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Optimization of the Circular Channel Size and the A.C. Magnetic Field Parameters for Application in a Channel-Type Induction-Heating Tundish

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Abstract: In this paper, the appropriate channel design and operating conditions for the simultaneous operation of the inclusion removal and the induction heating of the molten steel by imposing the A.C. magnetic field around the circular channel have been studied. (1) The effect of the lift force and the turbulence force on the inclusion in the transition zone of the channel has been computed; the results show that when the diameter of the inclusion is not less than 0.1 mm, both forces can be neglected because they are less than the electromagnetic pinch force, especially when the shielding parameter is not less than 5.0. (2) The minimal channel length to remove the inclusions out of the dead zone was computed without the lift force and the turbulence force; the shielding parameter of 10.0~15.9 is optimal to obtain the shortest channel length. Furthermore, the slow velocity of the molten steel is desirable. (3) The molten steel temperature increase per unit channel length by the induction heating can be controlled by the A.C. magnetic field frequency; a high frequency condition is better for the efficient thermal supply in this calculation condition. (4) When the flow velocity of the molten steel in the channel with a length of 1 m and a radius of 0.075 m is 0.1 m/s, the shielding parameter of 15.9 is the optimal parameter to simultaneously remove the inclusions and heat up the molten steel in the circular channel. And when the non-dimensional magnetic field intensity of the A.C. magnetic field is 31.7, the removal rate of the 0.1 mm inclusion in the channel can reach more than 95% and the molten steel temperature can be heated over 10 K.



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1. Introduction

The cleanliness of molten steel is becoming more and more important with the increasing demand for high-quality steel year by year [1,2]. The tundish, working as a buffer and distributor of molten steel between the ladle and continuous casting mold, plays a key role in ensuring continuous metal casting [3–5]. To obtain ideal fluid flow characteristics in the tundish, flow control devices, such as weirs, dams, baffles with inclined holes, and turbulence inhibitors, have been widely used in the continuous casting tundish [6–9]. All of them are designed to increase the residence times and plug flow volume of molten steel in the tundish for enhancing inclusion removal from the molten steel. However, the temperature of molten steel significantly decreases with the increasing residence times, which goes against the process of continuous casting [10–12]. The technology of channel-type induction heating in the tundish developed in recent decades [13–17]. The schematic diagram of the tundish is shown in Figure 1. A tundish with a channeled induction-heating device at its sidewall is presented. By imposing the A.C. magnetic field on the molten steel flowing in the tundish channel, the thermal loss of the molten steel in the tundish can be compensated effectively and the inclusions move towards the channel's inner wall by the



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electromagnetic force acting on them and are trapped on the channel inner wall. Thus, this method has two functions: (1) heat loss compensation by Joule heating and (2) inclusion removal by electromagnetic force. The A.C. magnetic field with a commercial frequency (50 Hz or 60 Hz) is generally used in the induction-heating system. Taniguchi et al. [18,19] used the trajectory method to solve the removal efficiency of non-metallic inclusions in the molten steel with the A.C. magnetic field. In their investigation, the molten steel had a laminar flow in a circular channel and the frequency of the A.C. magnetic field was 60 Hz. Wang et al. [20,21] numerically simulated the inclusion motion in a channel-type induction-heating tundish with the 50 Hz A.C. magnetic field. On the other hand, Maruyama and Zhang et al. [22–24] carried out a numerical calculation of the inclusion motion in the molten steel under the A.C. magnetic field imposition and clarified the presence of an optimum magnetic field frequency for speedy inclusion removal. In this paper, the model of the inclusion motion has been improved by considering the turbulence force and the lift force acting on the inclusion. And not only the inclusion removal but also the heat compensation are considered simultaneously to find out the optimum A.C. magnetic field parameter and the channel design.

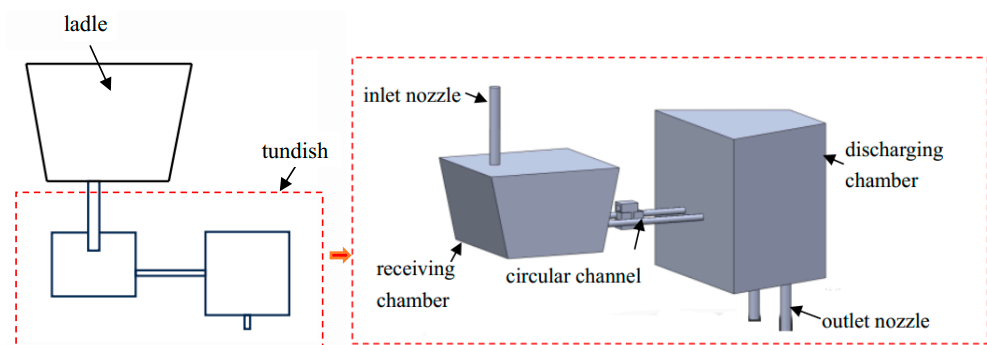


Figure 1. Schematic diagram of the channel-type induction-heating tundish.

2. Mathematical Model

A horizontal circular channel with a radius b is adopted as a numerical model and is shown in Figure 2, in which u_f is the flow velocity of the molten steel in the bulk region. An A.C. magnetic field (frequency is f and amplitude is B_0) in the z direction surrounds the wall of the circular channel. Therefore, the induced current in the molten steel flows in the θ direction and the electromagnetic force acts in the r direction. The electromagnetic force is beneficial to removing the inclusion and the induced current can heat the molten steel in the circular channel. Both the removal of the inclusions and the induction heating of molten steel are studied in this paper.

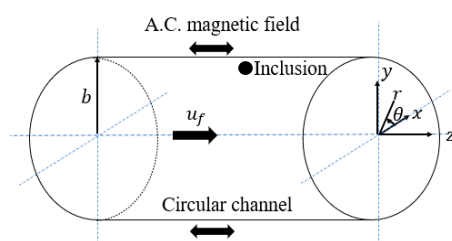


Figure 2. Analytical model in this study.

2.1. Removal of Inclusions in the Circular Channel

The flow conditions in this analysis are summarized in Table 1, in which the Reynolds number of the channel flow Re is defined as $Re = (2bu_f\rho_f)/\eta$, where ρ_f is the density of steel, η is the viscosity of steel, and the molten steel flow in the circular channel is turbulence because $Re > 19000$. Thus, the circular channel can be divided into three regions: complete

turbulence zone, transition zone, and laminar viscous bottom layer. In the complete turbulence zone, the forces acting on the inclusion are drag force, electromagnetic force, buoyancy force, and turbulence force. In the transition zone, the inclusion is also subjected to lift force, as shown in Figure 3.

