, low-variance introductio machine learning for physicists. Physics Reports. 2019;810:1–124.

SELF-HEATING-INDUCED OFFSET DRIFT IN NTC THERMISTOR FOR DOMESTIC INDUCTION HEATING SYSTEMS

C. Carretero[(1), (2)], O. Lahuerta[(2), (3)], I. Lope[(1), (2)] and J. Acero[(2), (3)]

[(1)]Department of Applied Physics, University of Zaragoza,
Pedro Cerbuna, 12, 50009 Zaragoza, Spain
[(2)]Aragon Institute for Engineering Research, I3A, University of Zaragoza,
Mariano Esquillor, sn, 50018 Zaragoza, Spain
[(3)]Department of Electronic Engineering and Communications, University of Zaragoza,
Maria de Luna, 1, 50018 Zaragoza, Spain

ABSTRACT. Accurate temperature control in domestic induction heating appliances, DIH, necessitates continuous monitoring at one or more selected positions. Typically, the temperature sensor is placed at the center of the inductor, in direct contact with the ceramic glass cooking surface; however, alternative configurations positioning the sensor at an intermediate location within the coil have also been reported. In all cases, the sensor, often a Negative Temperature Coefficient (NTC) thermistor, is immersed in a time-varying magnetic field which drives the inductive heating process. The presence of this alternating magnetic field introduces a systematic measurement offset, thus requiring calibration to correct the measured temperature values. In this work, the physical origin of this measurement error is identified and experimentally characterized across relevant operating conditions. Furthermore, several mitigation strategies to address this systematic bias will be proposed.

INTRODUCTION

Domestic induction heating is becoming one of the most widespread solutions among cooking appliances due to its advantages, e.g., speed, cleaning, safety, and controllability (Acero et al., 2010). In such devices, the ease of controlling the power delivered to the vessel enables accurate temperature regulation. However, the main issue with temperature control is the precise measurement of temperature. Although alternative solutions based on infrared thermometry (Has & Wassilew, 1999; Imaz et al., 2014; Paesa et al., 2011) as well as temperature estimation from electrical parameters (Heo et al., 2022) have been proposed, they exhibit drawbacks with respect to the classical solution based on NTC thermistors placed below the cooking surface (Paesa et al., 2009) which presents a good trade-off between simplicity and performance at a reduced cost. However, temperature measurements in practical implementations of this NTC solution exhibit a temperature offset that appears when the burner is powered on but disappears when the coil is not active. In this paper, the experimental characterization of the offset in NTC thermistor temperature measurements for induction heating appliances is performed to identify its sources and plan corrective actions to address the issue.

TEMPERATURE SENSOR STRUCTURE

The temperature sensor for the domestic induction heating appliance under study is a customized device consisting of a commercial NTC sensor inserted into a hole in an alumina case. The thermal contact between the NTC and the alumina case is enhanced by filling the case hole with a thermally conductive cement. The shape of the alumina case facilitates the correct positioning of the device and provides good thermal contact with the cooking surface, thereby increasing the NTC sensor's exposed surface area. The NTC thermistor consists of a small piece of semiconductor material with a large temperature coefficient of resistance soldered to two sensing terminals. The semiconductor is enclosed in an ellipsoidal glass bulb to protect it from air. The terminals are made of FeNi42 alloy because of its similar expansion coefficient to the bulb's glass, to avoid mechanical stress associated with the extended operating temperature range, as was previously employed in incandescent lamps.

IDENTIFICATION OF THE TEMPERATURE OFFSET

A dedicated experimental setup was developed to investigate the origin of the temperature offset observed in an NTC thermistor under a time-varying magnetic field. In this configuration, the magnetic field is generated by a solenoid, which produces a longitudinal alternating magnetic field within its interior. Through systematic experimental testing, the source of the temperature drift was identified as the interaction between the longitudinal time-varying magnetic field and the thermistor terminals.

Subsequently, electromagnetic simulations reveal that the directionality of the power dissipated within the terminals is governed by their intrinsic magnetic properties. Furthermore, thermal simulations of the NTC assembly demonstrate that power losses in the terminals generate a temperature gradient between the thermistor element and the NTC's contact measurement surface, thereby providing a physically consistent explanation for the observed temperature drift in the acquired measurements.

REFERENCES

Acero, J., Burdio, J. M., Barragan, L. A., Navarro, D., Alonso, R., García, J. R., Monterde, F., Hernandez, P., Llorrente, S., & Garde, I. (2010). Domestic induction appliances: an overview of recent research. *IEEE Industry Applications Magazine*, *16*(2), 39–47.

Has, U., & Wassilew, D. (1999). Temperature control for food in pots on cooking hobs. *IEEE Transactions on Industrial Electronics*, *46*(5), 1030–1034. https://doi.org/10.1109/41.793352

Heo, K. W., Kim, G. W., & Jung, J. H. (2022). Vessel Temperature Estimation Method using Equivalent Resistance Difference. *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, *1*, 1329–1332. https://doi.org/10.1109/APEC43599.2022.9773473

Imaz, E., Alonso, R., Heras, C., Salinas, I., Carretero, E., & Carretero, C. (2014). Infrared thermometry system for temperature measurement in induction heating appliances. *IEEE Transactions on Industrial Electronics*, *61*(5), 2622–2630. https://doi.org/10.1109/TIE.2013.2281166

Paesa, D., Franco, C., Llorente, S., López-Nicolás, G., & Sagüés, C. (2011). Adaptive simmering control for domestic induction cookers. *IEEE Transactions on Industry Applications*, *47*(5), 2257–2267. https://doi.org/10.1109/TIA.2011.2161629

Paesa, D., Llorente, S., Sagüés, C., & Aldana, Ó. (2009). Adaptive observers applied to pan temperature control of induction hobs. *IEEE Transactions on Industry Applications*, *45*(3), 1116–1125. https://doi.org/10.1109/TIA.2009.2020189

The influence of heating power on the sinters microstructure of new cobalt superalloys from the Co-Al-W and Co-Ni-Al-W systems

A. Smagór[1], P. Gradoń[2], G. Moskal[2], and A. Tomaszewska[2]

[1] Silesian University of Technology, Department of Industrial Informatics, Krasińskiego str #8, 40-019 Katowice, Poland
[2] Silesian University of Technology, Materials Innovation Laboratory, Krasińskiego str #8, 40-019 Katowice, Poland

Corresponding author: A. Smagór (adrian.smagor@polsl.pl)

ABSTRACT. The scope of this research involves the microstructural analysis of sinters produced by pressing alloy powders. A new type of cobalt-based heat-resistant material, heat-treated to achieve precipitation strengthening, was analysed. These alloys are reinforced with the γ′ - $Co_3(Al,W)$ phase, which is structurally akin to the well-known γ′ - $Ni_3(Al,Ti)$ phase found in precipitation-hardened cobalt-based superalloys. The corresponding new cobalt superalloys are characterised by a melting point approximately 50°C higher, significantly broadening the operational temperature range of these materials compared to nickel superalloys. The materials examined belong to the tungsten alloy group of the Co(Ni)-Al-W type. While they are mainly produced via casting technologies, information on powder consolidation methods is also available, which is the focus of this publication. The research utilised the sintering-pressing method, which involves induction heating of a graphite mould containing a mixture of cobalt, nickel, aluminium, and tungsten alloy powders. This approach allowed the production of two material compositions: Co-9Al-9W and Co-30Ni-9Al-9W. These are among the most frequently studied variants of these alloys and will serve as reference materials for more complex compositions. The sintering process will be carried out at three temperatures: 800, 900, and 1000°C, with the study covering basic morphological characteristics such as porosity, chemical composition uniformity, phase composition, and grain size as a function of temperature (induction system power).

***Keywords*—** Co-base superalloys, sintering, microstructure.

INTRODUCTION

The development of a new class of cobalt-based superalloys initially stemmed from the 1970s identification of phases with an $L1_2$-type lattice in Co-Al-X systems (X = W, Mo, Ta, ...) with the general formula $Co_3(Al,X)$ [1]. Structurally, these phases closely resembled the γ′-$Ni_3(Al,Ti)$ phase, which enhances the properties of nickel-based superalloys through precipitation. This discovery opened the door to designing new materials with melting points roughly 50 °C higher than those of nickel-based superalloys. The first data on these alloys appeared in [2], focusing on materials from the Co-Al-W system. Since then, research into their manufacturing processes and functional properties has been ongoing. In 2015, information was published [3] on tungsten-free Co(Ni)-Al-Mo-Nb/Ta alloys with lower densities. Following the identification of the $Co_3(Al,W)$ phase, efforts concentrated on refining their production techniques. The predominant approach has been casting, as in nickel superalloys [4]. However, these materials often display macro- and microsegregation of alloying elements, especially those with high density and low lattice diffusion coefficients. They are also prone to casting shrinkage and the formation of secondary phases, particularly in interdendritic regions [5], which are typical microstructural defects of such processes. One solution is to adopt powder metallurgy to produce more homogeneous materials, leveraging the synergistic effects of temperature and pressure inherent in this method [6].

PROBLEM DESCRIPTION

The main objective of the research is to evaluate the feasibility of producing a material with a specified chemical composition and microstructure from feedstock powders composed of pure alloying elements: cobalt, nickel, aluminium, and tungsten. Literature on powder metallurgy processes for these alloys primarily focuses on using alloy powders with the desired chemical composition. This approach is simpler for obtaining a component with the correct composition, but it requires preparing (or purchasing) powders through mechanical alloying. Each of these intermediate steps can, for example, influence aluminium evaporation and does not guarantee exact reproduction of the intended compositions. Therefore, the research will investigate the feasibility of producing final alloys using "pure" feedstock powders. The second phase of the study will examine the microstructure of the produced sinters with respect to metallurgical quality, including chemical composition segregation, porosity, and phase identification.

CONCLUSIONS

The results of preliminary tests indicate that the proposed method for consolidating alloying element powders enables the production of sinters of acceptable metallurgical quality that require the required further heat treatment.

REFERENCES

1. Lee CS. Precipitation-hardening characteristics of ternary cobalt-aluminum-X alloys. Ph.D. dissertation, University of Arizona; 1971

2. Sato J, Omori T, Oikawa K, Ohnuma I, Kainuma R, Ishida K. Cobalt-base high-temperature alloys. Science. 2006; 312, 90–91

3. Makineni SK, Nithin B, Chattopadhyay K. A new tungsten-free γ–γ'Co-Al-Mo-Nb-based superalloy. Scripta Materialia. 2015; 98, 36-39.

4. Mikuszewski T, Tomaszewska A, Moskal G, Migas D, Witala B. The Induction vacuum smelting of Co-Al-W superalloys–optimizing the feedstock based on the alloy's chemical composition, elemental segregation, and slag formation. Journal of Mining and Metallurgy, Section B: Metallurgy. 2022; 58, 179-189.

5. Tomaszewska A, Moskal G, Migas D, Mikuśkiewicz M, Maciąg T. Thermal parameters determination of Co–Al–W as-cast alloy homogenization by DTA analysis. Journal of Thermal Analysis and Calorimetry. 2018: 134, 157-164.

6. Cartón-Cordero M, Campos M, Freund LP, Kolb M, Neumeier S, Göken M, Torralba JM. Microstructure and compression strength of Co-based superalloys hardened by γ′ and carbide precipitation. Materials Science and Engineering: A. 2018: 734, 437-444.

HESUIE 26 - International Conference on Heating by Electromagnetic Sources
September 15-18, 2026 – Padova (Italy)

Current tomography for electroheat process monitoring

T. Wondrak[1], M. Sieger[1], L. Krause[1] and S. Eckert[1]

[1] Helmholtz-Zentrum Dresden-Rossendorf, Institute of Fluid Dynamics, Department Process Diagnostics, Bautzner Landstraße 400, 01328 Dresden, Germany
Corresponding author: S. Eckert (s.eckert@hzdr.de)

ABSTRACT. A novel concept of a measurement technology to localize and determine the void fraction, position and size of non-conductive inclusions in an otherwise electrically conductive matrix is currently under development at Helmholtz-Zentrum Dresden-Rossendorf. The so-called *current tomography* can detect local disturbances of the electrical conductivity by contactless measurements of the related magnetic field outside of the volume of interest and thereby reconstruct spatial and temporal information on hot-spots or insufficiently heated zones inside current-conducting reaction vessel.

***Keywords*—** current tomography, electroheat process monitoring, inductive measurements, magnetic field measurements, process control

FUNCTIONAL PRINCIPLE OF CURRENT TOMOGRAPHY

The current density distribution $\boldsymbol{j}$ inside a current-conducting reactor is depending on the electric conductivity σ within the vessel (Fig. 1: → Ohm´s law). The electric currents are generating a weak magnetic field (→ Biot Savart law, forward problem) that can be measured outside of the reaction vessel with magnetic field sensors. By solving the associated invers problem based on these measurements, the inner conductivity distribution of the reactor can be reconstructed (→ inverse problem).
The method consists of two steps:

1. Contactless measurement of the distribution of the magnetic field outside of the vessel
2. Reconstruction of the distribution of the current density or the conductivity inside the vessel by solving the invers problem.

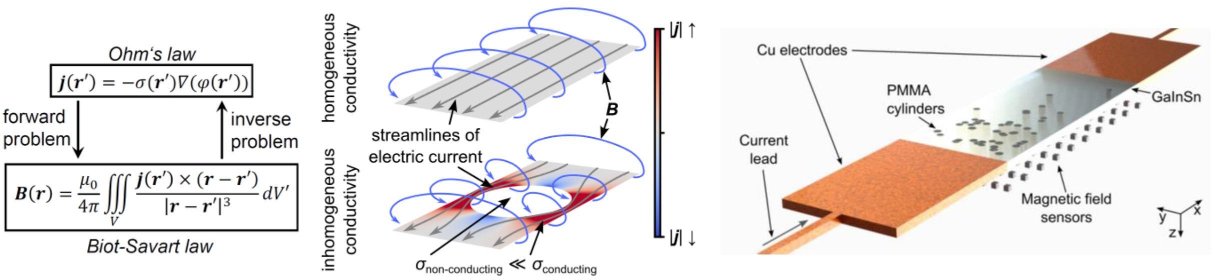


Figure 1. left: Relation of the distribution of electric conductivity, current density and magnetic flux density. / right: Current tomography proof-of-concept model

The applicability of the measurement method was investigated in a coupled numerical and experimental proof-of-concept study (Fig. 1 right) including invertible neural networks for the reconstruction step, that will be presented in detail in the presentation.

Innovative industrial process monitoring by inductive measurements

T. Wondrak[1], M. Sieger[1], L. Krause[1] and S. Eckert[1]

[1] Helmholtz-Zentrum Dresden-Rossendorf, Institute of Fluid Dynamics, Department Process Diagnostics, Bautzner Landstraße 400, 01328 Dresden, Germany
Corresponding author: S. Eckert (s.eckert@hzdr.de)

ABSTRACT. Inductive measurement techniques are extremely sensitive and thus offer a high potential for monitoring industrial processes that include electrically conductive fluids e.g., casting processes in metallurgy, numerous flows in the chemical industry and in process engineering, in particular the characterization of multiphase flows, e.g., in the detection of gas bubbles in conductive fluids. The term *inductive measurements* comprises several methods that are all based on the interplay of electric currents and magnetic fields.

***Keywords*—** bubble detection, contactless inductive flow tomography, process control

CONTACTLESS INDUCTIVE FLOW TOMOGRAPHY

The *contactless inductive flow tomography* (CIFT) is developed at HZDR over the last 20 years to visualize three-dimensional velocity fields in liquid metals. The method is based on the principle of induction by motion: very weak induced magnetic fields rise from the fluid motion under the influence of one or several primary excitation magnetic field(s) and can be precisely measured from the outside by magnetic field sensors. As the induced magnetic fields carry a “fingerprint” of the causative flow field, the solution of the associated linear inverse problem is a reconstruction of the velocity field. Due to its non-contact nature, CIFT enables to reconstruct the time-resolved global velocity vector field even in chemically aggressive and/or very hot liquid metals.

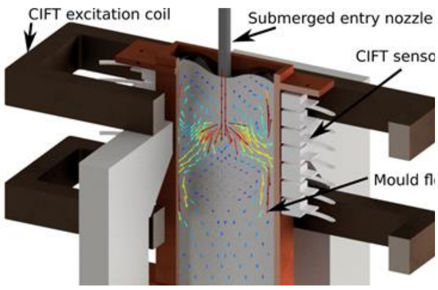


Figure 1. Schematic of a CIFT application to determine the liquid metal flow in continuous casting.

CONTACTLESS INDUCTIVE BUBBLE DETECTION

Many liquid metal-based technologies suffer from a lack of proper measurement tools to detect and characterize gas bubbles or other inclusions to enhance safety of operation, process efficiency and/or product quality. The *contactless inductive bubble detection* (CIBD) consists of an excitation coil generating an alternating magnetic field that induces eddy currents in the fluid. Gas bubbles and other electrically non-conducting inclusions in the otherwise well-conducting fluid perturb the eddy currents what can be detected outside of the fluid by magnetic field sensors. One sensor is sufficient to verify the existence of gas bubbles robustly and to estimate its velocity. Multiple-sensor detection systems enable the reconstruction of bubble parameters as size, shape and position within the liquid metal.

