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COMBINING MODELS AND MEASUREMENTS TO BETTER UNDERSTAND STEEL CONTINUOUS CASTING

Abstract

Computational models can simulate the details of the phenomena and mechanisms which govern complex commercial processes such as the continuous casting of steel. When combined together with experimental measurements in the laboratory and plant, they become an accurate and powerful tool to gain quantitative understanding, and to enable improvements in the commercial process. This paper shows several examples to illustrate how to apply models and measurements together to gain new insights into steel continuous casting.

Firstly, models can augment laboratory experiments to measure fundamental properties. For example, the crystallization properties of mold slags can be extracted from videos of high-temperature experiments of small liquid samples. A recent computational model of the double-hotwire-thermocouple test (DHTT) shows how temperature gradients and crystal motion driven by surface-tension (Marangoni) flow convection influence the nucleation and growth of crystals during the experiment.

Computational models can also augment plant measurements. For example, velocity across the top surface of the mold can be quantified using nailboard measurements, with the help of results from computational model simulations of the free surface shape around the nails. This enhances the ability of nailboard measurements to quantify flow conditions at the top surface, and thus to serve as a validation tool for computational flow models.

Finally, Large Eddy Simulation of transient turbulent flow in the mold have been validated with plant measurements, matching the surface velocities, flow directions, and surface level profiles. In addition to quantifying the flow pattern, the results reveal insights into flow instabilities in the mold under nominally steady casting conditions. The general methodology presented here is readily applicable to other processes.

Keywords

Computational Models, Fluid Flow, Validation, Velocity, Measurements, Steel, Casting

1. Introduction

Mature commercial processes, such as the continuous casting of steel, are difficult to improve without full understanding of the fundamental phenomena and mechanisms which govern product quality. Owing to the complexity of the process, and difficulty of measuring the real process, this understanding is difficult to obtain. Computational models are able to extend the knowledge gained from both laboratory experiments and plant measurements, in order to improve understanding. This paper presents several examples involving the crystallization of mold slags, and turbulent flow in the mold, especially near the top surface.

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2. Model of laboratory experiments: DHTT measurements

The Double Hotwire Thermocouple Test (DHTT) has been used to measure slag crystallization behavior, in order to better understand and quantify heat transfer across the interfacial gap between the mold and solidifying shell in continuous casting processes. In this experiment, two heated thermocouples suspend a small sample of molten slag by surface tension forces, while also measuring the temperature history [1]. The formation of crystals is video recorded during controlled cooling of the thermocouples, and image analysis is used to quantify the crystal fraction evolution with time.

Further insight into this laboratory measurement can be gained with a computational model of thermal-fluid flow during the experiment. The model solves the coupled transient heat conduction equation, continuity (mass balance) and momentum transport equations [2]. Coupling is necessary owing to thermal buoyancy forces due to natural convection, and Marangoni forces caused by surface tension gradients on the surface of the slag sample. The model domain includes the actual measured shape of the slag sample, with the boundaries with the thermocouples fixed at their measured temperatures, and natural convection and radiation cooling from the other surfaces. Details of the model are presented elsewhere [1].

The calculated steady-state temperature distribution in a slag sample after preheating is shown in Fig. 1 [1], before starting the cooling stage of the experiment. Without an extra heat source, the center of sample is ~350K cooler than edges of this sample with 2.5mm width. These large temperature gradients are not easy to quantify from experimental images, such as that shown at the bottom right. Ignoring the temperature variations would produce misleading results. Knowing this distribution from the model, however, it is possible to account for the temperature variations when analyzing the results of "isothermal" tests. Alternatively, many researchers use smaller samples and external heating in order to achieve more uniform temperatures in the sample [3]. In either case, such model computations are useful to improve the interpretation of the experimental measurements.

