Flow and Heat Transfer Characteristics of Melt Droplet with Non-uniform Heating Temperature

Ji-min WANG,1,2* Xi CHEN,1,2 Li-xin HAN,1,2 Kun JIAO,1,2 Yu-xi WU1,2 and Zhi-min ZHENG1,2

1) Anhui Province Key Laboratory of Metallurgical Engineering & Resources Recycling, Anhui University of Technology, Ma’anshan, Anhui, 243002 China.
2) School of Energy and Environment, Anhui University of Technology, Ma’anshan, Anhui, 243002 China.

(Received on February 21, 2022; accepted on April 2, 2022)

According to the spreading dynamics of a single melt droplet on the heated substrate, the mathematical model of the melt droplet contacting hot dry wall is established, and the transport process of the melt droplet is numerically simulated by the VOF method. The effects of the wall temperature profile on the spreading behavior and the heat transfer characteristics of the melt droplet are elaborated. With the increase of the wall temperature difference, the Marangoni convection is strengthened, the spreading diameter and the spreading height of the melt droplet become large and the spreading rate slows down periodically. The wall heat flux also increases and decays periodically. The droplet temperature increases periodically in the early stage of spreading, and increases linearly in the later stage. The melt droplet moves right under the Marangoni force, which results in an obvious difference in the velocity field and the phase interface between the right half and the left half of the melt droplet. The melt droplet temperature distribution shows layered and radial for uniform and linear wall temperature, respectively. This would help to reveal the spreading behavior and the heat transfer mechanism between the melt droplet and the horizontal hot dry wall, make up for the lack of experiment, and provide theoretical guidance for enhancing iron and steel smelting.

KEY WORDS: melt droplet; non-uniform heating; Marangoni effect; flow and heat transfer.

1. Introduction

In the engineering field, especially in the material preparation and processing, the interface phenomenon plays an important role in grasping the physical and chemical characteristics of the non-equilibrium system and pursuing correct representation and prediction. Pyrometallurgical processes are carried out in the multiphase system including the metal phase, the slag phase, and the gas phase etc., so the interface phenomenon has an important impact on the iron and steel smelting. These are important knowledge for revealing multiphase reaction mechanism, and developing new methods to improve quality.

The Marangoni effect is an interphase interface phenomenon caused by component concentration gradient or temperature gradient. It can significantly determine the mass and heat transfer at the phase interface in the multiphase system, which may strengthen or weaken the transport process. As a result, the Marangoni effect is widely discussed in chemical operations such as absorption, condensation, extraction, evaporation, and drying. To understand the influence of droplets on the heat transfer effect, Pasandideh-Fard et al. established the heat transfer model of droplet impacting on the flat plate. Compared with the experiment, it is found that increasing the droplet velocity can enhance the heat transfer. Francois et al. showed that the heat flux density is very high at the initial stage of droplet impacting on the heating surface, especially around the contact line.

Gao et al. studied the heat transfer efficiency of droplets when impacting on the heating surface by using the finite volume method, and pointed out that reducing the initial diameter and increasing the initial velocity of droplets are conducive to improving its cooling effect. Through high-speed photography and digital image processing technology, Zhu carried out a visual study on the droplet impacting on a homogeneous solid surface under constant temperature and non-isothermal conditions, and analyzed the effects of solid surface materials, temperature and other factors. In contrast, the spreading behavior of the melt droplet with non-uniform heating is not as well characterized and is currently the investigation subject. During the processing of metallurgical materials, Lange et al. and Belton et al. designed a sophisticated experimental system to verify the existence of the Marangoni convection phenomenon in high
temperature smelting environment,\textsuperscript{11,12} which expanded the idea of the Marangoni effect about the mass and heat transfer at the interface of the non-equilibrium multiphase system. The research about the Marangoni effect in the iron and steel smelting process is on the rise.\textsuperscript{13} Lee et al. numerically studied the influence of the Marangoni effect on the behavior of removing bubbles and inclusion particles in liquid steel during continuous casting.\textsuperscript{14} Muhmood et al. discussed the Marangoni effect on the mass transfer kinetics of sulfur at the slag-metal interface.\textsuperscript{15} Yin et al. observed the direction and the velocity of the liquid steel flow at the solid-liquid interface with the Marangoni effect.\textsuperscript{25}\textsuperscript{25)} The Marangoni effect can aggravate or weaken the corrosion of the iron droplet velocity by Marangoni convection using the erosion model, and explored the corrosion evolution caused by the Marangoni effect in the nonequilibrium system. Kurikkala et al. examined the contact angle of Fe–C melt in O\textsubscript{2} and SO\textsubscript{2} atmosphere, which shows that the Marangoni effect significantly promotes the droplet movement due to the action of highly active elements S or O.\textsuperscript{20}}

