Experimental and Numerical Modeling of Fluid Flow Processes in Continuous Casting: Results from the LIMMCAST-Project

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Abstract. The present paper reports about numerical simulations and model experiments concerned with the fluid flow in the continuous casting process of steel. This work was carried out in the LIMMCAST project in the framework of the Helmholtz alliance LIMTECH. A brief description of the LIMMCAST facilities used for the experimental modeling at HZDR is given here. Ultrasonic and inductive techniques and the X-ray radioscopy were employed for flow measurements or visualizations of two-phase flow regimes occurring in the submerged entry nozzle and the mold. Corresponding numerical simulations were performed at TUBAF taking into account the dimensions and properties of the model experiments. Numerical models were successfully validated using the experimental data base. The reasonable and in many cases excellent agreement of numerical with experimental data allows to extrapolate the models to real casting configurations. Exemplary results will be presented here showing the effect of electromagnetic brakes or electromagnetic stirrers on the flow in the mold or illustrating the properties of two-phase flows resulting from an Ar injection through the stopper rod.

1. Introduction
During the last decades, continuous casting has become the dominant process of steel casting, accounting for approximately 95% of the annual world steel production [1]. Nevertheless, research is still being done with great effort to further develop and improve the process. It became obvious that the flow of the liquid steel in the tundish, the submerged entry nozzle (SEN) and the mold is one of the major issues, which is decisive for the steel quality at the end of the process [2]. In particular, the surface quality of the casted strand or the incorporation of inclusions is influenced by the structure and intensity of the mold flow. An efficient adjustment and control of the fluid flow and the related transport processes ensure a good quality of the product or facilitates a stable and efficient process. The steel flow is usually influenced by plant design, i.e. the geometry of the SEN, but this is fixed throughout the operation of the continuous caster. More flexible tools for flow control are electromagnetic fields, which are already in industrial use since about 30 years. There are basically two types of electromagnetic actuators in operation: so-called electromagnetic brakes (EMBr) generate a static magnetic fields for damping the turbulent flow and electromagnetic stirrers (EMS) use an alternating...
magnetic fields for stirring and pumping the liquid metal. However, the interaction between the turbulent steel flow and the diverse magnetic field appears to be rather complex and deserves further investigation.

Many numerical simulations have been conducted dealing with various aspects of the casting process, such as the submergence depth of the submerged entry nozzle [3], the design aspects of the nozzle ports [4], the particle wall interactions and nozzle clogging [5, 6] or the effect of electromagnetic fields [7, 8]. However, numerical models for multiphase flows and turbulent flows in large scales need to be validated by reliable experimental data. A comparison of the numerical results with plant trials require the availability of robust and suitable measuring techniques.

Flow measurements in liquid steel are very difficult. Because of the high temperature of about 1500°C and the harsh environment at the casting machine, there are almost no measurement techniques available. Some rough information might be retrieved from observations of the free surface by dipping paddles or nail-boards into the melt [9–13], but flow measurements from deep inside the liquid steel in a real casting machine are still missing and there is no solution foreseeable for years to come. During the last decades water experiments are used for modeling the flow in the SEN and the mold. Respective investigations of the flow field were done by optical methods, e.g. [4, 14]. The modeling activities have to consider the significant differences in the material properties of water and liquid steel. While an appropriate scaling of the experimental model can achieve the similarity in terms of Reynolds and Froude number, the dramatic deviations in the surface tension and the thermal as well as the electrical conductivity render serious investigations of many flow problems actually impossible (like heat transfer, influence of magnetic fields, two-phase flows). This is illustrated by the mismatch in other dimensionless numbers, e.g. Morton, Hartmann or Prandtl number.

Model experiments in liquid metals provide an attractive possibility for investigations of fluid dynamic aspects in continuous casting. Three experimental facilities have been designed and assembled at HZDR in the framework of the LIMMCAST program [15]. The LIMMCAST-project within the LIMTECH alliance deals with the experimental and numerical modeling of the continuous casting of steel. Therefore, it covers both essential modeling strategies and allows a comparison of results and a validation of numerical models. This paper will give an overview about the experimental and numerical activities inside this project and present some recent results.

2. Modeling of the continuous casting process
2.1. The experimental models
The experimental facilities LIMMCAST and mini-LIMMCAST have been build up at HZDR for investigations of flow phenomena being relevant for the continuous casting process [15]. A third model setup has been realized for the visualization of two-phase flows in the submerged entry nozzle and the mold by X-ray radiography [16].

The design concept of all three experimental facilities contains the main components of a continuous caster, which are: the tundish, the submerged entry nozzle (SEN) and the mold. The facilities were planned and assembled as a flexible construction allowing for an easy modification of the setup at a reasonable effort and time. The transport of the liquid metal is achieved by induction pumps operating with permanent magnets. The liquid flow rate through the submerged entry nozzle is controlled by a stopper rod device. Experiments have been conducted using rectangular molds of different sizes and aspect ratios. Moreover, various geometrical configurations of submerged entry nozzles can be applied. A photograph of each setup is presented in figure 1 with indications of some major parts.

