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Effect of graphite content and heating temperature on carbon pick-up of ultra-low-carbon steel from magnesia-carbon refractory using CFD modelling

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A B S T R A C T

In order to study the effect of refractory graphite content and heating temperature on carbon pick-up of ultra-low-carbon steel from magnesia-carbon refractory, a transient axisymmetric mathematical model has been established. The momentum, heat and mass transfer between the refractory and the molten steel was modeled by using porous medium. Arrhenius law was employed to define the rate of the carbothermic reduction reaction of the magnesia. Besides, a series of experiments were carried out to verify the model. The results indicate that the carbon content of the molten steel rapidly rises when the refractory graphite content ranges from 3 mass% to 10 mass%, and the carbon pick-up induced by direct dissolution is significantly promoted. The influence of the heating temperature on the carbon content in the molten steel however is negligibly small, and the proportions of the carbon pick-up caused by the direct dissolution and the chemical reaction basically remain the same although the heating temperature increases by 100 K. The effect of the refractory graphite content on the carbon pick-up of the molten steel far outweighs that of the heating temperature.

1. Introduction

Magnesia-carbon refractory is now extensively used in the steelmaking process because of its high melting points and good wear resistance. Valuable properties such as good thermal shock resistance and excellent slag resistance could be provided by the combination of graphite and magnesia, which are essential in steelmaking practice for the lining of ladles, arc furnaces and oxygen converters [1]. These advantages attracted refractory manufacturers to add more graphite into the magnesia-carbon refractory. Nevertheless, the increase of the graphite content has some drawbacks including refractory wear through decarburization and carbon pick-up of molten steel due to the susceptibility of graphite to oxidation.

Ultra-low-carbon steel is used in processes where maximum ductility is required such as forming and drawing operations, given that interstitial carbon adds strength, but lowers ductility. Since there is a greater driving force for carbon transport compared to higher carbon steel, ultra-low-carbon steel is particularly sensitive to carbon pick-up [2]. Actually, carbon in contact with steel can be directly dissolved into the molten steel [3]:

$$C_s \rightarrow \underline{C} \tag{1}$$

Another path for carbon transport into the molten steel is the dissociation of carbon monoxide, which is generated by carbothermic reduction of magnesia under high temperature:

$$MgO_s + C_s \rightarrow Mg_g + CO_g \tag{2}$$

$$CO_g \rightarrow \underline{C} + \underline{O} \tag{3}$$

The oxidation of carbon occurred within the magnesia-carbon refractory brick has been investigated by many researchers [4–7]. They found that carbon in the refractory would be directly oxidized by gaseous oxygen at temperatures lower than 1673 K. The oxidation reaction of carbon with solid oxygen in magnesia then became increasingly important at temperatures higher than 1673 K, and the effect of the temperature on the oxidation reaction became more pronounced with the increasing refractory graphite content.

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The oxidation of the magnesia-carbon refractory when contacted with the ultra-low-carbon molten steel however was few studied. Brabie experimentally studied the reaction between magnesia-carbon refractory and aluminum deoxidized steel [8]. The molten steel was observed to be able to infiltrate the refractory lining until its solidification temperature was reached. Dissolution of the refractory lining and reaction between magnesia and carbon simultaneously happened within the infiltrated area. Carbon in the refractory lining was therefore transferred to the molten steel [9]. In order to investigate the recarburization of interstitial free steel from alumina-graphite refractory materials, Ruan et al. heated the interstitial free steel in an alumina-graphite crucible with flux cover at 1873 K for 120 min by using a medium frequency induction furnace [10]. They found that the steel carbon content rapidly increased in the first 10 min, and then decreased, since a decarburized layer formed on the refractory, which separated the molten steel from the refractory. Meanwhile, decarburization via oxygen through the flux and liquid layer started to reduce the carbon content in the molten steel. Russo et al. studied the kinetic mechanism of carbon transport to ultra-low-carbon steel from magnesia-graphite refractory through laboratory dip tests in a vacuum induction furnace [3]. They inferred that the carbon transfer was controlled by the molten steel penetrating into the refractory and dissolving carbon. The rate controlling step was the convective of carbon into the molten steel.