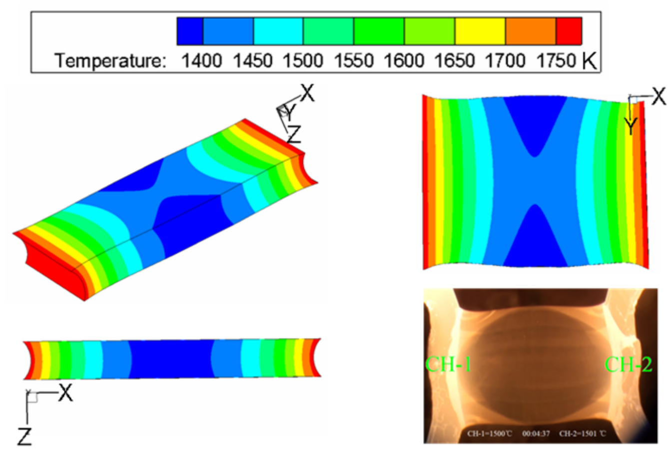


Fig. 1. Temperature in DHTT before cooling, (3D and side views on left; top views on right)

Calculated temperatures and velocities in the slag sample during a DHTT cooling experiment are shown in Fig. 2, where the temperature of the upper right thermocouple is cooled at 30K/s. The natural convection caused by the temperature variations is relatively small. However, the steep temperature gradients also cause surface tension gradients, which produce strong fluid flow, termed "Marangoni" flow. Fluid flows from the hotter region to the cooler region along the surface of the mold slag sample; and then recirculates back from the cooler region to the hotter region through the interior, reaching 7mm/s. This explains the observed movement of crystalline aggregations in molten slag in the small lump-shaped DHTT sample, which is dominated by surface effects. This behavior in the experiment differs from the commercial continuous-casting process, where the slag is a thin sheet, and fluid flow is driven mainly by other forces such as mold oscillation and shell withdrawal.

By including the important governing phenomena, the computational model can explain the thermal - flow behavior in both the lab experiment and the real process.

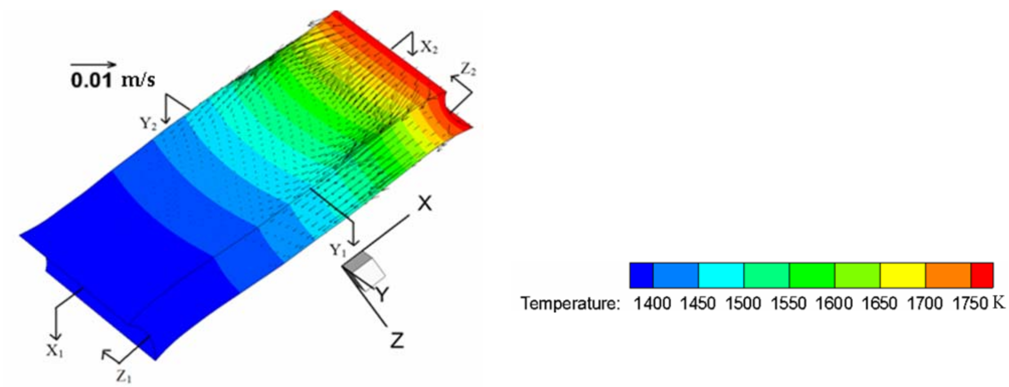


Fig. 2. Temperature and velocity in slag sample at 35s during DHTT cooling experiment [1]

The predicted and measured evolution of the crystallization fractions are compared in Fig. 3. The predictions are based on the measurements of a corresponding single-hot-thermocouple test, and the temperature histories predicted at each point in the DHTT sample [1]. Without the predicted temperatures from the model, the nucleation of crystals starting in the sample center, where temperature is lowest, and growing outwards, would be unexpected. The validated computational model can be extended to simulate the real process.