The dimensions of the model experiments are designed to meet the requirements with respect to the similarity. Main dimensionless numbers are the Reynolds number, Froude number, magnetic Reynolds number, Hartmann number or the magnetic interaction parameter. These
dimensionless numbers achieved at the experimental setups are well within the range of the literature values of real casters [17]. The maximum of the Hartmann number, which can be reached in the experiments with the actual existing electromagnets, is a little bit over 400 at mini-LIMMCAST [18] and around 1800 at LIMMCAST [15], whereas an exemplary reference from a real caster reaches a value of about 350. So, the electromagnets needn’t to be operated at full power in the experiments to achieve similarity according to the Hartmann number in the given example. The simple geometric scaling of the model molds is in the range of 1:3 to 1:10. The cross sections of the prototype casters cover a wide region from thick to thin slab geometries. Basically, the experimental setups in this paper are modeling such slab casters. The rectangular cross sections of the molds have an aspect ratio of 1:4 to 1:6.7.

2.1.1. LIMMCAST
The LIMMCAST facility is the largest experimental facility available at HZDR for modeling the continuous steel casting process. The tin-bismuth-alloy (Sn$_{60}$Bi$_{40}$) is used as model liquid here. The physical properties of the alloy were measured and reported in [19]. The liquidus temperature of this alloy is 170 °C requiring operating temperatures in the range of 200 °C to 350 °C. All components and connecting pipes are made of stainless steel and are equipped with electric heaters and thermal insulation. In the first stage the facility is operated under isothermal conditions. Experiments with cooling and solidification are considered as a future option.

2.1.2. Mini-LIMMCAST
The mini-LIMMCAST setup is a small-scale model operating with the eutectic alloy GaInSn. That alloy is liquid at room temperature. The absence of electrical heaters eases the experimental effort and reduces potential interferences with sensitive measurement techniques significantly. The material properties can be found in [20]. The mold and the SEN are made of acrylic glass. The application of plastic materials enables a very flexible modification and a quick realization of complex geometries. The electrical wall conductivity plays an important role in experiments with an electromagnetic brake. Thin metal plates have been inserted at the inner mold wall for achieving electrically conducting boundary conditions in the mini-LIMMCAST mold.

2.1.3. X-LIMMCAST
The third experimental setup X-LIMMCAST was especially designed for the visualization of liquid metal/Argon two-phase flows by X-ray radiography. It is also made of acrylic glass and operated with GaInSn. The mold has a rectangular cross section with a maximum mold thickness.

Figure 1. Pictures of the three experimental setups
of 15 mm. This important restriction is caused by the high X-ray attenuation coefficient in the liquid metal. The damping of the X-ray becomes too strong at a larger thickness of the liquid metal domain and the number of photons is then no longer sufficient to provide a sufficient image contrast at sufficiently small exposure times. A scintillation screen located just behind the flow vessel to be investigated and a CCD-camera are used for the image acquisition. The observation window area can be shifted which allows for covering the area of gas injection at the stopper rod or the lower part of the SEN and the mold.

2.1.4. Velocity measurement techniques suitable for liquid metal modeling
The experiments at the liquid metal models of the LIMMCAST-family and the investigation of the related flow phenomena require an appropriate tool-box of measurement techniques. Flow measurements in liquid metals are a challenging task but nevertheless an inevitable condition for performing model experiments. The well-established optical methods in fluid dynamics cannot be applied due to the opaqueness of the metal melts. Other measuring principles relying on ultrasonic techniques or inductive methods can be used, however, ready-to-use commercial products for spatially and temporally resolved measurements in liquid metals are very rare. Therefore, new measurement techniques have been developed and qualified at HZDR for liquid metal flows. Ultrasonic techniques are a very attractive candidate for substituting the optical methods in the field of non-transparent liquids. In the 90’s the Ultrasound-Doppler-Velocimetry (UDV) was established as a powerful tool for velocity measurements in fluid dynamics [21–23]. Meanwhile the equipment (sensors and instruments) were adapted to the specific operational conditions in liquid metal flows and the application range was extended towards higher temperatures, e.g. [24, 25]. This method is used as the main and reference method for the mold flow. A fully new approach for the reconstruction of three-dimensional flow pattern in liquid metals is the Contactless Inductive Flow Tomography (CIFT) [26, 27], The technique relies on the detection of flow-induced magnetic fields outside the liquid metal, which result from the interaction between the fluid flow and an externally applied excitation magnetic field. The capabilities of CIFT for measurements of the mold flow could be successfully demonstrated [28]. CIFT results were compared with UDV measurements and showed a very good agreement. Further research work has been done to improve the robustness of this method against disturbances. A detailed insight into this measurement principle and its first application to an continuous casting model experiment can be found in [28].

Another contactless velocimeter is the Local-Lorentz-Force-Velocimetry (LLFV). This technique is based on the principle of the Lorentz-Force flow meters [29]. The extension of the measurement devices towards local velocity measurement is a more recent development and had already been tested at a duct flow in a closed liquid metal loop [30]. The feasibility of LLFV measurements was tested at the mini-LIMMCAST facility.

2.2. Numerical model
The geometric dimensions for the calculation domain and corresponding material properties are taken from the experimental setups. The flow is assumed to be isothermal, incompressible, turbulent and under the influence of external magnetic fields.

