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Using a Numerical Model to Study the Transient Clogging Phenomena in SEN During Continuous Casting of Steel

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INTRODUCTION

Clogging of submerged entry nozzle (SEN) is one problem, which annoys metallurgists since 1960s as the technology of steel continuous casting appeared [1]. Despite of vast research efforts on this topic both experimentally [1-6] and numerically [6-8], no reliable and efficient method is available for the steel industry to eliminate it. The current authors have recently published a numerical model for the nozzle clogging [9-11]. Following phenomena of clogging were considered: transport of the non-metallic inclusions (NMIs) as particles in the turbulent flow of steel melt; deposition of the NMIs and buildup of the initial layers of clog on the SEN wall; continuous growth of clog region (as porous medium) due to further deposition of NMIs; the interaction of the clog region with the melt flow; possible solidification of steel melt in the porous clog region. This contribution is to present a test simulation of industry scale based on this model. The aim is to explore the model capabilities or limitations. The coincidence/agreement between the numerical simulations and the industry observations/experience will be discussed, leading to an outlook of the open topics for further study.

NUMERICAL STUDY

Model in brief

The key mechanism as considered in this clogging model is the transport and deposit of indigenous non-metallic inclusions (NMIs), as de-oxidation products in the steel melt, towards/on the SEN wall, leading to a gradual build-up of clog layer. An Eulerian-Lagrangian approach is used to track the motion of NMIs. The morphology of NMIs is assumed spherical. To handle the turbulence effect on the NMI motion, a standard random walk model is used in the bulk melt region; while in the near-wall region a stochastic coherent-structure model for particle deposition is used [12]. As soon as the NMIs hit the SEN wall, it is assumed to be captured by the wall. At the early stage, the deposition of NMIs on the SEN wall is just treated as a part of the SEN wall roughness, whose height increases with the further NMI deposition. When the roughness height exceeds half of the computational cell (boundary), the clog layer is treated as porous medium, i.e. the boundary cell is considered to be partially-filled porous medium. An algorithm is implemented to track the clog growth, i.e. the further deposition of NMIs on the clog front. The clog region interacts with the fluid flow. The melt can flow through the clog region, and the permeability of the clog depends on its porosity. This parameter (porosity) cannot be determined by the current model. It must be predefined experimentally through the postmortem analysis of the as-used SEN. Details of the model were described elsewhere [9-11].

Test simulation

A test calculation of real SEN during steel continuous casting is performed (Fig. 1) [10]. A rough estimation is made for the number flux of NMIs which enter into SEN. If the oxygen content of the steel melt in the tundish before entering SEN is around 30 ppm and all of the oxygen reacts with the dissolved aluminum to produce Al_2O_3, the concentration of Al_2O_3 in the melt would be 1.24×10^{-4} vol%. The domain as shown in the zoomed view in Fig. 1(a) would contain a total volume of 0.018 m^3, corresponding to 20 billion Al_2O_3 particles with average size of 6 µm. Simulation of such large number of particles is not feasible. Here an artificial factor (N-factor) is introduced to reduce the calculation cost. We assume that one particle represents N particles.

A preliminary result of the simulation is depicted in Fig. 1(b). The clog front in SEN is shown with a zoomed view of the thickness of the clog after 30 min. It shows that the critical regions of clogging are located (1) on the SEN wall in the stopper-SEN gap region, (2) upper part of SEN just below the stopper. This result cannot be quantitatively verified, but it agrees with the practical operation experience. During operation of continuous casting, in order to keep the constant casting speed (i.e. melt flow rate through the stopper-SEN gap), the position of stopper rod has to be adjusted in response to the clogging which occurs in the stopper-SEN gap. In the practice it is not possible to detect the clog in the SEN-stopper gap region. Indirectly, the clog there will reduce the total flow rate of the steel melt through the SEN-stopper gap, which in turn leads to sink of the meniscus level in the mold. It is the information of the meniscus level that gives an indication about the clog, and helps to adjust the stopper position in maintaining the constant casting speed.