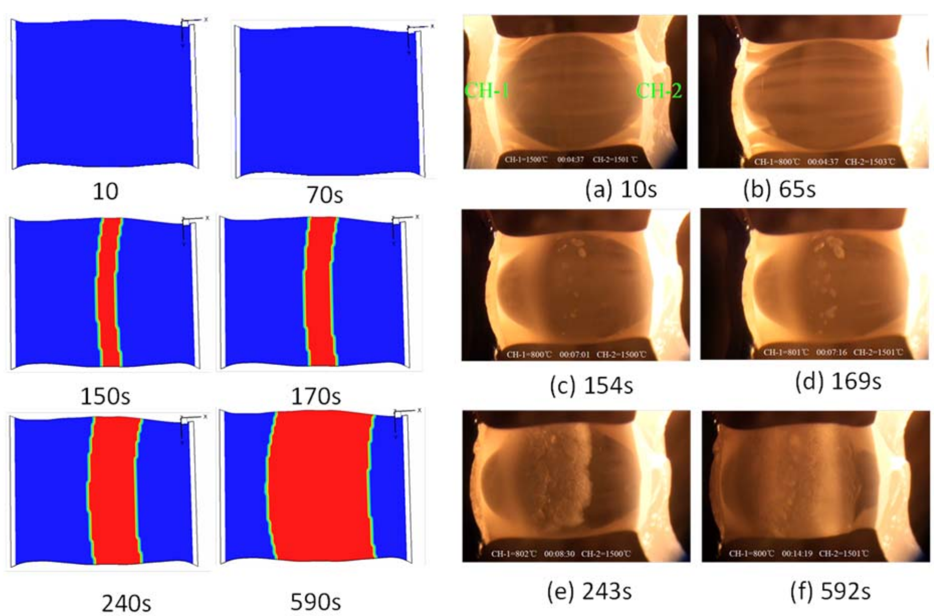


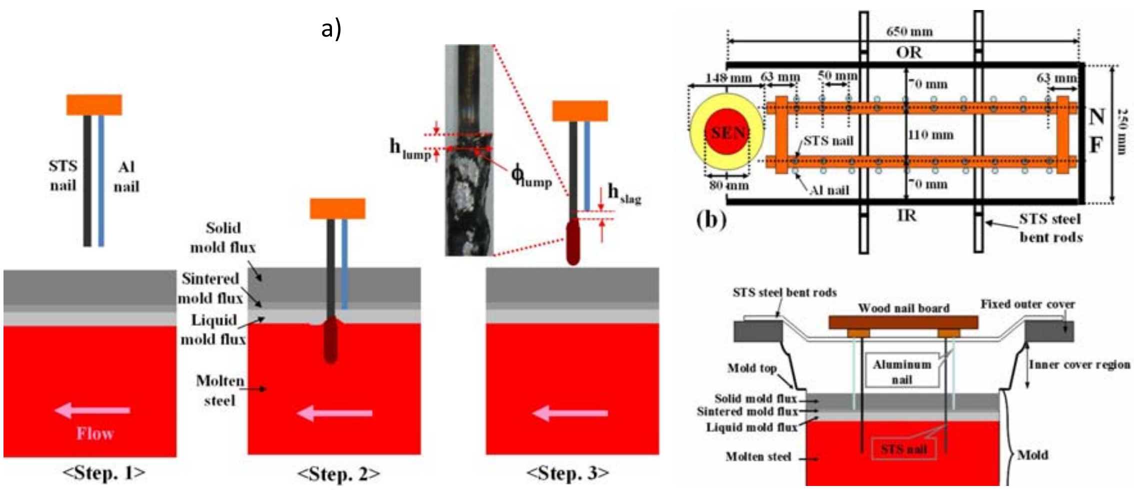
Fig. 3. Comparison of predicted crystallization (red regions) with DHTT photos (right) [1]

3. Model of plant experiments: nailboard tests

A simple method to sample the slag layer and surface level conditions in the commercial continuous casting mold using nail boards [4] has recently been enhanced [5-7] to measure surface velocity. In addition to measuring instantaneous surface velocities of the steel in the mold and the direction of flow, the nail board method can also provide the mold level (slag-steel interface) profile across the top surface, and the thickness profile of the slag layer [4].

For both nail board and single nail dipping tests, nails are inserted through the top-surface powder and slag layers into the molten steel, held for 3~5 seconds, and removed, as shown in Fig. 4. A lump forms on the bottom of each nail, due to the solidification of the liquid steel and slag. By measuring the lump shape and lump height difference between the side facing the flow side and the opposite downstream side, the magnitude and direction of the surface steel velocity can be determined.

To quantify the relationship between steel surface velocity and shape of the solidified lump on each nail, a finite-element CFD model of the nail dipping test was developed to study the multiphase flow of liquid steel past a nail with a liquid slag layer on top [7,8]. The model solves the mass and momentum conservation equations, assuming incompressible flow. The k-e model is used to handle turbulence in the molten steel phase, with wall laws at the steel / slag interface, and the effect of temperature is handled by the input properties, without solving the energy equation. This steady-state three-phase flow model tracks the two free surfaces, by deforming the mesh to maintain cell boundaries along the liquid slag / steel interface and the slag/powder interface (spines method) [9]. This model includes the effects of interfacial tension at the slag-steel interface (assuming 1.6 N/m) and predicts the interface shape and the height difference across the nail for a given bulk velocity of the steel beneath the surface [7]. Complete details on the model are given elsewhere [8,9].