2.2.1. Governing equations
The flow in the continuous casting process can be described by the conservation equations for mass and momentum:
\[ \nabla \cdot \bar{\mathbf{u}} = 0 \] 
\[ \rho \frac{\partial \bar{\mathbf{u}}}{\partial t} + \rho (\bar{\mathbf{u}} \cdot \nabla) \bar{\mathbf{u}} = -\nabla \bar{p} + \nabla \cdot (\eta \nabla \bar{\mathbf{u}}) + \nabla \cdot \tau^{\text{mod}} + \mathbf{F}_{\text{EM}} + \mathbf{F}_{\text{MP}}. \] 

Here, \( \bar{p}, \bar{\mathbf{u}}, \mathbf{F}_{\text{EM}} \) and \( \mathbf{F}_{\text{MP}} \) are pressure, velocity, electromagnetic forces and multiphase forces. The quantities are either Reynolds-averaged or filtered, depending on the turbulence modeling method used. \( \rho \) and \( \eta \) denote the fluid density and the dynamic viscosity, respectively. The unknown stresses \( \tau^{\text{mod}} \) are either Reynolds stresses in case of RANS-type turbulence modeling or subgrid stresses in case of LES. They have to be provided by suitable turbulence models.

### 2.2.2. Turbulence modeling

Two different approaches are considered to describe turbulence. The first turbulent closure is realized through the unsteady Reynolds-averaged Navier-Stokes (URANS) approach. By using this type of model, a typical RANS model keeps an unsteady term in its transport equations. This enables the ability to resolve large-scale in the inertial domain.

The second one are Scale Resolved Simulations (SRS). In this concept turbulent scales are resolved in some amount, while the rest is modeled. The classic approach is the Large Eddy Simulation (LES), where the larger eddy motions are directly calculated by the filtered equations. The drawback is that the amount of resolved eddies has to be very high since the so-called subgrid scale (SGS) models are tailored towards small scale physics. In this study, the \( \sigma \)-model fulfills all requirements [31, 32] for this complex fluid flow. The model is able to switch to a two-dimensional turbulence description. This is of importance since two-dimensional turbulence can occur in turbulent flows under strong magnetic fields [33, 34]. Moreover, the model uses a proper wall modeling with cubical decay of the SGS viscosity normal to the wall. It uses singular values of the resolved velocity gradient tensor and therefore incorporates some structure of the turbulence. Moreover, it is comparable in its behavior to a dynamic Smagorinsky SGS. In a recent study, this was found to be most suitable for MHD turbulence at low magnetic Reynolds numbers [35]. Nevertheless, the calculation time and the mesh size in LES can become incredibly high depending on the flow type. A way to overcome these problems is represented by hybrid turbulence models. The Delayed Detached Eddy Simulation (DDES) pursues the concept of blending over between a near-wall RANS-like modeling and an LES-like modeling in the core flow. This eliminates the need of a near wall refinement and reduces the calculation time. The DDES model here utilizes the Spalart-Allmaras model for the RANS task and the SGS part in the core region [36]. Another idea incorporates more features of the URANS modeling concept. The so-called Scale Adaptive Simulation (SAS), makes use of inherent flow instabilities to generate more unsteadiness as a traditional URANS can render. The reason is that these instabilities are not damped by turbulent viscosity. Hence, large turbulent eddies can be resolved. However, it is necessary to have a finer mesh in regions, where these instabilities arise. The method is often called the second generation of URANS, because of its close link to the URANS model [37]. The most common formulation is the combination of the SAS method [38] with the Shear Stress Transport (SST) variant of the \( k-\omega \) RANS model [39]. Following the modeling equations, it can be observed that just one additional term is included in the specific turbulent dissipation rate equation that enables the SAS characteristics.

### 2.2.3. Electromagnetic forces

The electromagnetic forces \( \mathbf{F}_{\text{EM}} \) in equation (2) can be generally described by the induction equation for a varying magnetic field \( \mathbf{B} \). Since the length scale and the velocities in the experiment are small, the magnetic Reynolds number \( \text{Re}_m \) is smaller than unity. Hence, the
induced currents $\vec{j}$ do not affect the imposed magnetic field $\vec{B}_{0,y}$, which allows a simplification called quasi-static approximation. All in all, it represents a one-way modeling of the electromagnetic forces [40]. The electromagnetic forces act as Lorentz forces in the Navier-Stokes equations and require only the solution of an additional Poisson equation for the electric potential $\vec{\psi}$:

$$\nabla^2 \vec{\psi} = \nabla \cdot (\vec{u} \times \vec{B}_{0,y})$$

(3)

$$\vec{j} = \sigma (-\nabla \vec{\psi} + \vec{u} \times \vec{B}_{0,y})$$

(4)

$$\vec{f}_L = \vec{j} \times \vec{B}_{0,y}.$$  

(5)

The subscript 0 in the description of the magnetic field denotes the static character whereas $y$ denotes the alignment of the magnetic field with the $y$-direction in this study.

2.2.4. Multiphase modeling

Multiphase flow in the continuous casting mold appears in many ways. Here, a bubbly flow is considered, as it develops from argon gas injection at low and moderate gas flow rates. The resolution of the bubble interface is not expedient. Hence, a much cheaper technique is the point-particle approach within the Lagrangian frame. The bubble is seen as point mass which experiences different forces. The bubbles can move inside the Lagrangian domain, where the forces on the particle like drag, pressure, virtual mass [41], lift [42] and electromagnetic forces [43] are interpolated from the Eulerian domain. Integration of all the forces yields a bubble trajectory.

Since argon bubbles are subjected to break-up and coalescence, bubbles of different sizes can be observed. A recent study has measured these bubble size distribution in a liquid metal mold model [16]. This distribution was used for the simulations here.

