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A transient model for nozzle clogging

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ABSTRACT

This model has been developed for transient simulation of clogging (also called as fouling) in submerged entry nozzle (SEN) during continuous casting. Three major steps of the clogging have been taken into account: (a) transport of non-metallic inclusions (NMIs) by turbulent melt flow towards the SEN wall; (b) interactions between melt and wall, and the adhesion of the NMI on the wall; (c) formation and growth of the clog by NMI deposition. The computational domain is divided into bulk and near-wall regions. An Eulerian-Lagrangian approach is employed to calculate the transport of NMIs by the turbulent flow; a stochastic near-wall model is adopted to trace particles in the turbulent boundary layer (near-wall region). The early stage of clogging is modeled by the dynamical change in wall roughness, while the late stage of the clogging is modeled by building a layer of porous clog region from the wall. This layer is called as 'clog', and it continues to grow by attaching more NMI particles. To evaluate the model, a laboratory experiment, which was designed to study the clogging of SEN during steel continuous casting, is simulated. It is verified that the model can reproduce the experiment: the calculated clogged section of the nozzle is qualitatively comparable with as-clogged sections in laboratory experiments; the calculated mass flow rate through the nozzle agrees with the experimentally-monitored result as well. New knowledge is obtained. (1) Clogging is a transient process interacting with the melt flow, and it includes the initial coverage of the nozzle wall with deposited particles, the evolution of a bulged clog front, and then the development of a branched structure. (2) Clogging is a stochastic and self-accelerating process. Finally, model capabilities/limitations, uncertainties for choosing the modeling parameters such as mesh size, Lagrangian time scale, the correction factor in the interpolation of clog permeability are studied and discussed.

1. Introduction

Blockage of the fluid route due to the deposition and accumulation of solid suspended particles on the fluid passage wall is a common problem in a vast area of scientific fields and engineering applications such as heat exchangers [1], exhaust gas recirculation coolers in the automotive industry [2], food productions like wine microfiltration [3], membrane fouling in pharmaceutical industries [4], and nozzle clogging in steel continuous casting [5]. This phenomenon is usually termed as clogging or fouling. The Occurrence of clogging is a complex process. As depicted in Fig. 1, it mainly comprises four steps: (a) the turbulent fluid flow and the transport of the suspended particles towards the wall; (b) the interaction of the fluid with the wall and adhesion mechanism of the particles on the wall; (c) formation and growth of the clog; (d) fragmentation of the clog by the fluid flow to form fragments. In some cases, chemical reactions, electrostatic interactions at the fluid-wall interface, or even freezing (solidification) of the fluid on the wall might occur. Extensive research and great effort have been undertaken in order to gain a better understanding of clogging mechanisms in recent years.

Steps (a) and (b) of Fig. 1 are supposed to be major mechanisms for clogging/fouling, i.e. the hydrodynamic transport of particles and the adhesion mechanism [6]. For example, a study on fouling in a heat exchanger (water flow with silica suspensions of ~1 μm) shows that hydrodynamic lift forces gain complete control of the deposition process, and thermophoresis enhances deposition onto cooled surfaces [7]. A study on the transport and deposition of hematite particles on glass shows the importance of ionic charge strength [8]: at very low ionic strength, only monolayer deposition was observed, while at high ionic strength multilayer deposition became significant. This mechanism was further verified by another investigation on a polymeric microfluidic filtration device where fouling of the micro-channels by micron-sized (4.9 μm) particles occurred [9]. Particles at low ionic strength (more hydrophilic conditions) did not lead to the blockage of the micro-channels by fouling, while particles at high ionic strength (more hydrophobic conditions) led to rapid and complete fouling of the micro-channels.

During continuous casting of steel, the liquid melt is fed through a submerged entry nozzle (SEN) into the casting mold. SEN clogging is a long-term problem, leading to operation disruptions and different

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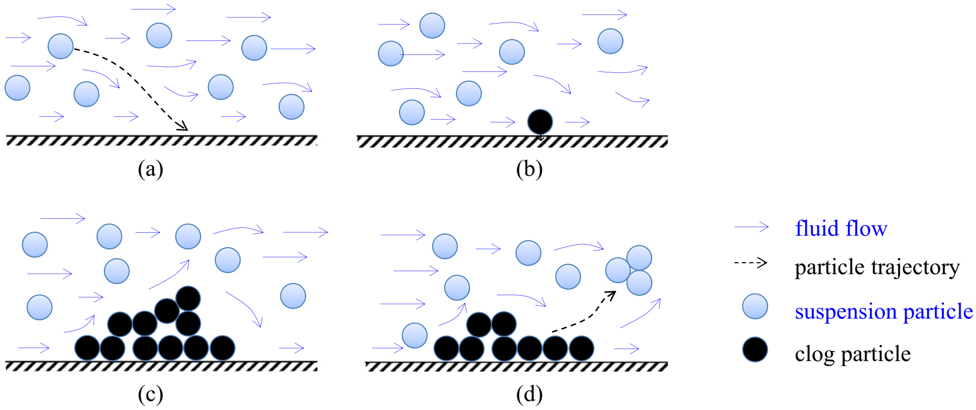

Fig. 1. Schematic of clogging/fouling phenomenon (four steps).