a) Steps in nail dipping method

b) Schematic of nailboard: top view (top) and narrow-face view (bottom)

Fig. 4 Nailboard test in steel casting mold [12]

Typical results from the model are shown in Fig. 5, where molten steel flows uniformly from the lower left to upper right across the bottom of the 3D views. As molten steel flows past the nail, the liquid steel builds up at the impingement point on the nail lump before it solidifies. The kinetic energy of the impinging stream is converted into potential energy at this stagnation point as the impinging flow rises up the nail. The liquid-steel / slag interface level drops at the opposite (downstream) side of the nail lump, due to the lower pressure in the wake region. This change in level of the slag-steel interface is recorded by the shape of the free surface, which should match that of the solidified lump, such as the example shown in Fig. 4 a). Fig. 6 a) shows the free surface shapes around the nail for several different steel velocities. Velocity in the slag layer is very low, owing to its much higher viscosity.

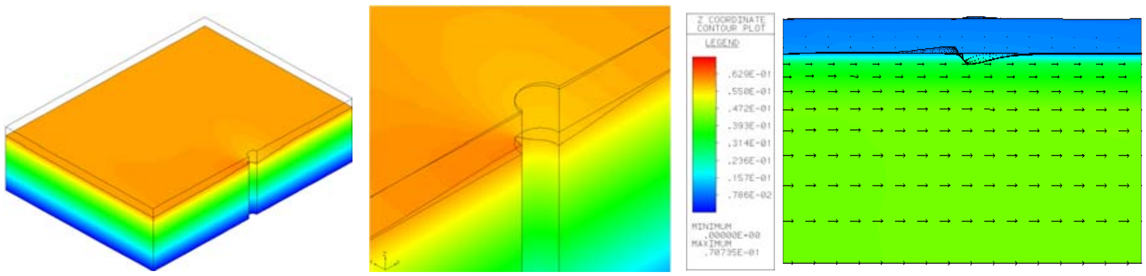


Fig. 5 Simulated flow around a nail, showing initial and final steel/slag and slag/powder interfaces in 3D domain and closeup near the nail (left); velocity vectors in front view (right) [8]

Based on the modelling results, a correlation was established [10] between the surface velocity V_{lump} (m/s) and the lump height difference Δh_{lump} (mm) as

$$V_{lump} = 0.624\,(d_{lump})^{-0.696}\,(\Delta h_{lump})^{0.567} \qquad (1)$$

where d_{lump} (mm) is the lump diameter. Increasing the velocity causes the lump height difference to increase, almost according to the theoretical exponent of 0.5 for a perfect flow barrier. Increasing nail diameter also increases the lump height difference, as the nail forms a better barrier to flow around it. Fig. 6 b) shows lines predicted from the new equation for 3 nail diameters, and the CFD model-calculated points that it was based on. Note that the least-squares regression that generated the correlation neglected the points calculated at the highest surface velocity (0.6m/s), because those simulations are believed to have experienced convergence problems.

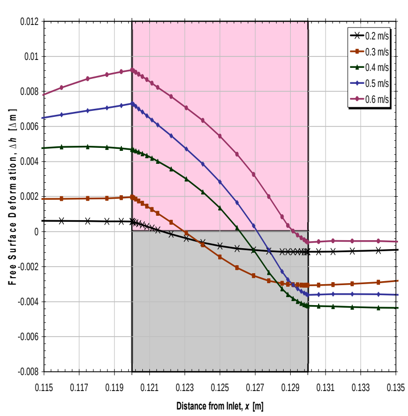


Fig. 6 a) Slag / Steel Interface Shape computed by CFD model [8]

