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CFD-DEM Simulation of the Scrap Hot Metal Interaction in Steelmaking Furnace

Numerická simulace metodou CFD-DEM: Interakce mezi šrotem a roztaveným kovem v konvertoru

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Abstract

Increasing scrap usage in the Basic Oxygen Furnace (BOF) process is essential for improving sustainability and circularity in steel production. However, this approach poses challenges such as scrap distribution forming piles and refractory wear. To better understand the hydrodynamic interactions between hot metal and steel scrap during hot metal charging and rotation of the BOF, this study employs a coupled computational fluid dynamics – discrete element method (CFD-DEM) approach. The two-phase flow of hot metal and air is modelled using the Volume of Fluid (VOF) method, while the motion of individual scrap particles is simulated using the DEM. The current study simulates 100 tonnes of scrap charged from the scrap-box into an industrial-scale 330-tonne BOF furnace. It evaluates two scrap packing strategies (horizontal and vertical) by quantifying refractory wear using DEM. The results show that the horizontal packing strategy leads to a less worn area compared to its counterpart (the vertical strategy). The coupled CFD-DEM model is used to predict a potential iceberg formation near the converter wall during furnace rotation (before blowing) for a case of retarded melting. The CFD-DEM framework presented here provides a valuable tool for simulating and optimizing BOF operations, thereby increasing the efficiency of scrap usage in the modern steelmaking industry.

Keywords: *CFD-DEM, scrap, hot metal, BOF, steelmaking*

Abstrakt

Zvyšování podílu šrotu v procesu kyslíkového konvertoru (BOF) je klíčové pro zlepšení udržitelnosti a cirkularity výroby oceli. Tento přístup však přináší řadu výzev, jako je nerovnoměrná distribuce šrotu vedoucí k tvorbě shluků a zvýšenému opotřebení žáruvzdorné vyzdívky. Pro lepší pochopení hydrodynamických interakcí mezi tekutým surovým železem a ocelovým šrotem během vsázky surového železa a naklápění konvertoru využívá tato studie sdružený přístup výpočetní dynamiky tekutin a metody diskrétních prvků (CFD-DEM). Dvoufázové proudění surového železa a vzduchu je modelováno metodou Volume of Fluid (VOF), zatímco pohyb jednotlivých částic šrotu je simulován pomocí metody DEM. Studie simuluje vsázku 100 tun šrotu ze šrotového koryta do průmyslového kyslíkového konvertoru o kapacitě 330 tun. Jsou hodnoceny dvě strategie uspořádání šrotu (horizontální a vertikální) na základě kvantifikace opotřebení vyzdívky pomocí DEM. Výsledky ukazují, že horizontální uspořádání vede k menší míře opotřebení ve srovnání s vertikální variantou. Propojený model CFD-DEM je dále využit k predikci potenciální tvorby tzv. „iceberg“ struktury v blízkosti stěny konvertoru během jeho naklápění (před dmýcháním) v případě pomalejšího tavení. Představený modelový rámec CFD-DEM prezentuje účinný nástroj pro simulaci a optimalizaci provozu BOF, a tím i pro zvýšení efektivity využití šrotu v moderním ocelářském průmyslu.

Klíčová slova: *CFD-DEM model, šrot, surové železo, kyslíkový konvertor (BOF), výroba oceli*

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1. Introduction

The Basic Oxygen Furnace (BOF) route accounts for approximately 70% of the global crude steel production. To reduce raw material consumption and enhance the circularity of the BOF process, scrap has become an essential input for operations. However, increasing scrap usage presents several challenges, such as refractory wear and iceberg formation (unmelted scrap in the hot metal).

Increasing scrap usage in BOF process under current industry conditions demands further detailed investigation of scrap melting efficiency and mechanisms. For this purpose, it is essential to understand the characteristics of solid-fluid phase interactions including mechanical (particle-particle and particle-fluid interactions), chemical (carbon dissolution and decarburization reactions), and thermal (heat transfer and phase change) phenomena - in order to maximize scrap usage without compromising metallurgical performance. Therefore, numerical simulations, more specifically VOF/CFD-DEM, are widely used to investigate fluid-solid interactions in such high-temperature systems [1], [2], [3]. In this study, we investigate the interaction of these phases from a hydrodynamic point of view.

2. Methods

2.1 Process Description

An industrial scale 330-tonne BOF is simulated using CFD-DEM. The process cycle begins with loading the scrap-box with various types and sizes of scrap. The scrap-box is tilted to discharge the scrap into the tilted BOF. The furnace is then rocked to promote a more uniform distribution of the scrap. This operation is important for preventing hazardous events associated with volatile materials, such as water, and for mitigating the risk of iceberg formation (apparent scrap above the hot metal interface).

