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COMPUTATIONAL FLUID DYNAMICS STUDY ON THE FLOW AND SPLASHING IN THE PLASMA FUMING PROCESS

Zhongfu CHENG[1], Samant NAGRAJ[2], Mathias CHINTINNE[2], Bart BLANPAIN[1], Muxing GUO[1]

[1] KU Leuven, Department of Materials Engineering, 3000 Leuven, Belgium
[2] Aurubis Beerse nv, 2340 Beerse, Belgium

zhongfu.cheng@kuleuven.be, s.nagraj@aurubis.com, m.chintinne@aurubis.com, bart.blanpain@kuleuven.be, muxing.guo@kuleuven.be

Introduction

Slag fuming is a highly significant technology that is applied for processing lead and zinc in blast furnace slags, which allows for the extraction of valuable metals, including copper, indium, germanium, zinc, and lead.[1] The resulting clean slag can be used as novel inorganic polymer materials. Among the various industrial-scale technologies, plasma fuming has demonstrated several unique advantages in valorising zinc-containing wastes.[2] In this process, Zn-rich slags are continuously fed into a molten bath and mixed with petroleum coke. Submerged non-transfer plasma torches convert compressed air into plasma, mixed with natural gas at a non-stoichiometric ratio in the tuyere to generate the tuyere gas. The tuyere gas, which serves as an energy source and reductant, is injected into the liquid bath. The reducing agents present in the bath reduce zinc and other volatile metal oxides to metallic vapours, which are fumed off. The resulting fume is subjected to post-combustion by introducing secondary air, and the resulting zinc oxide particles are recovered. Water-cooled freeze linings are generally employed to maintain the fumer's integrity and reduce heat losses. Plasma fuming is a promising advancement of the traditional slag-fuming process for treating lead and zinc blast furnace slags. Previously, the zinc slag fuming process has been numerically and experimentally studied. Compared to experiments that only obtain data at a few system locations, the Computational Fluid Dynamics (CFD) approach enables one to examine any location in the region of interest and understand the process through thermal and flow parameters.

In this paper, A 3D multiphase flow model was developed based on the Euler-Euler multiphase flow approach to study the flow and splashing behaviour in a plasma fumer. The drag force and non-drag forces, including lift, virtual, turbulent dispersion and wall lubrication forces, are incorporated into the model. The results of this study provide valuable insights into controlling and optimising the process parameters of the plasma fuming process.

Numerical methodology

The simulation of gas-slag two-phase flow in a plasma fumer is performed using the Euler-Euler multiphase flow approach combined with the RNG K-ε model. In this approach, the two phases are considered separate continua, and their governing equations are based on the conservation laws of mass, momentum, and energy. Interphase forces, including drag, lift, virtual, turbulent dispersion, and wall lubrication, are included in the momentum equation, namely:

$$\frac{\partial(\rho_i \alpha_i \vec{u}_i)}{\partial t} + \nabla \cdot (\alpha_i \rho_i \vec{u}_i \vec{u}_i) = -\alpha_i \nabla P + \alpha_i \rho_i \vec{g} - \nabla \cdot (\alpha_i \tau_i) + F_i \quad (1)$$

where α, ρ, τ, t, P, $\vec{u}$, and $\vec{g}$ are the volume fraction, density, shear stress, time, pressure, velocity and gravity acceleration, respectively. The subscript i (=g or l) represents the gas or liquid phases. The term F_i is the interfacial momentum exchange between the gas phase and the liquid phase, given by:

$$F_{lg} = -F_{gl} = F_D + F_L + F_{VM} + F_{TD} + F_{WL} \quad (2)$$

where F_{lg} (F_{gl}) denotes the momentum transfer from the liquid (gas) phase to the gas (liquid) phase, and the terms of F_D, F_L, F_{VM}, F_{TD} and F_{WL} on the right-hand side represent the drag force, lift force, virtual mass force, turbulent dispersion force and wall lubrication force, respectively.

