Study on the Consumption Mechanism and Lubrication of Mold Powder Based on Non-Sinusoidal Oscillation Mode

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Abstract: A two-dimensional mold model coupled multiphase flow, heat transfer, solidification and mold oscillation was established based on the casting parameters of the mold of plant. The accuracy of the model was verified by comparing the measured by plant and calculated mold powder consumption under the same casting conditions. The mechanism of mold powder consumption and lubrication was analyzed based on the non-sinusoidal oscillation mode, and the effect of non-sinusoidal oscillation parameters on mold powder consumption was discussed. Mold powder consumption was determined by the downward flow velocity of liquid mold powder and the thickness of liquid mold powder film, the liquid mold powder consumption decreased with the decrease of those. When the mold moved downward, the mold powder thickness and downward flow velocity decreased, the minimum mold powder consumption reached at the middle of the negative strip time, and the variation was to opposite when the mold moved upward, the maximum mold powder consumption appeared during the positive strip time. With the decrease of casting speed and modification ratio, and increase of oscillation frequency and oscillation amplitude, the mold powder consumption had the tendency to increase. The nonlinear regression equation was fitted by the Levenberg–Marquardt method combined with the universal global optimization method to evaluate mold powder consumption.

Keywords: mold powder consumption; lubrication; non-sinusoidal oscillation; oscillation parameters

1. Introduction

The liquid mold powder infiltrated from the mold powder pool into the gap between the shell and mold with the mold oscillation in continuous casting, forming a mold powder film which consisted of liquid and solid mold powder film. This mold powder film prevented the solidified shell from sticking to the mold wall and mitigated the occurrences of breakout. Sufficient mold powder consumption was the prerequisites to ensure the normal flow of liquid mold powder into the meniscus and shell growth. Hence, research on mold powder consumption and lubrication was extremely necessary.

Meng and Thomas et al. [1,2] developed a comprehensive model to predict the mold powder consumption and liquid and solid mold powder friction by a one-dimensional finite-difference mode (CON1D). Lopez and Mills et al. [3–6] analyzed the mold powder infiltration and mold powder consumption and discussed the effect of mold powder consumption with different casting parameters by a 2D mold model, and it was found that there was no negative mold powder consumption during the whole cycle. Tsutsumi K et al. [7] used an Sn-Pb alloy and stearic acid to simulate liquid mold powder infiltration, the results showed that the liquid mold powder flowed into the mold powder channel during the whole oscillation cycle and the powder consumption in the positive strip time period was consumed more than that in negative strip time period. Kajitani T et al. [8,9] concluded that the liquid mold powder inflow was at the end of positive strip time and the second half of the negative strip time by the cold model, the mold powder consumption...
increased by the decrease of casting velocity and viscosity of mold powder, but the slag rim was not considered in the model. Shin et al. developed a model based on measurements from plant trials to predict mold powder consumption, but the transient behavior of mold powder was not discussed [10]. Jonayat et al. developed a computational model for the meniscus zone and conducted a parametric study on the oscillation parameters on mold powder consumption [11], but the solidification shell was not considered in the model. Zhang et al. studied the transient behavior of mold powder near the lunar meniscus and the influence of casting parameters on mold powder consumption by mathematical models [12–14]. Yang et al. studied the decrease of the melting temperature of mold flux resulted in the mold powder pool deeper, promoting mold powder consumption [15]. Li et al. conducted that mold powder consumption was increased by the amount of protective mold powder added in the nozzle area [16]. Du et al. found that the friction state of the initial shell was affected by the mold powder consumption based on the analysis of the fluctuation of meniscus and mold powder flow [17]. Yan [18,19], Kong [20], and Yang [21] et al. investigated that the viscosity of the mold powder was increased by the generation of Al2O3 caused by the interfacial reaction between the steel and mold powder, the mold powder consumption decreased by that. The high Al2O3 content of mold powder also contributed to the decrease in mold powder consumption [22]. Ji et al. compared the thickness of solid and total mold powder layer and the infiltration of mold powder at the corner was analyzed [23–25]. The above mold oscillation modes were all based on the sinusoidal mode. The sinusoidal oscillation of mold could improve the surface quality of the slabs through high-frequency and small amplitude [26,27]. However, the positive strip time (t_p) was also limited by shortening the negative strip time (t_n). Compared with the sinusoidal oscillation mode, the non-sinusoidal oscillation had many advantages, such as reducing the t_n, increasing the t_p, reducing the depth of the oscillation mark, increasing mold powder consumption and improving the quality of the slabs [28,29].

