Kinetic Modeling on Nozzle Clogging During Steel Billet Continuous Casting

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In the current paper, a kinetic model was developed to study the entrapment of inclusions in the molten steel flowing through a Submerged Entry Nozzle (SEN) during billet continuous casting process. The trajectory of inclusions was calculated by considering the drag force, lift force and gravitational force. The entrapment locations of inclusions on SEN wall were predicted. The effects of nozzle diameter, casting speed, billet dimension, and inclusion diameter on SEN clogging were quantitatively discussed. The results indicate the inclusions with diameter larger than 100 μm are not able to be entrapped by the nozzle wall; and the entrapment probability will increase quickly with decreasing size of inclusions. The distribution of the entrapped inclusions along the nozzle length is non-uniform and the volume fraction of inclusions in the clogging materials should be considered in order to more precisely predict the accumulated weight of molten steel that can be poured before the nozzle is fully blocked by clogging. Under the conditions assumed: 150 mm $\times$ 150 mm billet, 2.0 m/min casting speed, approximately 25°C superheat, 1 m length of the SEN (Al_2O_3 -C materials), 20 μm inclusions diameter in a single size, 30 ppm T.O and 40 mm nozzle diameters, the prediction shows that $\sim$ 351 ton steel can be poured for the current billet continuous caster.

KEY WORDS: nozzle clogging; steel continuous casting; inclusions; fluid flow; kinetic model.

1. Introduction

The Submerged Entry Nozzle (SEN) is used between the tundish and the mold during steel continuous casting process. The function of SEN is to prevent the molten steel from being oxidated, decrease the emulsification of the top surface of the mold and lower the air absorption during casting. SEN clogging has been a long term problem for steel continuous casting process.^{1–30)} Causes and prevention of SEN clogging were extensively reviewed by Kemeny,²⁰⁾ Thomas,²³⁾ Cramb,¹¹⁾ and the current author Zhang.^{2,31)} Inclusion accretions, especially alumina inclusions for Al-killed steel, CaS inclusions for Ca-treatment steel and TiN inclusions for Ti-killed steels, are the main reason for the clogging.¹⁾ Inclusions moving in the molten steel through the nozzle may be entrapped once they walk close to the lining refractory. It was reported that clogging occurs preferentially at the locations where the stagnation and separation of the flow occur within the SEN.³²⁾ Thus, investigating the fluid flow and the motion of inclusions in the nozzle is important to understand the fundamentals of the SEN clogging. The kinetic study of SEN clogging has been reported by Mukai *et al.*³³⁾ and Zhang *et al.*^{2,4)} Based on the previous studies, the kinetic model for the SEN clogging was devel-

oped in the current paper to investigate 1) trajectory of the inclusions in the flowing molten steel in the nozzle; 2) entrapment of inclusions to the nozzle wall under different conditions; and 3) prediction of the accumulated weight of molten steel that can be poured before the nozzle is blocked by the clogging materials.

2. Model Formulation

The model developed here is based on the study by Mukai *et al.*,³³⁾ by which the classical empirical fluid flow velocity distribution in a pipe including that in the boundary layer was used and then the trajectory of inclusions were calculated by considering different forces acting on them in the fluid. Compared with the model developed by Mukai *et al.*, the current study has the following improvements:

- The thickness of the transition layer and laminar sub-layer are not fixed but varies with the fluid flow velocity in the pipe, while the fluid flow velocity depends on the casting speed and the dimension of the continuous casting billet. The roughness of the wall is considered.
- The injection of inclusions is not just from 300 μm away from the wall that was assumed by Mukai's model, but

from the entire cross section of the pipe.

- The suitable time step for solving the trajectory equation of inclusions is discussed in detail.
- The effects of inclusion size, casting speed, nozzle diameter, billet dimension, and the total oxygen in the steel on the entrapment of inclusions and the entrapment criterion are discussed.
- The accumulated weight of molten steel that can be poured before the SEN is blocked by the clogging materials is predicted, the fraction of inclusion in the clogging materials and the non-uniform distribution of inclusions entrapped along the nozzle height are considered and discussed in the current paper.

