Development of an OpenFOAM CFD model of the electromagnetically stirred steel flow in the mould of a billet caster

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Abstract

Computational Fluid Dynamics (CFD) is an important tool for studying and optimizing steel-making processes such as continuous casting flows, tundish flows, and the two-phase argon/steel flow in the Basic Oxiden Furnace. The often harsh process conditions make it difficult to assess the flow experimentally, and under those circumstances CFD is the only way to obtain more insight in the flow phenomena occurring in the process. At Corus/Tata RD&T, the commercial CFD packages CFX and Fluent have been used over the years to develop CFD models simulating this type of steel-making processes. The recent merger of Fluent and CFX into ANSYS CFX is considered as a negative development, as their new monopoly position allows to increase prices of licenses due to the dependence of one supplier only. On top of that, a growing interest in more computationally demanding CFD models such as Large Eddy Simulations (LES) exists, putting a larger demand on the use of parallel licenses which all need to be paid for separately. Due to these developments, Corus RD&T started to explore the possibilities to use the freely available open-source CFD package OpenFOAM as a potential modeling tool of steel-making processes over the last year. The present paper illustrates the development within Corus/Tata RD&T of an OpenFOAM model to optimize the electromagnetically stirred (EMS) flow in the mould of a continuous billet caster in order to study the influence of the EMS settings such as rotational speed and magnetic field strength on the flow in mould.

The EMS billet caster (see figure 1) is the final stage of the casting process where the liquid steel flow is poured into a water cooled mould in order to solidify the steel flow and form square billets which are processed further downstream in the fabrication line. Commonly, the flow is stirred below the meniscus level using a rotating magnetic field in order to enhance heat transfer to the water cooled mould walls and obtain a more homogeneous alumina inclusion distribution over the billet. Starting point to model these types of magnetic hydrodynamical (MHD) flows was mhdFoam, the default MHD solver which comes with OpenFOAM 1.6. MhdFoam solves the fully coupled magnetic (B) and velocity (U) field transport equations, whereas in continuous casting the magnetic Reynolds number is lower than one and therefore a full coupling is not strictly required. For this reason, a one-way coupled version was developed where it was assumed that the disturbances of the magnetic field due to the velocity field are negligible. The four step projection method (FSPM) solver for the magnetic field [1] was used which allowed to speed up the solver more than 50%. Both the one-way and two-way coupled solver were validated against the mathematical solution of the laminar flow in a square duct [2], demonstrating that accurate results could be obtained with both solvers for Hartmann numbers (ratio of Lorenz to shear forces) up to 200.

Although accurate results were obtain with the one-way coupled FSPM solver, the momentum source which enters the momentum equations due to the time dependency of the rotating magnetic field is not taken into account, and therefore the solver can only be used for static magnetic fields such as employed in thick slab casters to brake the flow entering the mould. Modeling the effect of the rotating EMS flow requires to take into account the B-field time dependency in order to impose the circumferential force due to the B-field rotation, and therefore a solver based on the fully coupled equations needs to be used. Although the standard mhdFoam solver is fully coupled, it is based on the PISO algorithm and hence not feasible for simulation of the EMS flow due to the stringent constraint on the time step size imposed by PISO, where especially the speed of diffusion of the magnetic field contributes to this constraint. For this reason, the PIMPLE (hybrid PISO/SIMPLE) algorithm was applied on both the velocity field and the magnetic field transport equations, where in the latter case the algorithm was referred to as BIMPLE. Using this newly developed mhdBimpleFoam solver, the constraint on the time step size was released from 0.01 ms to 1 ms, such that the model was feasible to simulate the industrially applied flow in the EMS billet caster. Next to the modification of the solution algorithm of the standard OpenFOAM MHD solver, an LES turbulence model with a damping term on the standard Smagorinksy eddy viscosity was employed to take into account the reduction of turbulent fluctuations due to the local magnetic field strength [3]. The implementation was tested against experimentally validated simulations of the turbulent channel with constant magnetic field [3] and good correspondence was obtained for both the one- and two-way coupled solver based on both the PISO- and PIMPLE-based algorithm.

