Comparison of different Methods to model Transient Turbulent Magnetohydrodynamic Flow in Continuous Casting Molds

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Abstract. Modeling of the processes in the continuous casting mold engaged many scientists once the computer-technology was able to accomplish that task. Despite that, CFD modeling of the fluid flow is still challenging. The methods allow deeper and deeper inside views into transient flow processes. Mostly two kinds of methods are applied for this purpose. URANS simulations are used for a coarse overview of the transient behavior on scales determined by the big rollers inside the mold. Besides, LES were done to study the processes on smaller scales. Unfortunately, the effort to set up a LES is orders of magnitude higher in time and space compared to URANS. Often, the flow determining processes take place in small areas inside the flow domain. Hence, scale resolving methods (SRMs) came up, which resolve the turbulence in some amount in these regions, whereas they go back to URANS in the regions of less importance. It becomes more complex when dealing with magnetic fields in terms of EMBr devices. The impact of electromagnetically forces changes the flow structure remarkably. Many important effects occur, e.g. MHD turbulence, which are attributable to processes on large turbulent scales. To understand the underlying phenomena in detail, SRS allows a good inside view by resolving these processes partially. This study compares two of these methods, namely the Scale Adaptive Simulation (SAS) and the Delayed Detached Eddy Simulation (DDES), with respect to rendition of the results known from experiments and URANS simulation. The results show, that the SAS as well as the DDES are able to deliver good results with higher mesh resolutions in important regions in the flow domain.

1. Introduction
Magnetohydrodynamic flows play an important role especially in casting processes where desired flow situations are created by means of so called electromagnetic braking (EMBr). The control of the jet flow inside a continuous casting mold can be seen as a good example. In the process, liquid metal is released from a tundish into the water-cooled copper mold through a submerged entry nozzle (SEN). By virtue of the two outlets positioned at the circumference of the SEN, usually two submerged jets build up. They impinge on the narrow mold walls, forcing the flow to go up to the free surface and down to the solidification region as well. As a result, typical two mirror-symmetrical recirculation roll pairs are created. In consequence of a whole range of different mechanisms (fluid flow, solidification, multiphase flow, clogging, etc.), strong variations in the structure of these recirculation rolls can be
observed. This can be the source of detrimental effects for the final product, e.g. through inclusion transport in the solidification zone. A good overview of plenty of these mechanisms gives Lee et al. [1].

Magnetic fields give the possibility to handle or curb instabilities in the fluid flow. This is done by reduction of jet velocity through Lorentz forces pointing against the flow velocity. Therefore, the name “electromagnetic braking” is given to this principle. However, the reduction of jet velocity can lead to acceleration at other flow regions because of mass and momentum conservation. Also the turbulence is influenced by the magnetic fields resulting in elongated vortex structure and forced anisotropy in every scale (magnetohydrodynamic turbulence). Unfortunately all these complex effects can lead to flows, which are initially not desired and can change the flow situation considerably.

This study compares different methods to model the turbulent flow, starting from two equation unsteady RANS (URANS) models. They are mostly used to describe turbulent flows in technical applications. Unfortunately, when it comes to complex flow physics like magnetohydrodynamic turbulence and relaminarization, the assumptions made for using classical RANS models are not fulfilled anymore. The next step can be the use of Reynolds stress models (RSM), but often a Large Eddy Simulation (LES) is used, which resolves the big turbulent eddies and models the physics on smaller scales through so called subgrid-scale models. The difference in the computational amount is huge. Hence, for a long time every engineer or physician had to make a compromise between accuracy and calculation speed. The problem comes also up if time resolved turbulence data is needed. As a result, hybrid methods are formulated which try to fill the gap between URANS and LES. Two of them are the Scale Adaptive Simulation (SAS) and the Delayed Detached Eddy Simulation (DDES). These are studied here in respect of the rendition of time-averaged and time-resolved data. The comparison is made by using experimental data from the liquid metal mold model mini-LIMMCAST from the Helmholtz-Center Dresden-Rossendorf [2].