For a billet continuous casting process, a bottom open SEN is usually used, just like a pipe. Though the inner diameter of the SEN at the top is a little different from the bottom, the turbulent pipe flow condition in the SEN is assumed. There are three zones of the fluid flow in the pipe: turbulent bulk zone, transition layer and laminar sub-layer, as shown in **Fig. 1**. The distribution of the velocity and the turbulent diffusion coefficient can be represented by Eqs. (1)–(8)³⁴⁾:

In the turbulent bulk zone ($y^+ > 30$)

$$\bar{u}_f^+ = \frac{\bar{u}_f(r_p, t)}{u^*} = 2.5 \ln(y^+) + 5.5 \quad (1)$$

$$D_t = 19.04 \mu_f / \rho_f \quad (2)$$

In the transition layer ($30 > y^+ > 5$)

$$\bar{u}_f^+ = \frac{\bar{u}_f(r_p, t)}{u^*} = 5.0 \ln(y^+) + 3.05 \quad (3)$$

$$D_t = (y^+ / 5 - 0.959) \mu_f / \rho_f \quad (4)$$

In the laminar sub-layer ($y^+ < 5$)

$$\bar{u}_f^+ = \frac{\bar{u}_f(r_p, t)}{u^*} = y^+ \quad (5)$$

$$D_t = (y^+ / 14.5)^3 \mu_f / \rho_f \quad (6)$$

Fig. 1. Schematic of the fluid flow and motion of inclusions in a pipe nozzle.

where u_f^+ is the dimensionless velocity of the fluid flow; D_t is the turbulent diffusion coefficient with different values in the turbulent bulk and boundary layers; $\bar{u}_f(r_p, t)$ is the mean fluid phase velocity in m/s; r_p is the distance of inclusion particles from nozzle center in radial direction (r direction) in meter; t is the time in second; u^* is the friction velocity in m/s; μ_f is the kinetic viscosity coefficient in Pa·s; ρ_f is the density of the molten steel in kg/m³; y^+ is the dimensionless distance of the fluid flow in the pipe represented by:

$$y^+ = u^* \rho_f (R - r_p) / \mu_f \quad (7)$$

where R is the radius of the nozzle in meter; u^* is the friction velocity in m/s, which can be calculated by

$$u^* = \sqrt{\frac{\tau_0}{\rho_f}} = u_{f, \text{bulk}} \sqrt{\frac{f}{8}} \quad (8)$$

where τ_0 is the shearing force at wall (N/m²); $u_{f, \text{bulk}}$ is the mean velocity of molten steel in the nozzle in m/s; f is the dimensionless friction factor derived by Darcy, it should be mentioned here this friction factor is four times of that by Fanning.³⁵⁾ The value of f is a function of Reynolds number of the flow in the pipe ($Re = D \cdot u_{\text{bulk}} \cdot \rho_f / \mu_f$) and wall roughness, as shown in **Fig. 2**.³⁵⁾ In the current model, the effect of roughness can be included. For the current stage, it is assumed the roughness to be zero. Qualitatively, more inclusions would be entrapped onto the nozzle lining wall with larger roughness. The quantitative effect of roughness on the entrapment of inclusions to the nozzle lining wall will be performed in depth in the future.

Inclusions enter the SEN together with the molten steel from the tundish. Due to the forces acting on the inclusions, they move not only along the longitudinal direction but also the transverse direction of the pipe, and may move from the turbulent bulk zone to the transition layer and the laminar sub-layer, and may be captured by the lining refractory wall.

The forces acting on a particle moving in a pipe include gravitational force, drag force, lift force, virtual mass force and pressure gradient force.³⁶⁾ For the current molten steel-inclusions-SEN system, the current study has revealed that the effect of the virtual mass force and pressure gradient force is less than 0.5%, thus these two forces are ignored. The location of inclusions can be calculated by inter-

Fig. 2. Relationship between friction factor and Reynolds number for the flow in the pipe (Re) and wall roughness (e/D).

grating the velocity of the inclusions over time by the equations below.