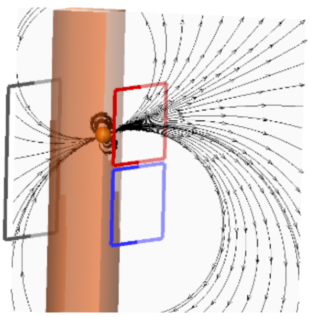


Figure 2. Principle of the contactless inductive bubble detection.

Some Aspects of Temperature Measurements in Induction Heating Systems

A. Smalcerz[1], and R. Przylucki[1]

[1] Silesian University of Technology, Faculty of Materials Engineering and Industrial Digitalization, Department of Industrial Informatics, Krasinskiego 8, Katowice, Poland
Corresponding author: A. Smalcerz (albert.smalcerz@polsl.pl)

ABSTRACT. They are several convenient methods making possible to identify and measure and/or control temperature in industrial electromagnetic processing systems used in modern metallurgy. However, the most popular measurement tool seems to be still simply classical thermoelements. They characterized by a wide measurement range, a direct voltage signal obtained from the transducer, low cost, and quite big resistance to many unfavourable factors which occur in an industrial environment. A week point seems to be, unfortunately, that thermoelements may not be resistant to interferences of a strong enough electromagnetic field. At present induction heating is the most commonly used type of metals heating in modern metallurgy. In order to guarantee the correctness of the carried out heating process, it is essential to precisely control the temperature of the heated element. The impact of a strong electromagnetic field upon the thermocouple temperature measurement of heated by induction elements has been analysed in this paper. The experiment includes dozens of measurements where the following parameters have been varied: frequency of the current which feeds the heating inductor, power supplied to the heating system, its geometry, material properties and geometrical dimensions of the inductor-workpiece system. Interferences of the powerline frequency have been eliminated in part of the carried out measurements..

Keywords— Electromagnetic field, Electromagnetic interference, Temperature, Thermocouple, Thermoelement.

INTRODUCTION

Temperature is one of the most important process parameters in majority of industrial heating technologies. Accurate temperature control determines product quality, process efficiency, energy consumption, and operational safety. In induction heating applications, precise temperature measurements are particularly challenging because strong alternating electromagnetic fields interact with measurement systems [1, 2]. The gradient of temperature determines the direction of heat transfer between bodies. Although temperature appears to be a simple physical quantity, accurate measurement is often affected by several factors, including [3]: quality of thermal contact, sensor response time, electromagnetic and electrical noise, environmental conditions, sensor installation.

The strong electromagnetic fields generated by induction heaters induce parasitic voltages in thermocouple circuits, which may significantly distort measurement results. Consequently, selecting an appropriate measurement technique is essential for obtaining reliable process data. The paper investigates the influence of electromagnetic fields on thermocouple temperature measurements under various induction heating conditions.

PROBLEM DESCRIPTION

A multivariate experiment was conducted, encompassing over a dozen measurements. The aim of the study was to determine the effect of the electromagnetic field generated by induction heaters on the accuracy of thermocouple temperature measurements. The variants included two completely different field frequencies (Fig. 1) and the type of thermocouple used (insulated and exposed) [4].

a) b)

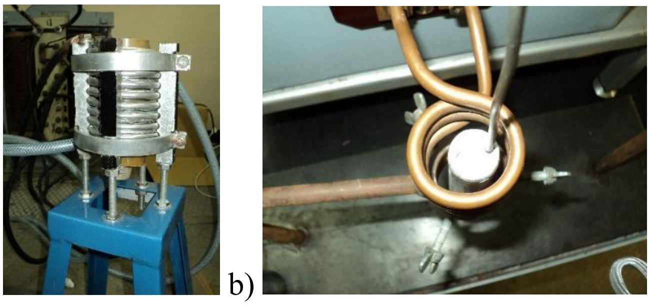


Fig. 1. Temperature measurement for two variants: a) frequency of 50 Hz and b) frequency of 330 kHz

a) b)

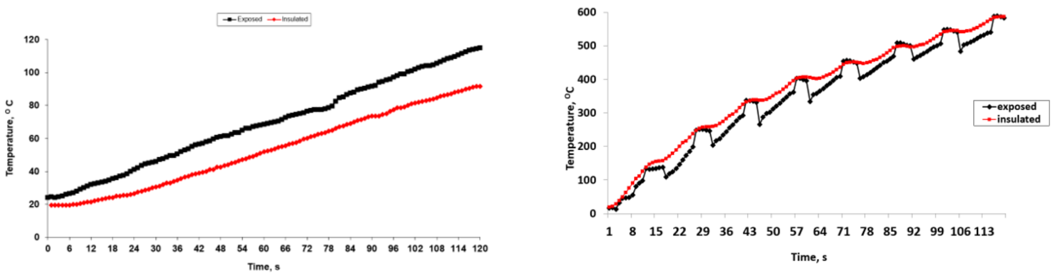


Fig. 2. a) Temperature measurement for stand 1 (50Hz), b) Temperature measurement for stand 2 (330 kHz)

CONCLUSIONS

The following conclusions can be drawn from the experiments conducted:

1. Thermocouples remain one of the most practical and widely used tools for temperature measurement in metallurgical and industrial applications.
2. Low-frequency (50 Hz) induction heating allows relatively accurate temperature measurements using conventional thermocouples.
4. During high-frequency (330 kHz) induction heating, insulated thermocouples provide significantly better measurement accuracy than exposed thermocouples.
5. Electromagnetic interference is the principal source of measurement error during high-frequency induction heating.

REFERENCES

1. M. Hering, Electrothermics Basics II (WNT, Warszawa, Poland, 1992) [in Polish]

2. J. Barglik, T. Wieczorek, R. Przyłucki, A. Smalcerz, Induction heating in heat and plastic metal treatment. Politechnika Śląska, 209 s., ISBN 978-83-7880-691-2. (2020). [in Polish]

3. E.L. Leonidas, A Comparative Review of Thermocouple and Infrared Radiation Temperature Measurement Methods during the Machining of Metals. Sensors, 22, 13, (2022).

4. A. Smalcerz, R. Przylucki, Impact of Electromagnetic Field upon Temperature Measurement of Induction Heated Charges. Inter. J. of Thermophysics, 2013, 34, 4: 667-679.

SAFETY ASSESSMENT ACCORDING TO THE EUROPEAN LEGISLATION AND IEC STANDARDS REGARDING THE INDUSTRIAL USE OF MICROWAVE TECHNOLOGY

Koen Van Reusel* (1)

(1) Engie Laborelec

The assessment of safety aspects according to the European legislation and IEC standards regarding the industrial use of microwave technology is illustrated by a case study.
As a first point of attention, it is illustrated how the temperature at the external boundary of the installation is measured and evaluated.
Concerning the safety for exposure to electromagnetic fields, the magnetic field around the equipment of electricity supply at power frequency (50 Hz) is measured, as well as the radiation level of the installation at the applied microwave frequency.
The presence of harmonics (multiples of the microwave frequency) is checked in order to assess whether the radiation at harmonic frequencies could be a safety problem.
In order to evaluate the possible consequences for the health of *workers* as well as of the *general public*, the measured values are compared to normative values. These normative values refer respectively to the “action levels” mentioned in the European Directive 2013/35/EU of 26 June 2013 (*workers*) and to the “reference levels” given in the European Council Recommendation 1999/519/EC of 12 July 1999 (*general public*). The intelligibility of the interaction models, that constitute the scientific base for the specifications formulated in these standards, is highlighted by referring to the ICNIRP guidelines.
It is illustrated how, according to the IEC standard 60519-6, an installation can be categorized in a specific risk class.
Some recommendations are formulated in order to enhance the safety situation for operators.
By some general considerations, it is finally shown how operators can be instructed on the possible risks caused by electromagnetic fields.

[1] Directive 2013/35/EU of the European Parliament and of the Council of 26 June 2013 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (electromagnetic fields), Official Journal of the European Union L179 Volume 56, 29 June 2013, p. 1-21.
[2] 1999/519/EC: Council Recommendation of 12 July 1999 on the limitation of exposure of the general public to electromagnetic fields (0 Hz to 300 GHz), Official Journal of the European Communities L149 Volume 42, 30 July 1999, p. 59-70.
[3] IEC 60519-1:2020 International Standard – Safety in installations for electroheating and electromagnetic processing – Part 1: General requirements.
[4] IEC 60519-6:2022 International Standard – Safety in installations for electroheating and electromagnetic processing – Part 6: Particular requirements for high frequency dielectric and microwave heating and processing equipment
[5] ICNIRP Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz) (2020), Health Physics 118(5), p. 483–524.

Microwave Assisted Recycling of CFRP Composites in a Continuously Operated Conveyor Belt Furnace - Process Parameters and Results

M. Juttu Vidyasagar[1], R. Behrend[1], M. Zöllner[2], T. Krampitz[2], H. Lieberwirth[2], H. Krause[1]

[1] *TU Bergakademie Freiberg, Institute of Thermal Engineering (IWTT), Chair of Gas and Heat Technology, Freiberg*

[2] *TU Bergakademie Freiberg, Institute of Processing Machines and Recycling Systems Technology (IART), Freiberg*

The specific strength of carbon fiber reinforced polymer (CFRP) composite material ranges around 1100 kNm/kg, compared to 75 kNm/kg for austenitic stainless steel. The exceptional specific strength makes CFRPs well-suited for mobility and high-performance applications, where mass reduction plays a crucial role in improving system efficiency. However, they require a high energy-intensive manufacturing process. The primary energy intensity required to manufacture a CFRP with a 50 % fiber volume fraction is approximately 710 MJ/kg, which is significantly higher than that of stainless steel (53-79 MJ/kg) and aluminum (55 MJ/kg). Global demand for CFRP is expected to reach 285,000 tons by 2025 and nearly double again by 2030. Currently, the end-of-life options for CFRP are mostly landfill or incineration. In order to ensure a sustainable future, it is essential that an industrial-scale process for recycling CFRP is developed.

The non-requirement of special solvents and catalysts makes the pyrolysis-based recycling process commercially acceptable on an industrial scale. In comparison to conventional methods, microwave-assisted pyrolysis offers several advantages, including gentle extraction of carbon fibers, selective volumetric heating of materials, higher heating efficiency, and higher heating rates, which enable it to reach the desired pyrolysis temperature quickly. In an earlier study conducted at IWTT, the pyrolysis parameters were optimized in a laboratory-scale plant. By considering the pyrolysis temperature, residence time, and energy consumption, it was found that pyrolysis at 450 °C, followed by an oxygen flash step, offers high-quality recycled carbon fiber. The primary objective of this study is to integrate knowledge from the laboratory scale into a newly designed demonstration plant.

The demonstration plant consists of a cylindrical oven (Ø 640 mm × 1300 mm) capable of reaching a maximum temperature of 500 °C and is powered by eight 2450 MHz magnetrons (900 W each, 7.2 kW total), evenly distributed along the wall in four quadrants. Oven walls are wrapped with a 5.5 kW resistance heating mat, and a 4.5 kW cartridge heater at the outlet brings the overall thermal heating capacity to 17.2 kW. A transverse conveyor belt transports CFRP samples from inlet to outlet. The first experiments were carried out in the commissioned demonstration plant. Nitrogen was used as the carrier gas during these experiments. Initial experimental results from the demonstration plant aligned with the findings of the laboratory plant will be presented.

Keywords: CFRP recycling, Microwave pyrolysis, Demonstration plant

Scaling up Microwave-Assisted Pyrolysis for Plastic Valorization: Design and Ongoing Challenges

M. Pola[1,2], I. Mellone[2], M. Albani[1]

[1] Department of Information Engineering and Mathematics, University of Siena, Siena, Italy
[2] Cognito Engineering Srl, Firenze, Italy
Corresponding author: M. Pola (m.pola@student.unisi.it)

ABSTRACT. This paper presents the design, preliminary testing, and critical engineering bottlenecks of a continuous Microwave-Assisted Pyrolysis (MAP) pilot plant (Techwave project). Designed to process around 100 kg/h of plastic waste, the system demonstrates exceptional chemical yields, converting polymers like Polystyrene and Polypropylene into high-value synoil. However, the industrial scale-up introduces severe hardware challenges. This work highlights the design of the microwave distribution network and focuses on the structural vulnerability of the custom WR340 isolation windows when exposed to the extreme thermo-chemical environment of the reactor, outlining the path for future R&D.

***Keywords*—** Microwave-Assisted Pyrolysis, Plastic Waste Recycling, Industrial Scale-up, Microwave Engineering, Isolation Windows

INTRODUCTION

Microwave-Assisted Pyrolysis (MAP) offers rapid, volumetric heating, presenting a highly efficient alternative for the chemical recycling of plastic waste [1,2]. While lab-scale results are well-documented, the industrial scale-up introduces severe thermo-chemical and electromagnetic challenges. This work presents the design, preliminary testing, and critical engineering bottlenecks of a continuous MAP pilot plant (Techwave© project) with a target capacity of around 100 kg/h.

PROBLEM DESCRIPTION

<u>*Pilot Plant Design*</u>

The microwave system utilizes several industrial magnetrons (6 kW each) operating at 2.45 GHz, delivering up to about 50 kW of total power (Figure 1a). The distribution network is built with WR340 waveguides and includes real-time power meters and tri-stub tuners for impedance matching. Advanced electromagnetic simulations (e.g., CST Microwave Studio) were employed to optimize the reactor's geometry, aiming to maximize field uniformity and energy absorption by the plastic load and microwave absorbers.

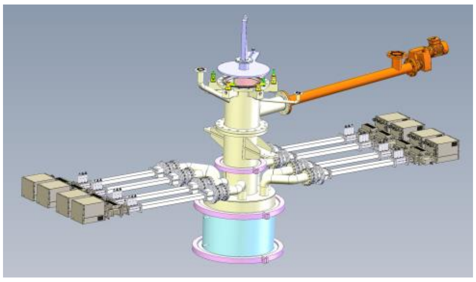
<u>*The Isolation Window Challenge*</u>

A major bottleneck in industrial MAP is physically protecting the microwave generators from the high temperatures and carbonaceous dust generated inside the reactor and transported by the gas. Custom WR340 isolation windows, featuring specially treated aluminum structures, were designed to seal the waveguides while maintaining high electromagnetic transparency ($S_{11} < -20$ dB) (Figure 2a).

However, in-situ testing revealed that these components are still vulnerable. The extreme thermo-chemical environment and severe thermal gradients currently lead to recurrent mechanical stress, material degradation, and eventual breakage of the windows (Figure 2b). Solving this structural fragility is the primary focus of ongoing R&D to enable long-term, massive industrial operations.

<u>*Preliminary Process Results*</u>

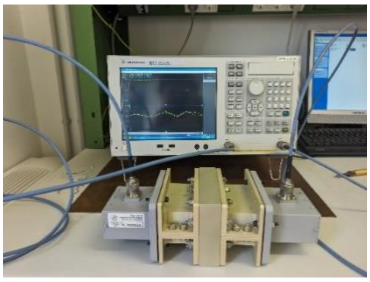
Despite the ongoing hardware challenges, the MAP process itself has proven highly effective during operational windows. Preliminary semi-batch and continuous tests validated the plant's capability to process thermoplastic polymers with outstanding liquid yields (Synoil) [3]. Liquid fractions reached up to 98 wt% for Polystyrene (PS) and 86 wt% for Polypropylene (PP). The recovered synoil presents excellent fuel properties, alongside a high potential for styrene monomer recovery, making it good for both waste-to-fuel and waste-to-chemical solutions. Finding the optimal power and feed-rate settings for mixed, heterogeneous plastic streams remains an active area of investigation.



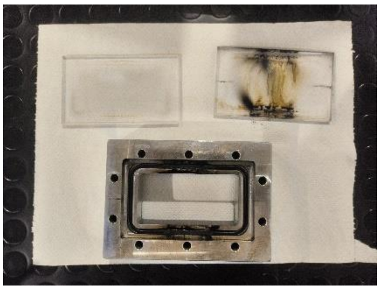
(a)

(b)

Figure 1. (a) 3D model of the reactor's main elements and (b) Techwave© pilot plant



(a)



(b)

Figure 2. (a) Custom isolation window measurements and (b) Example of window breakage

CONCLUSIONS

The innovative pilot plant confirms the immense potential of MAP technology to achieve exceptional synoil yields from end-of-life plastics. Nevertheless, achieving a fully continuous industrial regime requires overcoming critical hardware vulnerabilities. Future work will focus on advanced solutions for the isolation windows to withstand the aggressive pyrolysis environment and the refinement of process parameters for heterogeneous waste.