Table 1. Flow conditions used in this analysis.

d_p	b	u_f	U_c	Re_p	Re
0.01 mm	0.135 m	0.1 m/s	0.02 m/s	0.2636	35,580.68
			0.07 m/s	0.9224	
	0.075 m	0.1 m/s	0.02 m/s	0.2636	19,767.05
			0.07 m/s	0.9224	
		0.2 m/s	0.05 m/s	0.6589	39,534.09
			0.1 m/s	1.3178	
0.1 mm	0.135 m	0.1 m/s	0.02 m/s	2.636	35,580.68
			0.07 m/s	9.224	
	0.075 m	0.1 m/s	0.02 m/s	2.636	19,767.05
			0.07 m/s	9.224	
		0.2 m/s	0.05 m/s	6.589	39,534.09
			0.1 m/s	13.178	
1 mm	0.135 m	0.1 m/s	0.02 m/s	26.36	35,580.68
			0.07 m/s	92.24	
	0.075 m	0.1 m/s	0.02 m/s	26.36	19,767.05
			0.07 m/s	92.24	
		0.2 m/s	0.05 m/s	65.89	39,534.09
			0.1 m/s	131.78	

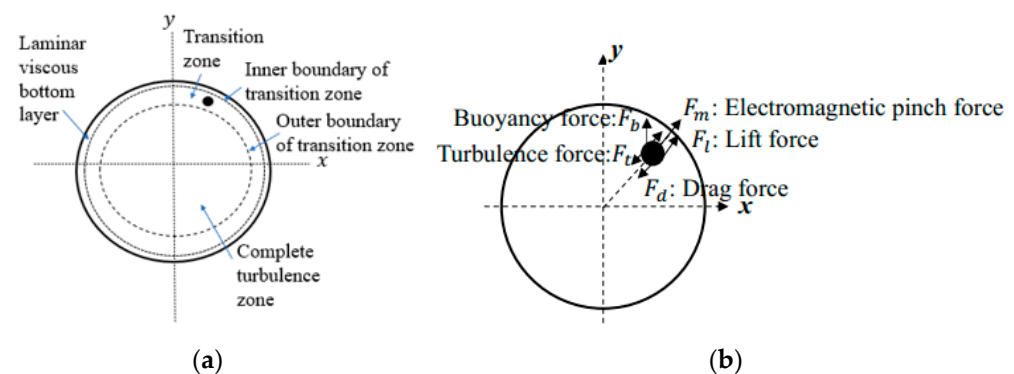


Figure 3. Three flow regions and forces acting on the inclusion in the transition zone. (a) Three regions in the channel; (b) Forces acting on inclusion in the transition zone.

Because the turbulence force F_t is due to the turbulence components of the molten steel flow, its direction is random and sometimes it inhibits the transfer of inclusions from

the bulk to the laminar viscous bottom layer. The expression of the turbulence force per unit inclusion's volume F_{tv} is shown in Equation (1):

$$F_{tv} (= \frac{F_t}{\frac{1}{6}\pi d_p^3}) = \frac{18\eta}{d_p^2} \sqrt{u_{f,r}^2} \quad (1)$$

Here, d_p is the inclusion diameter, $u'_{f,r} (= C_u u^*)$ is the fluctuation velocity of the turbulence, C_u is the coefficient and can be acquired according to the reference [25], its maximum value is 0.9, and $u^* (= 0.2Re^{-\frac{1}{8}}u_f)$ is the friction velocity.

When the inclusion moves in the transition zone of the circular channel, the lift force F_l acts on the inclusion because of the shear flow. The radial range r of the transition zone is decided by the equation $\check{r} = u^*(b-r)\rho_f/\eta$ ($5 < \check{r} < 30$), where $\check{r}$ is the non-dimensional radial position of the circular channel.

According to the analyses of Rubinow, Keller, and Saffman [26], when the particle Reynolds number $Re_p (= \frac{d_p U_C \rho_f}{\eta})$ is much less than unity, the lift force per unit inclusion's volume $F_{lv} (= \frac{F_l}{\frac{1}{6}\pi d_p^3})$ is given as Equation (2). The lift force always acts towards the higher-fluid-velocity side. This means that the lift force makes the inclusion far away from the channel wall in the transition zone because the velocity increases with the distance from the wall of the circular channel:

$$F_{lv} = \frac{9.72}{\pi d_p} U_C \sqrt{\eta \rho_f \alpha} (Re_p < 1) \quad (2)$$

Here, $U_C (= u_{f,z} - u_{p,z})$ is the velocity difference between the inclusion and the liquid parallel to the wall and $\alpha (= |\frac{du_{f,z}}{dr}|)$ is the velocity gradient in the transition zone of the circular channel, $u_{f,z} = [5.01\ln(\check{r}) - 3.05]u^*$.

Ryoichi Kurose and Satoru Komori [27] studied the effect of the shear flow and the spherical inclusion rotational speed on the lift force for the particle Reynolds number range of $1 \leq Re_p \leq 500$. The lift force per unit inclusion's volume F_{lv} they obtained is expressed as Equation (3):

$$F_{lv} = \frac{C_L \times \frac{\rho_f U_C^2 \pi d_p^2}{2}}{\frac{1}{6}\pi d_p^3} = C_L \times \rho_f U_C^2 \times \frac{3}{4d_p} \quad (1 \leq Re_p \leq 500) \quad (3)$$

Here, $C_L(Re_p, \alpha^*, \Omega^*) (= K_0 \alpha^{*0.9} + K_1 \alpha^{*1.1} + (K_2 + K_3 \alpha^* + K_4 \alpha^{*2.0} + K_5 \alpha^{*9.5}) \Omega^*)$ is the lift coefficient, $\alpha^* (= (\frac{d_p}{2U_C}) \alpha)$ is the non-dimensional shear rate of the fluid, $\Omega^* (= (\frac{d_p}{2U_C}) \Omega)$ is the non-dimensional angular velocity of the inclusion, and Ω is the angular velocity of the inclusion. In this study, the angular velocity of the inclusion was set to 1 rad/s ($\Omega = 1$ rad/s). And the $K_0 \sim K_5$ can be acquired from the reference [26], which is a function of the particle Reynolds number.

The lift coefficient C_L for a stationary sphere in a linear shear flow is a function of the non-dimensional shear rate of the fluid and the non-dimensional angular velocity of the inclusion; it rapidly decreases with increasing the particle Reynolds number and it has negative values in the range of $Re_p > 60$. This means that the lift force acts from the higher-fluid-velocity side to the lower-fluid-velocity side for the high particle Reynolds number. Thus, the negative lift force helps to push the inclusion into the viscous bottom layer in the channel.

An inclusion trajectory model in the radial direction of a circular channel was computed to study the removal of the inclusion using Equation (4):

$$\frac{du_{p,r}}{dt} = \frac{1}{\left(\rho_s + \frac{\rho_f}{2}\right)} [F_{mv} - F_{dv} + F_{bv} \pm F_{tv} - F_{lv}] \quad (4)$$

Here, $u_{p,r}$ is the velocity of the inclusion in the radial direction, t is time, $F_{dv} \left(= \frac{3C_D \rho_f}{4d_p} u_p^2 \right)$ is the drag force per unit inclusion's volume, and C_D is the viscous drag coefficient; $F_{bv} \left(= g(\rho_f - \rho_s) \right)$ is the buoyancy force per unit inclusion's volume and $F_{mv} \left(= C_1 [\cos(\varnothing_1 - \varnothing_2) + \cos(4\pi f t + \varnothing_1 + \varnothing_2)] \right)$ is the electromagnetic force per unit inclusion's volume. The detail of $C_1, \varnothing_1, \varnothing_2$ is expressed in the previous study [24]. Furthermore, the non-dimensional forms and solution of the inclusion trajectory model are also described in detail in the same reference [24].