Hirashima et al. and Zhu et al. found out that the Marangoni effect has a significant effect on the N absorption rate in Fe–C melt and the Marangoni effect had been already discussed.\textsuperscript{24} Recently, Yuan et al. described the shape evolution of PbO–SiO\textsubscript{2} slag and FeO–SiO\textsubscript{2} slag under the Marangoni force.\textsuperscript{25} Lian et al. considered the erosion and the dissolution of refractory oxides, modified the corrosion model, and explored the corrosion evolution caused by the Marangoni effect.\textsuperscript{26} Especially, Wang et al. explored the coalescence behavior of slag/metal droplets with the Marangoni effect.\textsuperscript{27} In a word, the Marangoni effect plays a significant role in strengthening smelting behavior.\textsuperscript{28} However, there are few reports on the Marangoni effect caused by the melt droplet contacting hot dry solid wall, and the spreading process of the melt droplet on hot dry solid wall can be driven and controlled by the external conditions, such as applying the temperature gradient, or adding the active agent, etc. The Marangoni effect would affect the spreading characteristics of the melt droplet on the heated solid wall, and then the droplet spreading dynamics would further affect the heat transfer characteristics.

Therefore, designing an excellent smelting system, the dynamic characteristics of the droplet collision, and the heat transfer effect can provide theoretical guidance for ensuring the safe operation and prolonging the service life of relevant equipment. Since the droplet size is very small, the droplet spreading process on the solid wall is very rapid, the experimental operation is difficult, and it hardly reveals the droplet movement mechanism in the spreading process. Using computational fluid dynamics tools and methods, this paper numerically analyzes the Marangoni effect of the melt droplet under different wall temperature profiles, and explores its flow and heat transfer characteristics. These results would enrich the scientific understanding of the transport behavior of the melt droplet in the high temperature smelting environment, and provide technical guidance for scientific quantitative description and fine regulation of metallurgical production.

\section{Mathematical Model}

The governing equations of fluid mechanics are the basis for solving the problems of flow and heat transfer. They are established based on mass conservation, momentum conservation, and energy conservation, combined with the constitutive equations of fluid mechanics:

\begin{equation}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad \text{..................(1)}
\end{equation}

\begin{equation}
\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u \vec{u}) = -\nabla p + \nabla \left[ \mu \left( \nabla \vec{u} + \nabla \vec{u}^T \right) \right] + \rho g + F \quad \text{..................(2)}
\end{equation}

\begin{equation}
\frac{\partial \rho T}{\partial t} + \nabla \cdot (\rho u T) = \nabla \left( \frac{\lambda}{c_p} \nabla T \right) + S \quad \text{..................(3)}
\end{equation}

Where, \( \vec{u} \) is the velocity vector, \( \rho \) is the density, \( \mu \) is the viscosity, \( p \) is the pressure, \( g \) is the gravity, \( \tau \) is the time, \( F \) is the momentum source, \( \lambda \) is the thermal conductivity, \( c_p \) is the specific heat, \( T \) is the temperature, \( S \) is the energy source.

The volume fraction for air is as follows:

\begin{equation}
\frac{\partial \alpha_2}{\partial t} + \vec{u} \cdot \nabla \alpha_2 = 0 \quad \text{..................(4)}
\end{equation}

Where, \( \vec{u} \) is the velocity vector, \( \alpha_2 \) is the volume fraction of the melt droplet.

And the volume fraction for air is as follows:

\begin{equation}
\alpha_1 = 1 - \alpha_2 \quad \text{..................(5)}
\end{equation}

Where, \( \alpha_2 \) is the volume fraction for the melt phase.

The numerical solution of the governing equation is based on the volume fraction and average parameters such as density, viscosity, and temperature, etc. The average parameters are obtained by each fluid in the grid cell according to the volume fraction, and the average density is specified as:

\begin{equation}
\rho = \alpha_2 \rho_i + (1 - \alpha_2) \rho_g \quad \text{..................(6)}
\end{equation}

Where, \( \rho_i \) is the liquid density, \( \rho_g \) is the gas density.

The average viscosity is given as:

\begin{equation}
\mu = \alpha_2 \mu_i + (1 - \alpha_2) \mu_g \quad \text{..................(7)}
\end{equation}

Where, \( \mu_i \) is the liquid viscosity, \( \mu_g \) is the gas viscosity.

The effect of surface tension is embodied in the source term of the momentum equation, which connects the morphological change with the surface tension. The surface tension is modeled by the continuous surface tension model, where the surface curvature is computed from local gradients in the surface normal at the interface. With this model, the addition of surface tension to the VOF model results in the source term of the momentum equation. The surface
tension is modeled as follows:

\[
F = \sigma \kappa n \left[ \frac{\alpha_1 \rho_1 + \alpha_2 \rho_2}{1/2(\rho_1 + \rho_2)} \right] \quad \text{................................(8)}
\]

\[
n = \nabla \alpha_i \quad \text{................................(9)}
\]

Where, \(\sigma\) is the surface tension coefficient, \(\kappa\) is the curvature, \(n\) is the surface normal, \(\alpha_i\) is the volume fraction of the \(i\)th phase.