REFERENCES

1. Lam SS, Chase HA. A Review on Waste to Energy Processes Using Microwave Pyrolysis. Energies; 2012. https://doi.org/10.3390/en5104209

2. Undri A, Frediani M, Rosi L, Frediani P. Reverse polymerization of waste polystyrene through microwave assisted pyrolysis. Journal of Analytical and Applied Pyrolysis; 2014. https://doi.org/10.1016/j.jaap.2013.10.001

3. Frediani M, Frediani P, Innocenti G, Mellone I, Simoni R, Oteri G. Microwave-Assisted Pyrolysis Process: From a Laboratory Scale to an Industrial Plant [Internet]. Recent Microwave Technologies. IntechOpen; 2022. https://doi.org/10.5772/intechopen.104925

Laboratory-Scale adaptation of microwave air heating technology for very low gas flow rates

R. De los Reyes[1], V. Sanz[2], E. Palomares[1] and E. De los Reyes[1]

[1] UPV, Camino de Vera, s/n 46022, Valencia, Spain
[2] UJI, Av. Vicent Sos Baynat, s/n 12071, Castelló de la Plana, Spain
Corresponding author: R. De los Reyes (rutdelos@upvnet.upv.es)

ABSTRACT. This work presents the laboratory-scale adaptation of a patented microwave air heating system originally designed for medium and large air flows. The system was redesigned to enable stable heating of very low gas flow rates while maintaining rapid thermal response and controllable temperature profiles. Experimental tests confirm the feasibility of microwave-based heating for precise laboratory gas-flow applications
Keywords**—** microwaves, air-heating, heat exchange.

INTRODUCTION

Microwave energy is an efficient heating source for many solid and liquid materials due to its rapid and volumetric energy absorption [2]; however, gases such as air exhibit very low dielectric losses, making direct microwave heating inefficient. Therefore, gas heating requires intermediate materials that absorb microwave radiation and transfer heat to the gas stream, as implemented in the system disclosed in patent ES2965960B2 [1], originally developed for medium-to-high air flow rates in pilot and industrial environments. Similar approaches have been explored for fluid heating applications using microwave-based systems [3]. While this system performs efficiently under such conditions, many laboratory-scale applications require heating of significantly lower gas flows under strict thermal control, particularly in catalytic testing, microreactor studies, and gas-phase reaction analysis.

PROBLEM DESCRIPTION

The adaptation of microwave air heating systems to laboratory-scale operation with very low gas flow rates involves several technical challenges. Under these conditions, efficient energy transfer is limited by reduced interaction volumes, while maintaining stable and uniform temperature profiles becomes more difficult. In addition, precise delivery of low microwave power requires solid-state technology for accurate control, and the strong coupling between power and flow rate demands coordinated strategies to avoid thermal instabilities. These challenges define the framework for adapting the patented system to low-flow operation.

System adaptation and experimental methodology

To address the challenges associated with low-flow operation, a laboratory-scale microwave air heating system was developed to ensure efficient energy transfer and precise thermal control. The system operates with air flow rates in the range of 30–50 mL/min, with most experiments conducted at 40 mL/min, regulated by a mass flow controller (Bronkhorst). The gas flows through a quartz tube with a 9 mm inner diameter, which passes through a microwave cavity designed and optimized using electromagnetic simulations (ANSYS HFSS).

Within the section of the tube located inside the cavity, a packed bed of silicon carbide (SiC) spheres acts as the microwave-absorbing medium, enabling efficient conversion of microwave energy into heat and its transfer to the gas stream. The size and amount of SiC spheres were optimized for low-flow conditions. In addition, the quartz tube is thermally insulated to minimize radiative heat losses to the surrounding cavity. The system is powered by a 2.45 GHz, 250 W solid-state generator (Leanfa), allowing precise power control. The gas enters and exits the cavity through cutoff waveguide sections, ensuring electromagnetic confinement. A combined schematic and photograph of the experimental setup is shown in Figure 1.

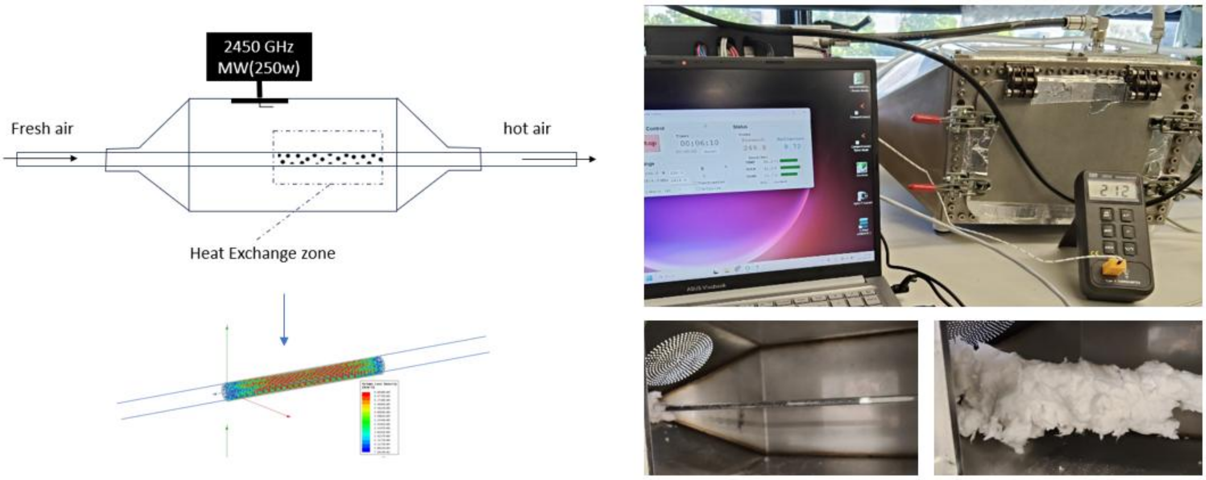


Figure 1. General caption. (a) content and (b) content

Results

System performance was evaluated by varying microwave power and gas flow conditions. Optimization of the SiC packed bed enabled an outlet temperature of 210°C at 250 W. With the addition of thermal insulation, the system achieved temperatures up to 500°C at the same power level, while reaching 300°C with only 125 W. These results demonstrate improved thermal efficiency and effective temperature control under ultra-low gas flow conditions.

CONCLUSIONS

This work successfully adapts a patented high-flow microwave heating technology for laboratory-scale applications with ultra-low gas flow rates. Precise thermal control is achieved at flow rates as low as 40 mL/min, demonstrating the feasibility of the approach under demanding conditions. The incorporation of internal thermal insulation is a key factor, enabling temperatures above 500°C. The resulting system, based on a solid-state microwave source and an optimized SiC packed bed within a compact cavity, provides a fast and efficient alternative to conventional resistive heating, making it suitable for catalytic and microreactor applications requiring rapid response and precise temperature control.

REFERENCES

1. Sistema de calentamiento de aire por microondas ES2965960B2, 2022.

2. Metaxas AC, Meredith RJ. Industrial microwave heating. London: IET; 1983.

3. Alcañiz D, Caccavale P, De Bonis MV, De los Reyes R, Ortolá MD, Ruocco G. Optimal design of an innovative microwave-based fluid heater. International Journal of Thermal Sciences. 2021;162.

Predictive models for copper slag based microwave susceptors

E. Colombini[1], M. Lassinantti Gualtieri[1], I. Lancellotti[1], C. Leonelli[1], P. Veronesi[1]

[1] Department of Engineering “Enzo Ferrari”, University of Modena and Reggio Emilia, Via P. Vivarelli 10/1, 41125 Modena, Italy
Corresponding author: E. Colombini (elena.colombini@unimore.it)

ABSTRACT

Copper slag, a by-product of copper production, was investigated as a microwave-active filler in metakaolin-based geopolymer composites for high-temperature applications. Composites with coarse and fine slag particles were produced at room temperature via alkaline activation to evaluate the effect of particle size on thermal and dielectric properties.

The material behavior is governed by coupled processes, including geopolymer dehydration and sintering (~915 °C), slag devitrification, and oxidation of iron phases. A predictive model of temperature-dependent permittivity was developed using a response surface method, highlighting the key role of slag content and particle size. The composites showed effective microwave absorption at 2.45 GHz, with improved stability after initial heating cycles due to microstructural evolution.

A processing window around 915 °C was identified, confirming the potential of these materials for microwave-assisted high-temperature processes.

***Keywords*—** microwave heating, predictive model, decarbonization

INTRODUCTION

Copper slag is a major by-product of pyrometallurgical copper production and is increasingly investigated as a secondary raw material in cementitious and alkali-activated systems. Due to its high iron content, copper slag exhibits interaction with electromagnetic radiation, making it a promising microwave-active component. Geopolymer-bonded copper slag composites represent a potential class of multifunctional materials for microwave-assisted high-temperature processes [1, 2]. In such systems, the geopolymer matrix ensures structural integrity, while the slag contributes to microwave absorption and heat generation.

PROBLEM DESCRIPTION

The electrification of high-temperature industrial processes via microwave heating offers significant potential for energy efficiency and emission reduction, but is limited by the lack of materials able to withstand high temperatures, mechanical loads, and intense electromagnetic fields. Conventional microwave absorbers often lack sufficient mechanical strength and thermal stability.

Geopolymer–copper slag composites represent a promising alternative, combining a thermally stable aluminosilicate matrix with an iron-rich, microwave-active filler. However, their performance is controlled by complex temperature-dependent transformations, including geopolymer ceramisation, slag devitrification, oxidation, and gas-induced expansion, which affect both structural integrity and microwave absorption.

The key challenge is to understand and control this coupled thermo-microstructural evolution to ensure stable mechanical behavior and effective microwave response. This work addresses this issue through the development of predictive models of thermal and dielectric properties, with particular focus on the effect of copper slag particle size.

EXPERIMENTAL AND RESULTS

Commercial copper slag (Techma, Italy) was used in two particle size fractions: coarse (<1 mm, as received) and fine (< 80 μm, ground). A metakaolin-based geopolymer paste was prepared using Argical 1000 (Imerys, France) and an alkaline activator (sodium silicate and NaOH solution). Composites were prepared by mixing geopolymer paste with copper slag. The geopolymeric matrix (GP) and two composites systems were investigated:

1. composites with coarse slag particles (GP_C), prepared by a wet route and shaped by casting;
2. composites with fine slag particles (GP_F), prepared by a dry route and shaped by uniaxial pressing

Samples were cured at room temperature and subsequently thermally treated under controlled conditions. Thermal and microstructural evolution was studied using optical dilatometry, TG/DTA, XRD, and SEM-EDS. Microwave response at 2.45 GHz was measured by modeling-assisted permittivity reconstruction using a rectangular waveguide applicator based on WR340 geometry. Temperature evolution during cyclic heating at 200W at 2.45 GHz, using a solid state generator (Lenagen, Leanfa, Italy) was monitored by infrared pyrometry to investigate possible modifications induced by repeated heating cycles.

The as-prepared composites display a dense microstructure with strong adhesion between copper slag particles and the geopolymer matrix. Thermal analysis indicates initial shrinkage below 300 °C due to water loss, followed by viscous sintering between 850–950 °C, with a peak shrinkage rate near 915 °C. Copper slag undergoes temperature-dependent transformations, including devitrification (700–900 °C) and oxidation of iron-bearing phases starting around 580 °C and intensifying at higher temperatures. Dilatometric analysis confirms irreversible volume changes at approximately 915 °C, linked to geopolymer sintering, followed by bloating above 1000 °C due to gas evolution.

Microwave heating experiments demonstrate efficient absorption and conversion of radiation into heat. Predictive models of temperature-dependent permittivity, developed via the response surface method, show strong dependence on both reinforcement volume fraction and copper slag particle size. Experimental results confirm that after initial heating cycles, the temperature–power response becomes more stable and reproducible. This effect is attributed to microstructural and chemical modifications during the first cycle, such as dehydration and changes in iron-bearing phases, which influence dielectric properties and improve microwave coupling.

CONCLUSIONS

Geopolymer–copper slag composites were investigated as multifunctional materials combining structural integrity with microwave responsiveness. The results show that the behavior of the system is governed by the coupled evolution of the geopolymer matrix and the iron-bearing slag phases. A consolidation window around 915 °C was identified, where geopolymer ceramisation occurs while limiting excessive expansion of the slag.

REFERENCES

1. Hu, C., Li, P., Zhu, Y., Zhao, Q., Zhang, H., Construction and Building Materials 341 (2022) 127850.
2. Guo, H., Wang, Z., An, D., Huo, J., Journal of Cleaner Production, 283 (2021) 124614

This work is part of the METAWAVE project funded by the European union under the Grant Agreement No 101138476

Microwave and induction heating of green carbon anodes for aluminum smelting

P.Veronesi[1], E. Colombini, and C. Leonelli

[1] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via P. Vivarelli 10/1, 41125 Modena, Italy
Corresponding author: Paolo Veronesi (paolo.veronesi@unimore.it)

ABSTRACT. A novel twin-chamber applicator, where the load (green anodes) moves from the top chamber (microwave powered) to the bottom one (induction powered) has been modeled and built. The baking process of green anodes is conducted by means of dielectric heating at 915±15 MHz frequency using a frequency controllable solid state generator up to an average load temperature of 600°C, then, as load conductivity increases, switching to induction heating at 10 kHz, using a graphite ring as auxiliary absorber. Numerical simulation allowed to identify the most promising heating conditions in terms of energy efficiency and heating homogeneity of the load. Based on the predictive models developed by modeling, an optimized heat treatment has been identified and testes to validate the numerical simulation results. The newly proposed system allows to process single anodes, with energy savings in excess of 35% compared to gas firing, when heat recovery from the graphite ring is implemented.

Keywords**—** microwave and induction heating, predictive model, CO2 reduction

INTRODUCTION

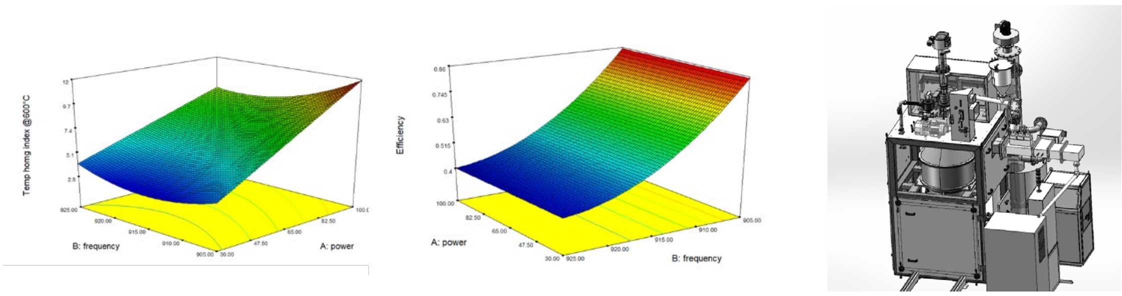
The EU-funded METAWAVE project aims to make industrial heating cleaner, faster, and more efficient by using innovative microwave technology [1]. By replacing traditional high-temperature heating methods, METAWAVE hopes to cut energy use, reduce CO_2 emissions, and boost productivity. The project also explores new eco-friendly materials, smarter control systems, and the use of renewable energy through a virtual power plant. Within this framework, baking of carbon anodes for the aluminium production alone is responsible for 7.23 $MtCO_2$ annually.

PROBLEM DESCRIPTION

Carbon anodes are widely used to smelt and extract aluminum through the Hall–Héroult process. During this process, aluminum is extracted from an aluminum-rich rock, bauxite, using carbon anodes as electrodes, which must present a low reactivity and high strength and conductivity. For this reason, carbon anodes are usually formed and baked [1]. Conventional baking of carbon anodes occurs in large furnaces, gas fired, where multiple anodes are piled up and slowly heated, with processing times lasting more than 20 day. Such baking process is extremely energy intensive and releases environmentally dangerous emissions, like nitrogen oxides (NOx) and the collective firing poses problem of anode quality, due to the existence of temperature gradients in the anodes during firing. [2]
A possible solution to mitigate such high energy consumption and environmental impacts, while improving anodes quality, could come from the use of electrical powered selective heating technologies applied to single anodes, with processing times requiring less than one day for the smaller anodes.

MATERIALS AND METHODS

The commercial software Comsol Multiphysics® v.3.5 has been used to simulate the microwave and induction heating of green carbon anodes, having a cylindrical shape, assuming a two step process where pre-heating up to 600°C occurs by means of dielectric heating at frequencies from 900 to 930 MHz, followed by induction heating at 10kHz up to 1050°C. Having decided to perform the microwave and induction baking of the anode separately in time and space, a simplified model considering only one excitation at a time has been developed. In both cases, the model is two-way coupled to heat transfer, and the whole system is simulated to assess the temperature existing in the different parts of the furnace because of the anode baking. Different frequency and applied microwave power have been simulated, coupling electromagnetic field and heat transfer simulations, in order to determine the temperature distribution inside the anode and defining a temperature homogeneity index which accounts for the variance of temperature within the anode and its average temperature. Based on modeling results, predictive models of efficiency and heating homogeneity have been developed, as shown in Figure 1a.



