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Heat transfer mechanisms in Electric Smelter Furnaces for ironmaking

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Electric Smelter Furnaces (ESF) are critical for the transition toward sustainable ironmaking, requiring precise control of plasma arc heat transfer to optimize efficiency. This study investigates the axial distribution of volumetric heat sources specifically Joule heating, radiation, and the Thompson effect within a DC brush arc configuration. Results demonstrate that extreme current density at the cathode tip drives intense Joule heating, creating a localized thermal hot spot at the emission boundary. As the arc expands, direct electrical heating rapidly decays, leaving radiation to govern energy transport through the plasma column toward the slag bath. Furthermore, while electron enthalpy transport by the Thompson effect is an order of magnitude smaller than radiation, and this is concentrated near the base of electrode, and it is essential for understanding the central heat flux as it relates especially to heat transfer in the plasma medium. By highly localizing energy delivery to the smelting zone, the brush arc effectively shields the surrounding furnace structure from excessive radiative loads. Future work will couple these arc heat transfer mechanisms with convective bath models to further optimize ESF thermal efficiency.

KEYWORDS: ELECTRIC SMELTER FURNACE (ESF); HEAT TRANSFER; OPEN SLAG BATH FURNACE (OSBF).

INTRODUCTION: THE EVOLUTION OF ELECTRIC SMELTING FURNACE

The transition towards decarbonized steel industry has created the scope for the development of Electric Smelter Furnaces (ESF) as an alternative for making molten iron rather than the Blast Furnace (BF). When combined with Direct Reduced Iron (DRI), utilizing an ESF rather than a conventional, coke-based blast furnace has the potential to reduce CO_2 emission intensity by up to 85% (1). A sub-technology in this domain is the Open Slag Bath Furnace (OSBF). It takes the open-arc flexibility of an EAF and combines it with the deep, resistive slag bath of an SAFmaking it the primary furnace choice for smelting fine, low-grade iron ore feeds (like H_2-DRI) into liquid hot metal.Unlike the SAF, where electrodes are fully submerged in a solid burden, the OSBF operates with an open slag bath, allowing for greater versatility in raw material chemistry and slag control (2). OSBF is operated in a brush arc where in the arc tends to be small and interacts with slag(3). In the "brush arc" configuration as shown in figure 1 the electrode tip is positioned such a way that the arc is partially submerged within the slag layer.

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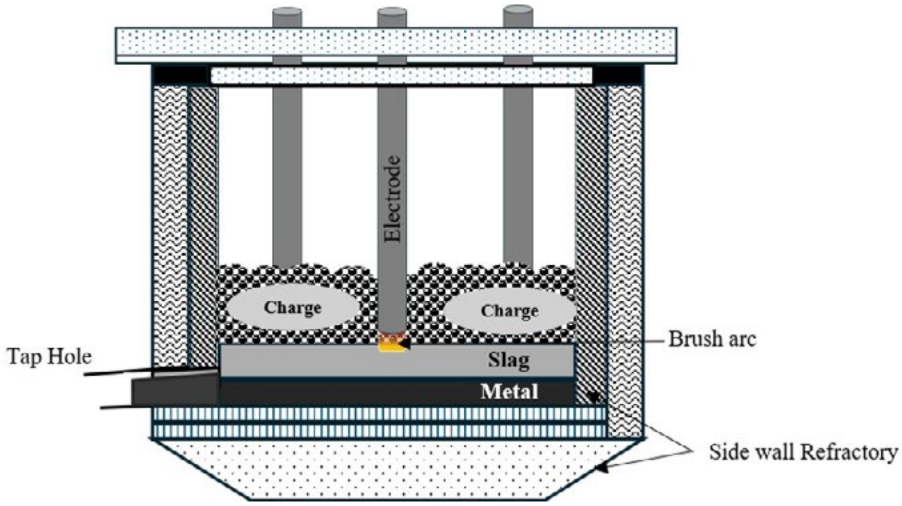

Fig.1 - Schematic of Open Slag bath furnace.

This partial submersion of the arc provides radiative shielding and Heat dispersion into slag providing better heat transfer and the heat transfer mechanisms from the electric arc are mentioned in figure 2 to melt the new DRI and save the walls and roof (4).

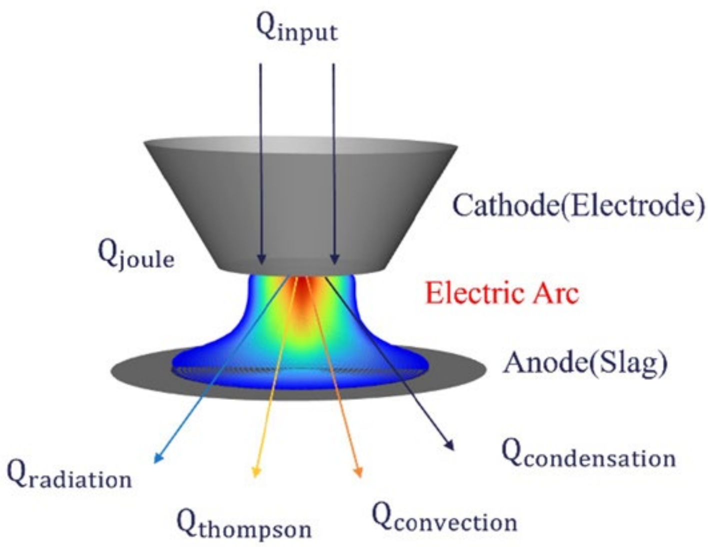

Fig.2 - Heat transfer mechanisms from Electric arc.

