Discussion on possible solidification during SEN clogging in steel continuous casting

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Abstract. Molten steel is conducted through the submerged entry nozzle (SEN) into the mold during the continuous casting process. Accretion inside the SEN, called clogging, is one of the major problems in continuous casting of steel. In addition to the mechanisms of attachment of de-oxidation and re-oxidation products (Al_2O_3 particles) on the SEN wall, chemical reactions of the melt with the refractory material of SEN, precipitation of alumina, etc., solidification of the steel melt on the SEN wall is also considered as a possible mechanism for clogging. A transient model considering two-way coupling between clog growth (due to particle deposition) and fluid flow is upgraded to a non-isothermal model; solidification of steel during the SEN clogging in continuous casting is investigated. The results show that solidification would not occur in a SEN if the molten steel has sufficient superheat and it flows with relatively high speed through the SEN. In contrast, clogging promotes the solidification inside the clog.

Introduction

Clogging of submerged entry nozzle (SEN) is a problematic phenomenon in steel continuous casting. As the molten steel is conducted through the SEN into the continuous casting machine, the flow path in SEN may be gradually blocked, resulting in various casting defects or operation disruptions. In Fig. 1(a), a schematic representation of SEN and clogging in steel continuous casting is presented. Clogging leads to decreased productivity of the casting, low quality of the final product, and enhanced costs. The mechanisms of clogging can be summarized in five categories: (1) attachment of de-oxidation and re-oxidation products on the SEN wall [1-3]; (2) thermochemical reactions in the melt at the SEN wall leading to in-situ formation of oxide products [4,5]; (3) negative pressure drawing oxygen through the SEN refractory pores into the inner SEN wall and reaction of oxygen with the steel melt to form oxides [6]; (4) temperature drop of the melt leading to lower solubility of oxygen in the steel melt and resulting in precipitation of alumina at SEN-steel interface [7,8]; and (5) possible solidification of the steel melt on the SEN wall [9,10].

The last mechanism, i.e. solidification of steel on the SEN wall, cannot be counted as a main mechanism, but it may promote the clogging. If the melt superheat is low, and the heat loss from the SEN wall is high, the steel may freeze on the SEN wall. Rackers and Thomas [9] stated that clogging material is a porous network of alumina (built up alumina particles). This alumina network individually is very weak and could be easily broken by the touch of finger. However, when an alumina network forms on the SEN wall, the solidified steel in the pores reinforces the whole clogging region. Therefore, the clogging material can withstand against the melt flow and cannot be washed away by the flow drag force. It is also concluded that solidification within the SEN will increase clogging rate. The practical evidence in steel plant [10] showed that increasing SEN preheating temperature reduces the deposition within SEN. It means that SEN preheating prevents or postpones solidification of steel within the clogging material. Therefore, the performance of the SEN is improved. Moreover, post-mortem microscopic analysis of clogging materials always shows solidified steel filling clog networks [11]. However, it is not clarified that the solidification of steel

has occurred during the casting process or the steel inside the clogging material was liquid and has solidified after sampling.

Theoretically, it is difficult to imagine that solidification would occur in a SEN because the steel melt temperature is around 15-20 °C higher than the liquidus temperature of the steel alloy and the flow velocity is ~ 1 m/s. The current work is a preliminary numerical study to find the answer of the main question: can solidification occur and lead to clogging in SEN?

Model

A transient model for clogging has been developed by the current authors [12]. The original model is for isothermal conditions including different steps of clogging: transport of the particles to the wall; interactions between wall, fluid, and particles; growth of clogging material (also named *clog*) due to the particle deposition. In this model, clog is considered as a porous medium made of alumina network and steel melt fills the network pores. In the current study, the model is upgraded to a non-isothermal model and solidification of steel in the clog is considered. An enthalpy based solidification model of mixture continuum is implemented.

$$\frac{\partial}{\partial t}(\rho h)+\nabla\cdot(\rho\vec{u}h)=\nabla\cdot(\alpha\nabla T)+\rho L\frac{\partial f_s}{\partial t} \tag{1}$$