(a) (b)

Figure 1. Temperature homogeneity index and microwave application efficiency (a) and 3D view of the microwave and induction heating system

Based on the numerical simulation results, a dedicated microwave and induction heating equipment has been designed and built to perform the anode baking tests, as shown in Figure 1b. Results confirm the feasibility of the proposed electroheat process, with baking times in the range of 23 hours for 146mm diameter anodes, 200 mm tall. Such apparently long processing time allows to maintain the temperature difference within the load below 5°C, thus preventing cracking and defects formation in the anode.

CONCLUSIONS

A novel microwave and induction heating application for baking carbon anodes has been designed and built. Design criteria and process parameters are selected so that the heating of cylindrical anodes occurs volumetrically and with minimum temperature gradients within the load. Namely, by properly selecting frequency and emitted power of the microwave generator and induction heating equipment, it is possible to keep such temperature gradients below 5°C.

The microwave and induction baking furnace is currently running instrumented baking tests, where the use of multiple fiber optic sensors allows to confirm the volumetric nature of the microwave heating and the expected low temperature gradient

REFERENCES

This work is part of the METAWAVE project funded by the European union under the Grant Agreement No 101138476.
[1] F. Grégoire and L. Gosselin, Comparison of three combustion models for simulating anode baking furnaces, International Journal of Thermal Sciences, 129 (2018), pp 532-544
[2] P.Nakate, D. Lahaye1, C. Vuik, M. Talice, Computational study of the anode baking industrial furnace, TRAVAUX 51, Proceedings of the 40th International ICSOBA Conference, Athens, 10 - 14 October 2022.

Microwave-Driven Electrification Strategies for High-Temperature Industrial Processes in Ceramic, Asphalt, and Aluminium Production

Carmen Alfaro[1], Ismael Viejo[1], Javier Sagües[1], Alberto Pascual[1], Javier Pardos[1], Begoña García[1], Ivan Echeverria[1], Jose Ignacio Tolosa[2], Ainhoa Bilbao[2], Saeed Kooshki[3], Paolo Veronesi[4], Elena Colombini[4], Panagiotis Davris[5], Efthymios Balomenos[5], María Herrando[1]

[1]Instituto Tecnológico de Aragón (ITA), Zaragoza, Spain
[2]SAMCA, Zaragoza, Spain
[3]FRICKE UND MALLAH Microwave Technology Gmbh, 31226 Peine, Germany
[4] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia,
[5] METLEN Group, Viotia, Greece
Corresponding author: Paolo Veronesi (paolo.veronesi@unimore.it)

ABSTRACT.
Industrial process heating is responsible for a large share of energy consumption and greenhouse gas emissions in Europe. The METAWAVE project addresses this challenge through the electrification of high-temperature industrial processes by means of microwave-based technologies. The project targets three sectors with high energy demand, ceramics, asphalt, and aluminium, and combines materials development, multiphysics modelling, advanced sensing, digital control, and renewable energy management. The proposed approach aims to improve thermal efficiency, process controllability, and sustainability, while supporting the transition away from fossil-fuel-based heating systems.
Keywords— microwave and induction heating, predictive model, CO2 reduction

INTRODUCTION

Process industries are a key component of the European economy, but they remain strongly energy-intensive. Process heating alone accounts for about half of industrial energy demand and contributes significantly to greenhouse gas emissions. Since these processes are still largely based on fossil fuels, their decarbonization is essential for achieving the objectives of the European Green Deal.

Among the available alternatives, electrification is considered a promising strategy to reduce direct emissions. In this context, microwave heating offers relevant advantages, including volumetric heating, selective energy absorption, and rapid thermal response. Based on these features, the METAWAVE project develops innovative heating systems for processes operating above 400°C, with the additional goal of enabling integration with renewable energy sources.

The project is focused on three representative applications: ceramic tile firing, asphalt production and recycling, and carbon anode treatment for the aluminium industry. These sectors were selected because of their high energy demand and their potential for process electrification and optimization

PROBLEM DESCRIPTION

Despite the potential of electrified heating technologies, many industrial processes still rely on conventional combustion-based systems, which are associated with high emissions, limited efficiency, and reduced controllability. At the same time, the large-scale adoption of microwave-based systems is constrained by the limited availability of materials suited for

microwave environments, the need for reliable modelling tools, and the lack of robust monitoring systems for harsh operating conditions.
Another major challenge is the achievement of uniform temperature distribution and stable process conditions in high-temperature industrial applications. In addition, the effective use of electrified systems requires suitable management of energy supply, especially when renewable energy sources are involved

MATERIAL AND METHODS

The METAWAVE project follows an integrated approach that combines material development, advanced modelling, and digital process control. A first activity concerns the development of circular refractory materials specifically designed for microwave applications. These materials, containing additives such as copper slag and graphene-based compounds, are intended to act as insulating materials, susceptors, or attenuators of microwave radiation. Their thermal and dielectric properties have been characterized, and predictive permittivity models have been defined to support design and optimization.
In parallel, multiphysics simulation tools have been implemented to describe microwave-assisted heating processes by coupling electromagnetic, thermal, and fluid-dynamic phenomena. CFD models have been applied to ceramic kilns, while coupled electromagnetic–thermal models have been developed for asphalt heating and carbon anode treatment. To accelerate the design phase, simplified approaches such as reduced-order models and one-way coupling have also been introduced.
The proposed technologies have been adapted to three industrial sectors. In ceramics, conventional gas-fired kilns are replaced by microwave plasma torch systems. In asphalt production and recycling, flame-based heating is substituted by a hybrid system based on microwave heating and hot air. In the aluminium sector, microwave heating is integrated with induction heating for carbon anode treatment, improving temperature control and reducing processing time. Preliminary results indicate homogeneous temperature distribution together with lower energy consumption and improved process efficiency.
The project also integrates monitoring, automation, and energy management solutions. Fibre optic sensors and multispectral imaging systems are under development for real-time operation in severe environments. The acquired data are managed through a distributed control architecture based on IEC 61499, enabling digital twins and predictive control. In addition, a Virtual Power Plant and an Energy Management System are introduced to optimize the use of renewable energy sources and improve overall system sustainability.

CONCLUSIONS

he METAWAVE project demonstrates the potential of microwave-assisted electrification for the decarbonisation of high-temperature industrial processes. By combining advanced materials, multiphysics modelling, sensing technologies, digital control, and renewable energy management, the project proposes an integrated framework for improving process efficiency and reducing dependence on fossil fuels.

The preliminary results obtained in the ceramic, asphalt, and aluminium sectors confirm the technical feasibility of the proposed solutions, showing improved temperature uniformity, lower energy consumption, and better process controllability. These outcomes support the potential industrial application of microwave-based heating systems and their contribution to more sustainable manufacturing processes.

REFERENCES

This work is part of the METAWAVE project funded by the European union under the Grant Agreement No 101138476.

Simultaneous 2D Phase & Velocity Field Measurements for Hele-Shaw Bubble Flow in Liquid Metal

M. Pīrs[1], A. Jegorovs[1], A. Jakovičs[1], and M. Birjukovs[1]

[1] Institute of Numerical Modelling, University of Latvia, Jelgavas 3, Riga, Latvia, LV-1004
Corresponding authors: M. Pīrs (maksimilians.pirs@lu.lv); M. Birjukovs (mihails.birjukovs@lu.lv)

ABSTRACT. Abstract of the paper.

Keywords— Magnetohydrodynamics, bubble flow, multiphase flow, magnetic control, measurement methods.

INTRODUCTION

Bubble flow in liquid metal is ubiquitous in modern industry, and is crucial in processes like continuous casting, liquid metal alloy stirring and purification, liquid metal-based chemical reactors, and more [1,2]. Magnetic control of bubble flow in liquid metal enables tailoring the process dynamics, but currently the unresolved practical problem is how exactly to apply magnetic field for bubble flow control to achieve desired outcomes, i.e., purer produced metal, greater reactor efficiency [1,2] The underlying issue is that fundamental properties and physics of magnetohydrodynamic (MHD) bubble flow are not yet sufficiently understood, especially how magnetic field magnitude and orientation affect collective dynamics of bubbles [1,2].

PROBLEM DESCRIPTION

One of the reasons is the lack of experimental methods enabling more direct comparisons between downscaled model systems with bubble chain flow typically used in the field against numerical models [2]. Phase imaging, i.e., bubble/metal phase segmentation, has been accomplished using X-ray [3], neutron [4] and more recently optical imaging [5]. Ultrasound Doppler velocimetry (UDV) is widely used for velocity field measurements in liquid metal [6,7]. However, concurrent phase and velocity field measurements for bubble flow in liquid metal have not yet been used for full reconstruction of both phase and velocity field in an experimental setup – critical for a more in-depth physical characterization and understanding of MHD bubble flow, as well as for direct validation of numerical models used for industrial process design and optimization. With this contribution, a method for simultaneous two-dimensional phase and velocity field measurements for Hele-Shaw MHD bubble flow in liquid metal is presented. Bubbles are visualized and detected using an optical imaging system combining backlight and sideways illumination, which exploits reflections off the metal meniscus formed at bubble boundaries for bubble shape reconstruction. The developed image analysis solution enables tracking bubbles and resolving their collective dynamics. The UDV setup augments the optical imaging system and delivers sparse measurements of the velocity field. Divergence-free interpolation, incorporating boundary conditions for metal vessel walls and bubble/metal phase boundaries, acts as a physics-based super-resolution technique that recovers the full two-dimensional velocity field. We present the current state of development for the proposed methodology, and outline future work, and potential extensions beyond Hele-Shaw bubble flow.

FUNDING
This research is funded by: project lzp-2025/1-0174 "Magnetic control of bubble flow in liquid metal for metallurgical and chemical engineering technologies"; University of Latvia, Faculty of Science and Technology.

REFERENCES

1. Eckert S., Gerbeth G., Raebiger D., Willers B., Zhang C., Experimental Modeling Using Low Melting Point Metallic Melts: Relevance to Metallurgical Engineering, Steel Res. Int., 78: 419-425. 2007.

2. Birjukovs M. "Investigating bubble- and particle-laden liquid metal flow and alloy solidification using novel image and data analysis methods" PhD thesis, University of Latvia. 2023.

3. Keplinger O., Shevchenko N., Eckert S., Experimental investigation of bubble breakup in bubble chains rising in a liquid metal, Int. J. Multiph. Flow, 116: 39-50. 2019.

4. Birjukovs M., Dzelme V., Jakovics A., Thomsen K., Trtik P., Phase boundary dynamics of bubble flow in a thick liquid metal layer under an applied magnetic field, Phys. Rev. Fluids, 5(6): 061601. 2020.

5. Jegorovs A., Birjukovs M., Telicko J., Jakovics A., Optical imaging of MHD bubble flow in Hele-Shaw liquid metal cells, Exp. Fluids, 65: 113. 2024.

6. Zhang, C. "Liquid metal flows driven by gas bubbles in a static magnetic field" PhD thesis. 2009.

7. S. Franke, D. Räbiger, V. Galindo, Y. Zhang, S. Eckert., Investigations of electrically driven liquid metal flows using an ultrasound Doppler flow mapping system, Flow Meas. Inst. 48: 64-73. 2016.

Shape & Collective Dynamics in Geometrically Confined MHD Bubble Flow

A. E. Zīvers[1], A. Ziemelis[1], K. R. Kangīzers[1], P. Zvejnieks[1], and M. Birjukovs[1]

[1] Institute of Numerical Modelling, University of Latvia, Jelgavas 3, Riga, Latvia, LV-1004
Corresponding authors: A. E. Zīvers (ansis_emils.zivers@lu.lv); M. Birjukovs (mihails.birjukovs@lu.lv)

ABSTRACT. Abstract of the paper.

Keywords— Magnetohydrodynamics, bubble flow, multiphase flow, magnetic control, measurement methods.

INTRODUCTION

Bubble flow in liquid metal has several applications, e.g. in metallurgical processes, such as metal stirring, purification and homogenization, in liquid metal-based chemical reactors, etc. [1]. However, bubble flow exhibits complex collective dynamics, and therefore appropriate experimental methods are necessary to study the underlying physics in hopes of ultimately optimizing industrial processes. One usually experiments with downscaled (via similarity criteria) systems of interest and using low melting point model liquids and inert gases [1]. One of the prospective contactless methods for bubble flow analysis is the high frame rate dynamic X-ray radiography (XR), which has been successfully validated both experimentally [2] and in silico [3]. XR allows direct observations of gas/liquid phase boundaries, enabling in-detail analysis of bubble shape dynamics and collective behavior.

PROBLEM DESCRIPTION

Bubble breakup [4], coalescence [5] and agglomeration are of special interest, but thus far XR studies have been limited to qualitative analysis due to challenges related to image processing [4, 5, 6]. Here, we present our bubble detection, tracking, shape analysis and deformation rate measurement methods. Bubbles are detected from X-ray images via background, dark current and artifacts corrections, followed by a segmentation algorithm combining global detection and local shape estimation refinement, which help resolve thin metal films between bubbles and accurately determine bubble interaction timings. Bubbles are then tracked using our MHT-X code [7], enabling reconstruction of collective dynamics. Shape analysis based on camber line and principal chord reconstruction allows quantifying bubble shape dynamics and to study breakup events. Further, combining MHT-X with principal component analysis (PCA) and our newly developed 2-way consistent Farneback with Singular Value Decomposition (2WCF-SVD) code for optical flow velocimetry, we measure bubble boundary deformation rates. Applicable to most types of bubble shapes, these tools are employed to study the effects of flow confinement, gas flow rate, and applied magnetic field on bubble collective dynamics in liquid metal. We express these dependencies in terms of relevant dimensionless numbers and provide a practical demonstration of the concept of magnetic control of bubble flow in liquid metal.

FUNDING

This research is funded by: project lzp-2025/1-0174 "Magnetic control of bubble flow in liquid metal for metallurgical and chemical engineering technologies"; University of Latvia, Faculty of Science and Technology.

REFERENCES

1. Eckert S., Gerbeth G., Raebiger D., Willers B., Zhang C., Experimental Modeling Using Low Melting Point Metallic Melts: Relevance to Metallurgical Engineering, Steel Res. Int., 78: 419-425. 2007.

2. Keplinger O., Shevchenko N., Eckert S., Validation of X-ray radiography for characterization of gas bubbles in liquid metals, IOP Conf. Ser. Mater. Sci. Eng. 228: 012009. 2017.

3. Krull B., Strumpf E., Keplinger O., Shevchenko N., Fröhlich J., Eckert S., Gerbeth G., Combined experimental and numerical analysis of a bubbly liquid metal flow, IOP Conf. Ser. Mater. Sci. Eng., 228: 012006. 2017

4. Keplinger O., Shevchenko N., Eckert S., Experimental investigation of bubble breakup in bubble chains rising in a liquid metal, Int. J. Multiph. Flow, 116: 39-50. 2019.

5. Keplinger O., Shevchenko N., Eckert S., Visualization of bubble coalescence in bubble chains rising in a liquid metal, Int. J. Multiph. Flow, 105: 159-169. 2018.

6. Birjukovs M. "Investigating bubble- and particle-laden liquid metal flow and alloy solidification using novel image and data analysis methods" PhD thesis, University of Latvia. 2023.

7. Zvejnieks P., Birjukovs M., Klevs M., Akashi M., Eckert S., Jakovics A., MHT-X: offline multiple hypothesis tracking with algorithm X, Exp. Fluids, 63: 55. 2022.

Numerical Shape Optimization for Uniform Direct Electrical Heating of Test Samples

V. Kotlan[1], I. Petrasova[1], R. Holota[1], and V. Georgiev[1]

[1] University of West Bohemia in Pilsen, Univerzitní 8, Pilsen, Czech Republic
Corresponding author: V. Kotlan (vkotlan@fel.zcu.cz)

ABSTRACT. This paper describes the uniform heating of steel specimens under the influence of a harmonic electric current. A coupled model combined with shape optimization was used to design the geometry of the grooved specimens. The proposed approach significantly improves temperature uniformity in the central region designated for mechanical testing.

Keywords— Direct electrical heating, Numerical modeling, Optimization.

INTRODUCTION

The automotive industry uses materials that are subsequently subjected to high loads and stresses during operation. These materials undergo various heat treatments during production, and it is therefore necessary to test their mechanical properties specifically after thermal exposure. To ensure the test results are verifiable, it is important to be able to control the temperature to which the sample is exposed and to ensure that the sample is heated uniformly and homogeneously. One method is to use direct electric heating with a harmonic current. However, due to electromagnetic induction, harmonic current causes a non-uniform temperature distribution. Following the initial tests, the sample was modified. The sample is wider at the sides and features teeth (trenches). The objective of this work was to use optimization to design the geometric parameters of these teeth so that the central portion—used for producing the final sample for mechanical testing—is heated homogeneously.