To accurately capture the phase interface, the geometry reconstruction method is used to reconstruct the gas-liquid interface. The first step in this reconstruction scheme determines the position of the interface relative to the center of each cell, based on the volume fraction and its derivatives in the cell. The second step is calculating the advecting amount of fluid through each face using information about the normal and tangential velocity on the face. The third step achieves the volume fraction in each cell using the fluxes calculated during the previous step. At the same time, in the case of the VOF method, the volume force is solved implicitly, and the pressure gradient caused by the volume force and the surface tension in the momentum equation would be balanced. To improve the convergence of the solution, some assumptions are also made in the simulation as follows:

1. At the beginning, the melt droplet contacting hot dry wall is hemispherical.
2. The shear force between the ambient gas and the melt droplet is not considered.
3. Both ambient gas and the melt droplet are incompressible.
4. The physical parameters of ambient gas are constant.
5. The chemical reaction between ambient gas and melt droplet is ignored.

3. Computational Condition

On the two-dimensional plane, it is assumed that the melt droplet with semicircular section impacts on the hot dry wall at the initial time, as shown in Fig. 1. The geometry model adopts an asymmetrical structure, the lower surface is set as the wall boundary, and the left, the upper, and the right boundaries are symmetrical. The wall temperature profile is defined as

\[
T_w = T_m + \Gamma \frac{T_m - T_{w0}}{L} x \quad \text{................................(10)}
\]

Where, \(T_w\) is the wall temperature, \(T_{w0}\) is the initial temperature for the gas phase and melt phase, \(T_{w0} = 1773 K\). \(L\) is the length of the computational domain, \(L = 5D\). \(T_m\) is the wall center temperature, \(T_m = 1923 K\). \(\Gamma\) is the temperature profile coefficient. \(D\) is the droplet diameter, \(D = 0.125 \text{ mm}\).

The melt droplet contacting the horizontal hot dry wall has a strong heat and mass transfer phenomenon, which involves the solid wall, the melt droplet, and the surrounding environment. Herein, the melt droplet is regarded as an incompressible Newtonian fluid, the melt droplet is assumed as liquid steel, the surrounding medium is air, and the substrate material is set as Al2O3. The contact angle is set to 140°. The thermophysical properties of the melt droplet are shown in Table 1, in which density, dynamical viscosity, thermal conductivity, thermal conductivity, and specific heat are regarded as constant.

In the calculation process, considering the gravity, the temperature \(T_{w0}\) at the wall center is taken as the reference temperature, and it is considered that \(T_{w0} = T_m\). When \(\Gamma = 0\), the wall temperature is greater than the ambient temperature, that is, the wall is heated. When \(\Gamma > 0\), the temperatures on the left \((x < 0)\) and right \((x > 0)\) of the wall origin are lower and higher than the ambient temperature, respectively. That is to say that the melt droplet is cooled and heated, respectively. It is supposed that the surface tension and temperature satisfy a linear relationship:

\[
\sigma = 2.5 - 0.00051T \quad \text{..................(11)}
\]

Where, \(T\) is the melt droplet temperature.

To ensure the flow of the melt droplet only occurs between adjacent cells, the moving distance of the melt droplet in each time step cannot exceed the grid size, so the time step must meet:

\[
\delta t < \min \left[ \frac{\delta x_i}{u_{ij}}, \frac{\delta y_i}{u_{ij}} \right] \quad \text{..................(12)}
\]

Where, \(\delta x_i\) is the x-direction cell size, \(\delta y_i\) is the y-direction cell size, \(u_{ij}\) is the cell velocity.

Secondly, when the surface tension is introduced into the computational model, the propagation distance of the

<table>
<thead>
<tr>
<th>Density, kg/m³</th>
<th>Dynamical viscosity, kg/m·s</th>
<th>Surface tension, N/m</th>
<th>Thermal conductivity, W/m·K</th>
<th>Specific heat, J/kg·K</th>
<th>Contact angle, °</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>1.225</td>
<td>1.7894 × 10⁻⁵</td>
<td>0.0242</td>
<td>1006.43</td>
<td></td>
</tr>
<tr>
<td>melt droplet</td>
<td>7.000</td>
<td>0.0065</td>
<td>(\sigma(T)) 40</td>
<td>680</td>
<td>140</td>
</tr>
</tbody>
</table>
capillary wave in each time step should be limited to be less than the grid size. The rough estimation for the time step is as follows:

$$\delta t < \frac{\rho}{8\sigma} \left( \min\{\delta x_i, \delta y_i\} \right)^3 \tag{13}$$

Where, $\delta x_i$ is the x-direction cell size, $\delta y_i$ is the y-direction cell size, $\rho$ is the density, $\sigma$ is the surface tension coefficient.

In the present simulation, the initial temperature of the melt droplet and gas phase is 1773 K, and the time step adopts $10^{-6}$ s. Further reducing the time step has little effect on the numerical results. When the melt droplet contacts the horizontal hot dry wall, the wall temperature, and the contact angle between the melt droplet and the solid wall are given. The boundary of the solution domain includes the axis symmetry and the solid wall. The velocity boundary of the axis symmetry is defined as:

$$u = 0, \frac{\partial v}{\partial x} = 0 \tag{14}$$

Where, $u$ is the x-direction velocity, $v$ is the y-direction velocity.