The quality of the slabs was affected by the poor lubrication or low consumption, resulting in surface indentation and cracks as shown in Figure 1. However, the mold powder consumption mechanism of non-sinusoidal oscillation was not discussed. Therefore, a two-dimensional mold model with mold oscillation of non-sinusoidal mode was established in present study based on the parameters of the plant mold model. The consumption mechanism of mold powder based on non-sinusoidal oscillation mode was analyzed by studying the downward flow velocity of liquid mold powder and pressure in mold powder channel, the thickness of liquid mold powder film and shear stress (liquid friction) acting on shell surface at different positions below the meniscus. The influence of non-sinusoidal oscillation parameters on mold powder consumption was compared and a regression equation was fitted to evaluate the mold powder consumption.

Figure 1. Surface detects.

2. Mathematical Mold

2.1. Assumption

1) The taper and arc of the die had little influence on the mold powder consumption, hence, the taper and arc of the die were not considered;
(2) Half of the mold was analyzed based on the symmetry of the fluid flow and heat transfer in the mold;
(3) The heat transfer of the slabs was in a stable state when the casting speed was constant;
(4) The flow of molten steel in the mold was incompressible steady flow.

2.2. Governing Equation

In this study, a two-dimensional mathematical model was established, which coupled multiphase (steel, mold powder and air) flow, heat transfer, steel solicitation and mold oscillation. Then, the Fluent 19.2 software was used to solve the N-S equation. The volume of fluid (VOF) method, the \( k - \varepsilon \) model, and solidification model was used to calculate the phase volume fraction, the turbulence flow and the solidification of steel, respectively. The continuum surface force method (CFS) was used to track the phase interface. The governing equations solved were shown in Equations (1)–(3).

Continuity equation

\[
\frac{\partial (\alpha_q \rho_q)}{\partial t} + \nabla \cdot (\alpha_q \rho_q \vec{v}) = \sum_{p=1}^{n} (m_{pq} - m_{qp})
\]  
where: \( \vec{v} \) was velocity vector, m/s; \( m_{pq} \) was mass transfer from \( p \) phase to \( q \) phase, kg/s; \( m_{qp} \) was mass transfer from \( q \) phase to \( p \) phase.

Momentum equation

\[
\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} = -\frac{1}{\rho_{mix}} \nabla P + \nabla \cdot \left[ \nu_T \left( \nabla \vec{v} + \nabla^T \vec{v} \right) \right] + g + \frac{F_\sigma}{\rho_{mix}} - \frac{S_s}{\rho_{mix}}
\]
where: \( P \) was pressure, Pa; \( \nu_T \) was viscosity of turbulent motion, kg/m·s; \( F_\sigma \) was the source term of the interfacial tension; \( S_s \) was source terms due to solidification; \( g \) was gravity kg/m\(^3\).

Energy equation

\[
\frac{\partial (\rho_{mix} E)}{\partial t} + \nabla \cdot \left( \vec{v} (\rho_{mix} E + P) \right) = \nabla \cdot \left( K_{eff} \nabla T + \left( \tau_{eff} \cdot \vec{v} \right) \right)
\]
where: \( E \) was enthalpy of solidification, J; \( K_{eff} \) was effective thermal conductivity, W/m·K; \( T \) was temperature, K; \( \tau_{eff} \) was effective shear stress, Pa.