ρ, h, $\vec{u}$ and T are density, enthalpy, velocity, and temperature, respectively. α stands for thermal conductivity. L is latent heat of solidification and f_s is the volume fraction of solid steel in a control volume. In Eq. 1, mixture values of quantities are considered. A control volume comprises three components: liquid, solid, and particle. Therefore,

$$f_s+f_\ell+f_p=1. \tag{2}$$

In the clogging model [12], a drag force of the clog on the melt flow is applied. It is assumed that the clog is a porous medium with open pores. So, the source term of clogging materials in the momentum and turbulence equations is defined as

$$S_{\mathrm{clog},\phi}=\mu\frac{108\left(\bar{f}_p^{\,1/3}-\bar{f}_p\right)}{\left(1-\bar{f}_p\right)\left(1-\bar{f}_p^{\,1/3}\right)}\frac{f_{\mathrm{clog}}^{n}}{D_{\mathrm{pore}}^2}\phi, \tag{3}$$

where $\bar{f}_p$ is the average particle volume fraction; D_{pore} is the diameter of pores; $f_{\mathrm{clog}}=f_p/\bar{f}_p$ is volume fraction of clog in a control volume; and n is an interpolation correction power.

By implementation of solidification, the drag of the solidifying mushy zone on the melt has to be considered as well. Hence, a corresponding source term is defined for the mushy zone.

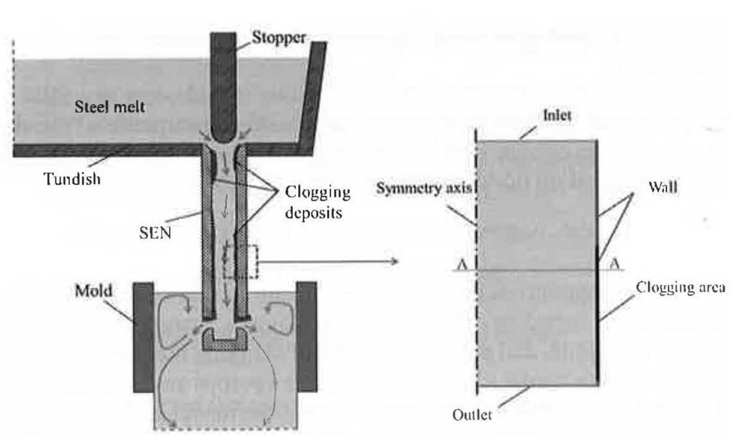
$$S_{\mathrm{solidification},\phi}=\frac{(1-f_\ell)^2}{f_\ell^3}\frac{\mu}{6\times10^{-4}\lambda_1^2}\phi, \tag{4}$$

where λ_1 is the primary dendrite arm spacing. In Eq. 3 and Eq. 4, ϕ can be velocity, kinetic turbulence energy, and its dissipation rate.

The applied source term is an average of the clog and the solidification terms according to the particle volume fraction (f_p),

$$S_\phi=f_pS_{\mathrm{clog},\phi}+(1-f_p)S_{\mathrm{solidification},\phi}. \tag{5}$$

Clogging and solidification in a vertical tube relating to the SEN size is simulated. For the sake of calculation time, 2D axisymmetric conditions are considered, as shown in Fig. 1(b). The dimensions, boundary conditions, and physical properties of materials are summarized in Table 1. The heat transfer coefficient of wall is an efficient value including heat conduction through SEN wall (with ~50 mm thickness) and heat convection by air on the outer side of the SEN.



(a) (b)

Figure 1. (a) Schematic presentation of continuous casting machine, (b) 2D-axisymmetric domain and boundary conditions used in the current simulation.