The wall boundary employed the non-slip condition, that is, each velocity component on the solid wall is zero. When the melt droplet spreads on the solid wall, the wall adhesion is defined as the surface vector:

$$\vec{n} = \vec{n}_w \cos \theta + \vec{r}_w \sin \theta \tag{15}$$

Where, $\theta$ is the contact angle.

The SIMPLE algorithm is used to solve the pressure-velocity equation, the VOF equation and the convection term are discretized by QUICK scheme, and PRESTO scheme is applied for the pressure term.

4. Grid Independence Test

The computational domain is set as $5D \times 5D$, which was filled with air except for the region occupied by the melt droplet. The meshing applied a quadrilateral structured grid. To verify the grid independence, three different grids are examined, respectively. As shown in Fig. 2, the gas velocity gradually decreases periodically due to the viscous force and surface tension, and finally tends to be stable. The results show that the gas velocity at 3 ms is 0.0101 m/s, 0.00159 m/s and 0.00263 m/s for different grids, respectively. And the gap of gas velocity between the grids decreases gradually. When the melt droplet contacts the hot dry wall, the melt droplet continues to spread and retract in the early stage, and the gas velocity decreases periodically, that is, it reaches the maximum spreading diameter, and then retracts to reach the maximum spreading height. In the later stage of spreading, due to the viscous force, the kinetic energy of the melt droplet is consumed continuously, and the gas velocity decreases and ultimately approaches near zero.

Compared with the grid number of 39111, the calculation accuracy of gas velocity is improved by 0.747% when the grid number is set to 49680. When the grid number is reached 57612, it increases by 0.104%, but the computer time increases significantly. However, the trend of the two curves is the same, and the grid number has little effect on the spreading diameter. Considering comprehensively, the grid number is taken as 49680, as shown in Fig. 3, and the computational domain is divided structurally. It can not only ensure computational efficiency but also have high enough accuracy. Furthermore, the correctness of the simulation...
results can also be guaranteed by the volume conservation during the evolution process of the melt droplet.

5. Model Validation

Figure 4 depicts the wetting process between the simulation results and the experimental results of the diesel droplet contacting the horizontal dry wall at room temperature. The verification simulation was carried out on a two-dimensional domain with 20 mm × 4 mm for the diesel droplet with an initial radius of 2 mm and an impact velocity of 0.37 m/s. Parameters used in the current simulation for validation were similar to those used in the experiment.31) During the experimental process, to control the droplet size, the microinjector is used as the droplet generator. The level is mainly used to adjust the horizontal position of the wall, including quartz glass, stainless steel, and aluminum. The high-speed camera with a macro lens is used to record the droplet morphology. The metal halide lamp is used as the auxiliary light source to enhance the image acquisition effect.

The initial shape of the diesel droplet is spherical. The left and right droplets reach the maximum spreading, and subsequently the droplet contracts and recoils under the surface tension. After that, the droplet undergoes multiple spreading and recoiling oscillation processes until it reaches equilibrium. It can be seen that the droplet motion of the simulation results is consistent with the experimental results. It has experienced the spread, and recoil, and the free surface changes from time to time, which is consistent with the actual situation. Although the physical parameters of diesel and liquid steel are different, their physical processes are similar, this is caused by surface tension and viscous force. Finally, a similar tendency is obtained, indicating that the mathematical model is reasonable, and the numerical method can further simulate the spreading behavior of melt droplet on the horizontal hot dry wall.

6. Effect of Wall Temperature Profile

Because of the length- and time-scales involved, the experimental method is powerless to detect the flow field inside the melt droplet, which determines the droplet shape. Numerical modeling can not only visually predict the morphological evolution of the melt droplet, but also deeply reveal the flow field, understand the evolution essence, and master the controlling mechanism for droplet shape. One important factor that affects the spreading dynamics of the melt droplet on the solid wall is the wall temperature profile. Regardless of the wall wettability, it is considered that the equilibrium contact angle is fixed, and examines the spreading process of single melt droplet on the horizontal hot dry wall and the motion law of its free interface, and explores the influence of wall temperature profile on spreading behavior and heat transfer characteristics. The non-uniform wall temperature profile is presented in Fig. 5. Herein, when the temperature profile coefficient is set as zero, the wall temperature remains constant. While the temperature profile coefficient is specified as 0.5 or 1, the wall temperature is linear, and the wall temperature difference at $\Gamma=1$ is greater than that at $\Gamma=0.5$.