2.3. Mold Model

The model consisted of submerged entry nozzle (SEN), mold, copper plate and secondary cooling zone, half of the model was simulated due to the symmetry of the model. The mold model was as shown in Figure 2, where the mold powder layer was added to the upper surface of the molten steel initially, the mold powder naturally infiltrated into the wall between the mold and the shell with the oscillation of the mold, forming the slag film, which was more in line with the actual production situation. The total mesh was about 170,000. The interfaces between the fluid and solid, as well as between the steel and mold powder, should be refined to accurately capture the conditions within the mold powder channel, the model mesh was depicted in Figure 3. The parameters of the mold model were presented in Table 1.
mold powder, should be refined to accurately capture the conditions within the mold powder channel, the model mesh was depicted in Figure 3. The parameters of the mold model were presented in Table 1.

Figure 2. Mold model and boundary condition.

Figure 3. Model mesh.

Table 1. Parameters of the mold model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section of slab, mm</td>
<td>1300 × 250</td>
</tr>
<tr>
<td>Thickness of copper plate, mm</td>
<td>50</td>
</tr>
<tr>
<td>Length of first cold zone, mm</td>
<td>1000</td>
</tr>
<tr>
<td>Length of secondary cooling zone, mm</td>
<td>1000</td>
</tr>
<tr>
<td>Nozzle angle, °</td>
<td>15</td>
</tr>
<tr>
<td>Inner diameter of SEN, mm</td>
<td>65</td>
</tr>
<tr>
<td>Port of SEN, mm</td>
<td>45 × 70</td>
</tr>
<tr>
<td>Depth of immersion, mm</td>
<td>165</td>
</tr>
<tr>
<td>Oscillation mode</td>
<td>Non-sinusoidal</td>
</tr>
<tr>
<td>Casting speed, m/min</td>
<td>0.95</td>
</tr>
</tbody>
</table>

2.4. Boundary Conditions

The upper surface of the mold was set as a free surface, the pressure was set to atmospheric pressure \( P_{\text{top}} = 101,325 \text{ Pa} \), and the temperature was set to room temperature \( T_{\text{top}} = 303 \text{ K} \). The SEN inlet was set as the velocity inlet boundary, the temperature of inlet was set to pouring temperature \( T_{\text{in}} = 1825 \text{ K} \), and the inlet velocity was determined by mass conservation as shown in Equation (4).

\[
v_{\text{inlet}} \times s_{\text{in}} = v_c \times S_{\text{out}}
\]
where: $v_{inlet}$ was the inlet velocity, m/s; $s_{in}$ was the inlet area, m$^2$; $S_{out}$ was the exit area, m$^2$.

The outlet was set as the outflow boundary, assuming that the flow at the outlet was fully developed and the gradient value of each variable along the flow direction was zero. The copper plate and SEN walls had a small amount of heat loss, which was no heat loss by default. The fluid-solid interface was set as a coupling wall, and the heat flux and velocity transfer are realized through coupling. The first cold zone and secondary cooling zone were set as convection. The heat transfer coefficient of the first cold zone ($h_c$) was determined by Equation (5) [30], and the temperature of the boundary ($T_c$) was 305 K. The heat transfer coefficient of the secondary cooling zone ($h_{spray}$) was used to determine as in Equation (6) [30], and the boundary temperature ($T_{spray}$) was set to 300 K. The initial thickness of mold powder and air were 25 mm, which were patched on the top of the model. Initially, the steel in the mold was liquid, hence, resulting initial temperature of 1805 K of fluid, while initial temperature of copper plate was 405 K. The specific boundary condition was depicted in Figure 2. The break temperature was used to distinguish between solid and liquid mold powder films, as the viscosity increased dramatically below the break temperature. The detail material properties were listed in Table 2.