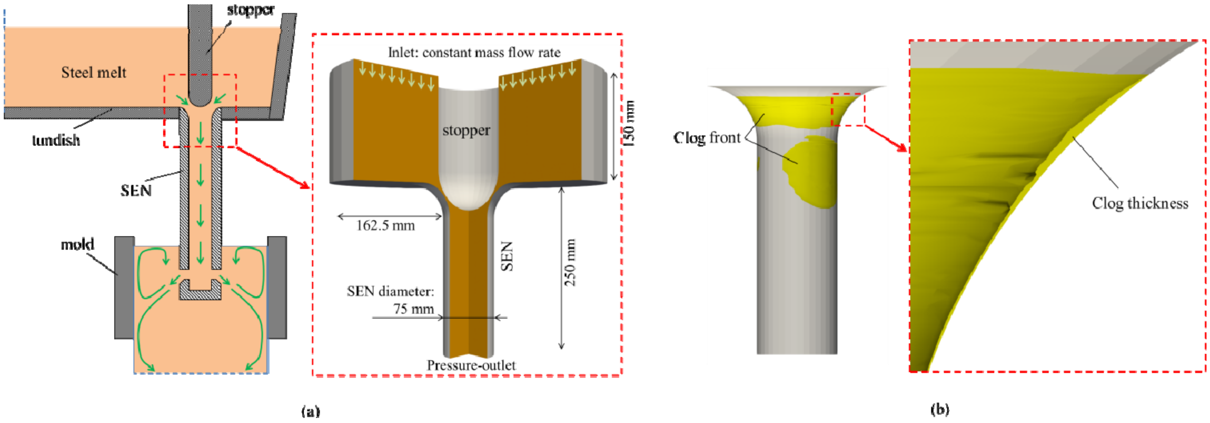
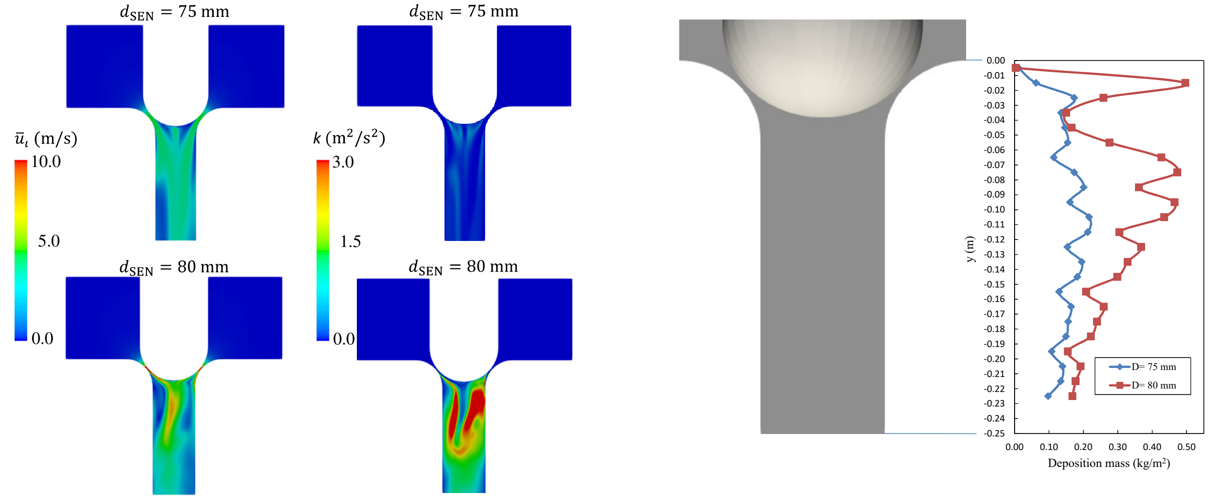


Figure 1 (a) Schematic of steel continuous casting and the configuration of calculation domain for the simulation of SEN clogging, and (b) the preliminary results of clog growth in SEN after 30 min. Reproduced from [10], with permission from Springer Nature, 2019.

Operation parameter study

Clogging is a complex metallurgical phenomenon. Apart from many other influencing factors from the primary/secondary metallurgy and the alloy and SEN chemistry, the process parameters of casting play also important role in clogging, such as the casting temperature and speed, tundish level, SEN geometry, etc.



a) Velocity magnitude b) Tur. kinetic energy c) Mass deposition of NMIs

Figure 2. Influence of SEN diameter on the melt flow and clogging (15 min).