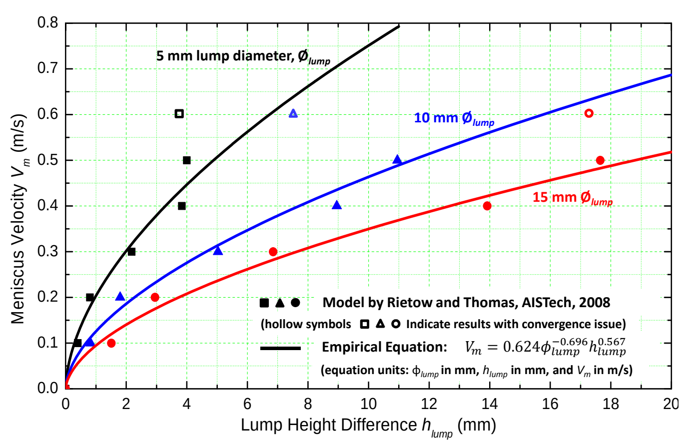
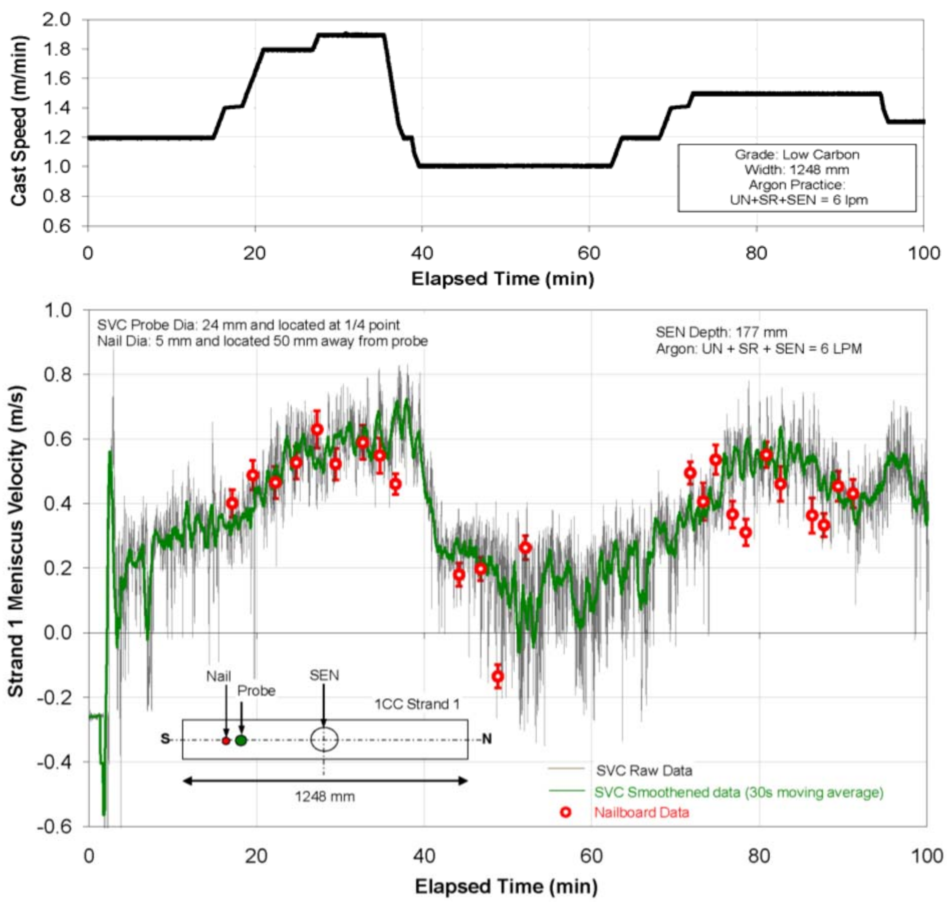


Fig. 6 b) Curves to convert nail lump height difference into velocity at the top surface [11]

To validate the correlation, plant experiments were conducted using two different methods to measure the surface velocities at the same time [10,11]. Casting speed was varied greatly as shown in Fig. 7 a) and the corresponding steel surface velocity histories monitored by both SVC and nail dipping are shown in Fig. 7 b). The SVC sensor involves dipping a rod into the molten steel and measuring the deflection angle and torque, and converting them into an average velocity near the surface [10,11]. In addition to the instantaneous SVC surface velocity measured, Fig. 7 b) also shows a 30-second moving average SVC velocity. Positive meniscus velocities indicate flow towards the SEN, and negative velocities indicate flow towards the narrow face. The locations where the nail and SVC probe were inserted are also shown in Fig. 7 b). Error bars for the nail dipping test results were obtained assuming an uncertainty of 0.5 mm in measuring both the lump diameter and the lump height difference.