### Table 2. Material parameter.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel (data from [31])</td>
<td>Density, kg/m$^3$</td>
<td>7020</td>
</tr>
<tr>
<td></td>
<td>Viscosity, kg/m·s</td>
<td>0.0063</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity, W/m·K</td>
<td>$= 13.86 + 0.01113 \times (T - 273.15)$</td>
</tr>
<tr>
<td></td>
<td>Liquidus temperature, K</td>
<td>1805</td>
</tr>
<tr>
<td></td>
<td>Solidus temperature, K</td>
<td>1790</td>
</tr>
<tr>
<td></td>
<td>Specific heat, J/kg·K</td>
<td>750</td>
</tr>
<tr>
<td></td>
<td>Latent heat, J/kg</td>
<td>270,000</td>
</tr>
<tr>
<td>Mold powder (data from [31])</td>
<td>Density, kg/m$^3$</td>
<td>2500</td>
</tr>
</tbody>
</table>
|                            | Viscosity, kg/m·s          | $3.0, T \leq 1347$
|                            |                              | $-0.4414(T - 273.0) + 476.64, 1347 < T < 1352$
|                            |                              | $-0.00173 \times (T - 273.0) + 2.4074, 1352 \leq T \leq 1573$
|                            |                              | $0.18, T > 1573$    |
|                            | Break temperature, K        | 1352                |
|                            | Thermal conductivity, W/m·K | $2.0, T \geq 1352$
|                            |                              | $1.2, T < 1332$     |
|                            | Specific heat, J/(kg·K)     | 830                 |
| Air                       | Density, kg/m$^3$           | 1.225               |
|                            | Viscosity, kg/m·s           | $1.8 \times 10^{-5}$|
|                            | Thermal conductivity, W/(m·K)| 0.0242              |
|                            | Interfacial tension between steel and mold powder, N/m | 1.3                 |
|                            | Interfacial tension between mold powder and air, N/m | 0.8                 |
| Copper plate               | Density, kg/m$^3$           | 8973                |
|                            | Heat capacity, J/(kg·K)     | 390                 |
|                            | Thermal conductivity, W/(m·K)| 387                 |

The displacement and velocity expressions of the non-sinusoidal oscillation of the mold were exhibited in Equations (7) and (8), and the specific oscillation parameters during plant operation were shown in Table 3, the user-defined functions to use to achieve the mold oscillation:

$$h_c = \left( \frac{0.23}{\rho_{water} \mu_{water} D} \right)^{0.8} \left( \frac{C_{water} \rho_{water}^{0.4}}{k_{water}} \right) \cdot \frac{k_{water}}{D}$$ (5)

$$h_{spray} = 0.581 \rho_{water}^{0.451} (1 - 0.0075 T_{spray})$$ (6)
where: \( \rho_{\text{water}} \) was water density, kg/m\(^3\); \( v_{\text{water}} \) was flow velocity of water, m/s; \( D \) was hydraulic diameter, m; \( \mu_{\text{water}} \) was water viscosity, kg/m·s; \( C_{\text{water}} \) was specific heat of water, J/kg·K; \( k_{\text{water}} \) was thermal conductivity of water, W/m·K; \( W_{\text{water}} \) was cooling water flow rate, L/min; \( T_{\text{spray}} \) was temperature of cooling water spray, K.

\[
    s_{\text{mold}} = A \sin\left\{ 2\arctan[M \tan(\pi(60f)/t)] \right\}
\]

\[
    v_{\text{mold}} = \frac{4MA(60f)\pi \cos\{2\arctan[M \tan((\pi(60f)/t)]\}}{1 + M^2 + (1 - M^2) \cos(2\pi(60f)/t)}
\]

where: \( M = \cot\left(\frac{\pi}{4}(1 + \alpha)\right) \); \( s_{\text{mold}} \) was mold displacement, m; \( v_{\text{mold}} \) was mold velocity, m/s; \( A \) was oscillation amplitude, m; \( \alpha \) was modification ratio, which characterized the extent of asymmetry of the non-sinusoidal mode; \( f \) was oscillation frequency, cpm.

Table 3. Oscillation parameters.

<table>
<thead>
<tr>
<th>Oscillation Frequency, (cpm)</th>
<th>Oscillation Amplitude, (m)</th>
<th>Modification Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The time step was set at 0.00001 s, which could be increased to 0.0001 s when the solution reached steady state. The calculations were performed over a duration of one month.