PROBLEM DESCRIPTION

A sample of the most common steel, 22MnB5, was used to verify the heating functionality in the experimental system. During previous work on this topic, the effect of grooving the sample surface was verified. However, the heating remained non-uniform (Fig. 1).

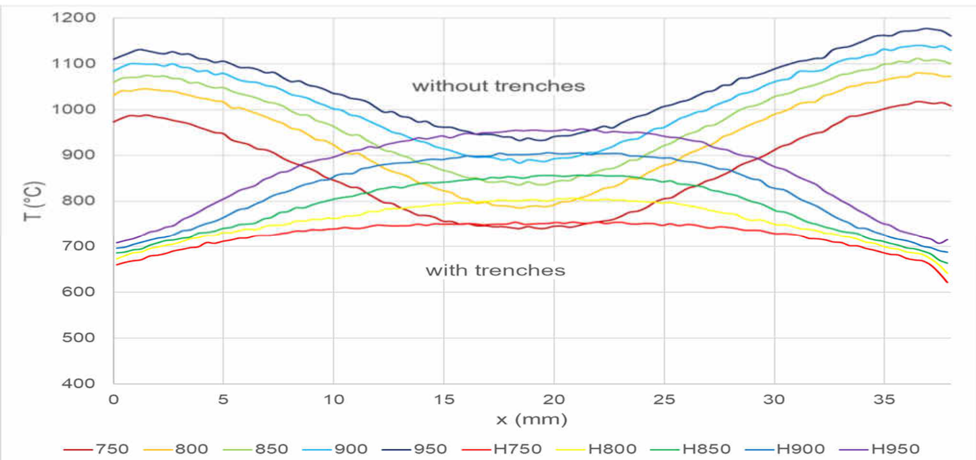


Figure 1. Temperature distribution across the sample with and without the trenches.

The goal is therefore to achieve the most uniform heating possible across the widest possible area of the sample's center.

For the forward part of the problem, we used a standard coupled electromagnetic and thermal field numerical model for the 22MnB5 steel, which is well known (e.g., [1]). The model created in COMSOL Multiphysics was calibrated by comparing it with actual experimental data, and an optimization problem was subsequently formulated based on the model, which tracked a total minimization of two objective functions

$$OF1 = \sqrt{(T_{av} - T_{req})^2}, \quad (1)$$

$$OF2 = \sqrt{(T_{max} - T_{min})^2}, \quad (2)$$

where T_{av} is the average temperature in the middle part of the sample (will be explained in more detail in the full paper), T_{req} is the requested temperature for the sample (in our case 950 °C), T_{max} and T_{min} these are the maximum and minimum temperatures in the middle section of the sample. We used and compared several optimization techniques like EGO, Nelder-Mead, BOBYQA, and similar procedures like in our previous works [2] to find the optimal geometry of the heated sample. In Fig. 2, you can see the first results; others will be in the full paper.

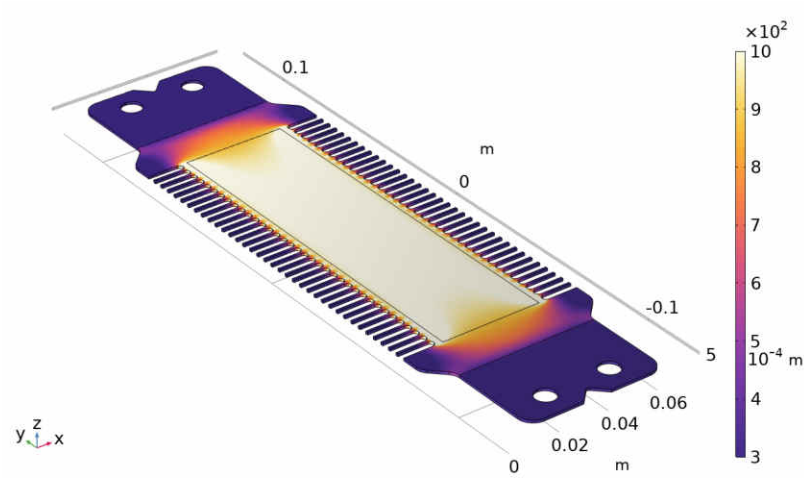


Figure 2. Distribution of temperature in the sample in time $t = 5$ s after optimization of the geometry.

CONCLUSIONS

In the paper, an optimization technique to improve the temperature distribution across the sample heated by DEH is used. Optimization was used to calibrate the numerical model and then to find the dimensions of teeth along the sample.

REFERENCES

1. Hart-Rawung, T., Buhl, J., Horn, A., Bambach, M., Merklein, M.: A unified model for isothermal and non-isothermal phase transformation in hot stamping of 22MnB5 steel. Journal of Materials Processing Technology, Vol. 313, April 2023, 117856, doi: 10.1016/j.jmatprotec.2023.117856.

2. Petrasova, I., Kotlan, V., Sroubova, L., Karban, P., Dolezel, I.: Calibration of laser welding model based on optimization techniques. COMPEL, Vol. 39, No. 1, 2020, pp. 43–52.

2WCF-SVD: 2-way consistent Farneback with SVD-based artifact filtering for multiphase optical flow velocimetry

A. E. Zīvers[1], K. R. Kangīzers[1] and M. Birjukovs[1]

[1] Institute of Numerical Modelling, University of Latvia, Jelgavas 3, Riga, Latvia, LV-1004
Corresponding authors: A. E. Zīvers (ansis_emils.zivers@lu.lv); M. Birjukovs (mihails.birjukovs@lu.lv)

ABSTRACT. Abstract of the paper.

***Keywords*—** Multiphase flow, optical flow, velocity field reconstruction, image analysis.

INTRODUCTION

Multiphase flow is omnipresent in natural and industrial physical processes and includes flow classes like particle-laded fluid flow, bubble and droplet flow, as well as flow of miscible phases [1]. Examples in industry include particle- and bubble-laden liquid metal flow in metal alloy stirring, purification, continuous casting, and more [2]. When assessing multiphase flow, including in model systems for research purposes, a common problem/objective is to reconstruct the flow field given some experimentally measured observable or flow tracing objects [3]. To this end, there are three most employed classes of methods – optical flow velocimetry (OFV) [3], particle image velocimetry (PIV) [4], and particle tracking velocimetry (PTV) [5].

PROBLEM DESCRIPTION

In many cases, however, tracers that PIV and PTV rely on are either not contrast enough, or simply not present in the system, in which case OFV is the only viable option of the three. While there are plenty of OFV types and implementations [3,6-8], many if not most are difficult or infeasible to apply to cases with low and/or strongly variable signal-/contrast-to-noise ratio (SNR/CNR), experiments with systems exhibiting generally fast motion and a broad spectrum of fluid and object velocity. In papers introducing the methods, they are often tested on sequences of high quality, clear images. Here, we present the current state of development of our optical flow pipeline designed to handle low SNR/CNR cases with (dynamic) artifacts, where the images may further be affected heavily by prior image filtering or enhancement. Our approach is based on the parallelized implementation of the Gunnar-Farneback method [9], which uses polynomial expansion of the image luminance and image pyramids for robust multiscale motion estimation. We augment it with a flow field filtering routine based on two-way optical flow consistency estimation, which produces a weight-averaged velocity field based on derived confidence and applicability scores. We further assist the optical flow algorithm by pre-filtering images for static/dynamics artifacts using vectorized 3D SVD (singular value decomposition) for the spatiotemporal 3D image (stacked image sequence), identifying and eliminating artifact-containing 3D basis images from the SVD reconstruction via Fourier analysis. We demonstrate the performance of our code (open-source) on several cases of varying difficulty: neutron imaging of droplet/liquid impact and mixing; solutal convection in X-ray imaged binary alloy solidification [10]; red blood cell flow [11]; neutron imaging of particle flow in liquid metal [4]; magnetohydrodynamic bubble flow in liquid metal [12], and more, showcasing the enabled physical analysis and validating our approach.

FUNDING
This research is funded by: project lzp-2025/1-0174 "Magnetic control of bubble flow in liquid metal for metallurgical and chemical engineering technologies"; University of Latvia, Faculty of Science and Technology.

REFERENCES

1. R. Clift, J. Grace, M. Weber., Bubbles, Drops, and Particles, Academic Press 012176950X. 1978.

2. Eckert S., Gerbeth G., Raebiger D., Willers B., Zhang C., Experimental Modeling Using Low Melting Point Metallic. Melts: Relevance to Metallurgical Engineering, Steel Res. Int., 78: 419-425. 2007.

3. Liu T., Shen L., Fluid flow and optical flow, Journal of Fluid Mechanics 614: 253-291. 2008.

4. T. Lappan, M. Sarma, S. Heitkam, P. Trtik, D. Mannes, K. Eckert, S. Eckert., Neutron radiography of particle-laden liquid metal flow driven by an electromagnetic induction pump, Magnetohydrodynamics 56, 167. 2020.

5. M. Birjukovs, P. Zvejnieks, T. Lappan, M. Klevs, S. Heitkam, P. Trtik, D. Mannes, S. Eckert, A. Jakovics, Particle tracking velocimetry and trajectory curvature statistics for particle-laden liquid metal flow in the wake of a cylindrical obstacle, Exp. in Fluids 65. 2024.

6. Liu T., Salazar D.M., OpenOpticalFlow_PIV: An Open Source Program Integrating Optical Flow Method with Cross- Correlation Method for Particle Image Velocimetry, Journal of Open Research Software, 9(1) : 3. 2021.

7. B. D. Lucas, T. Kanade., An Iterative Image Registration Technique, Proceedings of Imaging Understanding Workshop, 121—130. 1981.

8. B.K.P. Horn, B.G. Schunck., Determining Optical Flow, Artificial Intelligence, 17 : 185–203. 1981.

9. G. Farnebäck., Two-Frame Motion Estimation Based on Polynomial Expansion, Scandinavian conference on Image analysis, Springer : 363–370. 2003.

10. M. Birjukovs, N. Shevchenko, S. Eckert., An image processing pipeline for in-situ dynamic X-ray imaging of directional solidification of metal alloys in thin cells, Exp. in Fluids 64. 2023.

11. L. Lanotte,J. Mauer,S. Mendez,D.A. Fedosov,J. Fromental,V. Claveria,F. Nicoud,G. Gompper, & M. Abkarian. Proc. Natl. Acad. Sci. U.S.A., Red cells' dynamic morphologies govern blood shear thinning under microcirculatory flow conditions, 113 (47) : 13289-13294. 2016.

12. Birjukovs M. "Investigating bubble- and particle-laden liquid metal flow and alloy solidification using novel image and data analysis methods" PhD thesis, University of Latvia. 2023.

Identification of anisotropic material properties and heat losses in soft magnetic composites

M. Fuchs[1], and E. Baake[1]

[1] Leibniz University Hannover, Institute of Electrotechnology,
Wilhelm-Busch-Str. 4, 30167 Hanover, Germany
Corresponding author: M. Fuchs (fuchs@etp.uni-hannover.de)

***Keywords* —** Induction heating, Numerical identification, Anisotropic material properties.

INTRODUCTION

Induction heating applications like high frequency induction tube welding or induction hardening often require magnetic flux concentrators (MFC) to influence the impedance of the inductor-workpiece-system to increase the heating process's energy efficiency. Soft magnetic ferrites are the first choice for frequencies over 50 kHz but provide a limited saturation induction which induction heating setups in many cases exceed. In comparison, soft magnetic composites (SMC) offer a higher saturation induction but need sufficient cooling to prevent overheating. To develop induction heating systems with SMC flux concentrators, the precise knowledge of the material properties is important for the parameterisation of numerical models.

PROBLEM DESCRIPTION

SMCs mainly consist of ferromagnetic particles and a polymer binder keeping the particles in a solid machinable shape while electrically insulating them against each other. During the manufacturing process this mixture is compressed in one direction. This pressure leads to an anisotropic behaviour of the relative magnetic permeability and the thermal conductivity. Furthermore, the relative magnetic permeability is nonlinear function of the magnetic field strength. The heat generation rate in the SMC materials depends on the magnetic induction (which itself depends on the magnetic permeability) and on the frequency of the alternating magnetic field. Commonly used models for this dependency are the iron loss equations by Steinmetz [1] and Bertotti [2]. Since it is difficult to conduct direct measurements of the material properties and the heat generation rate, an identification method is chosen to fit input parameters of a numerical model to experimental data. The measured time-temperature-curves of three reference points for each material orientation on the SMC's surface are compared to the numerically simulated curves. The identification is performed by iteratively changing the material properties in the numerical model until the difference between the time-temperature-curves is minimal. This can by achieved by minimising the root mean squared error (RMSE).

PRELIMINARY RESULTS

To reduce computational time consumption, the identification of the anisotropic thermal conductivity is performed with a two-dimensional model and two parameters (thermal conductivity and heat generation rate) at first. Secondly, the identified parameters are validated in a three-dimensional model. Table 1 shows the results of this method for the material *Ferrotron 559H®* distributed by the company *Fluxtrol Inc*. The magnetic permeability is applied according to official manufacturer's datasheets [3]. The manufacturer's heat generation formular is multiplied by a coefficient K_P.

The comparison between the 2D and 3D results shows no difference for the thermal conductivity λ. Meanwhile, the heat generation must be reduced from 2D to 3D by approximately 37% due to the change from areas to volumes.

Table 1: Preliminary identification results for *Ferrotron 559H*®

Orientation to pressing direction	$K_{p,2D}$ [-]	$K_{p,3D}$ [-]	λ [W/(m·K)]	$RMSE_{2D}$ [K]	$RMSE_{3D}$ [K]
x-parallel	0.57	0.361	4.4	0.39	0.73
z-parallel	0.575	0.362	4.4	1.65	2.7
y-parallel	0.53	0.33	2.8	4.29	2.5

CONCLUSIONS

The latest investigations with two- and three-dimensional numerical models show promising results for the identification of the anisotropic thermal conductivity of soft magnetic composites. Ongoing experiments and simulations focus on the identification of the anisotropic permeability and the coefficients for the frequency-dependent heat loss equations.

REFERENCES

1. C. Steinmetz, On the law of hysteresis, AIEE Transactions, vol 9, pp 3-64 (1892).

2. G. Bertotti, General Properties of Power losses in soft ferromagnetic materials, IEE Trans. On Magn., 24, 621-630 (1998).

3. https://www.fluxtrol.com/service/ferrotron-559h/

Load detection strategy in new non-resonant inverters applied to domestic induction heating applications

Pablo Burgos[1], Héctor Sarnago[1], and Óscar Lucía[1]

[1]Universidad de Zaragoza, Zaragoza, Spain
Corresponding author: Pablo Burgos (pburgos@unizar.com)

ABSTRACT. This paper presents a load detection strategy for non-resonant inverters based on the estimation of the quality factor from the ratio between the RMS and average currents. The proposed expressions allow the quality factor to be determined unambiguously regardless of the converter's operating point. In addition, the analysis of a boost-based topology is carried out to derive closed-form expressions for these currents. Experimental results validate the proposed load detection strategy when applied to an inductor-pot system.

Keywords— Induction Heating, Load Detection, Boost converter

INTRODUCTION

Load detection has been a crucial feature in many domestic induction heating topologies because of its importance for achieving efficient and safe operation. In the past, resonant power converters have been widely used in domestic applications due to their high efficiency and power density [1]. In such systems, pot placement introduces significant variability in the equivalent load; thus, load detection is required for proper operation. For this reason, many methods have been proposed, including those relying on complex algorithms or harmonic analysis [2, 3]. However, in recent years, new topologies based on half-bridge boost configurations have been proposed. These inverters operate in non-resonant mode, simplifying control strategies and eliminating safety issues associated with pot removal. Nevertheless, load detection strategies are still required for efficient operation, and new approaches must be developed.

PROBLEM DESCRIPTION

Newly developed non-resonant topologies reduce the control complexity of the system, enabling their implementation in low-cost architectures. However, new load detection techniques are required that can be implemented in such architectures, which cannot support neural networks or even computationally intensive algorithms. Since these topologies, and their associated waveforms, differ from those of conventional resonant converters, new and simpler approaches become feasible.