As discussed above, most researchers used high temperature experiment to study the decarburization of the magnesia-carbon refractory nowadays. The information acquired from experiments however was limited. The flow pattern and the temperature distribution in the crucible were unknown. The mechanism of carbon transport from magnesia-carbon refractory to ultra-low-carbon steel has still not been profoundly understood, and furthermore the effect of the refractory graphite content and the heating temperature on the carbon pick-up of ultra-low-carbon steel remains unclear. With the continuous increase of computation resources, numerical simulation is an adequate way to provide useful insights into the carbon mass transfer. In the present work, we established a transient axisymmetric mathematical model, including the fluid flow, heat transfer and carbon redistribution, to understand the effect of the refractory graphite content and the heating temperature on the carbon pick-up of ultra-low-carbon steel from the magnesia-carbon refractory. The penetration of the molten steel to the refractory lining was described through the application of the porous medium module. Arrhenius law was employed to define the rate of the carbothermic reduction reaction of the magnesia. A standard pressure interpolation scheme was used to compute the face values of pressure from the cell values. SIMPLE algorithm was applied in pressure–velocity coupling in the segregated solver to adjust the velocity fields by correcting the pressure field. In order to obtain a higher accuracy, the governing equations were discreted by second order upwind scheme. In addition, a series of experiments were conducted to validate the model.

2. Mathematical model

2.1. Assumptions

The following assumptions have been proposed to simplify the model:

(1) The computational domain included three regions: the molten steel (fluid medium), the magnesia-carbon refractory lining (porous medium) and the alumina crucible (solid medium) as shown in Fig. 1. The inert argon atmosphere was ignored as it did not participate in reactions.

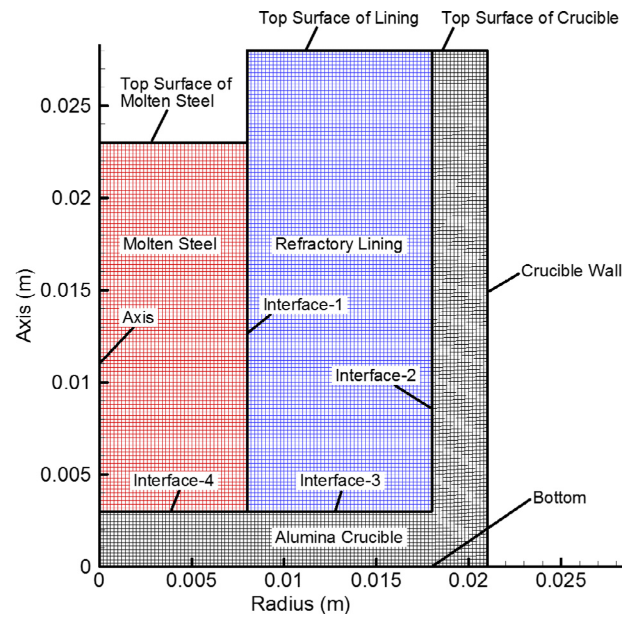

Fig. 1. Boundaries and mesh model used in the simulation.

(2) The molten steel was incompressible Newtonian fluid, and its density was a function of the temperature. Other properties of the molten steel were assumed to be constant and taken at the temperature of 1873 K. Due to the slight change, the properties of the magnesia-carbon refractory lining and the alumina crucible were also treated as a constant and taken at 1273 K.

(3) Other chemical reactions were ignored except the carbothermic reduction reaction of the magnesia occurred within the refractory.

2.2. Fluid flow

The mass continuity and the Navier-Stokes equations for the molten steel were expressed as follows and applied to the molten steel and refractory lining regions [11–13]:

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \vec{v}) = 0 \quad (4)$$

$$\frac{\partial (\rho_m \vec{v})}{\partial t} + \rho_m \vec{v} \cdot \nabla \vec{v} = -\nabla p + \nabla \cdot (\mu_{eff} \nabla \vec{v}) + \rho_m \vec{g} + \vec{F} \quad (5)$$

where ρ_m was the molten steel density, $\vec{g}$ was the gravitational acceleration, $\vec{v}$ was the velocity, p was the pressure, μ_{eff} was the effective viscosity, and t was the time. The term $\rho_m \vec{g}$ in Eq. (5) represented the thermal buoyancy force determined by the Boussinesq approximation. The last term $\vec{F}$ was an additional friction term due to the porous medium. As mentioned above, we treated the refractory lining as a homogeneous porous medium, and the momentum loss of the molten steel in the refractory lining was represented by:

$$\vec{F} = -\left(\frac{\mu}{\alpha}\vec{v} + C\frac{1}{2}\rho_m |\vec{v}| \vec{v}\right) \quad (6)$$

where μ was the dynamic viscosity of the molten steel, α was the permeability of the refractory lining and C was the inertial resistance factor. The first part of the above equation on the right side was Darcy's law, which accounted for the microscopic viscous drag. The second part expressed the inertial loss due to the strong geometrical variation of the streamlines at the pore scale. The inertial