The most important force acting on a moving bubble is the drag force. In a recent study [44] the authors found a large influence of bubble shape (by means of $C_{D,Dij}$) and swarm effects (by means of $C_{D,Rog}$) on the quality of the results using tailored drag models by [45, 46]. The drag model was then extended towards MHD effects (by means of $C_{D,Jin}$) using findings of a recent study [47]:

$$C_{D,Rog} = C_{D,Jin} + \left( \frac{22}{Eo + 0.4} \right) (1 - \alpha_c) C_{D,Jin}$$

(6)

with

$$C_{D,Jin} = \begin{cases} C_{D,Dij} (1 + 1.5N + 7.06N^2) & \text{if } 0 \leq N < 0.245 \\ 1.8 C_{D,Dij} & \text{if } 0.245 \leq N < 0.65 \end{cases}.$$  

(7)

Here, $\alpha_c$ denotes the phase fraction of the continuous phase, $Eo$ denotes the Eötvös number and $N$ denotes the magnetic interaction parameter.

2.2.5. Numerical method and computational cost

The coupled Navier-Stokes MHD equations (Equation (1)-(5)) were discretized on a hexa-dominant unstructured mesh using the finite volume method within the open-source CFD library OpenFOAM. The Lorentz force is added as an explicit source in the momentum equations. After the flow development, the flow fields are collected for 20 s for the mini-LIMMCAST geometry and 80 s for the upscaled mold geometry.

The different turbulence modeling methods demanding for different mesh resolutions. In a previous study, the authors have shown that the SAS needs at least 1.5 million cells in the case
of the mini-LIMMCAST geometry [48]. This is achieved by an overall cell size of 1.5 mm and a refined region of 0.75 mm cell size. During the paper, results of the SAS approach on a fine mesh are also shown, which consists of 3.5 million cells. The upscaled mold geometry consists of 5 million cells, where the majority of cells is located in the first 1.5 m of the strand. The simulation of the SAS on the medium size mesh of the mini-LIMMCAST takes about 6 days on 32 cores of 2.9 GHz Intel Xeon X5670 processors in the high-performance computation cluster at the TU Bergakademie Freiberg, while the fine mesh requires 25 days on 64 cores. The LES of the upscaled mold geometry takes about 30 days on 128 cores.

3. A short review on LIMMCAST results
The following sections will briefly summarize the research activities conducted by the LIMMCAST project within the LIMTECH alliance during the last five years.

3.1. Effect of electromagnetic fields on the mold flow
The impact of a static magnetic field on the mold flow was already a prominent topic in previous studies of the LIMMCAST program, e.g. [18, 49]. It was shown that the electrical boundary conditions at the mold wall have dramatic influence on the properties of the mold flow [17]. Insulating boundary condition can lead to dramatic flow oscillations whereas the flow becomes steady in case of conducting boundary conditions. Regardless of the electrical boundary conditions at the mold walls, a reverse flow close to the jet is triggered by the static magnetic field and a strong upward flow can be observed at the narrow mold wall above the jet. Moreover, a tendency to form two-dimensional flow structures along magnetic field direction becomes apparent. The insulating case showed some more special features, like an jet oscillation and the transition from a standard double roll flow in the mold to multiple rolls. In the lower mold one can now find a single roll over the whole mold width, which can also change its rotation direction over time. Generally, the symmetry was broken by the EMBr under insulating boundary conditions. These findings were also obtained by subsequent numerical simulations [7, 49–51]. The flow structures are sketched in figure 2. The standard double roll flow pattern under reference condition without magnetic field is shown in the left mold half. The effects of the EMBr especially at insulating boundary conditions is sketched in the right mold half. The strategy for applying electromagnetic actuators can vary in the magnetic field design or the positioning of the magnetic coils at the mold. Therefore, experimental studies about the effect of variations of the EMBr position at the mold were performed for different nozzle designs [17, 52]. The same problem was investigated again by numerical simulations [53].

Another study addresses the action of a rotary electromagnetic stirrer (EMS) at the mini-LIMMCAST facility in a round mold [54]. The round mold in the experiments was a 1:3 scale model of an actual caster. The flow measurements were obtained by means of the UDV method. Three different situations were investigated in this work: the jet from the nozzle without EMS, a purely EMS-driven flow and a superposition of both. The EMS driven mold flow revealed the structure of a primary swirling flow and a secondary flow in the meridional plane consisting of two toroidal vortices. The secondary flow is significantly weaker as the primary flow, but, it is responsible for a redistribution of angular momentum in the melt. The combination of the jet flow with the stirrer showed a dramatic increase of free surface velocities with the creation of vortices and strong surface deflections near the nozzle [54]. The measurement results were used for the validation of numerical models in corresponding simulations [55] which are supposed to provide reliable predictions of the flow in the real caster.

3.2. Mold surface
In the industrial process of continuous casting the mold surface is of particular interest because it is the only access for visual observation by the operator or the positioning of crude testing
probes. Moreover, the stability of the interface between the melt and the slag layer is regarded as a crucial issue with regard to achieving defect-free casting products [2]. Disadvantageous flow conditions can lead to entrainment of impurities, surface freezing, hook formation and other problems. This explains the desire for as low as possible surface disturbances and a sufficient heat transfer from the melt to the slag layer which ensures a sufficient melting of the flux powder for the lubrication of the strand. Therefore, some melt convection should exist just beneath the melt surface, but, the velocities should not exceed a certain limit to avoid the entrainment of impurities, slag or flux.