Motion equation of inclusions in x direction (longitudinal direction of the pipe):

$$\frac{dx_p}{dt} = u_p \quad \text{.....(9)}$$

$$\begin{aligned} \frac{du_p}{dt} = & \frac{3}{4} \frac{1}{d_p} \frac{\rho_f}{\rho_p} \frac{24}{\text{Re}_p} (u_f - u_p)^2 \frac{u_f - u_p}{|u_f - u_p|} \\ & - \frac{(\rho_f - \rho_p)}{\rho_p} g \quad \text{.....(10)} \end{aligned}$$

$$\text{Re} = \rho_f d_p |u_f - u_p| / \mu_f \quad \text{.....(11)}$$

Motion equation of inclusions in r direction (radial direction of the pipe):

$$\frac{dr_p}{dt} = v_p \quad \text{.....(12)}$$

$$\begin{aligned} \frac{dv_p}{dt} = & \frac{3}{4} \frac{1}{d_p} \frac{\rho_f}{\rho_p} \frac{24}{\text{Re}} (v_p - v_f)^2 \frac{v_f - v_p}{|v_f - v_p|} + \frac{F_L}{\pi d_p^3 \rho_p / 6} \\ & \text{.....(13)} \end{aligned}$$

$$\text{Re}_p = \rho_f d_p |v_f - v_p| / \mu_f \quad \text{.....(14)}$$

where x_p and r_p is the distance of inclusion particles in x and r direction in meter; u_p and v_p are the velocity of inclusions in x and r direction in m/s; t is the time in s; d_p is the diameter of the particles in meter; u_f and v_f are the velocity of molten steel in x and r direction in m/s; ρ_p is the density of inclusions in kg/m³; g is the gravitational acceleration; F_L is the lift force acting on the inclusion.

The Saffman lift force is expressed by

$$F_L = 1.62 \mu_f d_p (u_f - u_p) \sqrt{\text{Re}_G} \quad \text{.....(15)}$$

$$\text{Re}_G = \frac{\rho_f d_p^2}{\mu_f} \cdot \left| \frac{\partial u_f}{\partial r_p} \right| \quad \text{.....(16)}$$

The initial velocity of the inclusion at the entrance of the nozzle is expressed by

$$u_p(r_p, t=0) = u_f(r_p, t=0) - \frac{d_p^2 g (\rho_f - \rho_p)}{18 \mu_f} \quad \text{.....(17)}$$

$$v_p(r_p, t=0) = v'_p \quad \text{.....(18)}$$

The instantaneous velocity of the fluid flow is expressed by

$$u_f(r_p, t) = \bar{u}_f(r_p, t) + u'_f \quad \text{.....(19)}$$

$$v_f(r_p, t) = v'_f \quad \text{.....(20)}$$

where u'_f and v'_f is the turbulent velocity fluctuation in x and r direction in m/s, which is expressed by

$$u'_f = v'_f = v'_p = 1.49 \xi \frac{D_t}{0.4(R - r_p)} \quad \text{.....(21)}$$

where ξ is a Gaussian-distributed random number; D_t is the turbulent diffusion coefficient with different values in the turbulent bulk and boundary layers, as shown in Eqs. (2), (4) and (6).¹⁷⁾

In order to more precisely predict the entrapment of inclusions from entire cross section of the pipe to nozzle wall, two thousand inclusions are injected into the nozzle along the radius of the nozzle entrance. Then the trajectories of inclusions were calculated, and the entrapment locations of inclusions are predicted.

3. Results and Discussion

3.1. Discussion of the Entrapment Criterion

A simple entrapment criterion is used here: 1) for the case that the thickness of the laminar sub-layer is larger than the inclusion radius, the inclusion is entrapped if its center enters the laminar sub-layer; 2) for the case that the thickness of the laminar sub-layer is less than the inclusion radius, the inclusion is entrapped if the distance between the wall and the inclusion center equals its radius. The entrapment criterion can be expressed as below:

$$(R - r_p) \leq \begin{cases} L \\ \frac{d_p}{2} + e \end{cases} \quad \text{.....(22)}$$

where R is radius of the nozzle in meter; r_p is distance from the inclusion center to nozzle center in meter; L is the thickness of laminar layer in meter; e is the roughness of the nozzle in meter.