The final two-way coupled mhdBimpleFoam solver with turbulent magnetic damping was employed to model the

electromagnetically stirred flow in the open mould billet caster at two rotational speeds of 3 Hz and 5.5 Hz, respectively. Simulations at a coarse and a fine grid resolution of 1.1 million and 4.1 million cells, respectively, were carried out. The coarse grid simulations were performed at 32 CPU's in parallel using our in-house Linux cluster comprising 20 quad-core nodes, whereas the validation on the fine grid was carried out at 256 CPU's of the EKA supercomputer of the Computational Research Laboratory in Pune, India. An example of the flow in the mould under influence of the rotational magnetic field is shown in figure 2. Realistic flow features such as the secondary upward recirculation loops and a rotating meniscus surface were obtained. No significant difference was found between the mean flow field for both grid resolution. The results give a clear demonstration of the usability of OpenFOAM for industrial applications.

Key words: MHD, electromagnetic stirrer, steel-making, OpenFOAM, Workshop

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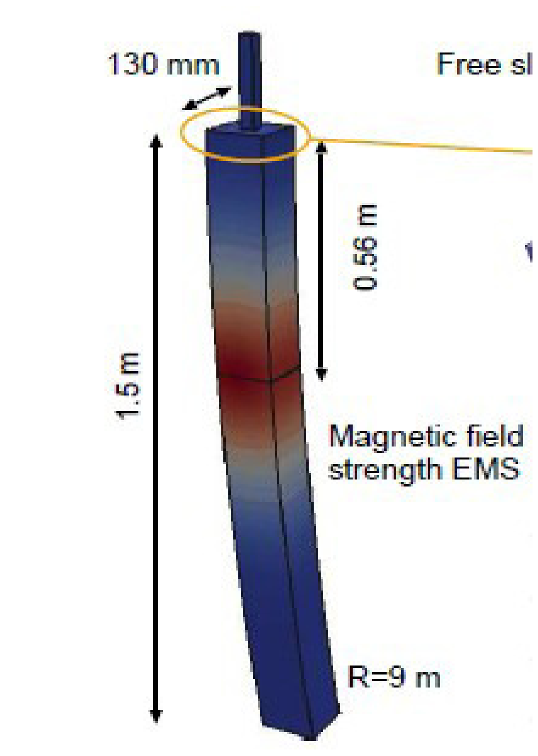

Fig. 1. View on the mould of the billet caster used in the present research. The color scale represents the strenght of the mean magnetic field imposed by the rotating EMS ranging from 0 Gauss (blue) to 500 Gauss (red). Steel enters the domain at the top of the mould via a free slip square section representing the free jet penetrating the mould. The centre of the EMS was located at the horizontal black line 0.56 m below the meniscus. The total mould length was 1.5 with a radius of curvature of 9 m.

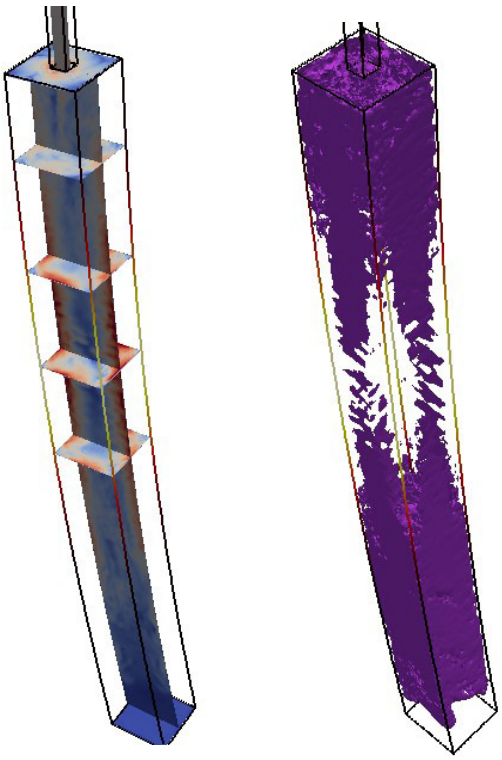

Fig 2. Velocity magnitude of the steel flow rotating in the mould due to the EMS operated at 5.5 Hz showing the increase in velocity in the EMS region (left) and the 10^{-5} m^2/s iso-contour of the eddy viscosity over the mould, demonstrating the local suppression of turbulence due to the magnetic field of the EMS (right).