The melt surface was also examined in the mini-LIMMCAST experiments. Here, a slag layer does not exist, but the free surface of the liquid metal is covered by a certain oxide layer. In particular, the surface level in the mold and the tundish can be detected by an ultrasonic distance sensor. The sensor tracks the temporal behavior of the melt level at one location, e.g. [15]. A comparison of such results with an analytical assessment by the extended Bernoulli equation (including friction losses and accelerations) showed a good agreement [17]. As a second possibility, a video camera was applied for the visualization of the melt surface [17]. The recorded images revealed a specific frequency of the free surface in a slab configuration without electromagnetic actuators. This natural frequency is related to a surface wave with a wavelength of twice of the mold width [17]. Another approach uses line lasers in combination with video imaging for an improved quantitative evaluation of the surface behavior. A laser scanner provides time series of the surface profile along the central line at the mold surface [56]. For instance, the observation of the melt surface at the mini-LIMMCAST setup also showed the detrimental influence of an ill-posed EMBr at insulating boundary conditions. In this case,
the melt surface becomes obviously unstable and shows intensive sloshing and bulging. The differences in the surface behavior are also sketched in figure 2 and an example of the surface profiles measured by the line laser is depicted figure 3. Such strong level oscillations were not observed in case of electrically conducting mold walls.

3.3. Argon injection

The effect of Argon gas injection has been studied at the X-LIMMCAST facility by X-ray radiography [16]. Two observation windows were chosen covering the injection point of argon gas at the tip of the stopper rod and the jet region in the mold, respectively. The monitoring of the two-phase flow in the injection region revealed the occurrence of large void zones in the upper part of the SEN just below the stopper rod. An exemplary picture from the injection point including the clearly visible void zones can be seen in the left of figure 4. The majority of the bubbles detaching from the stopper rod were captured by the void zones. The detachment of relatively large bubbles were observed at the end of the void zones. Smaller bubbles are formed by strong shearing in the bottom part of the SEN just before the nozzle ports [16]. The rather flat geometry of the X-LIMMCAST mold (see section 2.1.3) restricts the flow to an almost two-dimensional pattern. The liquid metal jets emerging from the SEN divide the mold flow in an upper and lower part. Because of the high inertia of the liquid metal jet the small bubbles are dragged into the lower recirculation zone in the mold. A direct ascending motion of the bubbles is blocked by the jet. The increasing gas concentration in the lower part of the mold promotes coalescence resulting in larger bubbles. The mean bubble size grows until the related buoyancy force becomes strong enough to overcome the jet barrier [16]. An sketch of the two-phase flow phenomena observed at X-LIMMCAST is depicted in the middle of figure 4. The right picture in figure 4 presents a snapshot of the two-phase flow in the mold. The two X-ray images in figure 4 reveals also the challenging task of identifying the fast moving bubbles.

![Figure 4](image-url)  
**Figure 4.** Sketch of two-phase flow in the SEN and the mold as it was observed at X-LIMMCAST (middle) and exemplary X-ray images of the argon injection (left) and the two-phase mold flow (right), both with an gas flow rate of 1.67 cm³/s and an melt flow rate of about 110 cm³/s.
3.4. Application and test of new measurement techniques

The development of the CIFT method for applications in the field of continuous casting has been reviewed in [57]. Further progress has been made to improve robustness and applicability of the method. A measuring configuration was designed and realized for the LIMMCAST facility. Related reconstructions of the flow field can be found in [58]. The detection of the weak induced magnetic field created by the melt flow is a challenging measurement task, especially in the presence of other disturbing external magnetic fields. A feasibility study about the applicability of the CIFT technique at a mold equipped with an EMBr was carried out for the mini-LIMMCAST setup [59]. It became obvious that the acquisition of the CIFT signals in presence of a much stronger EMBr can be successfully performed by specific induction coils [58, 60]. Another task is the application of gradiometric magnetic field sensors instead of flux gate sensors or single induction coils. Measurements by gradiometric coils are more robust against electromagnetic disturbances. First test measurements at mini-LIMMCAST are reported in [61].

The Local-Lorentz-Force-Velocimetry (LLFV) is dedicated for a localized and contactless measurement of the melt velocity. The applied LLFV sensor is able to measure the induced force as well as the torque in all three dimensions, resulting in six measurable parameters. Both, force and torque, can be used to determine the local velocity in all three directions. Test measurements were carried out at the mini-LIMMCAST setup [62]. These experiments revealed that the torque is less sensitive to noise than the force measurement [62]. The comparison of LLFV data with corresponding UDV measurements obtained in the mold center plane revealed some qualitative differences. These deviations can be associated with the restriction of the LLFV measuring volume to regions close to the mold wall and three-dimensional flow effects in the flat mold. A better agreement between LLFV and UDV data were obtained for UDV measurements conducted close to the mold wall [62].

3.5. Validation and comparison of different turbulence models

Since turbulence modeling concepts are based on canonical flow problems, the models are not universally applicable to every flow problem. Therefore, the first study was intended to find the most suited RANS turbulence model for mold flows [63]. The study came to the conclusion that the k-ω SST model is in favor of all the other models considered. Moreover, second order discretization was found to be crucial for reasonable results. The first observation with the OpenFOAM MHD numerical model has identified an active flow oscillation once an magnetic field is applied [48]. The study has also shown that conventional URANS modeling lacks of the MHD turbulence aspect which has either to be included in the model or tackled by models which allow more unsteadiness of the flow. The latter concept was pursued in subsequent studies [64, 65]. First, the SAS concept by Menter et al. [66] was utilized to the MHD flow problem. The model exhibits dependence on the mesh resolution of the refined mesh region. Nevertheless, the flow shows more fluctuation and unsteadiness (see Fig. 5 c)).