It has been observed that there are frozen steel net form structures generated on the surface of the nozzle lining refractory, as shown in **Fig. 3**. Lots of Al₂O₃ inclusions (dendrites and clusters) entrapped inside the hole of the net form structures. The holes of the net form are in dimension of approximately 1mm, thus, once inclusions (usually less than 50 μ m) enter these holes they will be entrapped. Thus the current entrapment criterion is reasonable.

3.2. Determination of the Time Step

The motion of inclusions is stochastic in the turbulent flow of the molten steel inside the SEN. The Lagrangian stochastic model for the motion of particles in fluid flow has been reported.³⁷⁻⁴³⁾ For the stochastic model, the time step is very important since it has a great effect on the trajectory of the particle. In the current paper, several different time steps were tried. The results indicated that since the fluid flow inside the SEN was assumed to be in a steady state in the current paper, a variable time step should be used, as that is used in Fluent software. The time step Δt used in the current model can be expressed by:

$$\Delta t = \min \left(\frac{L_s}{|v_f - v_p|}, \frac{L_s}{|u_f - u_p|} \right) \quad \text{.....(23)}$$

where L_s is the length scale of 3.0 μ m. Since the relative velocity between the fluid flow and the inclusion motion may be very small at some times, the time step will be quite big

Fig. 3. Inclusions entrapped in the steel net form structure on the surface of SEN.

Fig. 4. The time step, space step and relative velocity between molten metal and particle during the life time of the particle.

and thus the particle may move a long distance in one time step, which will lead to a wrong result. Thus, in the current study, the space step that the inclusion moves in one time step is required to be less than 1.0 mm. **Figure 4** shows the example relative velocity between the molten metal, space step and the time step used during the life time of the particle in the system.

3.3. Trajectory of Inclusions

In the current paper, the entrapment of inclusions in the SEN ($\text{Al}_2\text{O}_3\text{--C}$ materials) with of a 150 mm $\times$ 150 mm billet continuous caster was simulated. The inner diameter of the SEN is 40 mm, and the mean velocity in the nozzle is 0.6 m/s, corresponding to a 2.0 m/min casting speed, superheat is 25°C. It is calculated that the thickness of the laminar sub-layer (L) is 0.13 mm under this condition. Two thousand inclusions were injected along the radius of the nozzle entrance; No. 1 particle is the one at the center of the nozzle entrance, while No. 2000 is the one close to the lining refractory wall. Example trajectories of 20 μm inclusions were shown in **Fig. 5**. When inclusions are injected close to the SEN center (at the turbulent bulk zone), the motion of inclusions is more random. The fluctuation becomes smaller once the inclusion walks close to the wall or enter the SEN through the transition layer. As indicated, No. 99 and No. 550 inclusions, which were released far from the nozzle wall, were not entrapped to the nozzle wall, but the other four inclusions were entrapped.

3.4. Discussion on Entrapment Probability

In the current paper, the entrapment probability of inclu-

Fig. 5. Trajectories of inclusions injected from different locations at the SEN entrance.

sions to the SEN wall is defined by Fig. 1 and Eq. (24)

$$P = \sum_i p_i = \frac{\sum_i \left[\frac{N_{0,i}}{N_{t,i}} (\pi(R_i + \Delta R)^2 - \pi R_i^2) \right]}{\frac{\pi}{4} D^2} \dots (24)$$

where $N_{0,i}$ is the number of inclusions entrapped by the SEN wall, $N_{t,i}$ is the total number of inclusions injected through the entrance area A_i ; and i is the sequence number of the annular position at which inclusions are injected. R is the radial distance from the nozzle center; D is the diameter of the nozzle in meter. Many factors have effect on the entrapment probability, such as the position from which inclusions are injected, size of inclusions, diameter of the SEN, casting speed, and the dimension of the billet.

Figure 6 shows the dependency of the entrapment probability on the size of inclusions. Smaller inclusions are easier to be entrapped by the nozzle wall. Inclusions larger than $100 \mu\text{m}$ are impossible to be entrapped. If the bulk velocity in the nozzle is 0.6 m/s and the nozzle is with a 40 mm diameter, the total entrapment probability for $10 \mu\text{m}$, $20 \mu\text{m}$, $40 \mu\text{m}$, $60 \mu\text{m}$ and $80 \mu\text{m}$ are 46.26% , 18.57% , 9.53% , 10.59% and 2.93% respectively, which indicates the entrapment probability of inclusions increases quickly with decreasing size of inclusions if inclusions were smaller than $15 \mu\text{m}$.