2.2. Heating up of Molten Steel in the Circular Channel

The heating rate per unit channel length Q_g can be calculated using Equations (5) and (6) [23]:

$$Q_g = \frac{\sqrt{2}\pi b B_0^2}{\sigma \mu^2} \cdot \psi(R_w) \quad (5)$$

$$\psi(R_w) = \frac{[ber_0(\sqrt{R_w})\{ber_1(\sqrt{R_w}) + bei_1(\sqrt{R_w})\} - bei_0(\sqrt{R_w})\{ber_1(\sqrt{R_w}) - bei_1(\sqrt{R_w})\}]}{\{ber_0^2(\sqrt{R_w}) + bei_0^2(\sqrt{R_w})\}} \quad (6)$$

Here, $R_w (= 2\pi f \sigma \mu b^2)$ is the shielding parameter, σ is the conductivity of steel, and μ is the permeability of steel.

Then, according to the thermal balance equation of the molten steel in the channel under the assumption that heat loss from the wall can be neglected and the cross-sectional temperature is uniform, $Q_g = \rho_f C_p \Delta T \pi b^2 u_f$, the molten steel temperature increase per unit channel length ΔT is given as follows:

$$\Delta T = \frac{\sqrt{2}B_0^2}{\rho_f C_p \sigma \mu^2 b u_f} \psi(R_w) \quad (7)$$

Here, C_p is the heat capacity of molten steel.

The electromagnetic parameters and physical properties used in this study are summarized in Tables 2 and 3, respectively.

Table 2. A.C. magnetic field parameters in this analysis.

	R_w						$\check{B}_0$
	0.159	1.59	5.0	10.0	15.9	159.0	
B_0 (T)	0.2	0.2	0.2	0.2	0.2	0.2	7.9
f (Hz)	1.5	15	50	100	150	1500	
b (m)	0.135	0.135	0.135	0.135	0.135	0.135	
B_0 (T)	0.2	0.2	0.2	0.2	0.2	0.2	14.1
f (Hz)	5	50	156	313	500	5000	
b (m)	0.075	0.075	0.075	0.075	0.075	0.075	

Table 2. Cont.

	R_w						$\check{B}_0$
	0.159	1.59	5.0	10.0	15.9	159.0	
B_0 (T)	0.3	0.3	0.3	0.3	0.3	0.3	31.7
f (Hz)	5	50	156	313	500	5000	
b (m)	0.075	0.075	0.075	0.075	0.075	0.075	
B_0 (T)	0.4	0.4	0.4	0.4	0.4	0.4	56.3
f (Hz)	5	50	156	313	500	5000	
b (m)	0.075	0.075	0.075	0.075	0.075	0.075	

Table 3. Physical parameters for the calculation (adapted from [22,23]).

Density of Inclusion $\rho_s/(\frac{\text{kg}}{\text{m}^3})$	Density of Steel $\rho_f/(\frac{\text{kg}}{\text{m}^3})$	Viscosity of Steel $\eta/(\text{Pa}\cdot\text{s})$	Conductivity of Steel $\sigma/(\frac{\text{S}}{\text{m}})$	Heat Capacity of Molten Steel $C_p/(\frac{\text{J}}{\text{kg}\cdot\text{K}})$	Thermal Conductivity of Molten Steel $\lambda/(\frac{\text{W}}{\text{m}\cdot\text{K}})$	Permeability of Steel $\mu/(\frac{\text{H}}{\text{m}})$
3880	6958	5.28×10^{-3}	7.2×10^5	795	35	$4\pi \times 10^{-7}$

3. Discussion and Results

3.1. Forces Acting on an Inclusion in the Transition Zone Near the Channel Wall

The lift force and/or the turbulence force might act on the inclusion in the opposite direction of the electromagnetic pinch force in the transition zone. And if the electromagnetic pinch force is less than the lift force or the turbulence force, the inclusion is inhibited from entering the viscous bottom layer of the circular channel and can not be removed. Thus, the lift force and the turbulence force acting on the inclusion were computed under various conditions.

Figure 4 shows not only the maximum and minimum lift force values in the transition zone for different particle Reynolds numbers but also the maximum and minimum electromagnetic pinch force values in the transition zone for different shielding parameters. These forces are normalized by the buoyancy force in the figure. The horizontal axis indicates the particle Reynolds number or the shielding parameter; the former corresponds to the lift force while the latter corresponds to the electromagnetic pinch force.

In Figure 4a, the circular channel with the 0.135 m radius was studied and the A.C. magnetic field condition of $\check{B}_0 = 7.9$ and the molten steel's flow condition of $u_f = 0.1$ m/s were used to compute the electromagnetic pinch force and the lift force. In Figure 4b,c, the circular channel with the 0.075 m radius was studied; the non-dimensional magnetic field of 14.1 and the flow velocity of 0.1 m/s or 0.2 m/s were selected to compute the electromagnetic pinch force and the lift force.

According to Figure 4, the following are recognized under the calculation conditions in this paper regardless of the radius of the channel and the flow velocity of the molten steel. The lift force acting on the inclusion is large in the small particle Reynolds number range. Especially when the particle Reynolds number is less than 1, the maximum lift force acting on the inclusion is greater than the electromagnetic pinch force in Figure 4a and the maximum lift force acting on the inclusion is greater than the electromagnetic pinch force, except the shielding parameter condition of 159 in Figure 4b,c. With the increase in the particle Reynolds number, the lift force acting on the inclusion decreases rapidly, even reaching a negative value. The lift force is beneficial to removing the inclusion if it is negative because its direction is the same as the electromagnetic pinch force. When the particle Reynolds number is greater than 1, the maximum lift force is smaller than the electromagnetic pinch force in the shielding parameter range of greater than 5.0. That is, the effect of the lift force on the trajectory of inclusion in the circular channel can be

neglected. According to Table 1, the particle Reynolds number is always larger than 1 when the diameter of the inclusion is not less than 0.1 mm.

