



A coupled mathematical model of oxygen transfer in electroslag remelting process

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ABSTRACT

A transient coupled mathematical model was established to study the oxygen transfer in electroslag remelting process. The electromagnetics, multiphase flow, heat transfer, mass transfer and species transport were simulated simultaneously with the aid of the finite volume method. The volume of fluid approach was employed to determine the interfaces among the slag, metal and air. An additionally kinetic and thermodynamic model was proposed to predict the mass transfer rates, which were related to the composition of each phase as well as the temperature. A laboratory experiment was carried out to validate the accuracy of the model. The increase of oxygen content in metal is primarily achieved during the formation of droplet, and the mass transfer process at the slag/metal pool interface also contributes to it. The oxygen in air is absorbed into slag causing a rise in oxygen potential of slag, which significantly affects the oxygen content in metal. With the increasing content of ferrous oxide in slag, the mass fraction of oxygen in the metal pool first increases and then flattens out with time. The maximum calculated oxygen content in the metal pool is about 123.52 ppm during the ESR process.

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1. Introduction

Electroslag remelting (ESR), as an important metallurgical technology, is widely used in the production of high performance steels and alloys due to good efficiency in controlling of chemical composition and improving solidification structure and surface quality of final ingots [1,2]. The schematic diagram of ESR process is shown in Fig. 1. An alternating current (AC) is passed from the consumable electrode to the baseplate, through the high-resistivity slag creating Joule heating to melt the electrode. Later, the molten metal sinks through the slag pool in the form of droplets periodically. The droplets feed up a liquid metal pool which then solidifies directionally [3]. The chemical reactions among the slag, metal and air occurs during the whole ESR process [4]. The dissolved oxygen in the molten steel will forms oxide inclusions during solidification, and finally declines the steel quality. Given these defects, the total oxygen content in steel plays a decisive role in many properties of ESR ingots, and represents the steel cleanliness to some extent [5,6]. Its removal has always been a hot issue in ESR process.

Due to the chemical reactions at the slag/metal interface, the oxygen will be absorbed into metal or slag. Part of the variable

valence oxides will be oxidized by the air at the slag/air interface. Mitchell and Carmona [7,8] experimentally studied the deoxidation mechanisms in the ESR process. The oxide inclusion composition and loss of alloy elements were closely related to the content of ferrous oxide (FeO) in slag. Zhou et al. [9] reported that in spite of different oxygen level of electrodes used, the oxygen content in ESR ingot was within 15–30 ppm. It follows that the slag composition was the main factor influencing the oxygen content in final ingot, rather than the initial oxygen content in electrode. Shi et al. [10] considered FeO as the source of oxygen potential of slag, and the employment of protective argon gas and the deoxidation treatment were essential to further reduce the oxygen content. However, the trial and error practices are prohibitively expensive in industrial ESR operations. The information provided by experiments is limited due to the opaque reactor. The effects of flow pattern and temperature distribution on the mass transfer process remain unclear. In this case, the progressive numerical simulation is able to provide deep insights into the oxygen transfer in ESR process.

Fraser et al. [11] modeled the reaction kinetic of Mn and Fe in ESR process. The mass transfer coefficients at all the reaction sites were calculated. The predicted results showed good agreement with measured results. Wei and Mitchell [12] proposed a more comprehensive model to study the transport phenomena in ESR process involving several simultaneous reactions. The concentra-