The velocity of the molten steel at the locations close to the nozzle center is larger than that close to the wall (as shown in **Fig. 7**), due to which the inclusions at the locations close to the nozzle center are more difficult to be entrapped by nozzle wall. Thus the entrapment probabilities of inclusions are diverse while injected from different loca-

Fig. 6. Relationship between the entrapment probability and the size of inclusions.

Fig. 7. Distribution of velocity, fluctuation velocity and the diffusion coefficient.

tions. Entrapment probability of inclusions versus the injection location of inclusions is shown in **Fig. 8**. The entrapment probability close to the wall is far larger than that close to the center. Inclusions injected from the nozzle center have the smallest entrapment probability. For $10 \mu\text{m}$ inclusions, they may finally be entrapped by the nozzle wall even though being injected from the nozzle center. While $>20 \mu\text{m}$ inclusions are hardly entrapped to the nozzle wall when they are injected from the nozzle center.

The effect of SEN inner diameter on the entrapment probability is shown in **Fig. 9**. With the same bulk velocity, larger inner diameter nozzle implies a higher casting speed. Since the friction factor decreases with larger inner diameter of the nozzle (Fig. 2), thus the larger diameter nozzle has lower entrapment probability. Thus, with the casting speed, smaller diameter SEN entraps more inclusions. For $20 \mu\text{m}$ inclusions moving in the molten steel inside a SEN

Fig. 8. Entrapment probability of inclusions injected from different locations at the SEN entrance.

Fig. 9. Effect of nozzle diameter on the entrapment probability.

with 0.6 m/s bulk velocity, the SEN with 40 mm diameter entraps 18.57% inclusions, while those with 20 mm, 60 mm and 90 mm diameter SENs entraps 27.49%, 13.83%, and 10.39% inclusions respectively. From Fig. 9, the following regression equation can be obtained between the entrapment probability and the inner diameter of the SEN

$$P = 2.14 \cdot D^{-0.66} \dots\dots\dots(25)$$

The current model indicates that smaller bulk velocity induces higher entrapment probability of inclusions to the SEN wall, as shown in Fig. 10. Under certain conditions (20 μ m inclusions and 40 mm inner diameter of the SEN), the entrapment probability with 0.6 m/s bulk velocity is 18.57%, while is 29.96%, 14.37%, 9.12% respectively for those with 0.4 m/s, 0.8 m/s, and 1.0 m/s bulk velocity. The following simple regression equation is obtained,

$$P = 64.76 \exp(-2.03u_{\text{bulk}}) \dots\dots\dots(26)$$

The relationship between the bulk velocity, inner diameter of the SEN, billet dimension and casting speed can be expressed by

$$u_{\text{bulk}} \times \frac{\pi}{4} D^2 \times \rho_f = \rho_s \times a \times b \times \frac{V_c}{60} \dots\dots\dots(27)$$

where V_c is the casting speed in m/min, a and b are the dimensions of the casting strand in m, ρ_s is the density of solid steel density (7800 kg/m³) and ρ_f is the density of

Fig. 10. Effect of the bulk speed in the SEN on the entrapment probability.

Fig. 11. Relationship between casting speed and inclusion entrapment probability.

molten steel (7020 kg/m³).

According to Eqs. (25)–(27), the relationship between casting speed V_c and the entrapment probability P can be written as:

$$V_c = -\frac{209.5}{a \times b} \times P^{-3.03} \times \ln(P/64.76) \dots\dots\dots(28)$$

For a 150 mm×150 mm billet continuous caster, the entrapment probability of inclusions as a function of casting speed to the SEN nozzle wall is illustrated in Fig. 11, indicating that smaller casting speed entraps more inclusions to the nozzle wall. At the same casting speed, the entrapment probability of inclusions is lower for the larger dimension casting strand.