Following scrap charging, the furnace is tilted again to allow hot metal charging. It is subsequently repositioned to a vertical orientation to initiate the refining stage, which combines top-blown oxygen injection with bottom stirring. Finally, the refined crude steel is tapped for downstream processing, and the converter is deslagged in preparation for the next process cycle.

2.2 Numerical Model

The BOF process operation involves principally 3 phases: solid steel scrap, liquid hot metal, and gas (for simplicity different gases e.g., oxygen, CO, CO_2 and slag formation are not included in the model). The two-phase flow of air and hot metal is modelled using the VOF approach. The advection equation is employed to track the interfaces of the volume fraction α_i. For more details about the variables definitions in Equation 1, refer to [4]. The void fraction ε is incorporated into the governing equations to account for the volume occupied by the discrete phase. The governing equations for the phase fraction α_i, mass, and momentum are presented in Equations 1, 2, 3, respectively.

$$\frac{\partial \varepsilon \alpha_i}{\partial t} + \nabla \cdot \left(\varepsilon \alpha_i \boldsymbol{u_f}\right) - \nabla \cdot \left(\boldsymbol{u_c} \alpha_i (1 - \alpha_i)\right) = 0 \tag{1}$$

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \left(\varepsilon \boldsymbol{u_f}\right) = 0 \tag{2}$$

$$\frac{\partial \varepsilon \rho_f \boldsymbol{u_f}}{\partial t} + \nabla \cdot \left(\varepsilon \rho_f \boldsymbol{u_f} \boldsymbol{u_f}\right) = -\nabla p^* + \nabla \cdot \boldsymbol{\tau} - \varepsilon \boldsymbol{g} \cdot \boldsymbol{x} \nabla \rho_f + \varepsilon \boldsymbol{F}^{\sigma} + \boldsymbol{F}^{B} \tag{3}$$

Here, $p^* \equiv p - \rho_f g \cdot x$ denotes the dynamic pressure (up to a constant), where g is the gravitational acceleration and x is the position vector. F^σ represent the surface tension force between the two phases, modeled using the Continuum Surface Force (CSF) approach. F^B denotes the fluid–particle interaction forces, calculated using Model B. This model assumes steady and uniform fluid flow through the solid phase. For more details, the reader is referred to [5] [6]. The drag force is computed using the Koch & Hill drag model [7].

For the solid scrap particles, the DEM, introduced by Cundall [8], is used to obtain particle trajectories by solving Newton–Euler Equation 4 and Equation 5 for translational and rotational motion, respectively.

$$m_i \frac{dv_i}{dt} = m_i \frac{d^2 x_i}{dt^2} = \vec{f}_i\left(\vec{x}_j, \vec{v}_j, \vec{\phi}_j, \vec{\omega}_j\right) \quad for\ j = 1 \dots N \tag{4}$$

$$I_i \frac{d\vec{\omega}_i}{dt} = I_i \frac{d^2 \vec{\phi}_i}{dt^2} = \vec{M}_i\left(\vec{x}_j, \vec{v}_j, \vec{\phi}_j, \vec{\omega}_j\right) \quad for\ j = 1 \dots N \tag{5}$$

The contact force $\vec{f_i}$ in Equation 4, is computed using the Hertz–Mindlin model. The force consists of both normal and tangential components. The normal component is calculated directly, while the tangential component is derived using a tangential history model until the Coulomb friction criterion is met ($f_t \leq \mu f_n$). In this study, the commercial software Aspherix (version 6.5.0) from DCS Computing [9] coupled with OpenFOAM-10 [10] using CFDEM-multiphase-6.5.0 framework was used to model the current system.

3. Simulation Results

There are different possible scrap arrangements and charging strategies. **Fig. 1** shows horizontally distributed scrap particles in the scrap-box with three different sizes (namely heavy, medium and light colored by red, gray and blue, respectively) being discharged. Heavy scrap particles are at the top and medium ones in the middle while light ones at the bottom. Another possible distribution strategy is vertically arranged scrap. In this work, we assumed similar density for all types of scrap particles. The influence of various scrap arrangements on the refractory wear is quantified using the Finne model [11].

