ENT9099ME09 - Design, Modelling and Optimization of an Induction Heating System for Industrial-Scale Processing of White Aluminum Dross

Principal Investigator

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Programme	ENT9099 Master of Science by Research in Mechanical Engineering
Research Area and Specialization:	Applied Fluid Mechanics and Multiphase Heat Transfer •Electromagnetic Heating Systems •Industrial Process Modelling •Sustainable Metallurgical Recycling
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Background of the problem

Efficiency, quality, and responsiveness are becoming increasingly important in the manufacturing and fabrication sectors. Due to their frequent lack of realtime insights, traditional process monitoring techniques frequently result in delays, bottlenecks, and inefficient use of resources. To solve this, a thorough data collecting system that records environmental parameters pertinent to different production processes, machine operational data, and real-time process metrics must be developed and put into place. Predictive models that precisely estimate process durations can be created by analyzing past process data using machine learning techniques. Continuous tracking Aluminum dross is a by-product generated during aluminum melting and recycling processes, consisting mainly of metallic aluminum, aluminum oxide, and smaller amounts of nitrides, carbides, and entrapped impurities. White aluminum dross, generated during primary aluminum melting, contains a relatively high percentage of recoverable metallic aluminum and therefore has considerable economic value. However, conventional recovery methods remain energyintensive and environmentally challenging. Recent studies emphasize the need for cleaner and more sustainable dross treatment technologies [1-3].

The most widely used industrial process for aluminum dross recycling is the rotary salt furnace (RSF), where NaCl–KCl salt flux promotes coalescence of metallic aluminum droplets while protecting them from oxidation [1,2]. Despite its effectiveness in metal recovery, this method generates hazardous salt slags and requires substantial thermal energy input, leading to environmental and disposal concerns.

Salt-free technologies, such as the DROSRITE process, were introduced to reduce hazardous waste generation by using controlled oxidation and inert atmospheres to improve aluminum recovery without salt additives [4,5]. However, these systems still depend on external heating and may suffer from limited thermal efficiency and uneven temperature control.

Induction heating has gained increasing attention in metallurgical applications because of its rapid heating rates, high energy efficiency, and precise temperature control. It has been widely applied in melting and heat treatment of homogeneous metallic materials, particularly aluminum and steel [6].

This creates a practical research need for assessing the feasibility and energy performance of induction heating for industrial white dross treatment [2,7].

List of publications related to the field

Anagnostopoulos J. and Bergeles G.: "Three-Dimensional Modeling of the Flow and the Interface Surface in a Continuous Casting Mold Model". Metallurgical and Materials Transactions B, vol. 30, no. 6, pp. 1095-1105, 1999. https://link.springer.com/article/10.1007/s11663-999-0116-4

Anagnostopoulos J., Bergeles G, Epple B., and. Stegelitz P.: "Numerical Simulation of Grinding and Drying Performance of a Fluid-Energy Lignite Mill". ASME Transactions, Journal of Fluids Engineering, vol. 123, no.2, pp. 303-310, June 2001.
https://asmedigitalcollection.asme.org/fluidsengineering/article-abstract/123/2/303/463158/Numerical-Simulation-of-Grinding-and-Drying?redirectedFrom=fulltext

Anagnostopoulos J.: "Discretization of Transport Equations on 2D Cartesian Unstructured Grids using Higher-order Schemes for the Convection Terms". Int. Journal for Numerical Methods in Fluids, vol 42, is 3, pp. 297-321, 2003.
https://onlinelibrary.wiley.com/doi/abs/10.1002/fld.514?msockid=32ae1f02395c6fbd046909ec381a6eb6

Anagnostopoulos J. and Mathioulakis D.S.: "A Flow Study Around a Time-Dependent 3-D Asymmetric Constriction", Journal of Fluids and Structures, vol. 19, pp. 49-62, 2004.

https://www.sciencedirect.com/science/article/abs/pii/S0889974603001737

Anagnostopoulos J.S. and Mathioulakis D.S.: "Unsteady flow in a square T-junction", Physics of Fluids, 16(11), pp. 3900-3910, 2004.

https://pubs.aip.org/aip/pof/article-abstract/16/11/3900/255526/Unsteady-flow-field-in-a-square-tube-T-junction?redirectedFrom=fulltext

Research Objectives and Expected Outcomes

Aim:

To design and optimize an energy-efficient induction heating system for industrial-scale processing of white aluminum dross through coupled thermos-fluidelectromagnetic modelling and system design.

Objectives:

1. Develop a thermo-physical property database for white aluminum dross with varying metallic content (10–90 wt%).

2. Analyse electrical conductivity and electromagnetic penetration depth as a function of frequency and material composition.