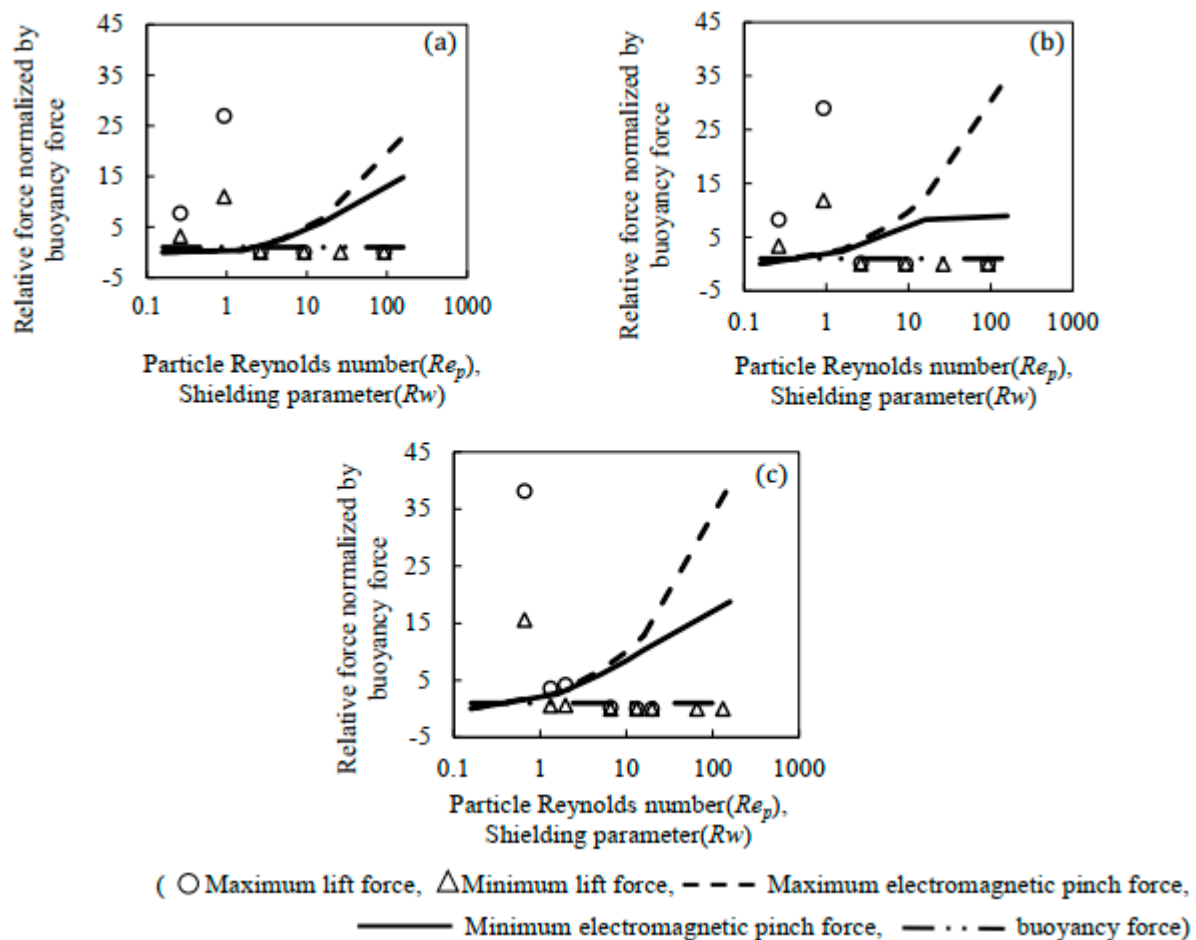


Figure 4. Comparison of electromagnetic pinch force and lift force on the inclusion under different conditions (a) $b = 0.135$ m, $\check{B}_0 = 7.9$, $u_f = 0.1$ m/s; (b) $b = 0.075$ m, $\check{B}_0 = 14.1$, $u_f = 0.1$ m/s; (c) $b = 0.075$ m, $\check{B}_0 = 14.1$, $u_f = 0.2$ m/s.

Figure 5 compares the turbulence force with the electromagnetic pinch force in which three inclusion diameters of $d_p = 0.01$ mm, 0.1 mm, and 1 mm and two shielding parameters of $R_w = 1.59$ and 5 were adopted in the calculation. The combination of the non-dimensional magnetic field intensity, the channel diameter, and the flow velocity of the molten steel was the same as that of Figure 4.

The horizontal axis is the non-dimensional radial position in the channel while the vertical axis is the relative force intensity normalized by the buoyancy force. It can be seen that the smaller the diameter of the inclusion, the greater the turbulence force and the greater the flow velocity of the molten steel, the greater the turbulence force. The electromagnetic pinch force in the case of $R_w = 5$ is larger than that in the case of $R_w = 1.59$. In the transition zone, the electromagnetic pinch force for the 0.1 mm diameter inclusion is larger than the turbulence force under every calculation condition if $R_w = 5$. When $R_w = 1.59$, the former is larger than the latter only under the calculation condition of the flow velocity being reduced to 0.1 m/s in Figure 5b.

The trajectory of the inclusion under the different diameters of $d_p = 0.01$ mm and 0.1 mm with the initial position of the channel center was calculated with and without the turbulence force. The A.C. magnetic field parameters of $\check{B}_0 = 14.1$ and $R_w = 1.59$, the molten steel's flow velocity of $u_f = 0.2$ m/s, and the channel radius of $b = 0.075$ m were used to compute the electromagnetic force, turbulence force, and the trajectory of the inclu-

sion. Figure 6 shows the results. The horizontal axis is the non-dimensional removal time $\tilde{t} \left(= \frac{t}{t_s} = \frac{d_p^2 g (\rho_f - \rho_s)}{18 \eta b} t \right)$, which is the normalized time by the inclusion removal time t_s when the initial inclusion position is the channel center under the non-magnetic field condition. For the inclusion with a diameter of 0.01 mm, the trajectory is not smooth because the turbulence force, which acts in a random direction, is far greater than the electromagnetic pinch force in the circular channel, as shown in Figure 5c. For the inclusion with a 0.1 mm diameter, the turbulence has little effect on its trajectory since the turbulence force, the buoyancy force, and the electromagnetic pinch force are almost the same order of magnitude.