3. Discussion and Results
3.1. Mold Powder Consumption and Validation of Model

Lubrication consumption (\( Q_{\text{lub}} \), kg/s) was mold powder consumption in liquid mold powder film. The \( Q_{\text{lub}} \) at 5, 10, 50, 100 mm below the meniscus was monitored. The transient lubrication consumption in the adjacent three cycles was illustrated in Figure 4, where “T” was the total period of the oscillation cycle. The mold powder consumption was within −0.092 to 0.19 kg/s. The variation of \( Q_{\text{lub}} \) exhibited periodic, it was negative consumption near the meniscus during the \( t_n \), that trend weaken to disappear with the increase of the distance below the meniscus. During the \( t_p \), the lubrication consumption increased with the increase of velocity difference between the mold and shell. However, during the \( t_n \), the velocity difference gradually decreased as the mold accelerated downward, and the lubrication consumption gradually decreased. The maximum \( Q_{\text{lub}} \) appeared during the \( t_p \), while the minimum occurred during \( t_n \). The increase in the distance below the initial meniscus from 5 mm to 100 mm, resulted in a decrease of the variation of \( Q_{\text{lub}} \) and gradually became stable, with average values of 0.0706, 0.0635, 0.0298, and 0.0237 kg/s, respectively. Mold powder consumption during the \( t_n \) and \( t_p \) at different locations below the meniscus was demonstrated in Figure 5, \( Q_{\text{lub}} \) during the \( t_p \) consumed more than \( t_n \), hence, increasing the \( t_n \) can increase the average lubrication consumption, which was beneficial to lubrication, reduce and eliminate the surface defects of the slabs.

![Figure 4. Transient mold powder consumption in the adjacent three cycles.](image-url)
3. Discussion and Results

3.1. Mold Powder Consumption and Validation of Model

In order to verify the accuracy of the model, we tracked the amount of mold powder required to pour each ladle in a second-stream continuous casting machine in a plant for the same cross section and casting parameters, and then obtained the mold powder consumption of per ton of molten steel. For the same cross section (1300 × 250 mm) and casting conditions (the oscillation parameters of \( A = 4 \text{ mm}, f = 120 \text{ cpm}, \alpha = 0.1 \) and \( Vc = 0.95 \text{ m/min} \)), a total of 90–100 kg of mold powder was required for pouring 135–150 t of molten steel, hence, the mold powder consumption of per ton of molten steel \( Q_{\text{Slag}}^{\text{Slag}} \) measured from the plant was 0.6 to 0.66 kg/t-steel. The calculated \( Q_{\text{Slag}}^{\text{Slag}} \) was obtained from the \( Q_{\text{lab}} \) at 100 below the meniscus according to Equations (9) and (10), the calculated \( Q_{\text{Slag}}^{\text{Slag}} \) was 0.6081 kg/t-steel. The comparison between the calculated and measured values of mold powder consumption was listed in Table 4, the error was 1.34% to 7.87%, which verified the correctness of the model, therefore, the mechanism of mold powder consumption and the influence of non-sinusoidal oscillation parameters on mold powder consumption can be studied by this model.

\[
Q_{\text{area}} = \frac{Q_{\text{lab}}}{P_{\text{Slab}} \cdot Vc}
\]

\[
Q_{\text{Slag}}^{\text{Slag}} = \frac{Q_{\text{area}} \cdot R^*}{f^* \cdot 7.6}
\]

where: \( Q_{\text{area}} \) was the mold powder consumption per unit strand area, kg/m²; \( P_{\text{Slab}} \) was the perimeter of slab, m; \( Q_{\text{Slag}}^{\text{Slag}} \) was the mold powder consumption per ton of steel, kg/t-steel; \( R^* \) was the ratio of surface area and volume of mold, m⁻¹; \( f^* \) was the fraction of powder forming slag which was equal to 1 in the current study.

<table>
<thead>
<tr>
<th>Calculate Value (kg/t-Steel)</th>
<th>Measurement Value in Plant (kg/t-Steel)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6081</td>
<td>0.6–0.66</td>
<td>1.34–7.87</td>
</tr>
</tbody>
</table>

3.2. Velocity and Pressure of Mold Powder in Mold Powder Channel

The downward flow velocity of the liquid mold powder and pressure of mold powder in mold powder channel were depicted in Figures 6 and 7, respectively, where the downward flow velocity of liquid mold powder was positive and the static pressure of molten steel was positive pressure. The variation of velocity and pressure exhibited were opposite, which was in accordance with Bernoulli’s principle. The variation in downward flow velocity of liquid mold powder exhibited a consistent correlation with the mold powder consumption. During the \( t_n \), liquid mold powder near the meniscus flowed upward, which was affected by the oscillation of mold and movement of slag rim, the pressure in mold powder channel increased.
With the increase of the distance below the meniscus from 5 to 100 mm, the downward flow velocity of liquid mold powder was within $-0.016$ to $0.037$, $-0.014$ to $0.042$, $-0.0059$ to $0.030$ and $0.0040$ to $0.022$ m/s, respectively, the downward flow velocity and variation decreased. Downward flow velocity was determined by velocity of mold oscillation and casting speed.