In the actual process, although many melt droplets are in contact with the solid wall at the same time, a single melt droplet can characterize the spreading characteristics between the melt droplet and the solid wall. Therefore, to simplify the calculation and numerical approaches, the spreading characteristics of a single melt droplet on the heated wall are considered in this study. The spreading diameter is the diameter of the contacted area. Therefore, according to the model assumption (1), the spreading diameter and the spreading height at $\tau=0$ are 0.25 mm and 0.125 mm, respectively. The spreading height and the spreading diameter of the melt droplet under different wall temperature profiles are described in Fig. 6. Due to the surface tension, the melt droplet rapidly contracts inward after contacting the hot dry solid wall, indicating that the surface free energy was converted to the kinetic energy, and then the melt drop-
let spreads under the inertial force. On the other hand, the droplet velocity gradually decreases owing to the viscous force. Specifically, during the recoiling process, the surface tension makes the melt droplet reaches the maximum height. At this moment, the surface free energy of the melt droplet is completely converted into the kinetic energy and the gravitational energy. At the end of the recoiling step, the surface free energy is almost depleted. Next, the melt droplet falls due to gravity. In the spreading stage, the inertial force plays a dominant role. At the end of the spreading step, the kinetic energy was almost depleted. The corresponding spreading diameter decreases firstly and then increases. The viscous dissipation gradually reduces the kinetic energy and the potential energy, decays periodically, and finally tends to be stable, while surface free energy is at the lowest. The spreading rate of the melt droplet is different under different wall temperature distributions. With the increase of wall temperature difference, there is greater temperature gradient at the interface of the melt droplet, which causes stronger Marangoni convection in the droplet surface. Therefore, the droplet velocity would become larger under Marangoni force and the inertial force, which prolonged the viscous dissipation time of the melt droplet, leading to slow down the spreading rate of the melt droplet. The spreading height of the melt droplet is opposite to the spreading diameter, meaning that when the spreading diameter of the melt droplet reaches the maximum, the spreading height reaches the minimum. It is found that the temperature gradient can accelerate the droplet spreading when the wall temperature profile is linear, the wall temperature difference at $\Gamma=1$ is higher than that at $\Gamma=0$, the generated Marangoni force is greater, the spreading height and spreading diameter of the melt droplet are larger, and the decrease speed is slower. Compared with the inertial force of the melt droplet in the oscillation process, the viscous force caused by the droplet viscosity and surface tension is very small, which makes the melt droplet almostly reach the maximum spreading and recoiling at the same time.

The different temperature profiles of the horizontal hot dry wall would inevitably affect the heat transfer process of the heated wall toward the melt droplet, and also determine the melt droplet spreading and recoiling on the horizontal solid wall. The movement and heat transfer of the melt droplet with different wall temperature profiles on the heating solid wall are discussed. Compared with the constant wall temperature, when $x > 0$, the solid wall heats the melt droplet, and when $x < 0$, the solid wall cools the melt droplet. Because the wall temperature profile is linear for $\Gamma=0.5$ and $\Gamma=1$, there is a temperature difference on the heated wall. The surface tension of the right half for the melt droplet is larger than that of the left half, which causes the inward flow from left to right. Therefore, the melt droplet moves toward the right under the Marangoni effect, and finally approaches an equilibrium state, and spreading ceases due to the viscous force. The moving distance of the melt droplet as the spreading time under different wall temperature profiles is exhibited in Fig. 7. At constant wall temperature ($\Gamma=0$) in this case, the wall temperature is uniform. Therefore, there is no thermal Marangoni force. This indicates that the spreading process of the melt droplet is only controlled by surface tension, the inertial force, and the viscous force, and the melt droplet does not move. When applying the temperature gradient such as $\Gamma=0.5$ or 1 at this time, the Marangoni effect formed by the thermal capillary force makes the melt droplet move towards the high temperature region, and the movement rate increases as the temperature profile coefficient. It shows that the temperature gradient has a remarkable effect on the driving droplet spreading.
process. By the Marangoni force, the melt droplet moves towards the right, and ultimately stops due to viscous dissipation inside the melt droplet. As the melt droplet moves from low temperature region to high temperature region, its movement rate increases gradually with the increasing wall temperature coefficient. This is because the wall temperature coefficient increases, the wall temperature difference increases, the Marangoni force of the droplet surface would go up. Therefore, the moving rate of the melt droplet would be increased, and the moving distance would become long. When \( \Gamma = 1 \), the average motion speed of the melt droplet is 0.02 m/s, and the moving distance of the melt droplet can be written as

\[
\tau = 0.07232 - 0.07249e^{4.2918x \times 10^{-9}} \quad (16)
\]

Where, \( \tau \) is the spreading time.

At 3 ms, the phase interface of the melt droplet at different wall temperature profiles is given in Fig. 8. When the wall temperature profile is uniform, the phase interface of the melt droplet is symmetrical about the origin in the whole spreading process. On the contrary, for non-uniform wall temperature, the phase interface of the melt droplet is asymmetric about the origin, and the phase interface of the melt droplet shifts to the right. Especially, the wall temperature difference at \( \Gamma = 1 \) is larger than that at \( \Gamma = 0.5 \), the Marangoni force is greater, the kinetic energy of the droplet movement is greater, the moving distance is longer along the solid wall, the droplet height is lower than the uniform case, the spreading diameter is longer than that at \( \Gamma = 0 \). When the temperature coefficient is taken as 1, the moving distance of the melt droplet from the origin is 0.06 mm, and if \( \Gamma = 0.5 \), the moving distance would be reduced to 0.05 mm.