3.5. Entrapment Probability along the Nozzle Length

The number of inclusions entrapped along the vertical distance from the SEN entrance is quite different, as shown in Fig. 12. In industry, the diameter of nozzle at the entrance is larger than that at the bottom, and argon gas may be injected from the upper nozzle. In the current model, the diameters of the nozzle at the entrance and the bottom were assumed to be the same and the effect of the argon injection was ignored, so the SEN wall entraps inclusions the most close to the entrance shown in the result. Except the nozzle entrance, inclusions entrapped to the nozzle wall slightly increases along the downward length of the SEN. This is because inclusions move longer time after they enter the SEN before being finally entrapped. The location entrapping more inclusions will be entirely clogged first, which implies that it may only some location of the nozzle is fully clogged by inclusions while other places still have free spaces. This fact has to be accounted for the prediction of the accumulated weight of molten steel that can be poured before the nozzle is blocked. In the current paper, the entirely blocking at the location where entraps the most inclusions was used to judge how much molten steel can be poured.

3.6. Prediction of the Accumulated Weight of Molten Steel that Can be Poured for a SEN

Different bath depth in the tundish results in different

Fig. 12. Distribution of the inclusions entrapped along the nozzle length.

flow rate in the SEN. The theoretical flow rate of the steel, Q_t in kg/s, in the SEN with a fully open slide gate can be estimate by⁴⁴⁾:

$$Q_t = \left(\frac{1}{\beta} + \frac{e_f}{6} \right)^{-1/2} \rho_f \frac{\pi D^2}{4} (2gh)^{1/2} \dots\dots\dots(29)$$

where β is a constant, equals 1 for turbulent flow and 0.5 for laminar flow; e_f is the friction loss factor, ~ 0.5 for the current case; h is the bath depth in the tundish in meter. This equation gives the theoretical flow rate. The real flow rate depends on the casting speed and the billet dimension. **Figure 13** shows the theoretical flow rate of the molten steel flowing through the SEN during pouring of billet continuous casting process. The flow rate decreases as the inner diameter of the SEN decreases. A lower bath level in the tundish corresponds to a smaller flow rate. Under the condition of $V_c=2.0$ m/min, $D=40$ mm, 150 mm $\times$ 150 mm billet, 1.0 m bath level in the tundish, the slide gate needs to open $\sim 15\%$ (ratio of opening area to the whole nozzle area) to achieve the flow rate required by the casting speed. As the clogging narrows the inner diameter of the SEN from 40 to 16 mm, the slide gate needs to be open more in order to ensure a constant casting speed. When the slide gate approaches 100%, the flow rate is no longer to ensure the 2.0 m/min casting speed any more, then the SEN has to be replaced, or the casting speed have to be reduced.

In the current paper, the inclusions were assumed to be pure alumina (Al_2O_3), the density of which was assumed to be 3 500 kg/m³, and the total oxygen in the molten steel was in the form of Al_2O_3 . Thus, the number of inclusions in one kilogram steel can be estimated with the total oxygen content and the size of inclusions, and then the accumulated weight of molten steel that can be poured before the nozzle is blocked can be predicted. The following casting conditions were assumed: 150 mm $\times$ 150 mm ($a=b=0.15$ m for Eq. (28)) billet, 25°C superheat, 2.0 m/min casting speed, 1 m bath depth in the tundish, and 1 m length of the SEN (Al_2O_3 -C materials). It is calculated that the thickness of the laminar sub-layer (L) is 0.13 mm under this condition. In the paper, the inclusions in the molten steel were assumed to be in a single size. When T.O is 30 ppm, and diameters of the inclusions are 20 μ m, it is calculated that the number of inclusions is around 5.4×10^5 /kg-steel in the molten steel.

Since the clogging materials include not only inclusions,

Fig. 13. Estimated theoretical and required flow rate of molten steel during casting with nozzle clogging.

but also frozen steel. The fraction of pure inclusions in the clogging materials has to be taken into account. **Figure 3** and **Fig. 14** show the micro- and macro-structure of the frozen steel in the clogged material.