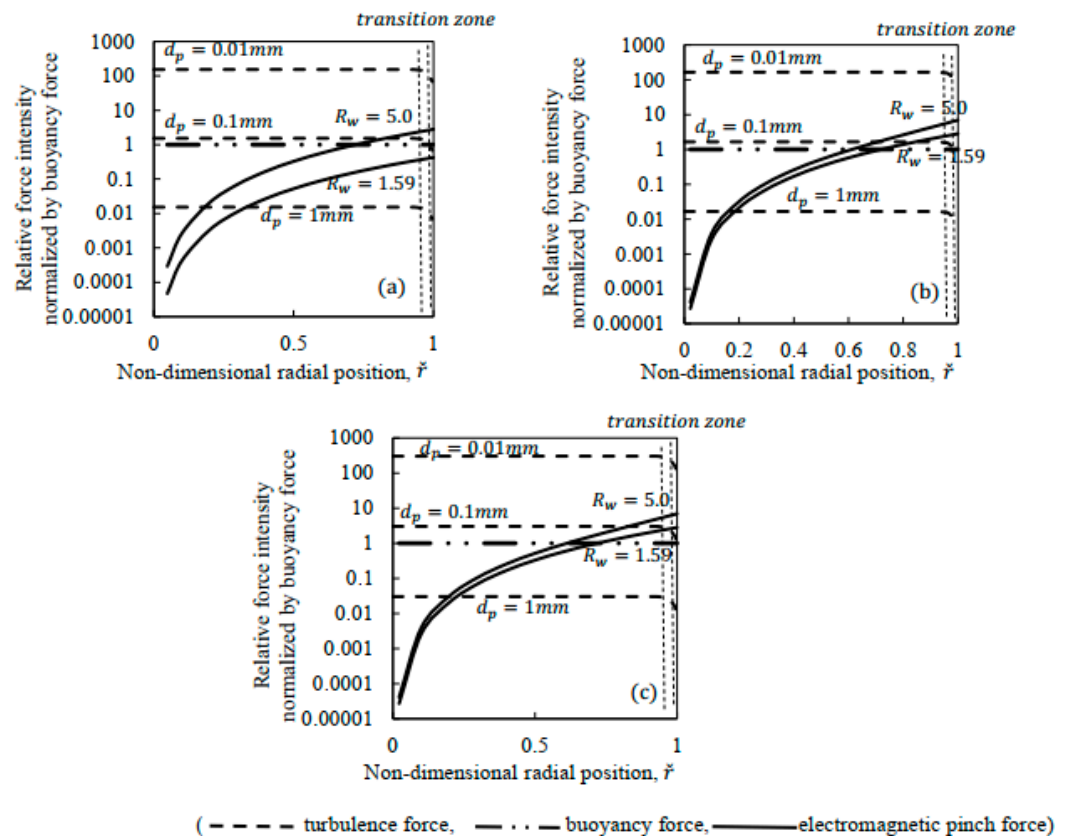


Figure 5. Comparison of electromagnetic pinch force and turbulence force on the inclusions under different conditions (a) $b = 0.135$ m, $\tilde{B}_0 = 7.9$, $u_f = 0.1$ m/s; (b) $b = 0.075$ m, $\tilde{B}_0 = 14.1$, $u_f = 0.1$ m/s; (c) $b = 0.075$ m, $\tilde{B}_0 = 14.1$, $u_f = 0.2$ m/s.

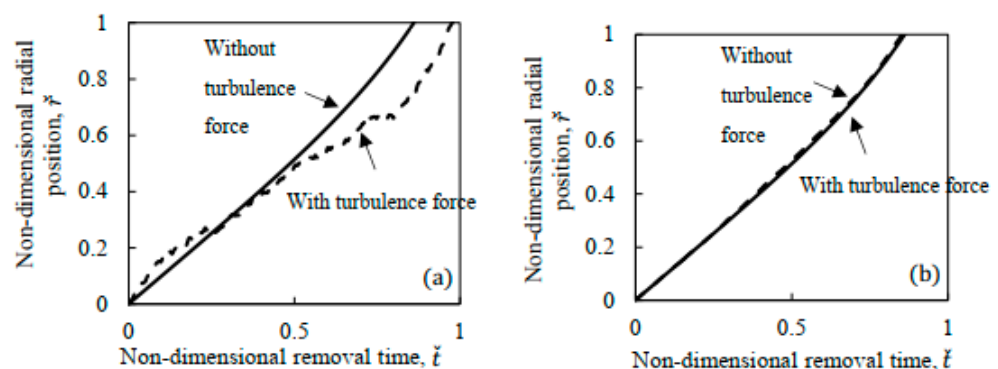


Figure 6. Effect of the turbulence force on the trajectory of the inclusion under the condition of $\tilde{B}_0 = 14.1$, $Rw = 1.59$, $u_f = 0.2$ m/s; (a) $d_p = 0.01$ mm and (b) $d_p = 0.1$ mm.

According to the above analytical results, the effect of the lift force and the turbulence force can be neglected when the diameter of the inclusions is not less than 0.1 mm under the calculation conditions in this paper, especially when the shielding parameter is greater than or equal to 5.0.

3.2. Removal of the Inclusions in the Circular Channel

In this section, the removal of the inclusion with a diameter greater than or equal to 0.1 mm is studied, in which the lift force and turbulence force acting on the inclusion are not considered.

According to the previous research [24], the dead zone for the inclusion's removal is defined where the removal time of the inclusion with the A.C. magnetic field is longer than that without the A.C. magnetic field. One of the dead zone regions obtained in the previous study [24] is shown in Figure 7, in which the lift and turbulence forces acting on the inclusion are not included. When removal of the inclusions in the dead zone is not considered, the maximum removal time is decided by the initial inclusion position of the lower boundary point of the dead zone. It is equal to the floating up time of the inclusion by the density difference between the molten steel and the inclusion. The removal time of the inclusion in the dead zone is longer than the maximum removal time under the magnetic field imposition condition. If the passing time of the molten steel in the channel is longer than the maximum removal time, the inclusions whose initial positions are out of the dead zone can be totally trapped by the channel wall before they reach the outlet of the channel.

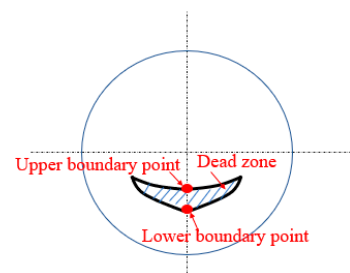


Figure 7. Dead zone of inclusion in the circular channel under the A.C. magnetic field.

The residual rate of the inclusions in the circular channel was computed as the ratio of the area of the dead zone to the cross-sectional area of the circular channel in which the dead zone under different A.C. magnetic field conditions was acquired in [24]. The effect of the A.C. magnetic field on the residual rate of the inclusion in the circular channel is shown in Figure 8. The larger the non-dimensional magnetic field intensity, the smaller the residual rate of the inclusions. The residual rate of the inclusions in the circular channel is less than 1%, even when the shielding parameter is 1.59.

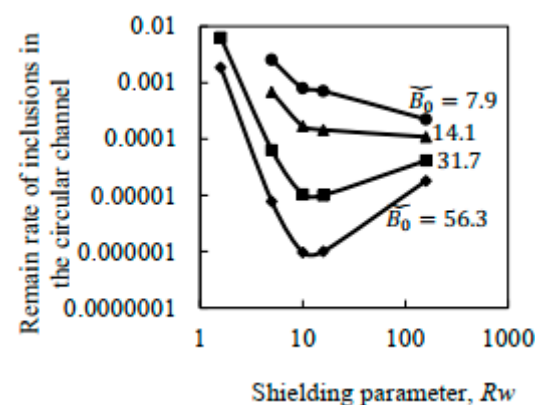


Figure 8. Residual rate of inclusions in the circular channel under different A.C. magnetic field parameters.