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Nomenclature

a_i	activity of species i	n	normal vector
a_{ij}	interaction energy between cations (J)	p	pressure (Pa)
\overline{A}	specific surface area for reaction (1/m)	P_i	partial pressure of species i (Pa)
\vec{A}	magnetic potential vector (V·s/m)	Q_j	Joule heating (W/m^3)
b	inverse Prandtl number	r	radius (m)
\overline{B}	magnetic flux density (T)	r_{\max}	inner radius of the mold (m)
c_p	specific heat ($\text{J}/(\text{kg}\cdot\text{K})$)	R	molar gas constant
C_p, C_μ	constants derived using RNG theory	Sc_t	turbulent Schmidt number
\overline{D}	electric flux density (C/m^2)	S_i	source term of species i ($\text{kg}/(\text{m}^3\cdot\text{s})$)
$D_{\text{eff},i}$	effective diffusion coefficient of species i (m^2/s)	t	time (s)
$D_{g,i}, D_{m,i}, D_{s,i}$	diffusion coefficient of species i in air, metal and slag (m^2/s)	T	temperature (K)
$D_{t,i}$	turbulent diffusion coefficient of species i (m^2/s)	\vec{v}	velocity of mixture phase (m/s)
e_j^i	interaction coefficient of the element j with respect to the element i	w_i	mass fraction of species i
E	internal energy of mixture phase (J/kg)	$w(i), w[i]$	mass fraction of species i in slag and metal
\vec{E}	electric field intensity (N/C)	x, y, z	Cartesian coordinates
f_H	electric current frequency (Hz)	X_i	molar fraction of the oxide in slag
$f_{i,i}$	Henry activity coefficient of species i		
\vec{F}_e	Lorentz force (N/m^3)		
\vec{F}_s	solute buoyancy force (N/m^3)		
\vec{F}_{st}	surface tension (N/m^3)		
\vec{F}_t	thermal buoyancy force (N/m^3)		
\vec{H}	magnetic field intensity (A/m)		
I'	conversion factor of activity coefficient		
I_{rms}	root mean square current (A)		
J	current density (A/m^2)		
k	turbulent kinetic energy (m^2/s^2)		
k_{eff}	effective thermal conductivity ($\text{W}/(\text{m}\cdot\text{K})$)		
$k_{g,i}, k_{m,i}, k_{s,i}$	mass transfer coefficient of species i in air, metal and slag (m/s)		
$k_{T,i}$	overall mass transfer coefficient of species i (m/s)		
K	reaction equilibrium constant		
L	latent heat of fusion (J/kg)		
L_i	interfacial distribution ratio of species i at equilibrium		
\dot{m}	melt rate (kg/s)		
M_i	molar mass of species i (kg/mol)		

Greek symbols	
α_i	volume fraction of phase i
$\alpha_g, \alpha_m, \alpha_s$	volume fraction of air, metal and slag
ϕ	mixture phase property
ϕ_g, ϕ_m, ϕ_s	property of gas, metal and slag
μ_0	permeability of vacuum (T·m/A)
μ_{0m}	vacuum permittivity (F/m)
μ	laminar viscosity (Pa·s)
μ_{eff}	effective viscosity (Pa·s)
μ_t	turbulent viscosity (Pa·s)
σ	electrical conductivity ($\Omega^{-1}\cdot\text{m}^{-1}$)
φ	electrical potential (V)
ρ	density (kg/m^3)
ρ_{em}	electric resistance of metal ($\Omega\cdot\text{m}$)
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
ν_g, ν_m, ν_s	kinematic viscosity of air, metal and slag (m^2/s)
γ_i	Raoult activity coefficient of species i
δ	electromagnetic skin depth (m)
η	power efficiency coefficient

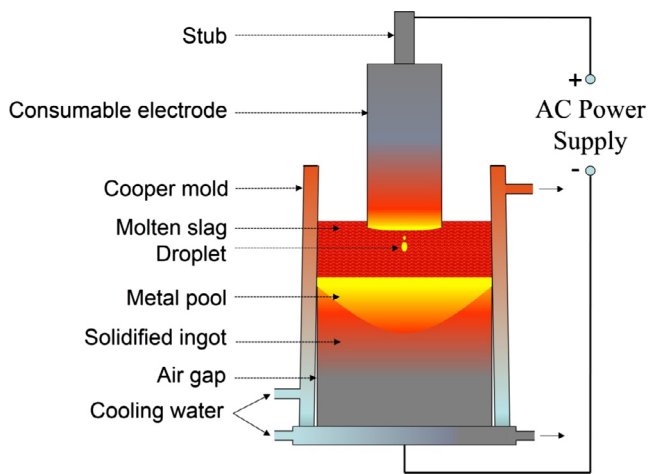


Fig. 1. Schematic of ESR process.

tion profile of each species could be deduced by Fick's second law. The mass balances proposed to close the numerical solution could be integrated by a Runge-Kutta technique. Then the composition of

both slag and metal would be accurately predicted. But the temperature field and velocity field which affected the mass transfer process were unknown. Gan et al. [13,14] established an improved 3D numerical model to simulate the thermal behavior, fluid flow, melting-solidification and multicomponent mass transport in direct laser additive manufacturing. As the melt pool is developed, the strong Marangoni convection dominated the heat and mass transfer in the melt pool. Wang et al. [15] numerically investigated the desulfurization behavior in ESR process. The solutions of mass, momentum, energy and species conservation equations were simultaneously calculated.

As mentioned above, there are few attempts to numerically investigate the oxygen transfer process coupled with electromagnetism, multiphase flow and heat transfer in AC ESR process. In the present work, a transient coupled model was established to understand the oxygen transfer process under an open air. A kinetic and thermodynamic model was proposed to calculate the mass transfer rate at the interfaces. The multi-physical fields were also included. Moreover, the coupled model was validated by a laboratory experiment.

2. Mathematical model

In order to simplify the model and reduce computation time reasonably, the following assumptions are necessary:

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