CFD MODELLING OF BRUSH ARC

To understand the heat transfer and slag chemistry within an Electric Smelter Furnace, a single-electrode Computational Fluid Dynamics (CFD) model was developed based on Magnetohydrodynamic (MHD) principles. The components of the model are an electrode and a furnace chamber, with the investigation focusing on the fundamental process of electric arc generation and its direct impact on the surrounding environment, particularly on heat transfer mechanisms. The model in figure 3 features a 10-millimeter-high electrode positioned within a furnace chamber. The furnace walls are defined as adiabatic boundaries, ensuring that heat transfer remains confined within the system to allow focused analysis of arc generated heat and the boundary conditions are mentioned in table 2 thermophysical properties, including temperature dependency, defined by User defined Function properties.

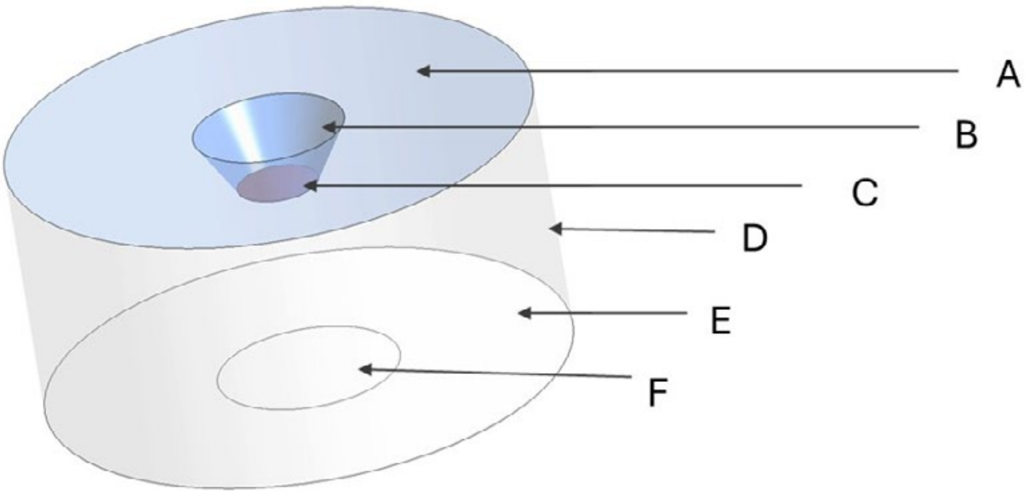

Fig.3 - 3D Geometry for modelling.

Tab.1 -Boundary Conditions for the model.

Area	P	T	V	A(x,y,z)
A	0	1000	0	0
B	—	3500	0	0
C	—	3500	J(x,y)	0
D	0	1000	0	0
E	—	1000	0	0
F	—	$\partial T/\partial z = 0$	0	0

Electrically, the bottom surface of the furnace representing the metal bed is maintained at zero electrical potential, while the electrode is supplied with a positive electrical potential and an associated electric flux at the cathode spot. This potential difference drives an electric current that, as it attempts to bridge the inter-electrode gap of approximately 2.5 millimetres, ionizes the gaseous medium to form and sustain the electric arc.

This model solves the coupled conservation equations for mass, momentum, and energy across the steady state electric arc from a single cathode spot on the electrode interacting with plasma and slag. The total energy transfer from the brush arc is a composite of convection, radiation, and electron-mediated transport. The energy transfer equation used for modelling electric arcs is mentioned in equation 1(5) and all the parameters of heat transfer mechanisms are mentioned in the table 2.

$$\frac{\partial(\rho v h)}{\partial z} + \frac{1}{r}\frac{\partial(\rho v r h)}{\partial r} = \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\sigma_T}\left(\frac{\partial h}{\partial z}\right)\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\mu_{eff}}{\sigma_T}\left(\frac{\partial h}{\partial r}\right)\right) + Q_j - Q_r - Q_t \quad [1]$$

Tab.2 - Heat transfer mechanisms equations in ESF(5).