The non-dimensional maximum removal time of the inclusion $t_{max}^{\check{}}$ under different A.C. magnetic field conditions was computed and the results are shown in Figure 9. Because the initial position of the inclusion is the lower boundary of the dead zone for the maximum removal time, the non-dimensional maximum removal time is always larger than 1. However, it is less than 2. The non-dimensional maximum removal time of inclusions also decreases with the increase in the non-dimensional magnetic field intensity. And it is the smallest when the shielding parameter is 10~15.9.

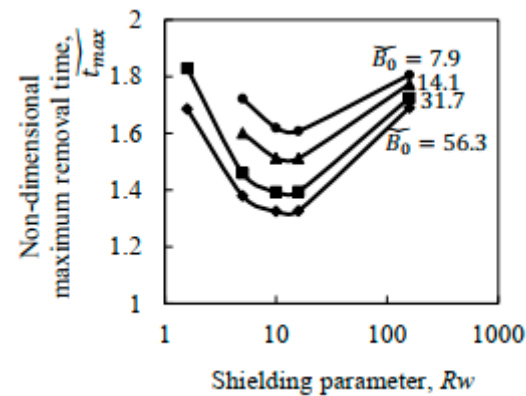


Figure 9. Non-dimensional maximum removal time of inclusions under different A.C. magnetic field parameters.

The maximum removal time of the inclusion under different A.C. magnetic field parameters is shown in Figure 10. The relationship between the maximum removal time t_{max} in Figure 10 and the non-dimensional maximum removal time $t_{max}^{\check{}}$ in Figure 9 is $t_{max} = t_{max}^{\check{}} \times \frac{18\eta b}{d_p^2 g(\rho_f - \rho_s)}$; the maximum removal time is not only related with the inclusion's diameter d_p but is also related with the radius of the circular channel b . Figure 10a indicates the maximum removal time of the inclusion with the diameter of 0.1 mm while Figure 10b indicates that with the diameter of 0.2 mm. It can be seen that the larger the diameter of the inclusion, the smaller the maximum removal time. The radius of the circular channel is 0.135 m when the non-dimensional magnetic field is 7.9 and that in other cases is 0.075 m, according to Table 2. Thus, in Figure 10, the maximum removal time of the inclusion with the condition of $B_0 = 7.9$ is much larger than that in other cases.

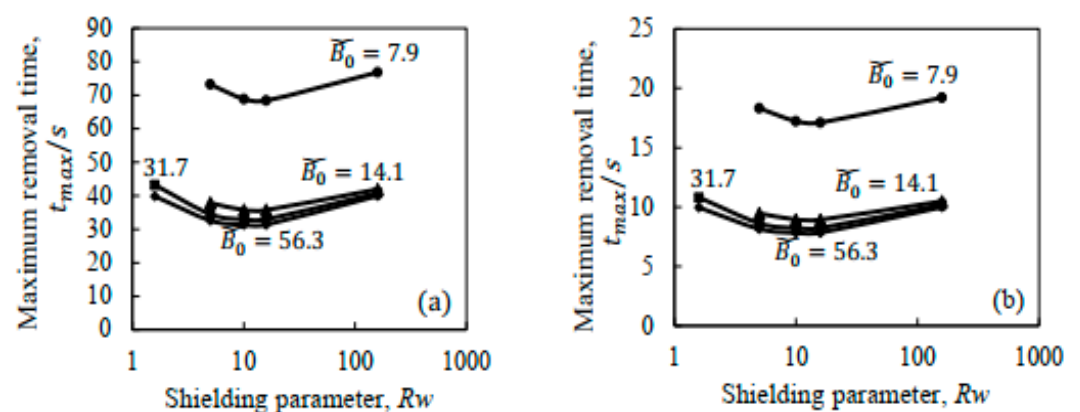


Figure 10. Maximum removal time of the inclusion under the different A.C. magnetic field parameters (a) $d_p = 0.1$ mm and (b) $d_p = 0.2$ mm.

To choose the appropriate channel length to remove the inclusions, the minimum length of the circular channel was computed by $L_{min} = u_f \times t_{max}$. When the length of the circular channel is larger than the minimum length, the inclusions in the circular

channel can be completely removed, except the inclusions in the dead zone. According to Figure 11, the optimal shielding parameter to minimize the channel length under the constant non-dimensional magnetic field condition is 10.0~15.9.

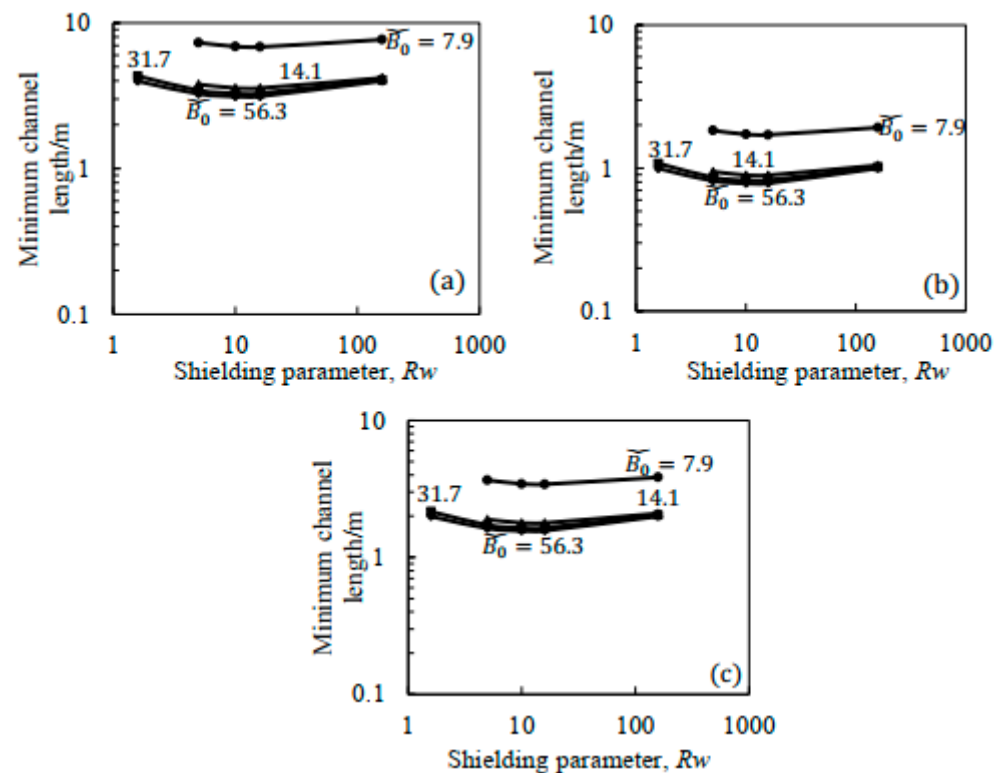


Figure 11. Minimum channel length to remove inclusions, except in the dead zone. (a) $d_p = 0.1$ mm, $u_f = 0.1$ m/s; (b) $d_p = 0.2$ mm, $u_f = 0.1$ m/s; (c) $d_p = 0.2$ mm, $u_f = 0.2$ m/s.