The density of the injected gas is calculated for each time step and in every cell using the ideal gas law, which is given as:

$$\rho_g = \frac{P_{op} + P}{\frac{R}{M_w} T} \quad (3)$$

where P_{op} represents the operating pressure, P is the local relative pressure, R is the universal gas constant, M_w is the molecular weight of the gas, and T is the static temperature in K.

To capture the turbulent nature of the gas-slag flow, the RNG K-ε turbulence model is employed. The temperature-dependent viscosity of the gas phase is calculated using the Sutherland viscosity law.

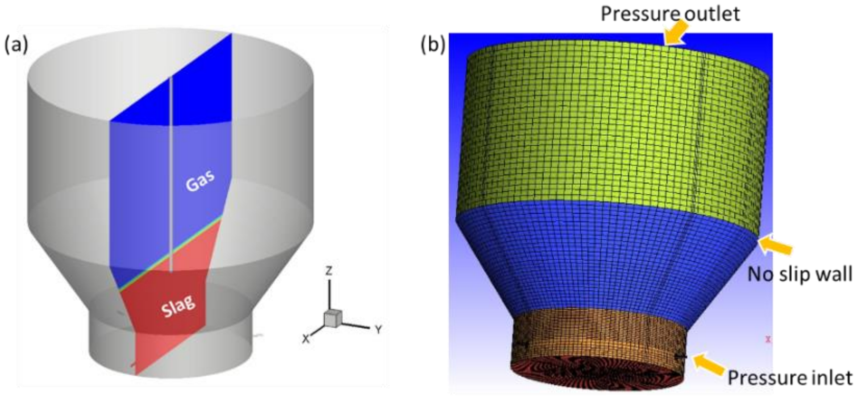

Figure 1: Illustration of **(a)** computational domain and **(b)** generated mesh

The schematic diagram of the plasma fumer is presented in Figure 1, with three submerged plasma torches used. The mesh with 587 000 cells is validated for mesh independence and considered sufficient for the 3D simulation. A no-slip wall boundary condition is applied to the surrounding and bottom wall, while the tuyere injection is set as the pressure inlet, and the top surface is an open boundary. The phase-coupled SIMPLE scheme is employed to solve the governing equations, with a time step size starting from 1×10^{-5} s. The simulation is run until a reasonably converged solution is obtained and the time step is appropriately scaled.

Results and discussion

Figure 2 shows the transient distribution of slag volume fraction in the fumer. The results demonstrate that the model effectively captures the fluctuating nature of the flow in the plasma fumer, and the predicted flow field is asymmetric and swirling, highlighting the importance of using a 3D model for accurate analysis. The top surface of the slag shows significant fluctuation, with typical slag splashing observed (*t*=35 s), resulting in a substantial increase in the gas-liquid interface area. This phenomenon facilitates the reduction of slag in the top surface region.

