A Time-Based Pellet Melting Approach to Model Feed Pile Formation in an Electric Smelting Furnace (ESF) Supported by Experiments

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INTRODUCTION

Steel production is responsible for approximately 7–9% of global CO_2 emissions, with the majority originating from conventional blast furnace routes [1]. To reduce emissions and meet climate targets, alternative ironmaking technologies are being developed. One promising route is based on Direct Reduced Iron (DRI), where iron ore is reduced using natural gas or hydrogen and subsequently melted in an Electric Smelting Furnace (ESF) [2]. This process offers increased flexibility in raw materials and the potential for significantly lower emissions compared to traditional methods. A schematic representation of the ESF process is shown in Figure 1a.

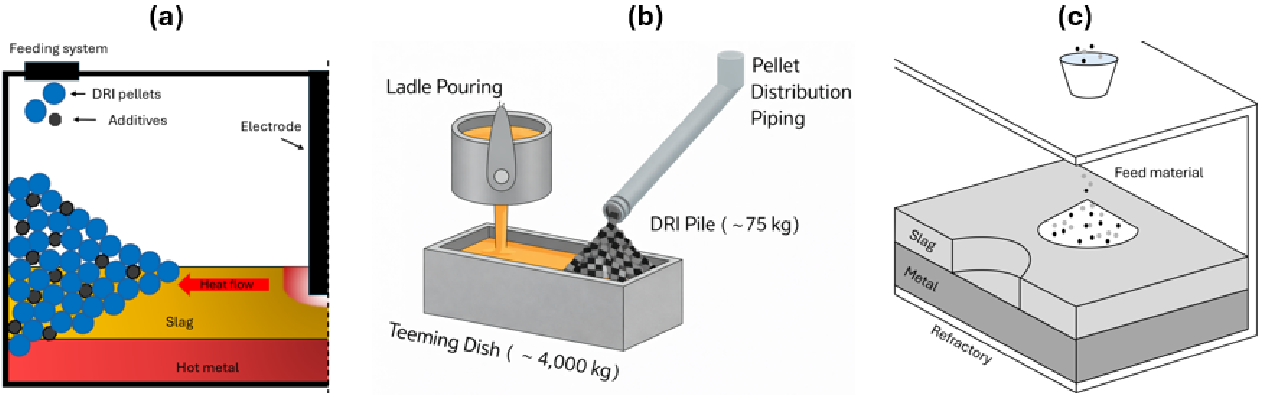

Fig.1 - (a) Schematic representation of the ESF showing the feed pile, slag, and hot metal; (b) experimental setup for feed pile formation used to support model development; (c) simplified computational domain used in the model.

In the ESF, DRI pellets are charged from the top and form a feed pile on the surface of the slag and hot metal layers. The behaviour of this pile is governed by complex interactions between solid particles, liquid phases, and gas, with heat transfer and melting controlling its evolution. A key uncertainty is the extent of slag penetration into the pile, which directly affects particle motion, heat transfer, and melting behaviour. In this study, feed pile behaviour is investigated using a coupled Discrete Element Method (DEM) – Computational Fluid Dynamics (CFD) framework, supported by experimental observations, considering two extreme cases of pile–slag interaction and incorporating time-based melting and cohesion models to capture particle-scale effects.

METHODOLOGY

Experimental observations were used to support the model development. A pilot trial was conducted to investigate feed pile behaviour in the ESF, as shown in Figure 1b. In this setup, molten metal at approximately 1680 °C was poured into a vessel, followed by top charging of DRI pellets to form a feed pile. Cross-sectional observations show that liquid penetration into the pile is limited to a few particle layers at the interface, indicating a predominantly dry pile with a thin interfacial zone where particles are wetted. Given the lower viscosity of liquid iron compared to slag, this observation suggests that penetration in the actual slag system may also be limited. However, due to slag solidification under the present conditions, a fully representative pile–slag interaction cannot be achieved, and further experimental work is required.

A coupled DEM–CFD model is developed to study feed pile formation and melting in the ESF. The simplified domain (Figure 1c) is used to represent the region around a single feed point and includes three phases: DRI pellets, slag, and molten metal. The freeboard is treated as void, and gas flow and electrodes are not explicitly modelled; their effects are represented through boundary conditions.

To describe pile–slag interaction, two cases are considered: a wet scenario with slag penetration and a dry scenario with gas-filled pores (Figure 2). These scenarios lead to different buoyancy force distributions (F_b) and represent the extremes of system behaviour [3].

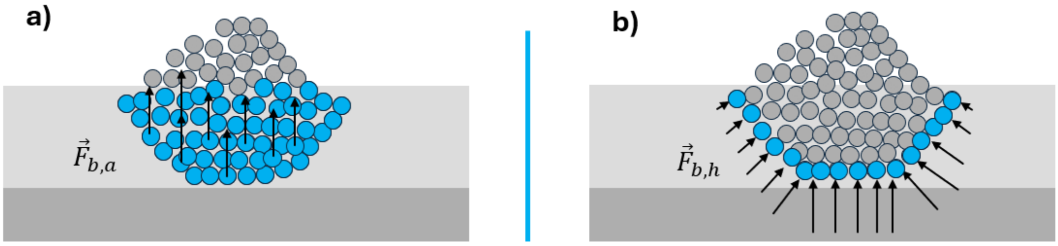

Fig.2 - Illustration of feed pile interaction with the slag layer under two extreme scenarios: (a) wet scenario, where buoyancy forces ($F_{b,a}$) act upward within the pile; (b) dry scenario, where buoyancy forces ($F_{b,h}$) act primarily at the pile-slag interface [3].