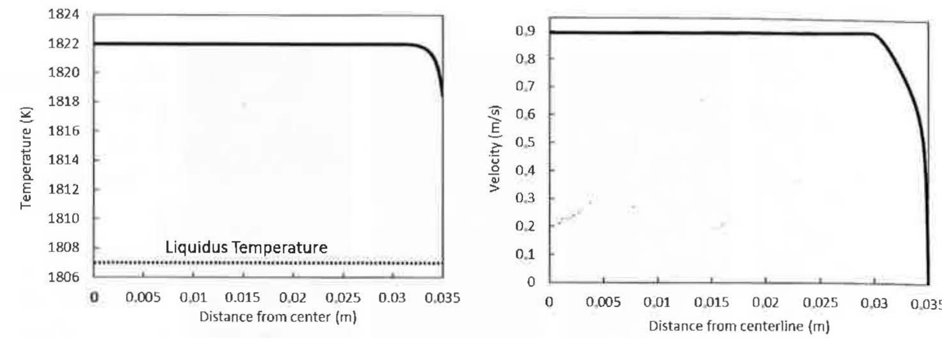
Table 1. The dimensions, boundary conditions, and physical properties of materials

Dimensions of domain		Physical properties	
Radius	20 mm	Steel	
Height	60 mm	Density	7020 kg/m^3
Boundary conditions		Viscosity	0.0052 kg/(m.s)
Inlet		Specific heat	700 J/(Kg.K)
Velocity	0.85 m/s	Thermal conductivity	26 W/(m.K)
Temperature	1822 K	Liquidus temperature	1807 K
Turbulence kinetic energy	0.00078 m^2/s^2	Solidus Temperature	1780 K
Specific dissipation rate (ω)	175.76 1/s	Latent heat	243 kJ/kg
Particle mass injection rate	0.0374 kg/s	Alumina	
Outlet		Density	3700 kg/m^3
Pressure-outlet	-	Specific heat	880 J/(Kg.K)
Wall		Thermal conductivity	35 W/(m.K)
No-slip	-	Particle diameter	10 μm
Heat transfer coefficient	100 W/(m^2.K)	$\bar{f}_p$	0.55
Free stream temperature	300 K	D_{pore}	20 μm

The turbulent flow is calculated by the shear stress transport (SST) k-ω model using commercial CFD code ANSYS-FLUENT. Particle tracking is performed by Discrete Phase Model (DPM). User-defined functions (UDFs) are used for considering the particle deposition, the clog growth, and the melt solidification.

Results and Discussion

The steady state temperature and velocity profiles along a horizontal line, when the no clogging occurs, are shown in Fig. 2. This result shows that temperature drop near the wall is about 4 K; the wall temperature is still 11 K above the liquidus temperature. Since the flow velocity is high enough to wash the cold melt close to the wall, solidification never happens on the SEN wall.



(a) (b)

Figure 2. Steady state temperature (a) and velocity (b) profiles along AA line shown in Fig. 1(b).

In the practical conditions of continuous casting, clogging may happen after several hours. Therefore, simulation of real conditions is not feasible due to the too long calculation time for clogging. To overcome this problem, an exaggerated number of particles is injected in the computational domain to see the clog growth in a shorter time. Hence, the clog growth rate in the current simulation is faster than that in reality. A rough estimation shows that the real injection rate of alumina particles would be around 8.15×10^{-5} kg/s (particle diameter is 10 μm). In the current simulation, the particle injection rate is set to 0.0374 kg/s.

In Fig. 3, the evolution of clogging is depicted. On the top row, the flow and temperature fields are shown. The thick and thin solid lines represent the clog front and the liquidus isoline of the melt, respectively. On the bottom row, the solid fraction is illustrated. Note that in the clog, the average volume fraction of particle ($\bar{f}_p$) is 0.55. According to Eq. 2, the maximum value of f_s can be 0.45, when all of the steel melt in a control volume solidified. The results show that the clog grows from the wall due to the continuous deposition of particles. The clog growth changes the flow field; consequently, the convective heat transfer by the fluid flow is changed. Therefore, the temperature field is adjusted by the clog growth. Due to the very low velocity of the melt in the pores of the clog, the temperature in this region decreases.