Heat transfer	Equation
$Q_{radiation}(Q_r)$	$Q_r = 4\pi(NEC)$
$Q_{thompson}(Q_t)$	$Q_t = \frac{5}{2}\frac{k_b}{e}\left(\frac{J_r}{C_p}\left(\frac{\partial h}{\partial r}\right) + \frac{J_z}{C_p}\left(\frac{\partial T}{\partial z}\right)\right)$
$Q_{convection}$	$Q_{cv} = \frac{0.915}{\sigma_T}\left(\frac{\rho_g\mu_g}{\rho_s\mu_s}\right)^{0.43}\left(\frac{\rho_s\mu_s V_g}{r}\right)^{0.5}(h_g - h_s)$
$Q_{joule}(Q_j)$	$Q_j = \frac{J_z^2 + J_r^2}{\sigma_e}$
$Q_{condensation}$	$Q_c = J_z(V_a + \emptyset_a)$

In these equations, vg represent the velocity of gas in the z directions and ρ denotes density. The term μ_g and μ_s is the viscosity of the gas and slag respectively, and J_r and J_z are the densities of current and in r and z directions. $\emptyset_a$ is the work function of the anode and furthermore, σ_T and σ_e denote the thermal and electrical conductivities, while h and, C_p are enthalpy and specific heat capacity, S_r is the radiation loss, k_b is the Boltzmann constant, and e is the electron charge and NEC is net emissive Coefficient (6).Due to the complexity and the turbulence behaviour of arcs this paper only discusses about Joule heat, Radiation and Thompson effect and their effect in the brush arcs with in carbon monoxide plasma.[PP1.1]

RESULTS AND DISCUSSION

Axial distribution of heat sources from the cathode tip of electrode to the slag bath is studied and different heat transfer mechanisms are predicted. As illustrated in figure 4, the electron enthalpy flux and joule heat peaks near the electrode base due to the localized concentration of high current density and extreme plasma temperatures at the cathode tip. Moving axially toward the slag bath, the expansion of the plasma column leads to a gradual decay in current density and thermal energy, resulting in a corresponding decrease in joule heat and electron enthalpy transport. In the highly constricted cathode region, Joule heating dominates but decays exponentially as the arc expands. Conversely, radiative heat flux decays slowly, overtaking Joule heating in the expanded column to become the primary mechanism transferring heat to the slag bath.

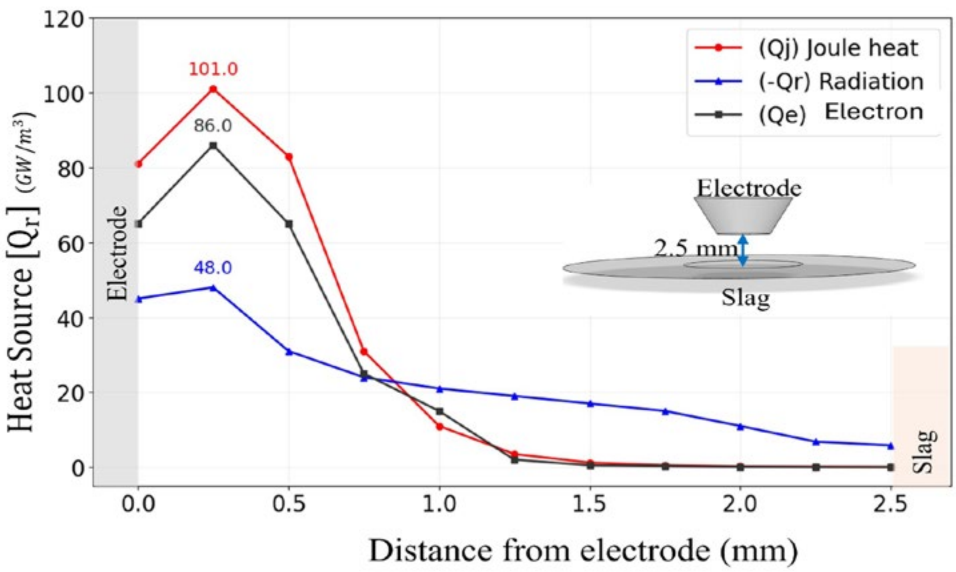

Fig.4 - Comparison of Heat transfer mechanisms in plasma medium.

CONCLUSION AND FUTURE WORKS

- **Joule Heating:** In the brush arc mode current density (J) at the tip drives intense Joule heating (proportional to $\frac{J_z^2}{\sigma_e}$) creating a massive thermal "hot spot" and elevated heat flux at the cathode boundary.
- **Radiation:** Radiation proves to be one of the dominant heat transfer mechanisms compared to joule and Thompson effect for distributing heat from the brush arc in an ESF.
- **Thompson Effect:** For shorter arc heights, enthalpy transport by electron drift is an order of magnitude smaller than thermal radiation. This is primarily due to the confined space for plasma gas circulation, which restricts overall heat transfer and localized Joule heating in this narrow gap

FUTURE WORK

In the future work we will be solving for convective heat transfer from the arc and study the heat transferred on to slag along with feed materials, roof and walls of the furnace and the validation will be done against industrial data from the partners involved in this project

DECLARATION OF CONFLICTS OF INTERESTS

The Authors declare that there is no conflict of interest related to this publication.

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