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On modelling parasitic solidification due to heat loss at submerged entry nozzle region of continuous casting mold

A. Vakhrushev[1], A. Kharicha[1], M. Wu[2], A. Ludwing[2], G. Nitzl[3], Y. Tang[3], G. Hackl[3], J. Watziger[4]

[1]Christian-Doppler Laboratory for Metallurgical Applications of Magnetohydrodynamics, Montanuniversität Leoben, Franz-Josef-Strasse 18, A-8700 Leoben, Austria
[2]Chair of Simulation and Modeling of Metallurgical Processes, Montanuniversität, Franz-Josef-Strasse 18, A-8700 Leoben, Austria
[3]RHI Magnesita, Austria
[4]Primetals Technologies, Austria

Nowadays the continuous casting (CC) is one of the most important processes of the steel manufacturing, combining its main advantages such as high production rate, close to the final product shape and its flexibility to be integrated into the heat treatment and rolling chains. However the well-known issues can arise during the crystallization of the solid shell: the surface or internal defects formation due to the rapid solidification, clogging of the submerged entry nozzles (SEN), possibility of the breakouts etc. The numerical simulation approach became a perfect tool for the described risks estimation and for the corresponding counter measures development. Enhanced mathematical models and their applications using computational fluid dynamics (CFD) were widely presented and improved for the last 30 years. Combining the solidification phenomenon [1-3] and the turbulent flow / two phase region interaction [4, 5] in the presented study, they are related to the complex heat transfer phenomenon during continuous casting. The aim of the authors is to give the insights into the problem of the heat loss at the upper region of the mold cavity in vicinity of the submerged entry nozzle. The parasitic solidification on the SEN refractory hot side is investigated by utilizing the solidification model previously developed by the authors in the OpenFOAM® open-source CFD package [6] and significantly enhanced here.

The presented numerical study considers the multi-area domain. A hot melt is fed via SEN into the CC mold. The top surface of the liquid metal is covered with a slag layer. Current model is simplified to consider fully liquid slag only. The cooling effect of the slag band by the ambient air is reflected by corresponding convective heat exchange. The cooling of the copper mold is considered by introducing the heat transfer coefficient (HTC) between the mold and water box. Secondary cooling zone below the mold exit is presented by HTC boundary condition as well. Slag skin of the predefined thickness is introduced between the mold and solidified shell playing insulating role as in the real CC process.

The advanced modelling technique is employed in the presented work. Traditionally a conjugated heat transfer approach is used with the full coupling on the boundary of the solid / liquid region. For the slag / melt interface typically algorithms are used based either on the multi-phase Eulerian or volume-averaged tracking approaches [7]. Combining multi-region conjugated heat transfer with the multiphase fluid flow modelling is computationally costly, thereby a novel 'single-mesh' approach was developed to simulate the complex phenomenon described here with the effective time marching. The general linear equation system is assembled for the whole domain by spatial integration of Navier-Stokes and heat transfer equations using finite-volume method (FVM) and implicit time integration scheme. By modifying corresponding matrix coefficients the velocity field is implicitly set to zero in the refractory and mold regions, where the convective terms in the energy equation are excluded as well to reduce it to conduction problem. Heat flux balance is fulfilled on the cell faces along the boundary between solid and liquid regions. Special treatment is done for the slag band / melt interface: since the slag entrapment is out of the scope in the current study, the interface is kept fixed. Nevertheless the coupling is done on the discretization level for the computational cells in vicinity of the slag / melt boundary. Thereby the momentum transfer from the upper roll of the mold flow, which develops due to the impingement of the fresh melt jets on the narrow walls of the copper mold, to the liquid slag layer is fully considered.

The momentum and heat transfer simulation results were obtained for the slag and melt flow, including the solidification the latter. Heat conduction task was solved for the SEN refractory and copper mold region. For the typical material properties and casting conditions it was possible to detect the areas on the refractory hot side where the parasitic solidification appeared inside the SEN. It was found that the convection in the liquid slag layer plays important role in the heat balance. Special attention was payed to the temperature distributions inside the SEN refractory: from the immersed region till the part of the SEN above the slag band the temperature of the melt drops below the liquidus close to the refractory wall causing steel to solidify. These sites can initiate a deposition of the non-metallic inclusions and enhance the clogging rate. The numerical results were verified by temperature measurements during real CC process and by observation of the SEN after its exhaustion. A great match was achieved for the temperature predictions. The analysis of the deposited material on the internal SEN surface showed the presence of the solidified steel and clogging material combination. After several casting heats, this clog can build a complete tube inside the SEN, significantly increasing the risk of its blockage. Thereby, the results of the presented studies and applied numerical model, verified by the experimental observations, can be directly used as a tool for further development of the SEN designs with an aim to reduce clogging rate and heat loss during continuous casting and to reveal the origins of the parasitic crystallization of the alloys during continuous casting.

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