The wall heat flux under different wall temperature profiles is shown in Fig. 9. Due to surface tension and viscous force, the wall heat flux decreases periodically until an equilibrium state is reached. With the melt droplet spreading, the contact area increases, and the spreading height of the melt droplet decreases. Consequently, the thermal resistance was lowered, which led to enhancing the heat transfer between the melt droplet and solid wall. The profile of the wall heat flux is consistent with the spreading dynamics of the melt droplet, that is, when the droplet spreading diameter reaches the maximum, the droplet height reaches the minimum, and the wall heat flux reaches the maximum, and vice versa. With the increasing temperature profile coefficient, the wall temperature difference becomes large, resulting in the enhancement of Marangoni convection, which promotes wall heat transfer, and finally, the wall heat flux is increased. At the initial moment of the melt droplet contacting the horizontal hot dry wall, the wall heat flux is the largest and then decreases gradually with the decrease of the temperature difference between the solid wall and the melt droplet. When the melt droplet approaches the equilibrium state, the wall heat flux also decreases as the wall temperature profile coefficient. It can be seen that the higher the wall temperature difference, the greater the wall heat flux, and the stronger the heat transfer between the horizontal hot dry solid wall and the melt droplet.

The wall heat flux along the solid wall under different wall temperature profiles at 3 ms is depicted in Fig. 10. When the wall temperature is kept constant, the wall heat flux along the solid wall is symmetrical about the origin, and when the wall temperature is variable, the wall heat flux along the solid wall is asymmetric about the origin. When the temperature profile coefficient is assigned to 0.5, the wall temperature difference is small, and the wall heat flux decreases periodically until an equilibrium state is reached. With the melt droplet spreading, the contact area increases, and the spreading height of the melt droplet decreases. Consequently, the thermal resistance was lowered, which led to enhancing the heat transfer between the melt droplet and solid wall. The profile of the wall heat flux is consistent with the spreading dynamics of the melt droplet, that is, when the droplet spreading diameter reaches the maximum, the droplet height reaches the minimum, and the wall heat flux reaches the maximum, and vice versa. With the increasing temperature profile coefficient, the wall temperature difference becomes large, resulting in the enhancement of Marangoni convection, which promotes wall heat transfer, and finally, the wall heat flux is increased. At the initial moment of the melt droplet contacting the horizontal hot dry wall, the wall heat flux is the largest and then decreases gradually with the decrease of the temperature difference between the solid wall and the melt droplet. When the melt droplet approaches the equilibrium state, the wall heat flux also decreases as the wall temperature profile coefficient. It can be seen that the higher the wall temperature difference, the greater the wall heat flux, and the stronger the heat transfer between the horizontal hot dry solid wall and the melt droplet.

Fig. 8. Phase interface of melt droplet under different wall temperature profiles. (Online version in color.)

Fig. 9. Wall heat flux under different wall temperature profiles. (Online version in color.)

Fig. 10. Wall heat flux along solid wall under different wall temperature profiles. (Online version in color.)
at $\Gamma=0.5$ is lower than that at $\Gamma=1$. When $x < 0$, the left wall temperature is less than the droplet temperature, that is, the solid wall cools the melt droplet, so the wall heat flux is negative. On the contrary, when $x > 0$, the right wall temperature is greater than the droplet temperature, that is, the droplet is heated on the solid wall, and so the wall heat flux is positive. Because the melt droplet exists the surface tension gradient, the Marangoni convection is generated, and the melt droplet gradually moves towards the right. Compared $\Gamma=1$ with $\Gamma=0$, the wall heat flux profiles also travels to the right. At the same time, it is found that the wall heat flux is different at different positions of the solid wall, because the spreading height of the melt droplet is different at different positions, resulting in different thermal resistance. When the wall temperature profile is linear, the thickness on the left of the melt droplet is much less than that on the right, and a large vortex appears on the right of the melt droplet, which strengthens the heat transfer between the solid wall and the right of the melt droplet, so the wall heat flux of the right is much greater than that of the left. With the continuous heat transfer by the solid wall, and the melt droplet spreading, the melt droplet temperature increases and the temperature difference along the solid wall decreases. Therefore, with the melt droplet spreading, the wall heat flux decreases sharply.

To investigate the temperature evolution inside the melt droplet, the selected points are located at positions 1, 2, and 3 respectively, as shown in Fig. 11. Point 1 is located on the left side of the origin, Point 2 is situated on the origin, and Point 3 is placed on the right side of the origin. Besides, Point 1 and Point 3 are symmetrical about Point 2, and the vertical distance between these points and the horizontal hot dry wall is set as $D/4$. According to the wall temperature profile, the wall temperature of $x > 0$ is higher than that of $x < 0$, so the final temperature of Point 3 is higher than that of Point 1. Here, the final temperature is defined as the droplet temperature at the steady state. In addition, when the wall temperature profile is linear, the wall temperature on the left side of the origin is lower than the droplet average temperature, while the wall temperature on the right side of the origin is higher than the droplet average temperature. When the wall temperature is fixed, the wall temperature distribution is even and equal to the temperature at the origin. Therefore, when the wall temperature profile is linear, the initial temperature of Point 1 and Point 2 at $\Gamma=0.5$ or $\Gamma=1$ at is lower than that at $\Gamma=0$, but the final temperature is higher than that at $\Gamma=0$. Moreover, the wall temperature difference at $\Gamma=1$ is higher than that at $\Gamma=0.5$, resulting in strong Marangoni convection, so the increasing rate of droplet temperature at $\Gamma=1$ is rapid, and the final droplet temperature is higher than that at $\Gamma=0$. The temperature of Point 3 varies with the increasing wall temperature profile coefficient. Owing to the viscous force and surface tension, the melt droplet periodically spreads and recoils, and gradually reaches an equilibrium state. Therefore, the droplet temperature increases periodically in the early stage of spreading, and increases linearly in the later stage because of the viscous dissipation and suppression of droplet oscillation. It can be seen that the higher the wall temperature, the faster the increase rate of droplet temperature and the higher the final temperature.