The pressure and variation of mold powder in mold powder channel was opposite to the downward flow velocity of liquid mold powder. The pressure of mold powder in the mold powder channel was within $-7454.17$ to $-2250.35$, $-11593$ to $-2379.68$ and $-17195.7$ to $367.54$ Pa with the increases of the distance below the meniscus, respectively. Pressure of the mold powder in mold powder channel was affected by the downward flow velocity of liquid mold powder and thickness of liquid mold powder film.

3.3. Thickness of Liquid Mold Powder Film and Shear Stress (Liquid Friction)

The thickness of liquid mold powder film was also one of the factors affecting mold powder consumption, the thickness of liquid mold powder film during three cycles was shown in Figure 8a, the variation of thickness of liquid mold powder film was similar to that of mold powder consumption. With the distance below the meniscus increased from 5 mm to 100 mm, the thickness and variation of thickness decreased, the thickness of liquid mold powder film was within 0.95 to 2.45, 0.82 to 1.38, 0.70 to 0.93 and 0.48 to 0.65 mm, respectively. The thickness of the liquid mold powder film was determined by the surface temperature of shell, the temperature of shell surface was presented in Figure 8b. The variation of the temperature of the shell surface was consistent with the thickness of the liquid mold powder film, and the thickness of the liquid mold powder was thickened with the increase of the surface temperature of the shell.
The shear stress (liquid friction) acting on the shell surface \( \tau_l \) was used to quantify the lubrication level, which played an important role in the smooth pulling of the shell from the mold, was calculated according to Equation (11):

\[
\tau_l = \mu_{\text{slag}} \frac{\partial V_y}{\partial y}
\]  

(11)

where: \( \mu_{\text{slag}} \) was the liquid mold powder viscosity (Pa\cdot s), \( \partial V_y \) was the velocity difference between the shell and the mold (m/s), \( \partial y \) was the thickness of liquid mold powder film (m).

The velocity difference between the shell and the mold was described in Figure 9, which was within \(-0.0189\) to \(0.0434\) m/s, the velocity difference was determined by the oscillation velocity of mold and casting speed. The shear stress (liquid friction) acting on the shell surface was presented in Figure 10, where the shear stress was positive in the upward direction, and the shear force was within \(-66.0115\) to \(55.1505\) Pa. The maximum upward \( \tau_l \) appeared at the middle of \( t_n \) and gradually increased with the distance below the meniscus increased from 5 mm to 100 mm, which was affected by the mold powder consumption in Figure 4. The variation of mold powder consumption was opposite to the shear stress. Therefore, sufficient mold powder consumption could increase the downward \( \tau_l \) and be conductive to the demold.
3.4. Mechanism of Mold Powder Consumption

Based on the above analysis, the mechanism of mold powder consumption and lubrication was proposed. Lubrication consumption was determined by downward flow velocity of liquid mold powder and the thickness of liquid mold powder film. During the \( t_c \), the mold accelerated downward movement, and the velocity difference between the mold and solidified shell decreased, the downward flow velocity of the liquid mold powder decreased and the thickness of liquid mold powder film affected by the decrease of the temperature of shell surface decreased, the mold powder consumption decreased. This trend of these variation exhibited a gradual increase. At the middle of \( t_{0} \), the flow velocity decreased to the minimum, the thickness of the mold powder layer became the thinnest, the mold powder consumption reached minimum affected by them, and the liquid friction reached the maximum. During the \( t_{0} \), the downward casting speed was faster than the downward oscillation velocity of the mold, and the liquid mold powder near the meniscus flowed upward under the effect of this, and the mold powder consumption was negative consumption. When the mold moved up again, the downward infiltration of liquid mold powder was enhanced, the thickness of liquid mold powder film was thickened, and the mold powder consumption reached the maximum.