The relationship between the accumulated weight of molten steel that can be poured and the volume fraction of inclusions in the clogging materials is illustrated in **Fig. 15**; indicating that the SEN will be blocked faster and less accumulated weight of molten steel can be poured if the volume fraction of the inclusions in the clogging materials is lower. According to the observation by Zhang,²⁾ the volume fraction of the inclusions in the clogging materials in the paper was assumed to be 50%. If the non-uniform clogging along the SEN length is not considered, the clogging mate-

Fig. 14. Macro-structure of inclusions and frozen steel in the clogging material of a SEN.

(a) Non-uniform clogging along SEN length

(b) Uniform clogging along the SEN length

Fig. 15. The accumulated weight of molten steel can be poured versus and its affecting factors.

(a) Non-uniform clogging along SEN length

(b) Uniform clogging along the SEN length

Fig. 16. Effect of T.O. on the accumulated weight of molten steel can be poured.

rial is assumed to be uniform along the SEN length, then the nozzle is blocked much slower, and thus the accumulated weight of molten steel that can be poured before the nozzle is fully blocked by clogging is much larger, which is not accurate. For example, with the condition of 40 mm inner diameter of the SEN, 20 μm inclusion size, 30 ppm total oxygen, and 50% inclusions in the clogging materials, around 351 ton steel can be poured for non-uniform clogging along the SEN length, however, around 668 ton steel can be poured if assuming uniform clogging along the SEN length. In order to more precisely predict the accumulated weight of molten steel that can be poured, both volume fraction of the inclusions in the clogging materials and non-uniform clogging along the SEN length should be taken into account.

With more clogging, even though 100% slide opening fails to assure the casting speed requirement. Then the real casting speed is decided by the bath depth in the tundish and the remaining free inner diameter of the SEN with clogging. Figure 15 also indicates that at this period, the clogging speed becomes very quick, and less than 55 ton steel can be poured.

The effect of the total oxygen in the molten steel (T.O.) on the accumulated weight of molten steel that can be poured before the nozzle is fully blocked is illustrated in Fig. 16. Lower T.O. implies less inclusions, thus less serious clogging occurs and the casting can be performed longer. If with the following condition: 20 μm inclusions, 50% inclusions in volume in the clogging materials, 2.0 m/min casting speed, 40 mm nozzle inner diameter, and non-uniform clogging along the SEN length, Fig. 16 predicts that for the molten steel with 20 ppm T.O., approximately 527 ton steel can be poured before the nozzle is fully blocked, while for the 40 ppm T.O. steel, less than 300 ton steel can be poured.

(a) Non-uniform clogging along SEN length

(b) Uniform clogging along the SEN length

Fig. 17. Effect of the inner diameter of the SEN on the accumulated weight of molten steel can be poured.

Figure 16 shows again that most of the molten steel is poured at the desired casting speed, and only a little steel is poured by reducing casting speed. Thus, reducing casting speed is inefficient to solve the issue of SEN clogging.

Figure 17 indicates that larger inner diameter of the SEN pours more molten steel than smaller inner diameter SEN before the SEN is totally blocked. Enlarging the inner diameter of the SEN is one possible measure to pour more steel. However, the diameter of the SEN is limited by the billet dimension and the bottom well and sliding gate system of the tundish. So the core solution to reduce the nozzle clogging is to remove more inclusions during steel refining and in the tundish and then the source for the nozzle clogging is reduced.

4. Conclusions

A kinetic model for SEN clogging is developed. The effects of nozzle diameter, casting speed, billet dimension, inclusion size and the total oxygen of the molten steel and several other factors on the clogging of the SEN are taken into account. The following conclusions are obtained:

- (1) Inclusions are more easily to be entrapped to the SEN wall under the following conditions: smaller inclusion size, more total oxygen of the molten steel, and smaller casting speed.
- (2) Inclusions larger than 100 μm are impossible to be entrapped by the nozzle wall, and the entrapment probability increases quickly with decreasing inclusion size if inclusions are smaller than 15 μm .
- (3) The entrapment probability of inclusions is not uniform along the length of the SEN. The entrance locations entrap more inclusions.
- (4) The kinetic model developed can predict the accu-

mulated weight of molten steel that can be poured before the SEN is blocked by the clogging. Changing casting speed or using a large inner diameter SEN can improve the clogging and cast more steel, but removing more inclusions from the molten steel during ladle refining and in the tundish is the key to solve the problem of SEN clogging.

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