When the flow velocity of the molten steel in a circular channel increases, the minimum channel length also increases. The minimum channel length for the 0.2 m/s flow velocity of the molten steel is twice that of the 0.1 m/s flow velocity. Under the condition that $\tilde{B}_0 = 31.7$ and $R_w = 10.0$, the minimum channel length is about 1 m to remove the inclusion with a 0.2 mm diameter when the flow velocity of the molten steel is 0.1 m/s. That is about 2 m for the inclusion with the 0.2 mm diameter when the flow velocity of the molten steel is 0.2 m/s and about 4 m for the inclusion with a 0.1 mm diameter when the flow velocity of the molten steel is 0.1 m/s. Thus, the slow velocity of the molten steel flow is desirable.

From the industrial viewpoint, a channel length of less than a few meters is desirable. For example, the channel length in Reference [28] is 1.04 m. Thus, in this paper, the circular channel length was assumed to be 1 m and the effect of the A.C. magnetic field on the removal of the inclusion with the diameter of 0.1 mm when the flow velocity of the molten steel is 0.1 m/s was studied. The maximum time of the inclusion movement in the circular channel is equal to the channel length divided by the flow velocity of the molten steel in the circular channel. It is 10 s here. Figure 12 shows the initial position for the 0.1 mm inclusion, which can move to the channel wall in 10 s under different shielding parameters when the non-dimensional magnetic field intensity is 31.7. The cross-section of the circular channel is segmented by the initial position, in the central region; the removal time of the inclusion is longer than 10 s while it is less than 10 s in the surrounding areas. That is, the inclusion located in the latter region can be trapped by the channel wall before it is out of the exit of the circular channel; it is called the “removal region”. According to Figure 12, the removal regions when the shielding parameters are 10.0 and 15.9 are almost coincident and their removal regions are the largest; when the shielding parameter is 1.59, the removal region is the smallest.

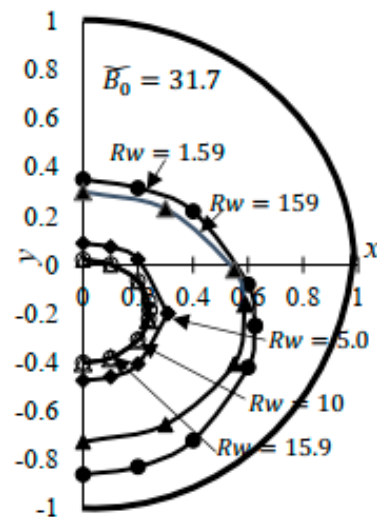


Figure 12. Removal region of the 0.1 mm inclusion for the 1 m length channel when flow velocity is 0.1 m/s.

By comparing the area of the removal region with the cross-sectional area of the channel, the removal rate of the inclusion with the 0.1 mm diameter in the 1 m length channel was obtained and the result is shown in Figure 13. When the shielding parameter is 10.0 or 15.9, the removal rate of the inclusion in the channel can reach more than 95% (0.95) while the removal rate of inclusions in the channel is only about 60% (0.60) when the shielding parameter is 1.59. Thus, the A.C. magnetic field frequency is an important parameter for removing the inclusion and a shielding parameter of 10.0~15.9 is the best choice.

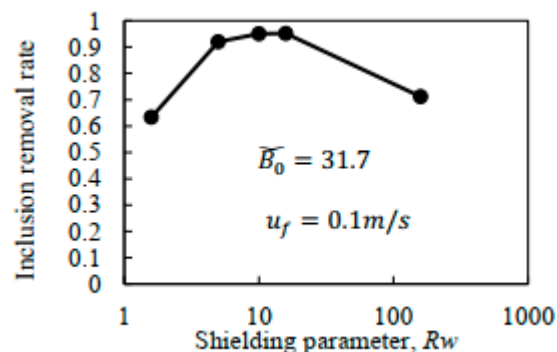


Figure 13. Removal rate of the 0.1 mm inclusion for the 1 m length channel when flow velocity is 0.1 m/s.

3.3. Heating up of the Molten Steel in the Circular Channel

According to Equation (7), the molten steel temperature increase ΔT per unit channel length can be acquired. It is not only related to the A.C. magnetic field parameter but also to the flow velocity of the molten steel in the circular channel. Figure 14 shows the required channel length for the molten steel heating of 10 K when the flow velocity of the molten steel is 0.1 m/s or 0.2 m/s. The required channel length l was obtained by $l = \frac{10}{\Delta T}$.

For heating up the molten steel in the circular channel, a large shielding parameter, a large non-dimensional magnetic field intensity, and slow velocity of the molten steel flow are suitable for reducing the channel length. For the circular channel with the length of 1 m and the radius of 0.135 m ($\check{B}_0 = 7.9$) and with the molten steel flow velocity of 0.1 m/s, the temperature of molten steel can be increased by 10 K under the A.C. magnetic field condition of $Rw = 10.0$. If the flow velocity of the molten steel in the same channel is increased to 0.2 m/s, the shielding parameter should be greater than 15.9. When the flow velocity of the molten steel is 0.2 m/s and the radius of the circular channel is chosen

as 0.075 m ($\check{B}_0 = 14.1, 31.7, 56.3$), the non-dimensional magnetic field intensity of 14.1 is enough for the 10 K heating up of molten steel under the condition of $Rw = 10.0$.

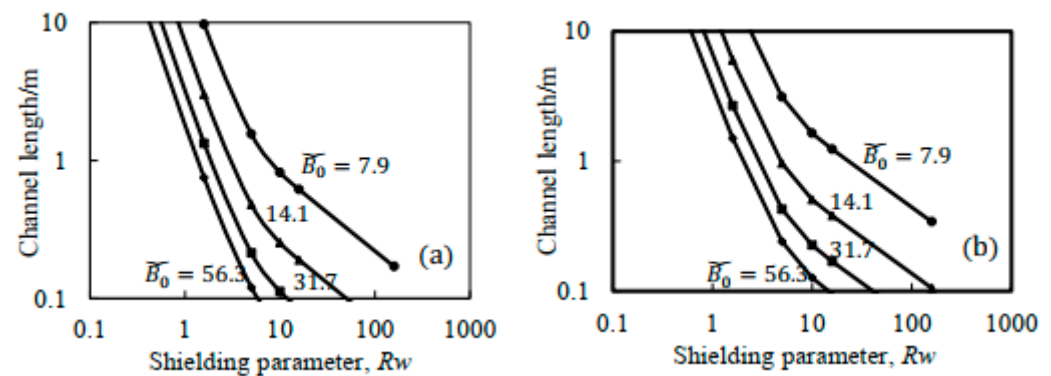


Figure 14. Channel length for the 10 K heating up of molten steel. (a) $u_f = 0.1$ m/s, (b) $u_f = 0.2$ m/s.