2. Governing Equations and Methods

The CFD model of the isothermal, incompressible, turbulent mass- and the momentum transport in the mold flow is based on the Reynolds-averaged or filtered Navier-Stokes equations, respectively.

\[
\nabla \cdot \bar{u} = 0
\]

\[
\rho \frac{\partial \bar{u}}{\partial t} + \rho (\bar{u} \cdot \nabla) \bar{u} = -\nabla \cdot \bar{p} + \eta \Delta \bar{u} - \nabla \cdot \left( \rho \bar{u} \bar{u} \right) + f
\]

(2)

Here, \( \bar{u} \) denotes the flow velocity, \( \bar{p} \) denotes the pressure, \( \eta \) is the dynamic viscosity and \( \rho \) is the density. The term containing the fluctuation velocities \( \nabla \cdot \left( \rho \bar{u} \bar{u} \right) \) is called Reynolds stresses. It accounts for effects attributable to turbulence. RANS-based models assume only momentum diffusion due to turbulence and relate the effect to turbulent properties, e.g. turbulent kinetic energy \( k \). RSM model this term directly through a conservation equation for the Reynolds stresses, while a LES resolves the term in some amount. The rest is solved with a subgrid scale model. In both prior methods the scale-resolving (SRS) methods try to mix both approaches with the purpose to reduce the computational amount compared to an LES while resolving the turbulence partially. The first investigated method in this study is the SAS. Its implementation in OpenFOAM can be found in Kratzsch et al. [3]. In short, the SAS based on a SST model [4] where turbulent quantities are adaptively changed by means of another turbulent length scale, the von Kármán length scale. Eventually, this results in a reduction of the eddy viscosity in these regions. Hence, LES-like unsteadiness inside a URANS simulation is created. For this method a strong disturbance is necessary to get the LES-like behavior. Contrarily, a DDES is stronger connected to an LES because it solves the core flow by LES whereas the near wall flow is solved by a favourable RANS turbulence model. The DDES method used in OpenFOAM is based on the work of Spalart et al. [5], where a Spalart-Allmaras one equation URANS turbulence model is used for the near wall flow.
As seen in equation (2), the Lorentz forces are added to the Navier-Stokes equations by \( \mathbf{f}_L \). Assuming that neither the length scale \( l \) nor the characteristic flow velocity \( U \) of the melt flow is high, the magnetic Reynolds number \( R_m \) is low.

\[
R_m = \frac{U l}{\lambda} = \mu \sigma U l \leq 1 \tag{3}
\]

The corresponding properties are the magnetic permeability \( \mu \) and the electrical conductivity \( \sigma \), respectively. This low magnetic Reynolds-number suffices the inductionless approximation, where induced magnetic fields can be neglected [6]. It is a loose coupling of velocity field and magnetic field. The Lorentz force is calculated from:

\[
\mathbf{f}_L = j \times \mathbf{B}_0 \tag{4}
\]

\[
\mathbf{j} = \sigma \left( -\nabla \psi + \mathbf{u} \times \mathbf{B}_n \right) \tag{5}
\]

\[
\nabla^2 \psi = \nabla \cdot \left( \mathbf{u} \times \mathbf{B}_n \right). \tag{6}
\]

Here, the electric field is replaced by an electric potential \( \psi \) due to vector identity in Faraday's law for static magnetic fields. In order to estimate the strength of the influence of the magnetic field onto the flow, the Hartmann number can be constructed:

\[
Ha = l B_0 \sqrt{\frac{\sigma}{\eta}}. \tag{7}
\]

The Hartmann number measures the ratio of electromagnetic forces to the friction forces. Hence, the Hartmann number is strongly connected to the generation of so called Hartmann-layers, which can be seen as electromagnetically influenced boundary layers. In the case studied here, the Hartmann number is \( Ha_{mold} = 417 \). Thus, the Hartmann-layers are very thin (approx. tenth of millimetres). Resolving these layers is not engaged in this study, which may result in an accuracy loss.

3. Governing Equations and Methods

In this study, we use the open-source CFD software OpenFOAM in version 2.3.x. The common flow solvers are extended to consider magnetohydrodynamic (MHD) flows with the inductionless approximation. The solver distributes the eddy current density to the cell faces. Then, the electric potential can be evaluated at the faces. Thereby, the solver includes balance of fluxes through cell faces to ensure charge conservation and a proper interpolation of \( \mathbf{j} \) from cell face to cell centre [7].