The movement and spreading process of the melt droplet on the heated solid wall would directly affect its spreading area and then affect its heat transfer. The spreading dynamics of the melt droplet are closely related to its internal flow and other factors. The droplet velocity under different wall temperature profiles is demonstrated in Fig. 12. When the wall temperature is constant, the melt droplet is heated by the uniform solid wall. Because Point 1 and Point 3 are

![Fig. 11. Droplet temperature under different wall temperature profiles. (Online version in color.)](image-url)
symmetrical about the origin, the droplet velocity of Point 1 and Point 3 are equal. And yet when the wall temperature profile is linear, the droplet velocity of Point 3 is higher than that of Point 1. The driving force for the convection inside the melt droplet for \( \Gamma = 0 \) is the surface tension of the melt droplet. At liquid-air interfaces, surface tension results from the greater attraction of liquid molecules to each other due to cohesion than to the molecules in the air due to adhesion. In any case, the droplet velocity decays periodically, and the decrease rate at \( \Gamma = 1 \) is lower than that at \( \Gamma = 0 \), however, due to the viscous force, the droplet velocity eventually tends towards zero.

The x-direction velocity in the melt droplet under different wall temperature profiles is plotted in Fig. 13. When the wall temperature profile is homogeneous, the x-direction velocity of Point 2 is about zero, and when \( \Gamma \) equals to 1, the x-direction velocity of Point 2 decays periodically and gradually tends to near zero. For the x-direction velocity of point 1 and the x-direction velocity of Point 2, they are almost the same, and the trend is identical. When \( \Gamma = 1 \), the x-direction velocity of Point 3 is significantly higher than that of Point 1 at \( \Gamma = 0 \). This is because when the wall temperature coefficient is increased to 1, there is a large temperature difference on the horizontal heated solid wall, and there is a gradient in the surface tension of the melt droplet, which produces Marangoni force and accelerates the x-direction velocity. In other words, the left half velocity of the melt droplet is not obvious, but there is an obvious difference in the right half, which further shows that Marangoni convection occurs inside the melt droplet when the wall temperature difference along the solid wall arises, which affects the droplet velocity distribution. The melt droplet
droplet undergoes many oscillation processes of spreading and recoiling until the droplet reaches a stable situation. The x-direction velocity also indicates the trend of droplet spreading and recoiling at the next moment.

The spreading dynamics and heat transfer characteristics of static melt droplet on the horizontal hot dry wall is determined by the interaction of gravity, viscous force, and surface tension. Surface tension is the key factor affecting the appearance evolution of droplet interface. It controls the deformation characteristics of the melt droplet. To further study the spreading dynamics of the melt droplet on the horizontal hot dry wall, the dimensionless $Ma$ number and $Oh$ number were defined as:

$$Ma = \frac{d\sigma}{dT} \cdot \frac{L \rho c_p \Delta T}{\mu \lambda}, \quad Oh = \frac{\mu}{\sqrt{\sigma_m \rho d}}, \quad \text{......(17)}$$

Where, $\sigma$ is the surface tension, $T$ is the droplet temperature, $c_p$ is the specific heat, $\mu$ is the dynamic viscosity, $\lambda$ is the thermal conductivity, $\rho$ is the density, $\sigma_m$ is the average surface tension, $d$ is the diameter, $L$ is the characteristic length.

The role of gravity, viscous force, and surface tension in the evolution process under different wall temperature profiles, i.e. droplet $Ma$ number and $Oh$ number, is listed in Table 2. When there is a linear temperature difference on the solid wall, a temperature gradient is generated, resulting in the melt droplet shifting to the right. The greater the $Ma$ number, the greater the movement speed, indicating the enhancement of heat transfer between the melt droplet and the solid wall. The smaller the $Oh$ number, the greater kinetic energy obtained by the melt droplet and the slower the dissipation.