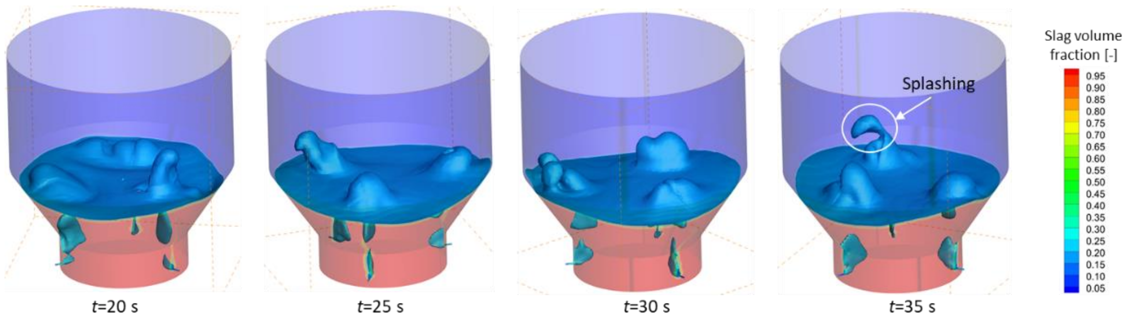

Figure 2: transient distribution of slag volume fraction in the plasma fumer

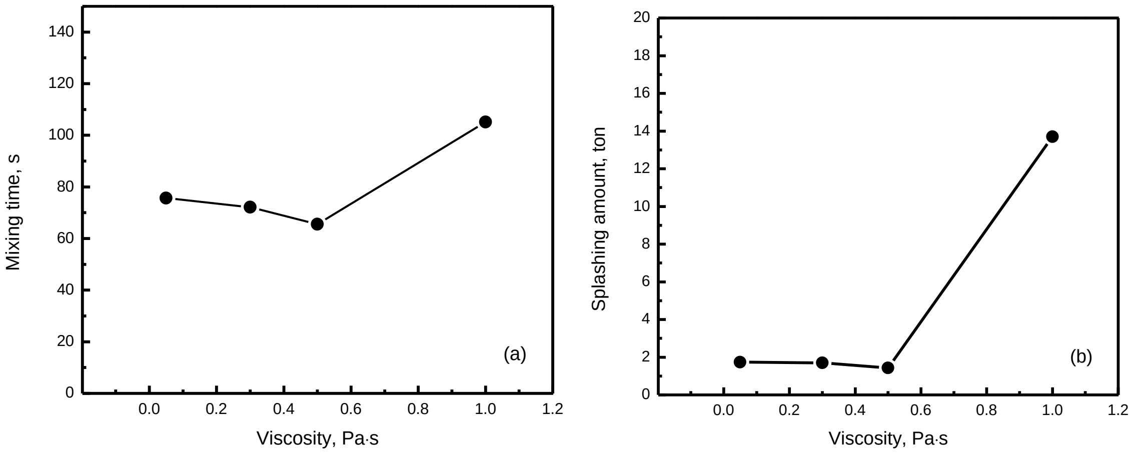

Figure 3: Influence of slag viscosity on **(a)** mixing time, and **(b)** splashing amount in the plasma fumer

The mixing time is the duration for all local tracer concentrations to reach a 5% deviation from equilibrium, where the local concentration-to-equilibrium value ratio ranges between 0.95 and 1.05.[3] Figure 3 (a) shows the influence of slag viscosity on the mixing time in the plasma fumer. Initially, as slag viscosity increases, the mixing time slightly decreases, reaching a minimum value at a viscosity of 0.5 Pa·s. This outcome can be attributed to the increased momentum transfer from the bubble column to the bulk slag phase, which enhances the circulation and mixing of the bath. However, when the slag viscosity exceeds an optimum level, the fluidity of the liquid bath is reduced, leading to a decline in mixing efficiency. Therefore, optimising the slag viscosity through controlling the slag composition can improve the bath mixing efficiency in the plasma fumer.

In this study, the slag splashing amount is defined as the integrated mass of slag present above the reference surface in the fumer. Figure 3 (b) shows the influence of slag viscosity on the splashing amount in the plasma fumer. The results indicate that the surface of the slag remains relatively stable when the viscosity is below 0.5 Pa·s. However, when the viscosity increases to 1 Pa·s, the amount of splashing increases significantly. This phenomenon occurs because the high viscosity restricts the momentum transfer from the bubble column zone to the liquid bath, causing the momentum to concentrate in the bubble column zone. As a result, the bubble column has higher kinetic energy, leading to increased slag fluctuation and splashing on the top surface.

Conclusions

A 3D multiphase flow model based on the Euler-Euler approach was developed to investigate the flow and splashing behaviour in a plasma fumer. The findings suggest that the viscosity of the slag plays a crucial role in bath mixing and liquid bath level stabilisation. Specifically, a low-viscosity slag enhances bath mixing and stabilises liquid bath levels. However, excessive viscosity slag impedes bath mixing and leads to significant splashing, thus negatively impacting the fumer's performance.

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