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Investigation of the coupled conductive and radiative heat transfer of molten slag in a cylindrical enclosure based on the zonal method

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ABSTRACT

Heat transfer of molten slag under high temperature is significant for industrial processes. Unlike other phase change materials, the phase change temperature of molten slag is always not a constant during cooling process. In this case, the basis of judging different phases could not be accurately obtained, which brings difficulties for the calculation of radiation-solidification coupled heat transfer. In present work, the coupled conductive and radiative heat transfer of molten slag during solidification is investigated by the zonal method with fixed grid and moving area. In order to determine the liquid fraction of molten slag during phase change, the enthalpy method is improved by using crystallization kinetics. In addition, ray tracing method based traversal algorithm is developed to analyze the multiple reflection among three layers. The results indicate that the diffuse radiation in multi-layer could be described by tracking the path of reflections. However, the ray tracing method is time-consuming for computation. Compared with the ray tracing method, it is more efficient to calculate the radiative heat flux by solving a system of linear equations established according to the energy balance on each surface element. In initial stage of solidification, radiation is the main way of heat transfer. After solid slag is formed, heat transfer is dominated by conduction, and the proportion of the radiative heat flux in the total heat flux is lower than 30%.

1. Introduction

Molten slag plays an important role in many industrial processes, such as ironmaking and steelmaing, continuous casting, and coal gasification [1–3]. The heat transfer in molten slag undergoing high temperature has an important effect on process control and quality of product [4,5]. Many studies about the coupled conductive and radiative heat transfer have been reported, and most of them are based on numerical simulation because it is difficult to carry out experiments at high temperature [6]. Among these numerical techniques, one of the main task is to solve the Stefan moving boundary problems for phase change materials [6,7], and this problem also exists during heat transfer of molten slag. Several methods were proposed to solve the Stefan problem, such as the moving mesh method, fixed grid front tracking method and the enthalpy method [8–10]. These methods are capable of analyzing heat transfer of materials with known melting point or solidification temperature, such as the eutectic alloy and the binary alloy. However, slag is different from metallic material, and its solidification temperature or crystallization temperature changes with cooling rate, which indicates that the temperature of the interface between the liquid layer and the solidified layer is not a constant during solidification [11]. The change of the phase change temperature makes it difficult to find an accurate criterion for judging different phases. Therefore, the moving mesh method and fixed grid front tracking method may not be applicable for the solidification of molten slag. The enthalpy method does not need to track the interface, but the value of phase change temperature is also necessary to calculate the liquid fraction [12]. Nevertheless, if the relationship between the liquid fraction and the temperature is obtained, the enthalpy method could also be used to solve the temperature field from the energy equation. Considering the difficulties in determining the phase change temperature, the kinetics of phase change is used in this paper to describe the evolution of liquid fraction during cooling process.

Compared with the conductive heat flux, the calculation of the radiative heat flux is more difficult. According to the radiative transfer equation (RTE), different methods were developed to evaluate the radiation effect, such as the discrete ordinates method, the finite volume method, the discrete transfer method, the Monte Carlo method and the zonal method [13–16]. These methods have been used to study the radiative heat transfer in different systems, such as medium with one layer and homogeneous radiative properties, medium with one layer and various radiative properties,

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Nomenclature

A	area of boundary surface
C	heat capacity of water
Cp	specific heat capacity of slag
D	thickness of solidified layer
dh	length of zone in z direction
dw	length of zone in y direction
E_λ	spectral emission of boundary surface
fs	solid fraction of molten slag
F	effective heat transfer on copper detector
H	enthalpy of slag
H	height of graphite crucible
I_λ	spectral intensity of emission
K	rate constant of crystallization
L	thermal conductivity
L	latent heat of molten slag
N	Avrami exponent
n_r	index of refraction
Nc	number of reflections
Q	radiative heat flux
q_t	total heat flux
Q_λ	spectral emission of surface element
R	distance between two surface elements
R	radius of bottom of crucible
Ra	apparent reflectivity of slag film
Rs	reflectivity for single refection
T	time
T	temperature
Tf	fluid temperature of molten slag
Ta	apparent transmittivity of slag film
Ts	transmittivity for single transmission
Δu	thickness of control volume
W	rate of cooling water
x, y, z	Cartesian coordinates

Greek symbols

α	degree of transformation
ε	emissivity
ρ	density of slag
κ	absorption coefficient
ω	solid angle
θ	angular variable
λ	wavelength
φ	angle factor
ϕ	radiative source term
σ	Stefan-Boltzman constant

Subscript

b	block body
cu	copper detector
f	solid slag film
g	graphite crucible
i, j, m, n	index of element
in	interface
p	index of sublayer
r, s	index of incident light
rad	radiative heat transfer
v	index of control volume

Superscript

m	time step number

medium with multi-layer and homogeneous radiative properties, medium with multi-layer and space-time dependent radiative properties. Generally, when molten slag is solidified, the media around the wall of mold contains three layers, including the liquid slag layer, the solid slag layer and the air gap. The radiative heat flux on each interface is influenced by the multiple reflection among the three layers. By using ray tracing method, the effect of multiple reflection among multi-layer could be investigated, and Refs. [17–19] present clear algorithm for tracking specular reflection. However, due to the precipitation of crystals during solidification, the interface between the liquid phase and the solid phase may not be smooth enough, which indicates that the diffuse reflection is more likely to occur on the interface between the two phases. Therefore, the reflection angle and the refraction angle could to be calculated accurately by the Snell's refractive law. On the other hand, the interface between the solid phase and the liquid phase is moving during solidification of molten slag, which indicates that the reflectivity of the interface is not a constant during solidification. Considering the effects of the diffuse reflection and the moving interface during solidification, the Fresnel equation and the Snell's law may not be appropriate to describe the optical properties of the interface. In order to solve this problem, a new method based traversal algorithm is proposed to track the path of diffuse reflection. Therefore, the effect of multiple reflection on distribution of the radiative heat flux could be studied.

Recently, more and more attention is paid to the development of effective method for solving the RTE. A simplified version of the plating algorithm for calculation of total exchange areas was developed to reduce CPU time for radiative heat transfer analysis [20]. Hitti et al. studied the transient radiation and conduction heat transfer in glass sheets, and it was found that the thin layer approximation is capable of increasing the CPU efficiency [21]. Ebrahimi et al. analyzed the three-dimensional radiative heat transfer in industrial furnaces, and it was found that the zonal method is an effective numerical method for modeling three-dimensional thermal performance of gas-filled enclosures [22]. These studies suggest that the zonal method is effective to analyze the radiative heat transfer. However, during the formation of the solidified layer, the position and the area of interface change continuously with time, which indicates that the solid angle obtained from the surface area needs to be calculated repeatedly for meeting the movement of the interface. Because of the importance of the computation efficiency, an approach based fixed grid and moving area is proposed in this paper to make the zonal method applicable for calculating the radiative heat transfer during solidification.

In this work, the coupled conductive and radiative heat transfer during solidification is simulated, and experiments are carried out to obtain the boundary conditions and the radiative characteristics of the solid slags. The liquid fraction of molten slag is analyzed based crystallization kinetics. Moreover, a new algorithm is developed to study the effect of multiple diffuse reflection on distribution of radiative heat flux.

2. Experimental

2.1. Sample preparation

Two slags with different compositions are used to study the effect of optical properties on radiative heat transfer. The compositions of slags used in experiment are listed in Table 1. The microstructure of the solid phase of slag 1 is different from that