This is of great importance due to the amplification of errors in calculation of \( \mathbf{j} \). Also, correction terms needed for arbitrary non orthogonal collocated meshes were included. The validation of the solver is realised by setting up a Shercliff-type laminar MHD channel flow and can be found in [8]. The flow domain of the CFD model mold is deduced from the mini-LIMMCAST facility located at Helmholtz-Zentrum Dresden-Rossendorf, which is a laboratory scale model of a continuous casting mold working with the eutectic liquid metal GaInSn as model melt. The case of a magnetic field in shape of a ruler is studied. The indication value of the magnetic field reads 0.31T. The distribution is shown in figure 2. Experimental flow data were captured by Ultrasound-Doppler velocimetry (UDV) [2].
Figure 1. Overview of the sampled line and point in the midplane of the mold geometry

For the CFD simulations, all the meshes are generated using the OpenFOAM meshing tool snappyHexMesh. The mesh contains about 1.5 million cells. Earlier studies reveal that the k-ω-SST model [4] by Menter yields best results for pure hydrodynamic flow [9]. Therefore, it is chosen for the URANS simulations. The scale resolving approaches (SAS and DDES) get their initial field from a SAS simulation on a coarse mesh which runs for $t = \frac{V}{V} = 13s$, the characteristic flow time. Here, $V$ denotes the volume of the mold and $\dot{V}$ denotes the flow rate at the inlet. Data were written out every 0.05s for a time of 20s. Point-probes are recorded with the simulation timestep ($\Delta t \approx 10^{-4}s$). Effects by MHD turbulence, like forced vortex anisotropy due to fluctuating Lorentz forces are not considered in the URANS turbulence model. However, the scale resolving methods should capture this effect in some amount. Regarding the discretization, higher order accuracy schemes are used preferentially in order to minimize the effects of numerical diffusion. For all the simulations, the Courant number is held below unity.

4. Results

In order to evaluate the simulations, mean and instantaneous velocities are plotted in various figures. Figure 1 gives an overview over the sampled lines, points and slices in this section. First, the mean velocity field in the midplane of the mold geometry is depicted in figure 3. It is obvious, that only the DDES simulation yields a symmetrical mean in the upper mold between the left and the right side,
while the SAS- and the URANS-velocity fields are asymmetrical. Despite that, every simulation yields two recirculation rolls in the upper mold, whereas the lower mold does not have a distinct twin roll structure. This behavior is pointing towards the already known jet oscillation enforced by the magnetic field.

![Graph showing mean velocity magnitude in the midplane of the mold geometry for URANS, SAS, and DDES.](image)

**Figure 3.** Mean velocity magnitude in the midplane of the mold geometry for the URANS, SAS, and DDES.

The oscillation is elucidated by figure 4 for the approaches SAS and DDES. Three timesteps are shown there. It can be seen, that both methods show a more or less periodical structure with downbending of one jet, a central position where both jets have equal angles and afterwards the downbending of the other jet. They are able to resolve a small amount of turbulent scales, like it can be seen at the jet breakup. Apparently, the magnetic field is strong enough at the SEN outlets to damp disturbances through the impingement at the SEN well. Hence, the flow in the SEN right before the release in the mold cavity is fixed compared to a pure hydrodynamic flow. Another reason for the lack of scales in the early jet region can be an insufficient mesh resolution.
Figure 4. Time-dependent velocity field of the magnitude velocity at three snapshots. SAS snapshots – 18.6s, 19.3s, 19.9s; DDES snapshots – 8.0s, 9.0s, 10.0s.
In order to evaluate the results quantitatively, the time-dependent lateral velocity at point P1 is analyzed with a Fast Fourier Transformation (FFT) depicted by figure 5. As figure 1 shows, the point is in close vicinity to the jet outlet and is located at the lower side of the jet. Thus, the point can contain characteristics from the flow of the lower mold because of the infrequent upward directed flow in the lower mold. The plot of the experimentally captured velocity shows one dominant single peak at 0.3 Hz. Comparing this results with the three approaches studied here, clear distinctions can be found. By taking a look on the SAS results, the best accordance in matching the experimental frequency can be observed. Besides, a sub-peak of about 0.6 Hz exists. The DDES graph shows a good agreement with the experimental data. It matches well the experimentally observed frequency without distinct sub-peaks. With the URANS simulations a main-peak can be observed at about 1Hz. Besides, multiple sub-peaks exist, which points to a less pronounced oscillatory behavior.
Figure 6. Spatio-temporal plot of the horizontal velocity $u_x$ over Line 1.