Topology description and analysis

The topology shown in Figure 1 represents a simplified boost converter. Thus, the following analysis is applicable to a wide range of inverters regardless of the preceding rectification stage. The use of a non-resonant capacitor introduces an additional current component that sustains steady-state operation throughout the conduction interval and must be accounted for. In general,

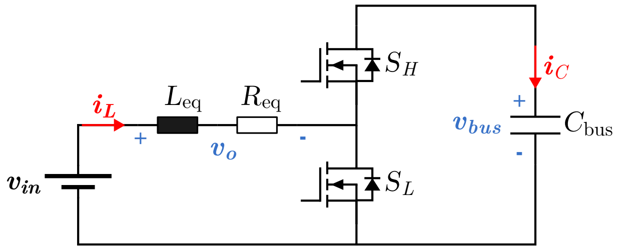


Fig.1 Schematic of the converter

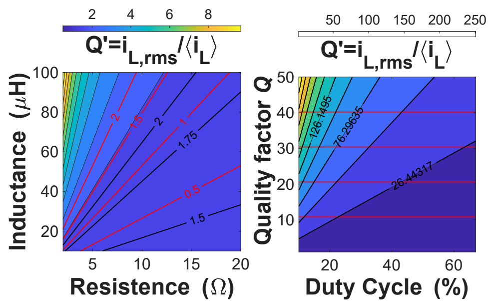


Fig.2 Q' dependence with equivalent load and point of operation

the average current is highly sensitive to the equivalent resistance of the system load, whereas the RMS current is strongly influenced by the operating duty cycle.

Quality factor estimation

The unequal dependence of the aforementioned expressions on the load parameters enables the definition of a factor Q' whose correlation with the equivalent load mirrors that of the quality factor. As stated above, the dependence of the RMS current on the inverter's duty cycle requires this control parameter to be taken into consideration (Fig. 2).

$$Q'(I_{rms}, I_{avg}) \propto Q \tag{1}$$

This makes it possible to estimate the quality factor Q using only current measurements and the duty cycle.

$$\hat{Q} = f(Q', D) \approx Q \tag{2}$$

$\hat{Q}$ offers a straightforward way to estimate the vessel's equivalent load or the degree of coverage between the inductor and the pot.

CONCLUSIONS

In this work, a non-resonant boost stage applied to induction heating has been analysed, yielding closed-form expressions for the average and RMS currents. Based on these quantities, a dimensionless parameter has been proposed to estimate the load quality factor. An explicit expression has been derived to compensate for the influence of the duty cycle. Experimental results validate the proposed method.

REFERENCES

1. Guillén P, Sarnago H, Acero J, Burdío JM, Llorente S, and Lucía Ó. Induction Heating Appliances: Fifty Years of Technological Success: Paving the Path for Sustainable Homes. IEEE Industrial Electronics Magazine 2025; 19:51–66
2. Li J, Luo W, and Chen C. Research on Load Parameter Identification of the Induction Heating. *2019 14th IEEE Conference on Industrial Electronics and Applications (ICIEA)*. 2019 :1665–8
3. Jiménez O, Barragán LA, Navarro D, Lucía O, Artigas JI, and Urriza I. FPGA-based real-time calculation of the harmonic impedance of series resonant inductive loads. *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*. 2010 :1715–20

A Coupled Inductors Non-Resonant Inverter Topology for Domestic Induction Heating

P. Guillén[1], H. Sarnago[1], O. Lucía[1], J. M. Burdío[1]

[1] Universidad de Zaragoza, C/ María de Luna 1, 50018 Zaragoza, Spain
Corresponding author: P. Guillén (pguillenm@unizar.es)

ABSTRACT. Non-resonant inverter topologies are especially suitable for domestic induction heating as power transmission depends on the coil-cookware relative position, displaying a self-protective response to cookware displacement. Being the required output voltage one of the main limitations of non-resonant inverters and aiming at reducing the number of power devices, coupled inductor topologies have been proposed in the literature to effectively doubling the output voltage. However, the coupled inductors design is critical. This paper proposes an inverter featuring coupled inductors and a bypass capacitor reducing the coupling requirements and simplifying inductor design. In addition, this solution requires a single controlled power device, with ground referenced driving, enabling a cost-effective implementation.

Keywords— Coupled inductors, Discontinuous conduction mode, Home appliances, Induction cooktops.

INTRODUCTION

The first commercial induction heating (IH) cooktops relied in non-resonant inverter topologies due to their inherent safe response to variations in cookware position. To improve the efficiency of the appliance, development shifted towards resonant converters, which present reduced switching losses and require lower voltages to achieve similar output power. The recent development and industrial adoption of SiC power devices enable a considerable reduction of the switching losses, opening the door to reevaluate the application of non-resonant converters to domestic IH [1].

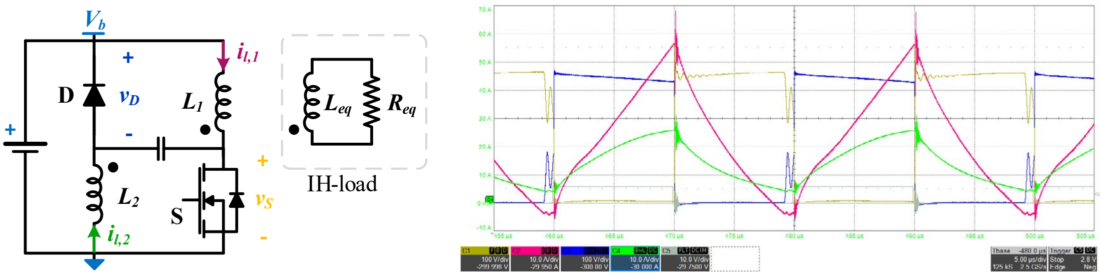
To solve the available power constraint due to limited voltage, typically full-bridge topologies have been used. To reduce the number of power devices, [2] proposes a coupled coils converter. However, the coil design presents high complexity as elevated coupling is required, leading to high voltage between strands and capacitive effects in the coil.

PROBLEM DESCRIPTION

In this article, a novel non-resonant inverter topology, based on coupled coils and with a single controlled power device is evaluated. The proposed topology presents inductors L_1 and L_2 in opposite winding direction and a bypass capacitor enabling leakage current recirculation and therefore relaxing the coupling requirements of the coils (Fig. 1.a)). The IH load, i.e. the cookware, is modelled as a third coupled coil L_{eq}-R_{eq} in order better convey the loss nature.

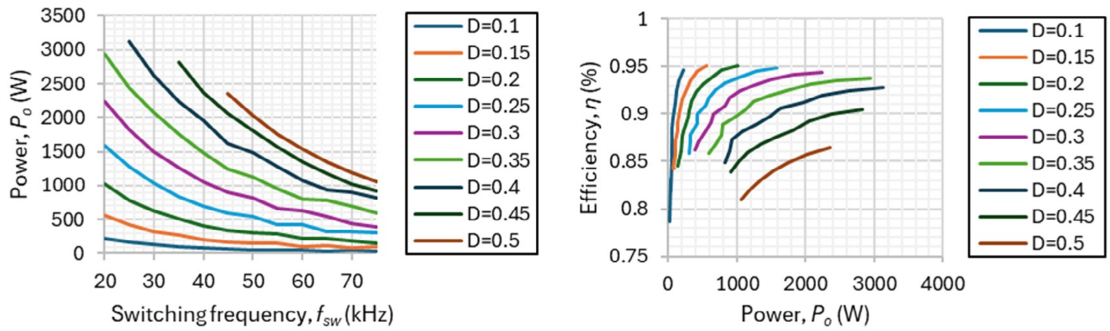
When S is active, current through L_1, and due to the coupling, through L_2, increases, flowing $i_{l,2}$ through the bypass capacitor. Once S is switched off, $i_{l,1}$ starts flowing through the bypass capacitor and through D. As a result, the voltage in the coil terminals vary between V_b and -V_b,

effectively doubling the bus voltage. Moreover, any mismatch in coil current is effectively circulated through the bypass capacitor, not leading to an increase in v_s (Fig. 1.b)).
Transmitted power control relies in modulating the switching frequency, f_{sw}, and duty cycle, D. As a result, it is possible to achieve full range power control (Fig. 2.a)).



(a) (b)

Figure 1. Proposed topology (a) and main waveforms during operation (b).



(a) (b)

Figure 2. Simulation results of converter operation under different modulation parameters. Output power as a function of switching frequency, f_{sw}, and duty cycle, D, (a) and expected efficiency when implemented with a SiC transistor (b).

CONCLUSIONS

The proposed topology simplifies the coupled inductors system design by enabling the leakage current recirculation. As a result, this current does not increase the transistor voltage, v_s. Therefore, the coupled coils do not require to be twisted to achieve coupling factors near the unity, relaxing the isolation requirements and reducing the capacitive effects.
When simulating and experimentally validating the proposed inverter, it can be seen that, for all power levels, maximum efficiency is achieved by minimizing f_{sw} and varying D.

REFERENCES

[1] M. Raeber, P. Amiras, and A. Heinzelmann, "Analysis on the use of non-resonant inverters in single-phase induction heating applications," in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*, 2020, pp. 4315-4319.

[2] F. Rehm, H. Sarnago, R. Schwendemann, L. Ó, and M. Hiller, "A Cost-Effective Nonresonant Inverter Topology for Domestic Induction Heating," *IEEE Open Journal of the Industrial Electronics Society,* vol. 6, pp. 637-650, 2025.

Design and Implementation of a Power Electronic Generator for Induction-Heated Electrified Biomass Pyrolisis Reactors

I. Álvarez-Gariburo[1], H. Sarnago[1], G. Costa[2], F. R. Viteri[2], T. García-Martínez[2], R. Murillo[2] and O. Lucía[1]

[1] I3A, Universidad de Zaragoza, Spain
[2] ICB-CSIC, Zaragoza, Spain
Corresponding author: I. Álvarez-Gariburo (ialvarez@unizar.es)

ABSTRACT. This work presents the design and implementation of a high-frequency power electronic generator for an induction-heated Auger-type biomass pyrolysis reactor. Conventional heating approaches based on electrical resistances or partial combustion of product gases suffer from limited efficiency, reduced controllability, and direct emissions.

To overcome these limitations, electromagnetic induction is employed to heat the external reactor casing, fully decoupling heat generation from the chemical process. The developed generator delivers several kilowatts of controlled high-frequency power while accommodating the temperature-dependent characteristics of the induction load. The proposed system enables efficient power transfer, fast dynamic response, and precise thermal regulation. Experimental validation up to 600 °C demonstrates stable operation and confirms the feasibility of induction-based electrification as a sustainable alternative for thermochemical biomass conversion.

***Keywords*—** Induction Heating, Power Electronic Generator, High-Frequency Power Conversion.

INTRODUCTION

The electrification of industrial thermochemical processes [1] is essential for enabling low-carbon heat supply with improved controllability and flexibility. In biomass pyrolysis systems [2], conventional heating methods rely on electrical resistances or partial combustion of process by-products, which introduce efficiency penalties, thermal inertia, and direct emissions.

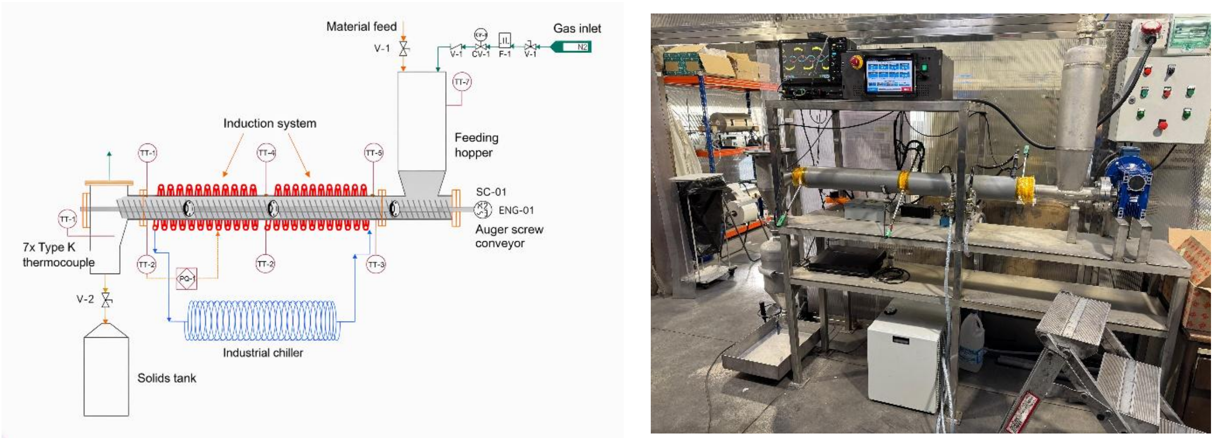
To address these limitations, this work proposes an induction-based heating system for an Auger-type pyrolysis reactor (Figure 1 (a)), where the external casing is heated electromagnetically. Heat generation is fully decoupled from the chemical reaction, enabling efficient electrical-to-thermal energy conversion and precise temperature control. A dedicated high-frequency power electronic generator is developed to excite the induction coil, providing stable and controllable operation compatible with electrified and renewable-driven process environments.

PROBLEM DESCRIPTION

The main technical challenge lies in delivering several kilowatts of controlled power to reach operating temperatures up to 600 °C while ensuring high efficiency, thermal stability, and fast regulation capability. Resistive heating systems exhibit significant thermal losses and high thermal inertia, limiting their suitability for dynamic operation. Combustion-based heat supply, on the other hand, compromises process sustainability by generating emissions and reducing the valorization potential of all product streams.

Induction heating [3] enables direct heat generation within the metallic reactor casing through induced eddy currents, minimizing intermediate energy conversion stages and improving overall system efficiency. However, this solution introduces substantial challenges from the power electronics perspective. The induction load presents a temperature-dependent and frequency-dependent impedance, requiring a power generator capable of operating at the appropriate switching frequency, adapting to load variations, and maintaining stable and efficient power transfer under dynamic conditions.

This work focuses on the design and implementation of the power electronic generator that excites the induction coil. The proposed system optimizes converter topology, control strategy, and impedance matching to ensure stable operation, high power transfer efficiency, and rapid transient response. The experimental setup is illustrated in Figure 1 (b).



(a) (b)

Figure 1. (a) System diagram. (b) Experimental setup

CONCLUSIONS

The developed power electronic generator successfully enables the electrification of the Auger-type pyrolysis reactor through electromagnetic induction heating. The system demonstrates stable operation at the required temperature levels, efficient power transfer, and precise thermal controllability under dynamic conditions. By eliminating combustion-based heat supply and reducing thermal inertia compared to resistive heating, the proposed solution enhances overall process efficiency, operational flexibility, and sustainability.

REFERENCES

1. Leibbrandt, N. H., et al. “Electricity-based fuels and chemicals: Industrial perspectives on power-to-X technologies.” Energy & Environmental Science, 2017.

2. Bridgwater, A. V. “Review of fast pyrolysis of biomass and product upgrading.” Biomass and Bioenergy, vol. 38, 2012, pp. 68–94. Inc.; 1971. p. 535–44.

3. Lucia, O., Maussion, P., Dede, E. J., & Burdío, J. M. “Induction heating technology and its applications: Past developments, current technology, and future challenges.” IEEE Transactions on Industrial Electronics, 2014.

Physics-Informed Neural Networks for characterizing thermistors immersed in a magnetic field

Óscar Lahuerta[1], Claudio Carretero[2], Denis Navarro[1], and Jesús Acero[1]

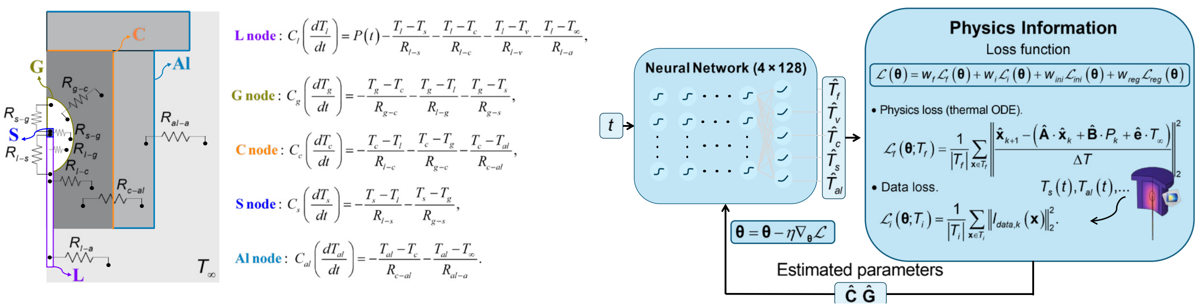
[1] Department of Electronic Engineering and Communications, University of Zaragoza, 50018 Zaragoza, Spain
[2] Department of Applied Physics, University of Zaragoza, 50018 Zaragoza, Spain
Corresponding author: Óscar Lahuerta (olahuerta@unizar.es)

ABSTRACT. This paper addresses the self-heating bias of Negative Temperature Coefficient (NTC) thermistors in domestic induction heating appliances, where the alternating magnetic field induces currents in the sensor leads and generates heat losses. A Physics-Informed Neural Network (PINN) embeds a lumped multimode thermal equivalent circuit in the loss function, enabling joint estimation of thermal conductances and capacitances and reconstruction of internal domain temperatures from limited measurements. Validation of the PINN performance with noisy COMSOL® simulation transients and with an experimental solenoid prototype shows consistent temperature profile reconstructions, plausible thermal parameters and a good estimate of the induced power losses.

Keywords**—** Equivalent circuit, NTC, Physics-informed neural network, thermal simulation.