Firstly, a numerical study by comparing two different SEN inner diameters is performed. One SEN has the inner diameter of 75 mm and the other has 80 mm. The calculation domains for two cases have to be generated differently to keep the melt flow rate identical. We set both cases an identical casting speed. The SEN-stopper gap size for the SEN of ϕ 80 mm must be smaller than that of SEN of ϕ 75 mm. The stopper-SEN gap size is determined by performing the whole tundish simulations (not shown here). The predicted velocity magnitude in the gap region and in the upper SEN region for the SEN of ϕ 80 mm is larger than that of the SEN ϕ 75 mm, (Fig. 2(a)). The turbulence kinetic energy is shown in Fig. 2(b). The enhanced velocity in the gap results in more turbulence. As the clogging phenomenon is strongly dependent on the turbulence, a faster clogging is expected for the case with SEN of ϕ 80 mm than that for the case with the SEN of ϕ 75 mm. The time integrals of total mass deposition of NMIs in the first 15 min are shown in Fig. 2(c). The results indicate that the small SEN diameter leads to smaller amount of clogging and more uniform deposition of particle along the SEN wall. This simulation results seem to contradict with an early experimental study [1], which proposed an oversized SEN for a possible solution (reduction) of clogging. The current simulation results show that an oversized SEN (inner diameter) does not help the improvement of clogging. This disagreement needs further explanation.

Secondly, two tundish fill levels are compared (0.5 m and 0.8 m). Different tundish fill levels mean different metallostatic pressure. The SEN-stopper gap must be adapted corresponding to the tundish fill level to maintain a constant melt flow rate. Global CFD simulations considering whole tundish must be performed to determine the corresponding gap sizes for the predefined tundish fill levels. Then, in the reduced domains the clogging simulations are performed. All other simulation settings are kept identical for both simulation cases (two tundish fill levels, 0.5 and 0.8 m). Deposition along the SEN wall is plotted in Fig. 3. No significant difference is found between the considered cases, although industrial experience showed that increasing the tundish fill level can lead to the reduction of clogging. Different tundish fill level practically may change the size and number of inclusions entering the SEN because of different residence time of inclusions in tundish. Coagulation and dynamic change of particle size and particle number inside the tundish were not considered in the model currently.

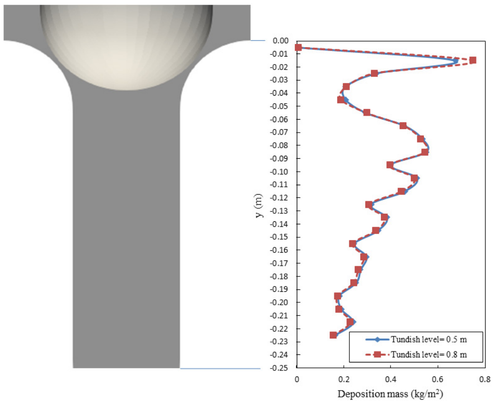


Figure 3. Influence of tundish fill level on the clogging (27 min).

SUMMARY

A numerical study was made for the SEN clogging during steel continuous casting of real industry scale.

- Referring to the nozzle configuration as considered in this study, two critical regions were found sensible to the clogging: (1) the stopper-SEN gap and (2) the upper part of SEN below the gap. This kind of clog distribution agrees with the practical operation experience for the SEN configuration of the current type.
- Tundish fill level showed only minor influence on the clogging. This result deviates from the industry observation. We assume that other mechanisms might contribute to clogging. The tundish fill level may influence the size, the number density and even the shape of NMI particles, which in turn influence the clogging.
- The inner diameter of SEN influences the clog inside the SEN. A smaller inner diameter of SEN tends to lead to a more homogeneous distribution of clog along the SEN wall. This finding may contradict to an early study [12]. Explanation to this simulation-experiment disagreement needs further study as well.

The current model is still not possible to reproduce all the industry observations. An outlook of topics for further studies are: (1) NMI origin and size distribution, and their dependency on the steel melt treatments during primary and secondary metallurgy; (2) the effects of alloy and SEN chemistry and thermodynamic which might lead to diverse reactions at the steel-SEM reactions; (3) the effect of Ar gas through the stopper rod; (4) the fragmentation/detachment of clog materials.

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