After 30, the temperature in the clog is still higher than liquidus temperature. At 40 s, a layer of steel solidifies in the clog. In Fig. 3, the liquidus temperature actually indicates the position of solidification front, considered in the simulation. At 50 s, the clog thickness increases significantly; therefore, a noticeable solidified metal shell forms in the clog. The results at 40 and 50 s declare that there always is a gap between the clog front and the solidification front (liquidus temperature). One can conclude that solidification during clogging is a consequence of weak melt flow in the clog pores. However, solidification in SEN cannot promote the clog growth because the clog front always is in a temperature close to the bulk temperature and far from the liquidus temperature.

As demonstrated in [12] and as can be seen in Fig. 3, clogging starts with covering of the nozzle wall by deposition of the particles (20 and 30 s). The growth of the clog front is not smooth. After a while, some bulges grow at different positions (40 and 50 s). Finally, bulges turn into branches. By impingement of the branches, the flow passage is blocked (this step is not shown in Fig. 3). When the bulges form on the clog front, the melt flow through the bulges is weakened. Therefore, the heating of the clog front by melt flow decreases. In this case (like 50 s), solidification front can be closer to the clog front than when the clog front is almost smooth (like 30 s).

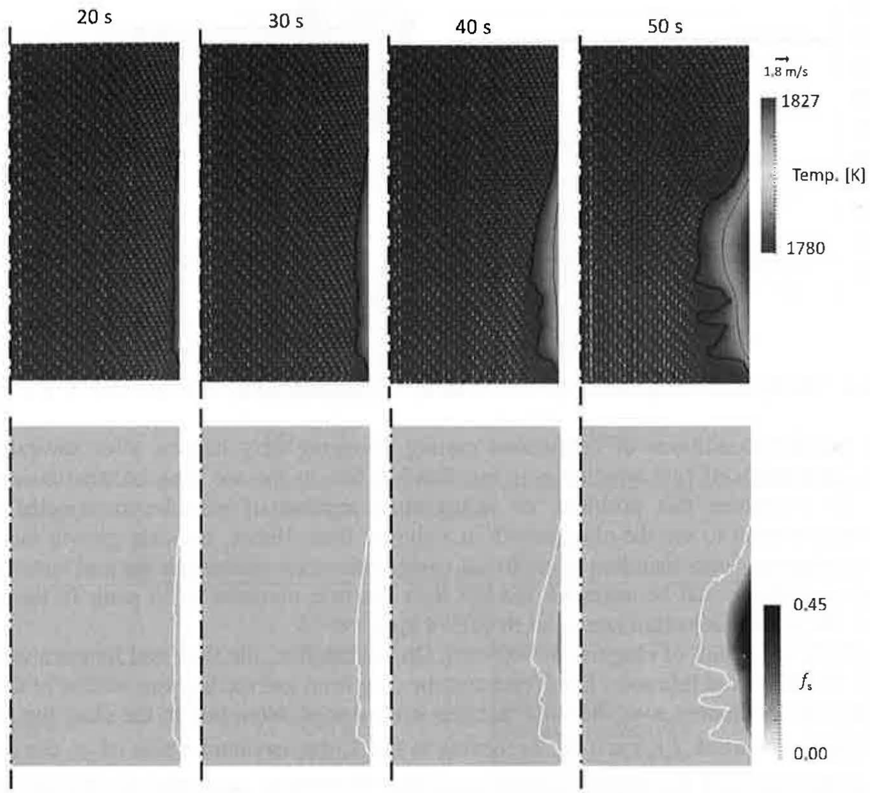


Figure 3. Evolution of clogging and its interaction with solidification. The temperature and flow fields are shown on the top row and the solid fraction of steel is indicated on the bottom row. The thick and thin solid lines represent the clog front and liquidus isoline (indicating solidification front), respectively.

Conclusions

A transient model considering two-way coupling between clog growth (due to particle deposition) and fluid flow is upgraded to a non-isothermal model. Solidification of steel during the SEN clogging in continuous casting is investigated.

- Before initiation of clogging, solidification of steel on the SEN wall is not possible due to the high velocity and high superheat of the melt in the SEN.
- Clogging promotes the solidification inside the clog.

Acknowledgments

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