The already found oscillation is rendered very well and additionally turbulent scales can be resolved which then underlie Lorentz forces. Therefore, MHD turbulence can be described to some amount. The vertical component of the velocity along a line from the surface to the bottom of the mold is shown in Fig. 5 a) and b). In case without an EMBr, the profiles show a significant peak of the jet and a recirculation with upward directed velocities in the lower mold. The numerical and experimental data of the temporal average are in very good agreement. In contrast to that, the profiles of the MHD case show strong differences between the used modeling methods and a left-right asymmetry as well. The reason is the oscillation that is not perfectly periodic since a small shift in the magnetic field has drastic effects. In addition the measurement period only captures a few cycles of the oscillation. Among the turbulence modeling methods, the LES gives the most reasonable results. The upper recirculation and the jet progression matches quite well, despite differences in the jet angle. Moreover, deviations
Figure 5. Left: Profiles of the time-averaged vertical velocity $\bar{u}_z$ in the midplane at $x = 20$ mm. (a) $B_{0,y} = 0T$; (b) $B_{0,y} = 0.31T$, insulating wall. UDV data filled with standard deviation. (c): Snapshots of the velocity magnitude $|\bar{u}|$ distribution in the midplane for a SAS on a fine mesh. $B_{0,y} = 0T$ (top); $B_{0,y} = 0.31T$ (bottom).

from the experimental profile can be found in the lower mold because of modification of the outlets in the case of an LES.

Another study incorporates the DDES modeling concept by Spalart et al. [36] to the comparison [65]. Once again, the SRS models seem to be in better accordance with experimental results of the average flow as well as in instantaneous flow features. Apart from the turbulence modeling, the dynamics of the free surface level in mold flows was investigated in another study [67] by means of thin slab mold model at TU Delft [68]. As a next step, a scale-up of the mold model was done using different EMBr concepts (see section 4.3).

With regard to argon injection at the mold apparatus, a validation study was performed to identify dependencies of the results on bubble drag models and bubble inlet conditions in an air-water system [44]. Especially the scarcely discussed inlet conditions have shown their strong influence on the results. In addition drag models which incorporate swarm effects of the bubble ensemble have shown the best accordance with experimental results. The current investigations used these results to extend the numerical MHD model with the multiphase part of bubbly flow in a full scale mold model (see section 4.3).
4. Recent Results

4.1. Electromagnetic stirring at the SEN

Recent studies were concerned with the application of rotary electromagnetic stirring at the continuous casting setup. The CIFT method was used to investigate the effect of electromagnetic stirring at the nozzle on the flow in a rectangular mold [69]. Another experimental study about the influence of magnetic stirring in the submerged entry nozzle (SEN) for continuous casting of round blooms has recently been performed at the mini-LIMMCAST facility. The experimental setup consists of a round mold made of acrylic glass (PMMA) with an inner diameter of 80 mm. A rotating magnetic field (RMF) is applied to the SEN by rotating permanent magnets. Velocity measurements have been carried out using the Ultrasound Doppler Velocimetry (UDV). Both an horizontal and vertical arrangement of ultrasonic sensors was employed where the transducers were mounted at several positions along the side wall of the mold or were dipped directly into the liquid metal through the free surface. The points of origin of the coordinate axes x and y are located on axis of the cylindrical mold and pointing radial outwards, while the origin of the z-axis is placed on the top edge of the mold. The free surface is located at \( z = 25 \) mm, the SEN outlet at \( z = 65 \) mm.

![Diagram of measurement configuration](image)

**Figure 6.** Sketch of the measurement configuration in the top view on the mold (left) and time average of the vertical velocity component split into negative and positive parts of four ultrasonic sensors in the vertical center-plane (at x = 0) with no RMF (right, top) and with RMF of \( f = 45 \) Hz at the SEN (right, bottom).

The distribution of the vertical velocity in the mold was measured in this setup up to a
depth of more than 300 mm from the free surface. Because of the highly dynamic conditions, the measured velocities are split into positive and negative components before the time average is computed to avoid averaging to zero. In figure 6 (left) it can be seen that close to the center of the mold, at $y = \pm 15$ mm, downward (positive) velocities are predominant while closer to the outside of the mold, at $y = \pm 30$ mm, upward (negative) velocities can be observed. The application of a rotating magnetic field in the SEN moves the area of highest velocities closer to the free surface (figure 6 right).

A detailed discussion of the phenomena observed in our experiments is currently in preparation and will be published in the near future.

4.2. EMBr with conducting walls at LIMMCAST

Static magnetic fields are used for an efficient control of the jet flow and the suppression of surface fluctuations at continuous casting of steel [2]. The effect of a static magnetic field on the mold flow has been investigated experimentally at the LIMMCAST facility. The model mold made of stainless steel has a cross section of 400 mm times 100 mm. The SEN has an inner diameter of 35 mm and the pipe axis of the SEN determines the vertical z-axis with downward orientation. The top edge of the nozzle port marks the horizontal x-axis, which is oriented towards the narrow mold face. The location of the coordinates is also illustrated in figure 8. The melt level is controlled by two electrodes detecting the melt level and the adjustable pump rotation speed. The mean melt level in the mold was adjusted at a position of about $-90$ mm. The first ultrasonic sensors is located at a distance of 8 mm from the narrow mold wall. Neighboring ultrasonic sensors have a distance of 37 mm between each other. So, the horizontal positions in the coordinate system correspond to $x = 115$ mm, 152 mm and 189 mm. The tips of the waveguides are positioned at a height of 13 mm above the upper port edge.