It is clear that this peak can be correlated with the jet oscillation and the lower mold flow structure created by the strong magnetic field. High frequencies as a source of the turbulence are damped by the magnetic field and vanish due to their low energetic level. The flow is left with large scale oscillations which have enough energy to preserve. The jets experience these oscillations and therefore the whole flow situation changes. Regarding the deviations between the URANS and the SRS methods, it seems that the attempt to resolve the regions where the strongest interaction of the magnetic field and the turbulence exist seem to work.

A more elaborate depiction is a spatio-temporal plot of a line, which crosses the jet (in this case line 1 sketched in figure 1). Therein, the jet oscillations can be seen over the half width of the mold. An upbended jet is denoted by high velocities in lateral direction while a downbended jet is denoted by low velocities. Low values in $x$ denoting close vicinity to the SEN. High values in $x$ denoting close vicinity to the narrow wall. It can be seen that the SAS and DDES results resemble the experimental results the best. However, the jet fluctuations towards the SEN (lower values in $x$) match better with
the experiments. The disruption patterns of the jet are hard to compare as well as the fluctuations towards the narrow walls.

5. Conclusion

The study has shown, that SRS methods can resolve turbulence in a limited amount with mesh resolutions compared to typical URANS simulations. This can give a brighter inside view in the flow behavior and the mechanisms of MHD turbulence and represents a justifiable step away from URANS simulations towards LES. It is confirmed that SRS approaches render a magnetic field enforced oscillation in good accordance with experimental data. The URANS approach lacks in reproducing this behavior. Apparently, the URANS model have to be augmented by adding sink terms for the effect of the MHD turbulence, e.g. by means of [10]. The evaluation of the SRS approaches will be pursued by comparison with LES using revised subgrid scale modeling regarding anisotropy and relaminarization.

References

[1] Lee, Peter D., et al., Review: The “butterfly effect” in continuous casting, Ironmaking & Steelmaking (2012), p. 244
[2] Timmel, K., et al., Experimental Investigation of the Flow in a Continuous-Casting Mold under the Influence of a Transverse, Direct Current Magnetic Field, Metallurgical and Materials Transactions B (2011), p.68 – 80.
[3] Kratzsch, Christoph, Asad, Amjad and Rüdiger Schwarze. "CFD of the MHD Mold Flow by Means of Hybrid LES/RANS Turbulence Modeling." Journal for Manufacturing Science and Production.
[4] Menter, F.R., Two-equation eddy-viscosity turbulence models for engineering applications, AIAA Journal (1994)
[5] Spalart, Philippe R., et al. "A new version of detached-eddy simulation, resistant to ambiguous grid densities." Theoretical and computational fluid dynamics 20.3 (2006): 181-195.
[6] Davidson, Peter Alan. An introduction to magnetohydrodynamics. Vol. 25. Cambridge university press, 2001.
[7] Ni, M.-J., et al., A current density conservative scheme for incompressible MHD flows at a low magnetic Reynolds number. Part II: On an arbitrary collocated mesh, Journal of Computational Physics (2007), p. 205 – 228.
[8] Kratzsch, Christoph, Schwarze, Rüdiger. "Modeling of the continuous casting mold flow under influence of magnetic fields." 8th European Continuous Casting Conference. 23 – 26 June 2014, Graz, Austria. pp. 239 – 245.
[9] Kratzsch, Christoph, et al. "URANS simulation of continuous casting mold flow: Assessment of revised turbulence models." steel research international 86.4 (2015), pp. 400 – 410.
[10] Widlund, Ola, Said Zahrai, and Fritz H. Bark. "Development of a Reynolds stress closure for modeling of homogeneous MHD turbulence." Physics of Fluids (1994-present) 10.8 (1998): 1987-1996.