Melting is modelled as a time-dependent process with three stages: shell formation, remelting, and core melting [4]. The particle diameter evolves from 12 mm to 14 mm and then decreases during melting, with a total melting time of 16 s. Particles are removed once their diameter reaches 6 mm. In addition, a time-dependent cohesion model based on a simplified JKR approach is included, where cohesive forces are applied only to particles in contact with the liquid and increase with residence time.

RESULTS AND DISCUSSION

A cross-sectional comparison of the feed pile shapes obtained from the two extreme scenarios is shown in Figure 3. Clear differences are observed between the wet and dry scenarios. The wet scenario results in a wider pile with pronounced lateral spreading, while the dry scenario forms a more compact and centred pile. These two cases represent the upper and lower bounds of possible pile behaviour in the furnace. Experimental observations indicate limited liquid penetration, suggesting that the actual system behaviour lies between these two extremes, with a predominantly dry pile and a thin interfacial zone where particles are wetted.

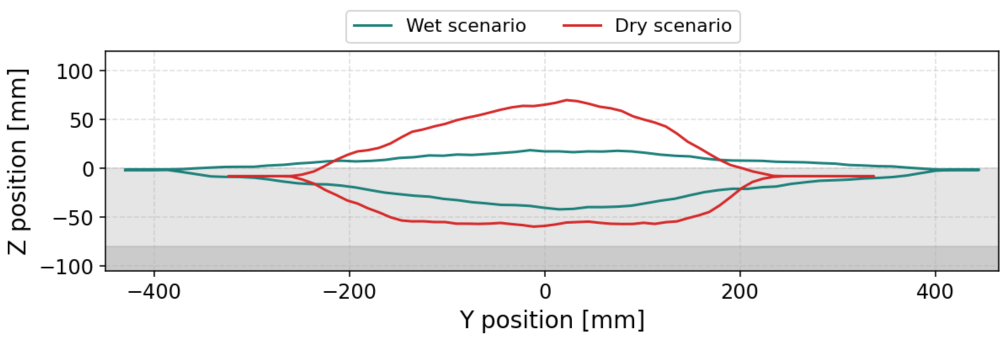

Fig.3 - Cross-sectional comparison of the feed pile shapes for the wet and dry scenarios.

The influence of melting and cohesion on feed pile behaviour is illustrated in Figure 4. Figure 4a shows the particle-scale melting behaviour, where the process is divided into shell formation, shell remelting, and core melting. Upon entering the liquid phase, particles initially expand from 12 mm to 14 mm due to shell formation, followed by remelting back to 12 mm within 5 s, after which the particle core melts to 6 mm in 11 s.

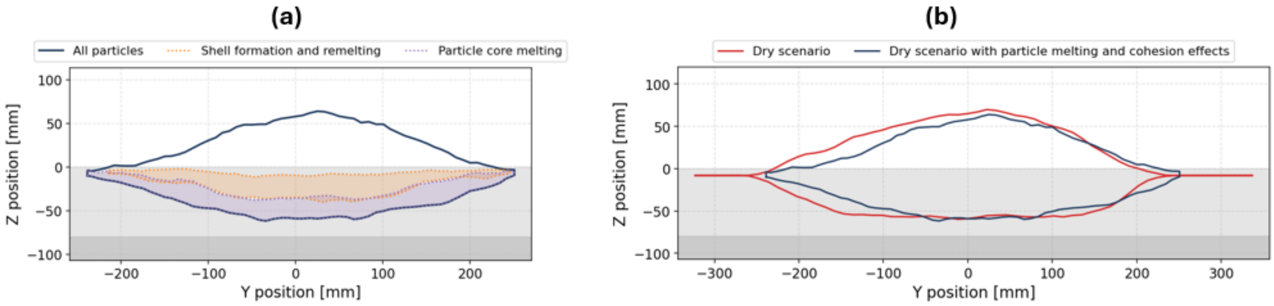

Fig.4 - (a) Particle-scale melting behaviour showing shell formation, shell remelting, and core melting stages, with corresponding changes in particle diameter; (b) comparison of feed pile shapes for the dry scenario and the model including melting and cohesion effects.

Figure 4b compares the pile shape obtained from the dry scenario flow model with the extended model including melting and cohesion effects. The inclusion of melting leads to a reduction in particle size and number, resulting in a smaller and more compact pile. The developed model provides a basis for future parametric studies to investigate the influence of process conditions and material properties on feed pile formation, and thus represents a valuable tool for ESF design strategies in support of a green steel transition.

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