The mold flow without applied magnetic field was calculated by numerical simulations. The velocity magnitude in the center-plane is illustrated in figure 7. The figure depicts clearly the jet flow emerging from the nozzle ports. Further, the flow shows the typical double roll pattern, where the jet splits up in an up- and downward stream after impinging at the narrow mold wall. These results of the numerical simulations are compared with corresponding measurements obtained by UDV. The ultrasonic measurement configuration is sketched in figure 8. Local flow measurements were carried out by means of the Ultrasonic-Doppler-Velocimetry applying specific waveguide sensors for high temperatures. Figure 9 presents the time-averaged vertical velocity measured by the waveguide-sensors at three different x-positions. The outermost sensor close to the narrow wall detected a strong ascending flow, which can be attributed to the upwards directed branch of the upper convection roll. The innermost sensor recorded the smallest velocities as it is located near the center of the roll pattern. The downward flow appearing at distances of about 100 mm can be related to the jet. The UDV results (solid lines) are compared to the outcome of the numerical simulation (dashed lines) and show a quite well agreement.

Next, the static magnetic field was applied to the flow. The top edge of the EMBrs pole shoes are located at a height of $z = -43$ mm. The pole shoes have a height of 200 mm and covered the nozzle ports completely. Figure 10 contains time-averaged profiles of the vertical velocity determined at the sensor position close to the narrow side wall for different values of the magnetic field strength, but otherwise for the same casting geometry like in figure 7 to 9. It becomes obvious that the upwards flow of the upper recirculation zone (above the jet and close to the narrow mold wall) is amplified by the magnetic field. Furthermore, the flow appears to be almost steady. This finding coincides very well with the data measured at the smaller mini-LIMMCAST setup for conducting walls [18], which indicates a similarity with respect to the electrical wall conductance ratio.
4.3. Upscaling to a real casting geometry

Based on the successful validation of the numerical model using the experimental data from the mini-LIMMCAST facility, the numerical simulations were extended to melt flows in a continuous casting mold in a full-scale geometry as being relevant for real casting machines. For that purpose a rectangular mold of 1500 mm width and 250 mm thickness was chosen. The reduction of the liquid cross section with increasing distance from the flow surface due to progressing solidification from the side walls is considered in the model. Other parameters included in the model are a strand length of 5000 mm, a casting velocity \( u_c \) of 1.5 m/min and an SEN inlet velocity \( u_{in} \) of 1.91 m/s. The specific geometry of the SEN was taken from [70]. At the top surface, a free slip boundary condition was applied. Numerical calculations were performed for the case...
Figure 10. Mean vertical velocity close to the narrow mold wall (at $x = 189$ mm) for different strengths of the electromagnetic brake.

without magnetic field and for two different types of electromagnetic brakes. The first EMBr configuration concerns a ruler brake whose pole shoes cover the entire width of the mold. The other magnetic system represents the so-called Flow Control Mold (FCM) EMBr with two static magnetic fields, which are situated below the jets and on the level height of the free surface, respectively. Electrically insulating boundary conditions are assumed for the mold walls.

Fig. 11 shows LES results of the mean flow in the midplane of the mold. A double roll pattern can be identified in case without EMBr. The jets show a rather flat exit angle and significant spreading. Moreover, a slight asymmetry between the left and the right jet can be observed. The reason might be a self-sustaining long-wave oscillation having a period of about 8 seconds. The limited calculation time allows for capturing only a few oscillation cycles within the simulation. The surface velocities are moderate and in a range which is seen as tolerable for avoiding adverse phenomena like slag entrainment [71].

The application of a level EMBr to this flow leads to an upwards directed bending of the jets. The flow pattern reveals a strong asymmetry and distinct oscillations of the jets. These features appear to be similar as those found by the experiments in the mini-LIMMCAST facility. Compared to the mini-LIMMCAST experiments a smaller SEN submergence depth was chosen for the real-scale configuration. This might be the reason that the characteristic oscillations are not found in the upper recirculation rolls. The significant bending of the jets cause large flow velocities at the free surface. Such a situation bears the risk to enable shear layer instabilities at the slag interface which could cause the entrainment of slag droplets into the melt [71].

A completely different flow pattern is shown for the case of the FCM EMBr. The jets discharge from the nozzle with a flat exit angle and show a low spreading. The flow pattern appears to be almost symmetric and stable. The upper vortices are very weak and the lower recirculation is shifted downwards by the magnetic field. The surface velocity is drastically reduced which might create the risk of meniscus freezing.

The corresponding turbulent kinetic energy (TKE) is shown in Fig. 12. For the case without magnetic field it becomes obvious that the TKE is very high in the jet region. The TKE is produced in the jet shear layers, from there it is transported into the zone of the upper recirculation rolls. As a result, the surface TKE is rather high as well. At the top surface maximum values of the TKE are found in the narrow flow regions at both sides of the SEN. In the case with a Level EMBr the TKE in the jet is lower since the magnetic field dissipates
**Figure 11.** Distribution of the mean velocity in the midplane and top surface of the full scale mold. No EMBr case (left); Level EMBr case (middle); FCM EMBr case (right).

