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Transport Processes in Continuous Casting of Steel

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Abstract

Continuous casting is the predominant way by which steel is currently made by steel companies worldwide. In continuous casting, molten steel is continuously poured in a tundish, which then flows to a mold via a submerged nozzle. The mold walls are oscillated and cooled to solidify the steel. As the steel flows down the mold, it is further cooled by jets of water, and rolled as a continuous slab of steel. Far downstream, this continuous slab is cut in desired sections prior to final cooling and shipping as finished product. A large number of complex flow and thermal processes are associated with this manufacturing process. First, as the liquid steel flows through the nozzle, the nozzle can get clogged due to stagnant regions and partial solidification. This causes asymmetric flow to the mold. In order to prevent this, argon gas is injected to stir the flow and also cause mixing in the mold region. The injected gas is in the form of bubbles, but can form gas pockets inside the nozzle. Once the steel enters the mold, it is a turbulent two-phase flow with bubbles and inclusion particles. The jets exiting the nozzles impinge on the steel shell and flow upward as well as downward, thus creating upward and downward recirculating zones. The recirculating zones carry with them the inclusions and the bubbles and are captured at the top slag surface of the mold. The slag can be sheared by the steel flow, entraining slag particles into the cast steel. Large shear velocities at the top surface are detrimental for entraining slag into the mold region, but slow flows are also unwanted due to meniscus freezing problems. The flow in the mold is further controlled by application of magnetic fields in the form of ruler bars, which also modify the flow field in the mold through electromagnetic braking (EMBr). Thus complex flow and heat transfer processes occur in the mold and nozzle regions of a continuous caster of steel, which need to be optimized for defect free manufacture of steel. Defective steel can lead to costly re-melting and plant inefficiencies.

Measurements in liquid steel are extremely difficult due to the high temperatures and the opaque nature of the molten metal. Hence accurate theoretical studies estimating the velocities, turbulence and inclusion transport are very valuable to designing the shapes of nozzle outlet, magnetic field strength, and casting speed. In addition, the shear rates and natural convection at the meniscus must be estimated in order not to freeze the slag region. High fidelity simulations of the turbulent transport processes can provide estimates of particle inclusion, turbulence intensities, and turbulence modification due to the magnetic braking. A popular modeling approach is solution of the Reynolds-averaged Navier-Stokes equations of the turbulent flow, along with other aspects of heat transfer, bubble transport and magnetic braking. However, the fidelity of such simulations is unknown especially because of the lack of actual data in plants or model experiments. The treatment of turbulence through turbulence models is the most uncertain element of the current modeling approach.

Over the past 15 years, we have pursued high-fidelity simulations of the casting process using the approach of Large-Eddy Simulations. LES solves the three-dimensional time-dependent Navier-Stokes equations resolving most of the large-scale structures of turbulence and modeling the small scales by subgrid scale models. Such a modeling is more realistic of the turbulence processes in the mold, although it requires significantly more computational resources. Over the years, the computing hardware have become increasingly powerful, and thus we are currently able to do calculations in the mold with as many as 16 million control volumes, and characterize the three-dimensional flow patterns more clearly. In this talk, I shall review some of the key contributions we have made in developing LES of the mold flow, including bubble and particle transport. Where possible, we have compared with plant data and water model experiments. A number of interesting observations made during these simulations will be presented.