In summary, a slow velocity of the molten steel in the channel is desirable for the inclusion removal and the heating up of the molten steel, simultaneously, to shorten the channel length. Relating to the shielding parameter, the inclusion removal efficiency is very good when it is around 10.0 and 15.9 while a large value is suitable for the heating up of the molten steel. If the flow velocity of the molten steel in the circular channel is 0.1 m/s, the A.C. magnetic field's shielding parameter of 15.9 is the optimal parameter to simultaneously remove the inclusions and heat up the molten steel in the circular channel with the length of 1 m and the radius of 0.075 m; under the condition of $\check{B}_0 = 31.7$, the removal rate of the 0.1 mm inclusion in the channel can reach more than 95% and the temperature of molten steel can be heated by over 10 K.

4. Conclusions

In this paper, to achieve the removal of the inclusion and the heating up of the molten steel, simultaneously, by imposing the A.C. magnetic field around the circular channel, the optimal condition of the channel size and the A.C. magnetic field parameters have been numerically studied. The radii of the studied channel are 0.135 m and 0.075 m and the flow velocities of the molten steel in the channel are 0.1 m/s and 0.2 m/s. The following are the conclusions of this research:

- (1) When the diameter of the inclusions is not less than 0.1 mm, the effect of the lift force and the turbulence force can be neglected under the calculation conditions in this paper, especially when the shielding parameter of the A.C. magnetic field is not less than 5.0;
- (2) The minimal channel length to remove the inclusions was calculated without the lift force and the turbulence force. When the shielding parameter of the A.C. magnetic field is 10.0~15.9, the minimal channel length is the shortest. Furthermore, the slow velocity of the molten steel is desirable. Under the condition of the A.C. magnetic field parameters $\check{B}_0 = 31.7$ and $Rw = 10.0$, the minimum channel length is about 1 m to remove the inclusion with the diameter of 0.2 mm and it is about 4 m for the inclusion diameter of 0.1 mm when the velocity of the molten steel is 0.1 m/s. The minimum channel length is about 2 m to remove the inclusion with the diameter of 0.2 mm if the flow velocity of the molten steel is 0.2 m/s;
- (3) For industrial applications, the removal rate of the 0.1 mm inclusions in a 1 m length channel was calculated. The A.C. magnetic field frequency is an important parameter for removing the inclusions and the shielding parameter of 10.0~15.9 is optimal. When the shielding parameter is 10.0 or 15.9, the removal rate of the inclusions in the channel can reach more than 95% while the removal rate of inclusions in the channel is only about 60% if the shielding parameter is 1.59;

- (4) For heating up the molten steel in the circular channel, a large shielding parameter, a large non-dimensional magnetic field intensity, and a slow velocity of the molten steel flow are suitable for reducing the channel length. If the length of the circular channel is 1 m and the flow velocity of the molten steel is 0.1 m/s, it is possible to increase the molten steel by 10 K under the A.C. magnetic field condition of $Rw = 10.0$ and $\check{B}_0 = 7.9$;
- (5) From the industrial viewpoint, when the flow velocity of the molten steel in the circular channel with the length of 1 m and the radius of 0.075 m is 0.1 m/s, the A.C. magnetic field's shielding parameter of 15.9 is the optimal parameter to simultaneously remove the inclusions and heat up the molten steel in the circular channel. And when the non-dimensional magnetic field intensity of the A.C. magnetic field is 31.7, the removal rate of the 0.1 mm inclusion in the channel can reach more than 95% and the temperature of molten steel can be heated by over 10 K.

According to Reference [29], the experiment about the inclusion removal and induction heating of the molten steel in the channel-type induction-heating tundish was conducted in plant; the results show that when the frequency of the A.C. magnetic field is 50 Hz, the heating power of the A.C. magnetic field is 400 kw, and the diameter of the inclusion is 50 μm , the removal rate of the inclusion in the circular channel is 52.95% and when the heating power increases from 400 kw to 500 kw, the removal rate of inclusions increases accordingly; however, the increase is not significant. When the heating power is 400 kw, the temperature increases by 10 K in the tundish for 28.1 min. It can be seen that the calculation results in this paper are basically consistent with the experimental results in the plant; however, the experimental conditions in the plant are not entirely clear, such as the size of the circular channel. It is necessary to establish our own experimental model to verify the calculation results of the paper in the future.

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Conflicts of Interest: Guangye Xu was employed by the company Japan Steel Works. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

b	radius of circular channel (m)
B_0	magnetic field intensity (T)
$\check{B}_0$	non-dimensional magnetic field intensity (-)
ber_0, bei_0, ber_1 , and bei_1	Kelvin functions
C_u	coefficient (-)
C_L	lift coefficient (-)
C_D	drag coefficient (-)
C_p	heat capacity of molten steel (J/Kg.K)
d_p	inclusion diameter (m)
F_l	lift force acting on the inclusion (N)
F_{lv}	lift force per unit inclusion's volume acting on the inclusion (N/m ³)
F_t	turbulence force acting on the inclusion (N)
F_{tv}	turbulence force per unit inclusion's volume acting on the inclusion (N/m ³)
F_{dv}	drag force per unit inclusion's volume acting on the inclusion (N/m ³)
F_{bv}	buoyancy force per unit inclusion's volume acting on the inclusion (N/m ³)
F_{mv}	electromagnetic force per unit inclusion's volume acting on the inclusion (N/m ³)

f	frequency of the A.C. magnetic field (Hz)
l	length of circular channel (m)
Q_g	heating rate per unit channel length (J/m.s)
r, θ	radial direction and circumferential direction in the cylindrical coordinate system (-)
$\check{r}$	non-dimensional radial direction of the inclusions (-)
R_w	shielding parameter (-)
Re_p	particle Reynolds number (-)
Re	Reynolds number of the molten steel (-)
t	inclusion removal time (s)
$\check{t}$	non-dimensional removal time of the inclusion (-)
u_p	inclusion velocity in the molten steel (m/s)
u_f	flow velocity of the molten steel in the bulk region (m/s)
$u'_{f,r}$	fluctuation velocity of turbulence in the radial direction (m/s)
$u_{f,z}$	flow velocity of the molten steel along the axis of the circular channel (m/s)
$u_{p,r}$	the velocity of the inclusion in the radial direction (m/s)
$u_{p,z}$	the velocity of the inclusion along the axis of the circular channel (m/s)
u^*	friction velocity (m/s)
U_C	velocity difference between the inclusion and the molten steel parallel to the wall (m/s)
x, y	x direction and y direction in Cartesian coordinate system (-)
z	axial direction in Cylindrical and Cartesian coordinate system (-)
α	velocity gradient in the boundary layer of flow velocity in circular channel
α^*	non-dimensional shear rate of the fluid
η	molten steel viscosity (Pa.s)
ρ_f	molten steel density (kg/m ³)
ρ_s	inclusion density (kg/m ³)
μ	molten steel magnetic permeability (H/m)
σ	molten steel electrical conductivity (S/m)
λ	thermal conductivity of molten steel (W/(m.K))
Ω^*	non-dimensional angular velocity (-)
ΔT	molten steel temperature increase per unit channel length (K/m)

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