INTRODUCTION

Domestic induction hobs rely on an inductor-load coupled system whose parameters, resistance and inductance, vary with temperature, so accurate sensing is required for control and protection [1]. An NTC thermistor placed near the induction coil center is a common solution [2], but the same alternating magnetic field that heats the cookware induces currents in the NTC leads, producing self-heating that biases the temperature measurement. This article proposes a PINN approach [3], to identify the thermal dynamics of the NTC assembly in order to eliminate that bias.



(a) (b)

Figure 1. Thermal identification of the NTC: (a) equivalent circuit and (b) PINN structure.

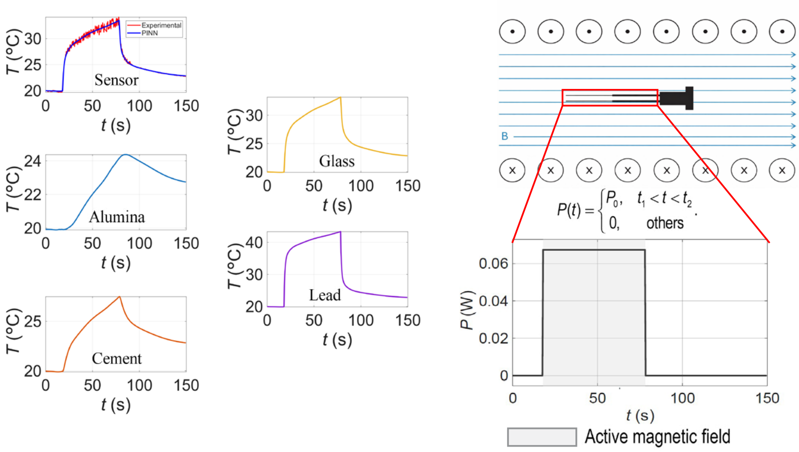


Figure 2. Experimental validation. Temperature and dissipated power estimation.

PROBLEM DESCRIPTION

The NTC assembly is modeled as a lumped thermal network with five temperature nodes, as depicted in Figure 1 (a), representing material domains and interfaces (sensor, glass, cement, alumina and lead regions). Each node follows an energy balance with conductive couplings and convection to ambient, yielding a low-order state-space ordinary differential equation (ODE) driven by a parasitic power term induced in the leads. The inverse problem is to estimate the network parameters, i.e. thermal conductances and heat capacities, and reconstruct the full node-temperature trajectories as these estimates quantify the self-heating contribution.

PINN-based identification

A feed-forward PINN takes time as input and outputs the node temperatures, Figure 1 (b). The thermal parameters are trainable variables optimized jointly with the network weights. The loss combines a physics residual enforcing the thermal ODE, an initial condition term, parameter regularization and a data term for the available measurements.

Experimental validation

Experimentally, a solenoid setup with PWM excitation provides only sensor temperature. Using only this temperature, the PINN reconstructs internal node temperatures and estimates the induced-loss pulse while enforcing physically consistent dynamics, Figure 2. The agreement between the PINN prediction and the denoised experimental sensor temperature yields an RMSE of 0.21 °C.

CONCLUSIONS

A PINN constrained by a lumped thermal network enables identification of NTC thermal dynamics and correction of self-heating bias in alternating magnetic fields. The approach reconstructs unmeasured internal temperatures and estimates the parameters needed for model-based subtraction, even when only the sensor temperature is observed.

REFERENCES

1. Guillén P, Sarnago H, Acero J, Burdío JM, Llorente S, Lucía Ó. Induction Heating Appliances: Fifty Years of Technological Success: Paving the Path for Sustainable Homes. IEEE Industrial Electronics Magazine. 2025;19(3):51–66.
2. Paesa D, Llorente S, Sagues C, Aldana O. Adaptive Observers Applied to Pan Temperature Control of Induction Hobs. IEEE Trans Ind Appl. 2009;45(3):1116–25.
3. Raissi M, Perdikaris P, Karniadakis GE. Physics-informed neural networks: A deep learning framework for solving forward and inverse problems involving nonlinear partial differential equations. J Comput Phys [Internet]. 2019;378:686–707.

Electrical Characterization System for 3D Tumor Spheroid Models in In Vitro Electroporation Studies

B. López-Alonso[1], I. Perisé-Badía [2], N. Dulanto[1], H. Sarnago[1], O. Lucia[1], I. Ochoa[1]

[1] Electronic Engineering and Communications Department, I3A, Universidad de Zaragoza. Maria de Luna, 1, 50018 Zaragoza. Spain.
[2] TME Lab; Aragon Institute of Engineering Research (I3A); Institute for Health Research Aragon (IIS); University of Zaragoza, Zaragoza, Spain
Corresponding author: B. López-Alonso (blopez@unizar.es)

ABSTRACT. Electroporation is a biomedical technique based on increased cell membrane permeability induced by high-intensity electric fields. Three-dimensional (3D) tumor spheroids have emerged as relevant in vitro models for treatment evaluation; however, their electrical characterization remains challenging due to their small dimensions and the need to preserve physiological conditions. This work presents an impedance measurement system for electrical characterization of 3D tumor spheroids suspended in culture medium. The proposed setup, based on a four-terminal impedance analyzer and a custom measurement cuvette, is aimed at enabling impedance measurements under conditions compatible with electroporation studies.

Keywords— Electroporation, impedance characterization, 3D tumor model.

INTRODUCTION

Electroporation is a phenomenon characterized by increased cell membrane permeability induced by high-intensity electric fields [1], enabling a wide range of biomedical applications such as electrochemotherapy and irreversible electroporation treatments. The evaluation and optimization of these therapies require experimental models based on viable cellular structures, since electroporation effects depend on membrane integrity and tissue organization.

Conventional in vitro models based on two-dimensional (2D) cell cultures provide limited representation of real tumor tissue properties, while animal experimentation involves high costs and reduced experimental controllability. In this context, three-dimensional (3D) tumor spheroids [2] have emerged as relevant in vitro models capable of reproducing key structural and microenvironmental characteristics of solid tumors.

Although 3D tumor models have demonstrated suitability for electroporation studies[3]. their electrical characterization remains challenging due to their small size and heterogeneous composition. Electrical characterization is required to support modeling and control of applied electric fields and to estimate variations in spheroid electrical properties. This work presents an electrical characterization system based on indirect measurement methods aimed at estimating electrical parameters of 3D tumor spheroids for in vitro electroporation studies.

PROBLEM DESCRIPTION

The electrical characterization of 3D tumor spheroids represents a significant challenge due to their reduced dimensions, typically around 100 µm. Direct electrical measurements at this scale are difficult to perform while preserving cell viability and physiological conditions. In addition, electroporation experiments require the sample to remain immersed in culture medium, introducing additional constraints for reliable impedance measurements.

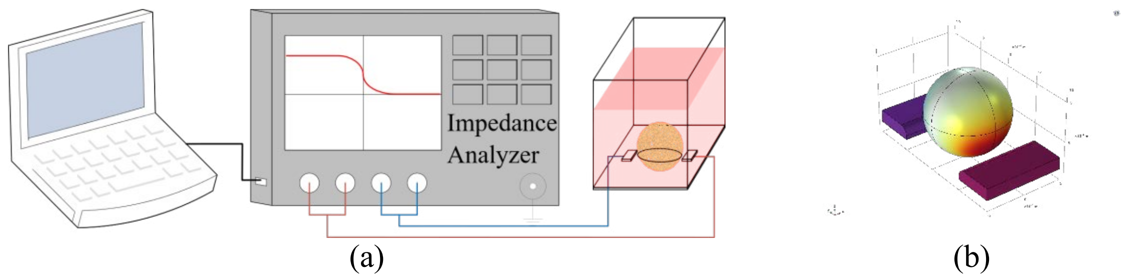


Figure 1 Proposed impedance measurement setup for tumor spheroid characterization. (a) Experimental implementation including impedance analyzer and custom electroporation cuvette. (b) FEA model used for measurement region optimization.

To address these limitations, a dedicated measurement setup has been developed to enable impedance measurements of microscale samples under conditions compatible with electroporation studies.

Measurement Setup and Modeling

The proposed setup is based on a commercial impedance analyzer (Keysight Technologies) operating in a four-terminal Kelvin configuration to minimize parasitic effects and contact impedance errors. A custom electroporation cuvette was designed to ensure stable positioning of the spheroid within the measurement region while remaining immersed in culture medium.

A finite element analysis (FEA) model of the measurement configuration was developed to support optimization of the electrode geometry and measurement region prior to experimental implementation. The complete system and numerical model are shown in Figure 1

System Characterization

Experimental measurements were performed using culture medium to evaluate the operating conditions of the proposed setup. The influence of excitation frequency and signal amplitude was analyzed in order to identify measurement parameters affected by electrode polarization, parasitic impedances, and medium conductivity dispersion.

This study allows defining suitable measurement conditions for stable impedance acquisition using the proposed system.

CONCLUSIONS

This paper presented an electrical characterization system for impedance measurement of 3D tumor spheroid models intended for *in vitro* electroporation studies. The proposed setup was developed to perform impedance measurements of micrometric biological samples under physiological conditions. System characterization allowed defining suitable operating parameters for stable measurements. The final version of this work will present the complete experimental and simulation results obtained using the proposed system.

REFERENCES

1. Yarmush ML, Golberg A, Serša G, Kotnik T, Miklavčič D. Electroporation-based technologies for medicine: principles, applications, and challenges. Annu Rev Biomed Eng. 2014;16:295-320.
2. Pinto B, Henriques AC, Silva PMA, Bousbaa H. Three-Dimensional Spheroids as In Vitro Preclinical Models for Cancer Research. Pharmaceutics. 2020;12(12).
3. Arroyo JP, Jacobs EJ, Ahmad RN, Amin AJ, Verbridge SS, Davalos RV. Characterization of glioma spheroid viability and metastatic potential following monophasic and biphasic pulsed electric fields. Bioelectrochemistry. 2025;165:109005.

Inductive Heating of Chemical Reactors: Experimental and Numerical Investigations

Tim Irlweck[1], Claudius Stockinger[1], and Ulrich Nieken[1]

[1] Institute of Chemical Process Engineering, University of Stuttgart, Böblinger Straße 78, 70199, Stuttgart, Germany
Corresponding author: Tim Irlweck (tim.irlweck@icvt.uni-stuttgart.de)

ABSTRACT High temperature chemical reactions are frequently heated by gas-fired furnaces. Inductive heating is a new approach for reducing CO_2 emissions due direct heat release in the catalyst bed. To better understand heating in packed beds of particles, an experimental test section and a coupled electromagnetic–thermal model was set up to study skin depth, heat generation, and heating efficiency of different susceptors. Good agreement was found for a hollow steel cylinder, whereas packed beds could not be described satisfactorily, indicating the need for improved electromagnetic models.

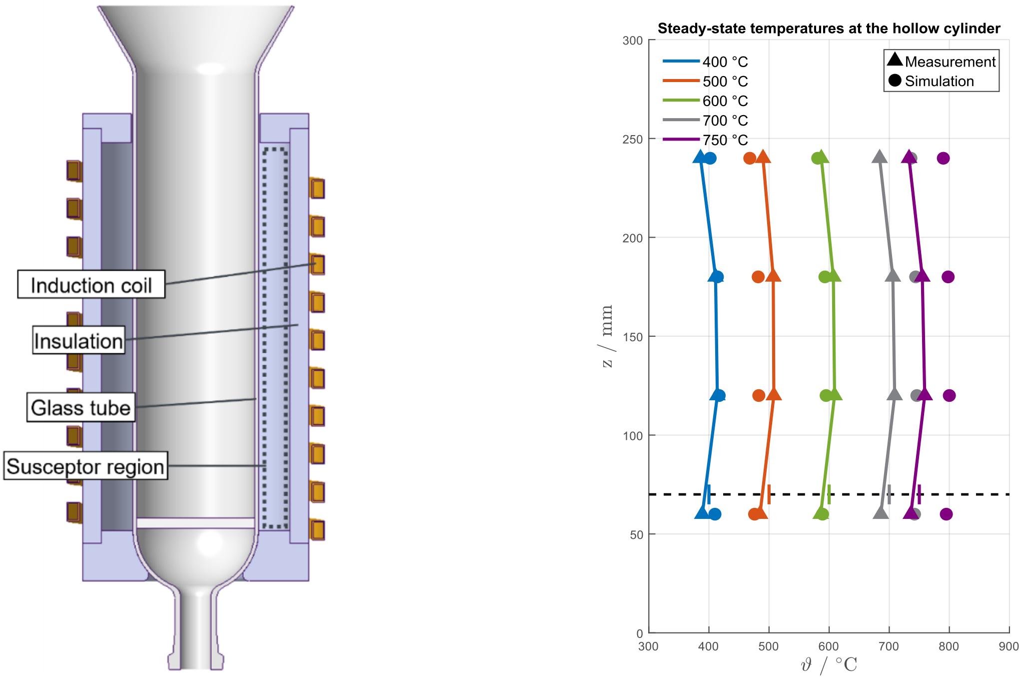
Keywords**—** Inductive heating, Skin depth, Packed beds.

INTRODUCTION

Industrial chemical processes are among the largest industrial energy consumers and currently constitute a significant source of CO_2 emissions [1]. A new approach for electrical heating is the use of inductive heating. For applications in the chemical industry, large skin depths are required to enable effective and homogeneous heating of the catalyst bed. Therefore, identifying suitable susceptor geometries that promote sufficient field penetration and efficient heat generation is of importance.

PROBLEM DESCRIPTION

For technical applications the skin depth of the magnetic field into the applied materials and the location of heat release are of interest. For an idealized flat, infinitely thick conducting plate, an analytical expression for the skin depth is available. For more complex geometries, such as packed beds, however, a comparable level of understanding is still lacking. To address these questions, a lab-scale experimental setup is employed, which is used to investigate the inductive heating of different susceptors and to determine the corresponding heating efficiencies, as shown in Figure 1a. In this setup, the susceptor is placed between a quartz glass body and an insulating shell. Inside the glass body, a fluidized bed allows to ensure a uniform temperature distribution. The induction coil is located outside the insulation. A detailed description of the experimental setup is found in [2]. A simulation model derived from the experimental test section is used to investigate the coupled electromagnetic and thermal response of the susceptor materials and structures, with a specific focus on the magnetic field skin depth, the spatially resolved heat generation within the susceptor and the heating efficiency. For validation purposes, a hollow austenitic steel cylinder was tested as the susceptor, and the results were compared with temperature measurements from the experimental setup, as shown in Figure 1b. The values for the thermal conductivity and the electrical conductivity of the steel were taken from [3]. The model is well suited for assessing the performance of different susceptor materials and for analyzing the associated skin depths. For technical applications, the investigation of packed beds is of particular interest, as they serve as a model of a catalyst bed. For this purpose, spheres were employed as a packed bed susceptor within the test section and their thermal behavior was characterized experimentally. The spatial temperature profiles cannot yet be satisfactorily reproduced by the simulation model, indicating that suitable models for the effective electromagnetic properties of packed beds are still lacking. This highlights a substantial need for further research into the characterization of packed beds in inductively heated systems.



(a) (b)

Figure 1. Experimental setup and validation of the simulation model: (a) schematic of the inductively heated test section; (b) measured and simulated steady-state temperature profiles of the hollow cylinder susceptor.

CONCLUSIONS

Inductive heating shows potential for the electrification of chemical processes due to its fast and efficient heat generation. The developed model successfully describes the thermal behavior of simple susceptor geometries, but its current limitations for packed beds reveal the need for improved effective electromagnetic models.

REFERENCES

1. Mallapragada DS, Dvorkin Y, Modestino MA, Esposito D V., Smith WA, Hodge BM, et al. Decarbonization of the chemical industry through electrification: Barriers and opportunities. Joule. Cell Press; 2023. p. 23–41. doi:10.1016/j.joule.2022.12.008
2. Kleschew D, Tuttlies U, Nieken U. Experimental Analysis of Inductive Heating of Catalytic Beds. Chem Ing Tech. 2024 Jun 1;96(6):769–73. doi:10.1002/cite.202300168
3. Chu TK, Ho CY. *Electrical resistivity and thermal conductivity of nine selected AISI stainless steels*. No. CINDAS45. Thermophysical and Electronic Properties Information Analysis Center; 1977.

Understanding What's Not on the Screen When Modeling Electromagnetic Processing

R. Goldstein[1]

[1] Fluxtrol, Inc., 1388 Atlantic Blvd., Auburn Hills, MI, USA
Corresponding author: R. Goldstein (rcgoldstein@fluxtrol.com)

ABSTRACT. Computer modeling of electromagnetic processes is a very powerful tool that has gained wide acceptance in the market. Over time, the development of electromagnetic processing applications has shifted from analytical and empirically based to progessively more virtual methods. While powerful, models still have limitations and in many processes the results can vary significantly from calculated values, which can cause significant issues. These factors become increasingly dangerous as automatic optimization techniques are employed increasingly over time and modelers are employed that have no knowledge of the actual process they are modeling. This presentation will provide some examples to demonstrate phenomena that occur in electromagnetic processing that are not commonly considered in virtual development that caused issues in practice.