**Figure 12.** Distribution of the mean total turbulent kinetic energy (TKE) in the midplane and the top surface for the full scale mold. No EMBr case (left); Level EMBr case (middle); FCM EMBr case (right).
turbulent by Joule heating. This effect reduces the TKE at the free surface, too. However, the high velocities at the surface and the left-right asymmetry cause remarkable flow detachment at the SEN. As a consequence, the development of von Kármán vortices is facilitated which are detrimental to the steel quality [71]. For the FCM EMBr the contour plot of the TKE distribution reveals a broad jet, but, the striking feature are the very low TKE values occurring at the top surface around the SEN and in the region below the SEN. Due to the low surface turbulence, an entry of slag into the liquid metal appears to be quite unlikely.

Another series of URANS calculations for two-phase flows in the mold was conducted using the $k$-$\omega$ SST model for the same three configurations as considered in the single-phase simulations: without magnetic field, ruler EMBr and FCM EMBr. For that purpose we assumed the injection of Argon bubbles at the SEN inlet. The URANS concept was chosen here because of expected uncertainties in the turbulent dispersion and the bubble trajectory obtained by SAS calculations. Fig. 13 shows the liquid volume fraction at the midplane of the mold and the free surface as well as the bubble size distribution along the top surface for an argon flow rate of 8% with respect to the melt flow rate. Since larger bubbles are supposed to ascend quicker,
their point of impact at the free surface is found to be closer to the SEN in all three cases. Smaller bubbles are more affected by dispersion due to the liquid flow and can be detected at larger distances from the SEN. It can be seen that the dispersion of argon bubbles along the x-direction is obstructed by a Level EMBr while such a damping effect on the horizontal bubble transport is not observed for the FCM EMBr. The distribution of the small bubbles in the FCM setup shows two peaks, one close to the SEN and the other almost in the center of the distance between SEN an narrow mold face. The second peak at a larger distance to the nozzle might be explained by the existence of quasi-two-dimensional vortices which are aligned with the magnetic field direction. Such vortices promote an effective bubble transport towards the side wall. The magnetic field also affects the transport of larger bubbles the distribution of which also shows higher bubble numbers at greater distances from the nozzle.

5. Summary & Conclusions
This paper presents a summary of experimental and numerical results produced during the LIMMCAST-project within the Helmholtz LIMTECH alliance. The project aims at the investigation of fluid flow aspects in the continuous casting process of steel. Special attention was paid to the influence of DC and AC magnetic fields on the flow in the mold. Furthermore, the issue of multiphase flows in the SEN and the mold due to Argon-injection at the stopper rod was addressed.

Three experimental facilities with liquid metals are operated at HZDR for modeling various essential aspects of fluid flow and related transport processes. Such an experimental program requires the availability of suitable measurement techniques for liquid metal flows. The measurements carried out at LIMMCAST rely on the ultrasonic Doppler velocimetry and inductive methods as the Contactless Inductive Flow Tomography (CIFT) and the Lorentz Force Velocimetry (LFV). In this respect, a fruitful cooperation was established with the Young Investigators Group of the LIMTECH alliance.

Several numerical schemes and different turbulence models were applied and verified. Finally, it can be concluded that the LES model provides the best results for the specific configurations considered here. This assessment is based on a comparison with the experimental data from the LIMMCAST experiments.

The action of static electromagnetic fields on the mold flow is one of the primary fields of interest in the project. The main finding is the non-trivial action of electromagnetic actuators on the mold flow. The electrical boundary conditions at the mold wall showed a dramatic influence on the temporal behavior of the melt flow under the influence of diverse electromagnetic actuators. For instance, the application of a DC magnetic field under insulating boundary conditions can promote the generation of biased flows characterized by large scale oscillations and instabilities of the jet. Different types of EMBr usually employ steady horizontal magnetic fields normal to the wide side of the mold. Under such conditions the mold flow tends to become quasi-two-dimensional which becomes apparent by the formation of strong recirculation zones. Other experimental research activities are related to the application of AC magnetic fields for electromagnetic stirring in the mold and SEN.

The coordinated and complementary use of numerical simulations and model experiments allow the acquisition of essential insights into the flow phenomena occurring in the continuous casting of steel. The model experiments provide valuable measurement data which can be used for the validation of numerical models.

Despite the progress in modeling and understanding of the mold flow in continuous casting, there remain still a lot of work in experimental and numerical simulations as well as the enhancement of measurement techniques. There are a lot of different kind of electromagnetic actuators in industrial operation and up to now this project selected just two of them as an exemplary. Further, the experiments about the two-phase flow due to Argon injection were just
a small beginning and even the combination of Argon injection with electromagnetic actuators is an interesting topic but also connected to challenging measurement and numerical modeling tasks. The CIFT measurement technique has made huge progresses in the last years, but there is still some more work and development necessary to push it towards a potential application at a real caster. The simulations in this study considered insulating walls only. In the real process, the solidified shell allows the induced currents to enter the shell and therefore influence the Lorentz force distribution in the mold. Future studies should include this feature. Moreover, the model is missing a free surface treatment, which should be added by combining the current model with a Volume-of-Fluid (VoF) approach. By means of this, important questions regarding slag emulsification can be addressed more thoroughly.

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