3. Determine optimal induction heating parameters for uniform heating of 1,000 kg dross batches.

4. Design induction coil geometry and estimate electrical power requirements for industrial operation.

5. Develop a coupled thermal-electromagnetic numerical model to simulate transient heating behaviour.

6. Evaluate cooling system requirements for coil operation and system stability.

7. Compare energy efficiency and cost performance against conventional heating technologies.

Expected Outcomes:

- A validated thermo-electromagnetic model for aluminum dross heating.
- A comprehensive material property database for heterogeneous dross
- Optimized induction coil design for industrial-scale heating
- Estimation of minimum energy requirements for batch processing
- Numerical simulation of temperature evolution during heating
- Design of cooling and power systems for industrial application
- Comparative assessment of induction heating versus conventional methods
- Recommendations for industrial implementation of energy-efficient dross recycling systems

Research Design & Methodology

The research will adopt a computational and design-based engineering methodology, supported by theoretical modelling and numerical simulation.

Material Property Development: A comprehensive database of thermo-physical properties (specific heat, density, thermal conductivity, electrical conductivity) will be developed for aluminum dross compositions ranging from 10–90 wt% metallic aluminum. Data will be obtained from literature and estimated using mixture models where required.

Electromagnetic Analysis: Maxwell's equations will be used to evaluate electromagnetic field distribution. Skin depth will be calculated as a function of frequency and conductivity. The influence of heterogeneous composition on effective penetration depth will be analysed.

Thermal Modelling: Transient heat transfer within the dross will be modelled using energy conservation equations. Internal heat generation due to eddy currents will be coupled with conduction and natural convection effects.

Numerical Simulation: Multiphysics simulation tools (e.g., COMSOL or ANSYS Maxwell/Fluent coupling) will be used to simulate: Electromagnetic field distribution, Heat generation rates, and Temperature evolution over time.

System Design: Induction of coil geometry (turns, diameter, spacing) will be designed based on required power input and efficiency. Electrical power requirements will be calculated for a 1,000 kg batch heated from 300°C to 800°C in 60 minutes.

Cooling System Design: A closed-loop water cooling system for the induction coil will be designed, including flow rate and heat removal capacity.

Comparative Analysis: Energy consumption and operational cost will be compared against conventional fossil fuel and resistance heating systems.

Ethical and Contextual Considerations: The study involves no human or biological subjects. Environmental considerations will focus on reducing industrial emissions and improving recycling sustainability.

Significance and potential impact of research in Bahrain

The proposed research contributes to the development of a cleaner, more energy-efficient method for aluminum recycling, which is critical for reducing industrial carbon emissions and improving circular economy practices.

Induction heating offers a potentially cleaner alternative to fossil-fuel-based dross processing, but its application to heterogeneous materials such as white aluminum dross remains underdeveloped. This research provides a systematic framework for understanding coupled electromagnetic and thermal behaviour in such materials.

The study has direct industrial relevance, enabling improved aluminum recovery efficiency, reduced energy consumption, and elimination of salt-based waste streams. It also supports sustainability goals by minimizing environmental pollution associated with conventional recycling processes.

From a scientific perspective, the project contributes to multiphysics modelling of heterogeneous conductive media, bridging gaps between electromagnetic theory, heat transfer, and materials engineering.

The results will be directly applicable to industrial furnace design and can be extended to other metallurgical recycling processes..

Alignment with Bahrain's national research strategy

This research supports Bahrain's industrial sustainability and circular economy goals by improving aluminum recycling efficiency and reducing hazardous waste generation. It contributes to cleaner production technologies aligned with national environmental objectives.

The project aligns industrial decarbonization strategies by reducing reliance on fossil-fuel-based furnaces and lowering greenhouse gas emissions. It also supports Bahrain's manufacturing sector by providing advanced engineering solutions for metal recovery processes.

From an industrial perspective, the proposed system can reduce operational costs, improve energy efficiency, and enhance material recovery rates for metal processing companies.

Contribution to Bahrain Society:

Improved aluminum recycling efficiency, reduced hazardous waste from salt flux processes, and enhanced environmental sustainability in metal processing industries.

Alignment with Industry:

Provides a scalable induction heating design framework for industrial dross processing, enabling lower energy consumption and improved recovery efficiency.

National Strategy Alignment:

Supports Bahrain's sustainability and circular economy objectives, industrial decarbonization policies, and energy efficiency initiatives.

Benefits for Industry Partner:

Reduced operational costs, improved recovery yield, elimination of salt waste, and adoption of advanced energy-efficient furnace technology.

Potential industry partners for future collaboration include aluminum recycling and metal processing companies operating in the GCC region, particularly

those involved in dross treatment and secondary aluminum production. Also, Regional metal recycling companies, Industrial furnace manufacturers, and Thermal equipment suppliers in GCC.