***Keywords*—** Electromagnetic Processing, Rapid Thermal Processing, Non-Equilibrium Thermal Processing, Residual Stresses, Distortion Engineering, Dimensional movement, Induction Heating, Induction Coil Design, Computer Simulation, Virtual Validation

INTRODUCTION

Modern computer hardware and software capabilities have improved drastically over time and it is now possible to solve multi-physics electromagnetic processing problems in 3D within reasonable amounts of time in many cases. Many papers have been published at previous HES events on multi-physics modeling for technologies including mass heating, heat treating, magneto-hydronamics, welding, crystal growing, inductive coupled plasma and melting. These models provide accurate calculations based upon the input data provided to them.

The challenge arises when the input data provided does not reflect the real-world situation. Common issues encountered include:

- Not considering a multi-physics module in the calculations
- Not considering processes that occur prior to the electromagnetic process
- Use of materials property data that is not based upon the processing conditions
- No good, known physical model exists for a physical phenomena
- Not understanding the power supply operating mode or limits
- Not understanding how the material may impact the power supply operation
- Not understanding the goal function and critical properties for component performance
- Not considering manufacturing tolerances on incoming product

In some cases, if we understand how these practical considerations can impact our process, it is possible to consider them in the modeling process and stress the model for various incoming conditions. In other cases, it can help us to quickly identify whether the condition occurring in the electromagnetic process is a result of the electromagnetic process or something which was present in the incoming material that needs to be addressed in order to have a successful process.

Induction Heat Treatment

Virtual validation techniques are commonly used for induction heat treated components. In the past, component specifications for induction heat treatment used to provide for a surface hardness level(s) over a certain region of the component along with total and effective case depths for the various regions. Manufacturers have learned over the past few decades that the residual stress distribution plays a very large role in the ability of the component to function effectively and reliably in service and have now begun specifying minimum residual stress levels for performance as opposed to just a hardness distribution [1]. These new standards require the use of not only electromagnetic and thermal models, but also at a minimum metallurgical and residual stress calculations. What can be especially challenging in some of these cases is that the database for these materials is not well developed for induction heat treating conditions, which is essential for the accurate prediction of residual stresses. Compounding the issue is that many of the tools that are commonly used for measuring material properties are not well suited to measuring the conditions present in induction heat treatment and can lead to incorrect property measurement, yielding incorrect results. Some of these factors are described below.

Spray Quenching Process

Practitioners have long known that the quench intensity, concentration, cleanliness, temperature and distribution and can have an impact on the final component dimensions, hardness distribution and can also result in part cracking. Li et. al. demonstrated using computer models that the heat transfer coefficient used for modeling has a large influence on the resulting residual stress levels in induction heat treating as well as play a strong role in the dimensional movement of the component on a progressively hardened axle shaft (Figure 1) [2]. The values used in these models were made using linear heat transfer coefficients developed using standard characterization tools for quenchants. There was some limited information on induction spray quenchants for induction heat treatment available that showed heat transfer coefficients orders of magnitude higher than the values used in this study and Nemkov, et. al published the influence that using a non-linear value for the heat transfer coefficient can have on the time for the component on martensite formation which is the main driver of heat treatment induced residual stresses [3].

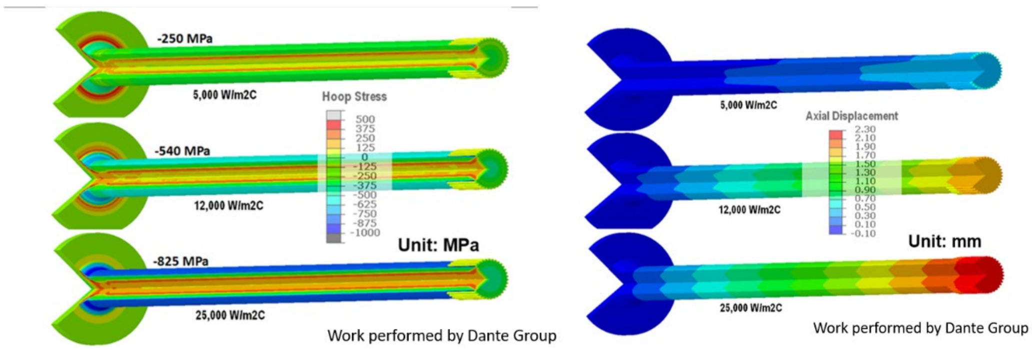


Figure 1. Dimensional movement and residual stresses for induction hardened axle shaft with different applied heat transfer coefficients to simulate quenching

Goldstein and Mackenzie showed that the values used were based not upon the spray quenchants themselves, but were actually the limits of the measurement devices that were used to measure the heat transfer coefficients due to thermal lag inherent in the device itself [4]. Proposals for potential improved designs of characterization devices were presented and suggested for use to expand the range of potential measurements possible, but further work is required to make appropriate tools for real component quench spray characterization as real induction quenching systems on real components tend to be much more complicated than a simple non-linear value.

As an alternative to the physical measurement, computation fluid dynamics models show promise, but these are not necessarily well validated for induction spray quenching conditions and are computationally very expensive. There is a significant amount of work required to convert this portion of the technology from a qualitative assessment to a quantitative tool over time.

A High-performance miniature synthetic jet pump for cooling applications

Guoqing Sun, Xiaobing Luo*

School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
Corresponding author: Xiaobing Luo (luoxb@hust.edu.cn)

ABSTRACT. Various electronic devices face severe thermal failure issues due to their inherent electromagnetic heating, and effective thermal management is a prerequisite for the reliable operation of electronic systems. In this work, a design concept for a high-performance synthetic jet pump dedicated to cooling applications is proposed. Based on the synthetic jet principle, the jet velocity is maximized by coupling mechanical anti-phase vibration with Helmholtz resonance. A synthetic jet pump with high-performance is developed, featuring an ultra-compact size of only 12×12×1.75 mm. Thermal performance tests demonstrate that the designed pump exhibits cooling effectiveness.

***Keywords*—** Synthetic jet, air pump, active cooling.

INTRODUCTION

The growing computational power requirements of portable electronic devices have led to severe thermal issues [1], rendering conventional passive cooling methods insufficient for high-performance applications. Active cooling solutions provide a path to further improve electronic system capabilities. Piezoelectric synthetic jet pumps, with no rotating parts, can be made very small [2], well accommodating the space constraints of computing devices. Nevertheless, enhancing the performance of synthetic jet pumps while reducing their size remains an urgent problem. This study presents a new design concept and performs thermal tests, which verify the effectiveness of the proposed design.

DESIGN PROCESS AND RESULTS

Synthetic jet pumps are usually driven by piezoelectric ceramics for their lightweight and thin design [3]. Nevertheless, the piezoelectric vibrator formed by a piezoelectric ceramic and a metal substrate has limited vibration amplitude, leading to small pressure fluctuations in the jet cavity and thus restricting the pump performance. Hence, increasing the pressure fluctuation in the cavity is critical for enhancing synthetic jet pump performance.

Design concept

The proposed design concept is illustrated in Fig. 1. Synthetic jet pumps generate a net mass flow rate through asymmetric ejection and suction processes. An equivalent circuit model is employed to elucidate the detailed design methodology. Unlike conventional designs, in the mechanical domain, we treat the jet orifice plate as an additional vibrator (i.e., the lower vibrator). Eigenfrequency simulations are performed to determine the geometric parameters of both the upper and lower vibrators, ensuring their fundamental vibration mode frequencies are close. In the acoustic domain, the volume of the jet cavity is designed such that its Helmholtz resonant frequency matches the aforementioned mechanical resonant frequency, thereby exciting the maximum pressure fluctuations within the jet cavity. The key geometric parameters of the synthetic jet pump are determined via finite element modeling, achieving the coupling of mechanical anti-phase resonance and Helmholtz resonance. Finally, the developed synthetic jet pump delivers a maximum flow rate of 4.05 L/min and a maximum back pressure of 642 Pa under a driving voltage of 90 Vpp, with an ultra-compact footprint of only 12×12×1.75 mm.

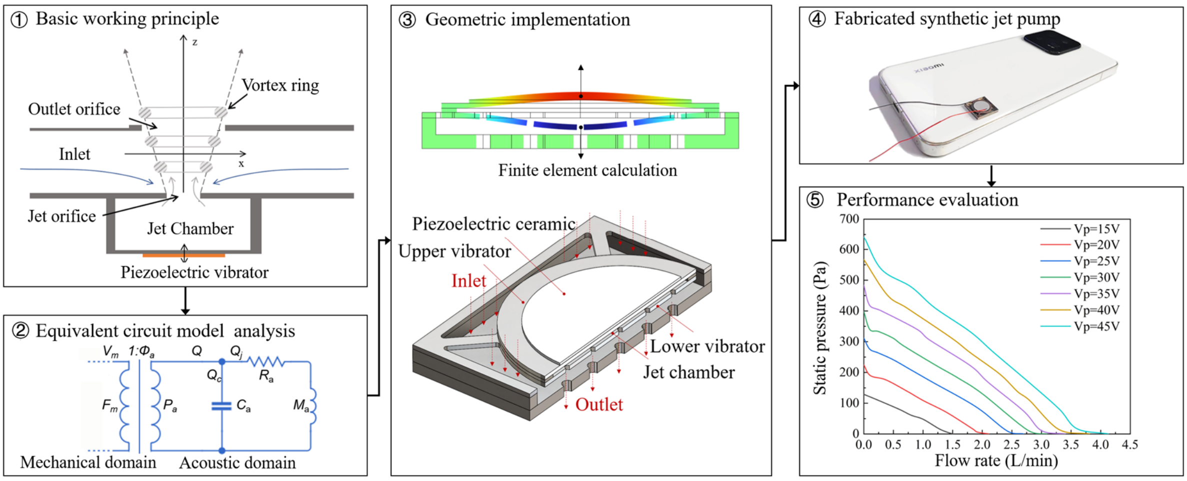


Figure 1. Design and development process of the proposed synthetic jet pump.

Thermal performance evaluation

Fig. 2 presents the cooling performance at different gap distances. At a gap distance of 5 mm, the achieved temperature reductions for heat sources of 3 W, 5 W, and 7 W are 78.3 °C, 107.9 °C, and 136.5 °C, respectively. The magnitude of temperature reduction decreases with increasing gap distance.

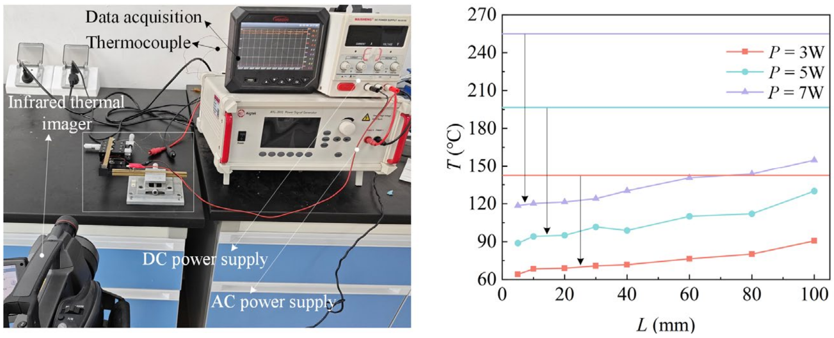


Figure 2. Thermal performance testing and results.

CONCLUSIONS

A novel design concept is proposed, which maximizes the jet velocity by coupling mechanical anti-phase vibration with acoustic Helmholtz resonance, thereby realizing a miniature high-performance synthetic jet pump. The fabricated pump delivers a maximum flow rate of 4.05 L/min with an ultra-compact size of 12 × 12 × 1.75 mm. Thermal tests show that the pump maintains a 3 W heat source below 70 °C, a 78.3 °C reduction from natural convection.

REFERENCES

1. Ghadim HB, Godin A, Veillere A, Duquesne M, Haillot D. Review of thermal management of electronics and phase change materials. Renewable and Sustainable Energy Reviews. 2025;208:115039.

2. Peng B, Yi Z, Fan Y, Li X, Wei X, Wang C, et al. Piezoelectric active air-cooling devices. Chip. 2026;5(1):100163.

3. de Luca L, Girfoglio M, Coppola G. Modeling and Experimental Validation of the Frequency Response of Synthetic Jet Actuators. AIAA Journal. 2014;52(8):1733-48.

RF heating for an energy storage system developed in the Horizion Europe Project Hystore

M. Bullo[1] C. De Massari[1] and C.Santoloce[1]

[1] Inova Lab S.r.l., vicolo Bellini 10F, Padova, Italy
Corresponding author: C. Santoloce (c.santoloce@inovalab.eu)

ABSTRACT. —Within the framework of the EU Horizon project HYSTORE (grant agreement N. 101096789) a thermochemical (TCM) prototype has been developed. The innovation in the TCM system involves using radiofrequency (RF) dielectric heating on Zeolite 13X instead of conventional microwave heating and use ground electrodes also as heat exchanger in the chamber.
***Keywords*—** energy storage, radiofrequency, zeolite.

INTRODUCTION

Power-to-heat strategies are being utilized to mitigate grid stability issues caused by renewable energy integration by converting surplus electricity into manageable thermal energy. Within the Horizon Europe HYSTORE project, an innovative thermochemical energy storage (TCM) system is being developed, utilizing a high-density, reversible solid-gas adsorption cycle based on Zeolite 13X and water.

During the endothermic charging phase, input electromagnetic energy breaks the water-zeolite molecular bonds via desorption, condensing the released vapor into a liquid state. Since the dry zeolite and liquid water are stored separately, the system avoids continuous temperature maintenance, achieving loss-free energy conservation over several months. During discharging, the water is re-vaporized and reintroduced into the bed, triggering an exothermic adsorption reaction that releases the stored heat for domestic applications.

PROBLEM DESCRIPTION

The primary obstacle in scaling conventional thermochemical reactors is the low thermal conductivity of porous zeolite pellet beds. Traditional conductive or convective heating methods rely on external heat transfer through the boundaries, creating severe internal thermal gradients and slowing down the process.

To overcome this, the Hystore TCM project utilizes radiofrequency (RF) heating operating at 27.125 MHz. At this frequency, the longer electromagnetic wavelength ensures deep penetration and a highly uniform field distribution in the chamber.
This method achieves direct volumetric heating from within the material, completely eliminating localized hotspots and power peaks that could damage the zeolite structure over thousands of cycles.*[1]* Furthermore, RF heating allows for highly efficient low-temperature desorption (120°C–200°C) under vacuum conditions. By pairing solid-state RF generators with automated impedance matching units, the system continuously maximizes real power delivery during the endothermic cycle.

System Engineering, Simulation, and Prototyping

The developed system features a cylindrical vacuum chamber geometry specifically designed to maintain strict axial symmetry and ensure a uniform electromagnetic field distribution throughout the material bed.

(a) (b)

Figure 2. System design. (a) complete system design and (b) HV and ground electrodes.

As illustrated in Figure 2, the system architecture integrates several components engineered to balance electromagnetic performance with optimal thermodynamic control. At the core of this configuration, a top-fed high-voltage electrode (Figure 2b) guarantees uniform electromagnetic field coupling into the chamber; the electrode structure consists of an internal perforated sheet metal cage immersed in the granular zeolite pellets to facilitate efficient moisture transport. Electrical grounding and thermal management are handled simultaneously by a network of internal copper coils, which function as both the radiofrequency ground electrodes and internal cooling heat exchangers. This internal assembly is supplemented by external coils welded directly onto the outer wall of the chamber, which rapidly extract heat to accelerate cooling and enable fast cycle repeatability (Figure 2b).

Following a rigorous virtual validation, a physical prototype was fabricated and installed at the CNR ITAE facility in Messina, where experimental testing is currently ongoing.

CONCLUSIONS

The RF-heated thermochemical reactor developed under the HYSTORE project offers a breakthrough solution for Power-to-Heat sector coupling. By shifting from boundary conduction to volumetric radiofrequency dissipation at 27.125 MHz, the system successfully bypasses the heat transfer limitations of porous zeolite beds. The combination of 3D numerical modeling and optimized vacuum chamber engineering ensures uniform thermal distribution and exceptional lifecycle stability. This advanced thermal battery represents a highly scalable, loss-free energy storage option designed to provide vital flexibility to future decarbonized energy grids.

REFERENCES

1. [1] Vasta S, Brancato V, La Rosa D, Palomba V, Restuccia G, Sapienza A, et al. Adsorption Heat Storage: State-of-the-Art and Future Perspectives. Nanomaterials 2018;8:522.

HES-UIE-26

Padua, September 15-18, 2026

Organized by
LEP - Laboratory for Electroheat Department of Industrial Engineering
University of Padua (Italy)

Università degli Studi di Padova

UIE - International Union for Electricity Application

ISBN 978-88-6938-543-8