Fig. 1 Horizontally packed scrap of three types namely heavy, medium, and light (colored red, gray, and blue, respectively) being discharged from the scrap box into the converter

Obr. 1 Typ šrotu – těžký, střední a lehký (označený červeně, šedě a modře) – se vykládá z šrotového koryta do konvertoru

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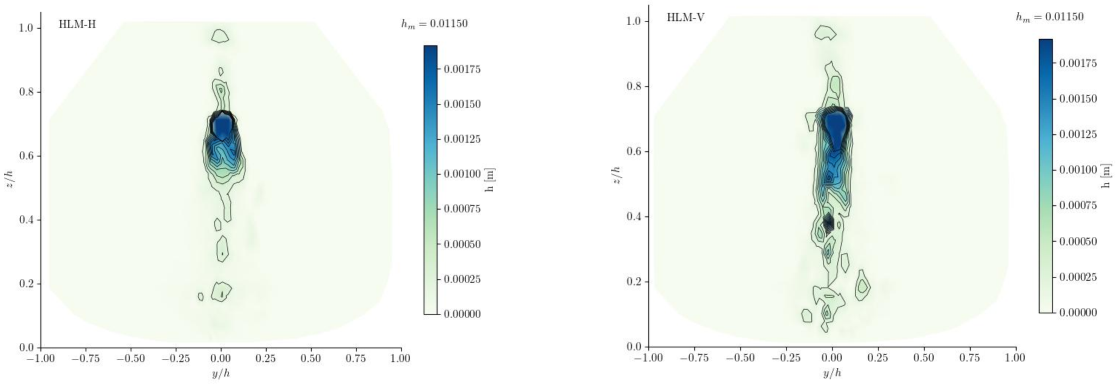
Fig. 2 compares the wear distribution of Heavy-Light-Medium (HLM) scenarios for the two scrap arrangements (Horizontal (a) and Vertical (b)). The wear distribution in the vertically distributed case is greater than in the horizontally distributed case. This is attributed to the difference in kinetic energy between the two cases. It is found to be more uniform in the horizontal compared to the vertical case.



(a) (b)

Fig. 2 Contour of refractory wear in the converter for different scrap arrangements: (a) horizontal and (b) vertical, using a total scrap weight of 100 tonnes

Obr. 2 Průběh opotřebení vyzdívky konvertoru při různém rozložení šrotu: (a) horizontální a (b) vertikální, při celkové hmotnosti šrotu 100 tun

As highlighted in the process description, rocking is employed to achieve a more uniform distribution of scrap within the converter. The simple rocking operation is defined as tilting the converter from the scrap charging position (50° relative to the y-axis) to the vertical position and back to the scrap charging position again. **Fig. 3** illustrates the state of the scrap after a simple rocking operation, with the furnace tilted to the vertical position, along with the unoccupied furnace volume shown at the bottom right. Such a configuration is unwanted during operation due to the resulting inhomogeneous distribution of scrap relative to the hot metal.

Fig. 3 Non-uniform scrap distribution inside the converter after simple rocking

Obr. 3 Nerovnoměrné rozložení šrotu uvnitř konvertoru po jednoduchém naklopení

This is further evident in **Fig. 4**, where both iceberg formation and non-uniformly distributed scrap persist, even after interaction with the hot metal during pouring and subsequent furnace rotation. It is important to note that in real situation, the scrap pile begins to melt upon initial contact with the hot metal due to the temperature gradient and carbon diffusion (commonly referred to as dissolution melting). As melting progresses, the pile gradually collapses, leading to potential reduction of iceberg formation. Therefore, these phenomena will be further investigated by the current author.

(a) (b)

Fig. 4 Iceberg formation near the furnace wall as a result of simple rocking furnace leading to uneven distribution of scrap (colored by type Red for heavy, gray for medium and blue for light) at the end of the furnace rotation and prior to the blowing stage. (a) the side view of the furnace, (b) the top of the scrap hot metal interface (colored by volume fraction)

Obr. 4 Vznik tzv. *iceberg* struktur u stěny konvertoru v důsledku jejího naklápění, vedoucího k nerovnoměrnému rozložení šrotu (červeně těžký, šedě střední, modře lehký) před foukáním: (a) boční pohled na pec, (b) horní část rozhraní šrot–tekutý kov

3. Conclusion

CFD-DEM model of the BOF converter is developed to simulate the scrap and the hot metal interaction in an industrial scale furnace. Results of DEM simulation indicate the importance of scrap arrangements within the scrap-box on refractory wear. Specifically, horizontally packed scrap tends to concentrate in localized regions (compared to vertical packing), increasing wear potential. The model further demonstrates the significance of rocking operations by capturing the redistribution of scrap inside the converter, which becomes even more pronounced during interaction with the hot metal. Additionally, the model successfully predicts iceberg formation along the furnace walls in case of retarded melting.

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