3.5. Effect of Non-Sinusoidal Oscillation Parameters on Mold Powder Consumption

The effect of casting speed on mold powder consumption was presented in Figure 11. With the increase of the casting speed from 0.8 to 1.2 m/min, the average mold powder consumption decreased, which was determined by the variation of mold powder consumption. With the decrease of the casting speed, the negative strip time decreased, the fluctuation of transient mold powder consumption decreased during this period. Hence, it was not conductive to lubrication by the increase of casting speed.

The influence of modification ratio on mold powder consumption was described in Figure 12. With the increase of the modification ratio from 0.1 to 0.3, mold powder consumption decreased, mold powder consumption decreased from 0.5637 to 0.4853 kg/m\(^2\) at a casting speed of 0.8 m/min, mold powder consumption exhibited a decrease from 0.7179 to 0.4479 kg/m\(^2\) at a casting speed of 1.2 m/min. The influence of the modification ratio on mold powder consumption was more obvious at high casting speed, hence, reducing modification ratio at high pulling speed was conducive to lubrication.
3.4. Mechanism of Mold Powder Consumption

Based on the above analysis, the mechanism of mold powder consumption and lubrication was presented in Figure 13. The average mold powder consumption increased with the increase of oscillation frequency, which was determined by the variation of mold powder consumption. The variation of mold powder consumption increased and the duration near the maximum mold powder consumption increased with the increase of frequency. With the oscillation frequency increasing from 90 to 150 cpm, the average mold powder consumption exhibits an increase from 0.4955 to 0.6556 kg/m$^2$ at a casting speed of 0.8 m/min, and 0.365 to 0.5731 kg/m$^2$ at a casting speed of 1.2 m/min. Therefore, increasing the mold powder consumption can be achieved by increasing the oscillation frequency when utilizing non-sinusoidal oscillation.

The effect of the oscillation amplitude on mold powder consumption was presented in Figure 14. The average mold powder consumption increased with the increase of oscillation amplitude, which was mainly caused by the increase of mold powder consumption fluctuation. The positive strip time increased and the maximum mold powder consumption increased with the increase of amplitude. With the increase of oscillation amplitude from 4 to 6 mm, the mold powder consumption was from 0.4117 to 0.5272 kg/m$^2$ with a casting speed of 0.8 m/min, 0.3592 to 0.4515 kg/m$^2$ with a casting speed of 1.2 m/min, mold powder consumption was significantly affected by the increase in oscillation amplitude at low casting speed.
\[ Q_{area} = -8.6219 \times V_C^{0.7108} \times \eta^{-7.782} \times \alpha^{0.868} \times f^{-1.6038} \times A^{-1.3036} + 0.7468 \ R^2 = 0.85 \]  

where: \( V_C \) was casting speed, m/min; \( \eta \) was Salg viscosity at break temperature, kg/m·s; \( \alpha \) was modification ratio; \( f \) was oscillation frequency; \( A \) was oscillation amplitude, mm.

The mold powder consumptions per unit strand area (\( Q_{area} \)) for different oscillation parameters were listed in Table 5. The Levenberg–Marquardt method, combined with the universal global optimization (UGO) method was used to fit the nonlinear regression equation of mold powder consumption, this process was completed by the software 1stOpt. The LM method had good convergence performance and high robustness. The UGO method could stochastically generate an initial value and efficiently converge towards the optimal solution. The root meaned square error, sum of squares due to error, square of the correlation coefficient and F statistics were used to test the significance of the regression effect for the equation. The nonlinear regression equation of mold powder consumption was shown in Equation (12). The significance test of the regression effect was presented in Table 6, which showed a strong fit between the variables. The comparison between the calculated average mold powder consumption with different casting parameters and the estimated mold powder consumption of Equation (12) was depicted in Figure 15, demonstrating a remarkable consistency. Therefore, the mold powder consumption for low viscosity of mold powder could be calculated by Equation (12).
Table 5. Mold powder consumption for different non-sinusoidal oscillation parameters.