casting defects [10–12]. Great attention has been paid to the issue of SEN clogging during continuous casting of steel, as it may result in asymmetrical melt flow in the mold and therefore affect the solidification pattern [10], introduce macro-inclusion through the detachment/resuspension of the clog periodically [13], even terminate the process in the worst case [12]. High process temperatures, potential chemical reactions, possible phase change of the melt (solidification), and the electro-conductive nature of molten steel might result in the occurrence of different clogging mechanisms in comparison with those as studied in other fields. Various mechanisms for SEN clogging are suggested: (1) attachment of de-oxidation and re-oxidation products on the SEN wall [14–16]; (2) thermochemical reactions in the melt at the SEN wall leading to in-situ formation of oxide products [11,17]; (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 [18]; (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 [19,20]; and (5) possible solidification of the steel melt on the SEN wall [21,22]. Although various diverse opinions on the SEN clogging mechanisms exist, evidence shows that the deposition of non-metallic inclusions (NMIs) of de-oxidation and re-oxidation products on the SEN wall is still the primary cause of clogging [5]. The inclusions mainly consist of Al_2O_3 in aluminum killed steel. Depending on the steel grade, other NMIs such as TiN, TiO_2, ZrO_2, CaS, and rare earth oxides have been observed [23,24]. They originate from the steel melt [16,25], and their typical size is 2–10 μm [26]. They also have different shapes and can occur as either globular, clusters, dendrites, coral-shaped clusters, faceted particles, and even irregular plates [26–30]. However, globular shaped NMIs most frequently appear. Similar morphologies and chemical compositions of NMIs can be observed in the melt, in the clog material, and in the as-cast product [31]. Moreover, investigations for nozzle materials did not find a statistical difference in the mean rate of clogging for alumina, zirconia, magnesia, and zirconia-graphite nozzles [32].

Different numerical models have been developed to simulate the clogging/fouling phenomenon by emphasizing one or more critical steps evident in Fig. 1. The simplest method is the single-phase-based Eulerian approach. The bulk flow is solved, while the motion of the particles is not tracked explicitly. For example, by changing the geometry manually to mimic the build-up of alumina clog on the inner wall of the nozzle, Bai and Thomas studied the effect of the clog on the flow through a slide-gate nozzle [33]. The simulation results showed that the initial clogging around the slide gate enhances the melt flow rate initially due to a streamlining effect. After severe clogging, the flow is eventually restricted, so the gate opening has to be enlarged to ensure a constant casting speed. Zhang and co-workers used a similar method, e.g. by blocking half of one out-port of the SEN manually, to study the clog-induced asymmetrical flow in the mold, the locally-superheated region and the increased risk of breakouts [10].

The most frequently-used numerical method is the Eulerian-Lagrangian approach, with which both fluid flow and particle motion are calculated. The particles are defined as a discrete phase, for which the motion trajectories are calculated in a Lagrangian frame of reference, while the fluid flow is calculated with Eulerian approach [28,34,35]. This type of model was used to correlate the flow pattern, as caused by different SEN designs, with the clogging tendency [23]. It could also be used to study the influence of the velocity gradient of the melt flow, the turbulent kinetic energy, and the irregularity of flow pattern on the particle deposition tendency [36]. Most studies based on this method focus only on the fluid flow and particle transport, i.e. step (a) of Fig. 1. Although some fluid-wall interactions (e.g. the wall roughness of the SEN and its influence on the flow) could be taken into account [24], the adhesion mechanism (step (b)) and the growth of the clog (step (c)) are ignored.

The Eulerian-Eulerian two-phase approach is also used to study the clogging phenomenon. Here the particles are treated as a secondary Eulerian phase. For example, Ni et al. used this approach to predict the inclusion deposition rate in a SEN where Brownian and turbulent diffusion, turbophoresis, and thermophoresis were considered as transport mechanisms [37,38]. Effects of different process parameters and materials properties on clogging were also studied. A similar Eulerian-Eulerian model was developed by Eskin et al. to explain particle deposition in a vertical, turbulent pipe flow [39]. Again, the adhesion mechanism of the particles on the nozzle wall (step (b)) cannot be considered and the growth of the clog (step (c)) is to be ignored.

The most promising model, which can really cover clogging steps ((a)–(c) in Fig. 1), was recently proposed by Caruyer et al. [40]. They simulated multilayer deposition of particles with a diameter of 80 μm on the bore surface of a pipe, by using an Eulerian-Lagrangian method. The researchers studied fluid velocity modification by deposition over time. In their simulation, the deposited material is supposed to be a closely packed, porous medium, formed by identically sized spherical particles. In addition, their findings lead to the conclusion that incoming particles will always deposit on the wall or other adhering particles.

The current paper presents a new model for simulating the transient clogging process in SEN during continuous casting of steel, covering steps (a)–(c). An Eulerian-Lagrangian approach is applied for the transport of suspended particles along with a special focus on fluid structure near the wall, similar to the method employed by [40] (step (a)). A simplified treatment is implemented to the model for the interaction between particles and the rough wall (step (b)) and a new algorithm is taken to track the growth of the clog (step (c)). This algorithm was originally developed for tracking the solidification front of the columnar dendrite structure [41,42], but here it has been modified to track the