At 3 ms, the distribution of the temperature field inside the melt droplet under different wall temperature profiles is represented in Fig. 14. When the wall temperature is invariable, the distribution of the temperature field inside the melt droplet is symmetrical about the origin and presents the stratification from the upper to the lower, that is, far from the solid wall, the droplet temperature decreases linearly. However, when the wall temperature profile is linear, due to the temperature difference on the solid wall, and the left wall temperature is higher than the right wall temperature, the droplet temperature distribution is radial, and the droplet temperature of the right half is higher than that on the left half. With the increasing wall temperature profile coefficient, due to the Marangoni convection, the origin of the radial distribution moves towards the right. In the current simulation, the melt density is constant. Owing to the temperature gradient, there is an obvious backflow on the right of the melt droplet by the Marangoni effect. Compared with the case where there is no backflow inside the melt droplet in the same condition, the heat transfer mode inside the melt droplet has changed from heat conduction to heat conduction and convective heat transfer, which promotes the

Fig. 14. Distribution of temperature field of melt droplet under different wall temperature profiles. (Online version in color.)

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$Ma$</th>
<th>$Oh$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.003889</td>
</tr>
<tr>
<td>0.5</td>
<td>107.75</td>
<td>0.003937</td>
</tr>
<tr>
<td>1</td>
<td>215.5</td>
<td>0.003985</td>
</tr>
</tbody>
</table>

Table 2. $Ma$ number and $Oh$ number of melt droplet under different wall temperature profiles.
the right of the melt droplet, making the heat transfer inside the melt droplet more intense. This also makes the internal temperature of the melt droplet show the high temperature on the right and low temperature on the left, which can be seen apparently from the temperature field.

The velocity vector and the phase field inside the melt droplet under different wall temperature profiles are illustrated in Fig. 15. When the wall temperature is uniform, the phase distribution is symmetrical about the origin, and when the wall temperature profile is linear, due to the temperature difference on the solid wall, the surface tension gradient is generated on the droplet surface, resulting in Marangoni force, which makes the melt droplet move right. Therefore, the phase field is asymmetric about the origin, and the melt droplet tends to the right of the origin. Additionally, from the velocity vector inside the melt droplet, it can be seen that the droplet velocity vector is consistent with the phase distribution. When $\Gamma=0.5$ or $\Gamma=1$, due to the Marangoni force, a vortex is generated in the right half of the melt droplet, and the vortex becomes large at $\Gamma=1$. The greater the wall temperature difference, the stronger the Marangoni convection and the greater the melt droplet velocity, which would strengthen the heat transfer between the solid wall and the melt droplet. There is the maximum velocity at the surface for $\Gamma=1$ or $\Gamma=0.5$.

During the droplet spreading on the hot dry wall, the droplet average velocity of the melt droplet changes both in the direction and magnitude, which determines the deformation process of the melt droplet. The average velocity of the melt droplet with different wall temperature profiles is displayed in Fig. 16. With the increasing wall temperature coefficient, the wall temperature difference increases, the Marangoni convection is strengthened, and the average velocity of the melt droplet increases. On the whole, when the wall temperature profile is held constant, the final velocity of the melt droplet is close to zero. The final velocity of the melt droplet is about 0.015 m/s at $\Gamma=0.5$. While $\Gamma$ is 1, the average velocity of the melt droplet firstly increases to the maximum of 0.115 m/s under the Marangoni force, then decreases gradually due to the viscous force, and finally reaches about 0.03 m/s.

7. Conclusions

Based on the spreading process of the melt droplet on the heated substrate, the spreading dynamics of the melt droplet contacting the horizontal hot dry wall with the uniform and linear wall temperature profile is numerically simulated with the VOF method. The effects of wall temperature distribution on flow and heat transfer characteristics are analyzed. The main conclusions are as follows:

(1) The spreading height of the melt droplet is opposite
to the spreading diameter. The spreading diameter and the spreading height of the melt droplet decrease periodically and gradually slow down to near zero. With the increase of the wall temperature difference, the Marangoni convection is strengthened, the spreading diameter and the spreading height of the melt droplet become large, and the spread rate becomes slow.

(2) By the Marangoni force, the melt droplet moves towards the right, and ultimately stops. The movement speed of the melt droplet is about 0.02 m/s at Γ = 1.

(3) The wall heat flux profile is consistent with the spreading dynamics of the melt droplet. The wall heat flux decays periodically and gradually tends to be stable. The spreading diameter of the melt droplet decreases periodically to the spreading diameter. The spreading diameter and the spreading height of the melt droplet decrease periodically and gradually slow down to near zero. With the increase of the wall temperature difference, the Marangoni convection is strengthened, the spreading diameter and the spreading height of the melt droplet become large, and the spread rate becomes slow.

(4) The melt droplet temperature increases periodically in the early stage and linearly in the later stage. When the wall temperature is uniform and linear, the melt droplet temperature presents layered and radial, respectively. The larger the wall temperature difference, the faster the melt droplet temperature changes, the higher the final temperature, and the larger the vortex, which appears on the right of the melt droplet.

Acknowledgment
This paper is supported by the Open Project Foundation of Anhui Province Key Laboratory of Metallurgical Engineering & Resources Recycling (SKF22-05) and the Natural Science Foundation of Anhui Province (1708085ME108). The authors also gratefully acknowledge the support from the National Science Foundation of China (52176148).

REFERENCES