<table>
<thead>
<tr>
<th>No.</th>
<th>Casting Speed, $V_c$ (m/min)</th>
<th>Modification Ratio, $\alpha$</th>
<th>Oscillation Frequency, $f$ (cpm)</th>
<th>Oscillation Amplitude, $A$ (mm)</th>
<th>Mold Powder Consumption, $Q_s$ (kg/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>90</td>
<td>6</td>
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</table>

Table 6. The significance test of the regression effect.

<table>
<thead>
<tr>
<th>Root Mean Square Error, (RMSE)</th>
<th>Sum of Squares due to Error, (SSE)</th>
<th>Square of the Correlation Coefficient, ($R^2$)</th>
<th>F-Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.04720</td>
<td>0.03787</td>
<td>0.8529</td>
<td>87.007325</td>
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</table>

Figure 15. Comparison of calculated $Q_s$ and estimated $Q_s$.

4. Conclusions

A two-dimensional mold model was established according to the mold model of plant, which coupled multiphase flow, heat transfer, solidification, and mold oscillation. The mechanism of mold powder consumption and lubrication was analyzed and the effect of non-sinusoidal oscillation parameters on mold powder consumption was discussed. The conclusions can be summarized as follows:
1. The accuracy of the model was verified by comparing the measured and calculated mold powder consumption of the plant under the same casting conditions, the error between the calculated and measured values of mold powder consumption was 1.34 to 7.87%.

2. The lubrication consumption was within $-0.092$ to $0.19$ kg/s. and exhibited a periodic variation under the influence of mold oscillation, decreasing first and then increasing. The lubrication consumption was negative consumption during the negative strip time. With the increase of the distance below the meniscus, the variation of mold powder consumption decreased and the negative consumption was weakened to disappear.

3. The variation of downward flow velocity of liquid mold powder and thickness of liquid mold powder film was opposite to shear stress (liquid friction) acting on shell surface and pressure in mold powder channel. The maximum value of mold powder channel pressure and upward liquid friction was reached near the middle of $t_p$, while the maximum value of mold powder thickness and penetration velocity appeared during $t_p$. With the increase of the distance below the meniscus, the downward flow velocity of liquid mold powder decreased, the pressure in mold powder channel, and the maximum upward shear stress (liquid friction) increased.

4. Lubrication consumption was determined by the downward flow velocity of liquid mold powder in mold powder channel and the thickness of liquid mold powder film. When the mold moved downward, the liquid mold powder film thickness and downward flow velocity of liquid mold powder decreased, the minimum mold powder consumption was at the middle of the $t_p$, and vice versa. Lubrication consumption during the $t_p$ consumed more than $t_n$, hence, increasing the $t_p$ which could increase the average mold powder consumption and was conducive to lubrication.

5. The mold powder consumption was related to the non-sinusoidal oscillation parameters. The mold powder consumption with different oscillation parameters was within $0.2615$ to $0.7179$ kg/m$^2$. With the decrease of casting speed ($V_c$) and modification ratio ($f$), and increase of oscillation frequency ($f$) and oscillation amplitude ($A$), the mold powder consumption had the tendency to increase. The Levenberg–Marquardt method combined with universal global optimization method was used to fit the nonlinear regression equation $Q_s = -8.6219 \times V_c^{0.7108} \times \eta^{-7.782} \times \alpha^{0.868} \times f^{-1.6038} \times A^{-1.3036} + 0.7468$, to evaluate mold powder consumption for low viscosity of mold powder.

Author Contributions: Conceptualization, Y.L.; methodology, M.C.; software, Y.L.; validation, M.C.; formal analysis, M.C. and Y.L.; investigation, M.C.; resources, M.C.; data curation, Y.L.; writing—original draft preparation, M.C.; writing—review and editing, M.C.; visualization, Y.L.; project administration, X.Z.; funding acquisition, X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Hebei Province Natural Science Fund (grant number E2020203128) and Hebei Education Department Higher Education Science and Technology Program (grant number ZD2021106).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to restrictions.

Conflicts of Interest: The authors declare no conflict of interest.
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