The SVC data and nail dipping results match closely with each other, as shown in Fig. 7 b). Furthermore, most nail dipping measurements match the moving average of the SVC data. At a few points, the nail dipping results fall outside the moving average, but still always fall within the range of the instantaneous SVC data. This demonstrates that the simulation-based method in Eq. (1), for extracting surface velocity from the nailboard measurements is reasonably accurate.



a)

b)

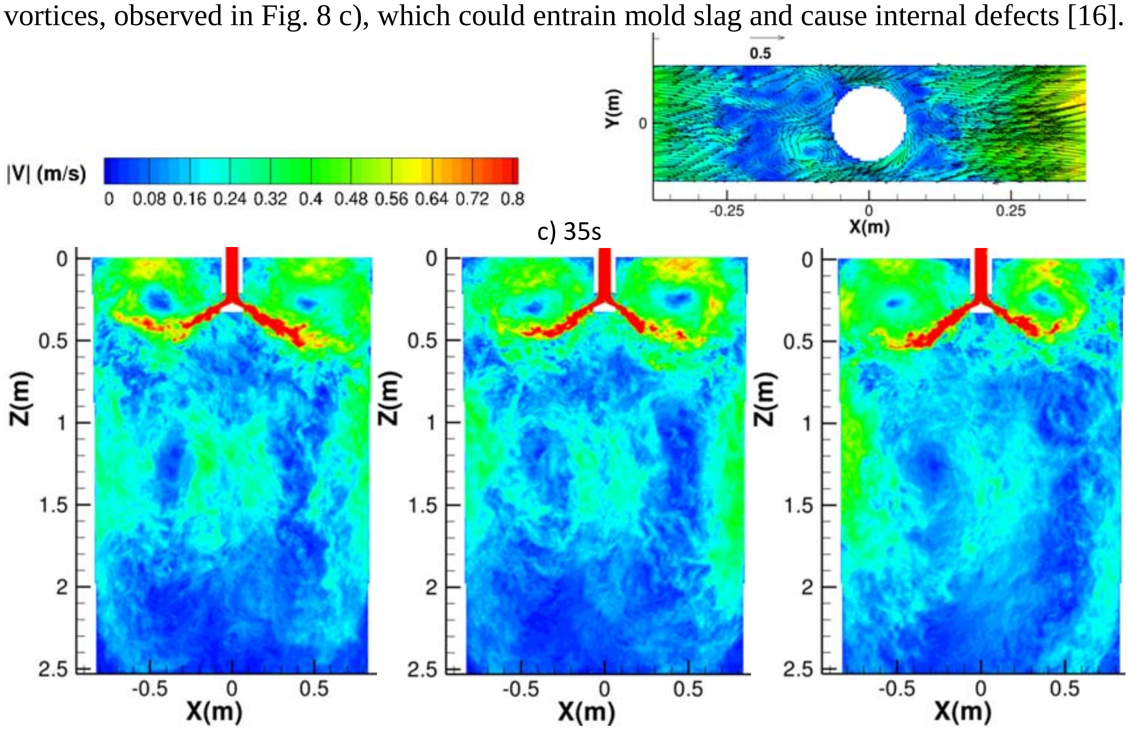
Fig. 7. Plant trial comparing two top surface velocity measurement methods [11]
a) Casting speed history; b) Velocity history from SVC and nail dipping tests.

4. Model of transient flow in steel continuous casting

Transient flow during nominally steady conditions is responsible for many intermittent defects during continuous casting of steel. Transient flow in a typical commercial thick-slab caster is modeled with an in-house large eddy simulation code CU-FLOW, using grids of over five-million cells with a fast GPU-based parallel solver [13, 14].

The computational model solves the continuity (mass balance) and incompressible Navier-Stokes equations for momentum transport using the Coherent-structure Smagorinsky Model (CSM) Sub-Grid Scale SGS model to capture the turbulence of the small undiscretized eddies. The Wall Adapting Local Eddy-viscosity (WALE) model is used to treat velocity gradients at the domain boundaries, chosen to be the solidification front that is given fixed downward velocity at the casting speed. Surface level is estimated simply by converting the pressure at the top surface into a height change of the potential energy [14]. Further details on the model are provided elsewhere [13]. The casting conditions include 203mm thick x 1760mm wide strand, a typical bifurcated downward-angled nozzle, and a casting speed of 1.4m/min. Further conditions are provided elsewhere [14].

As shown in Fig. 8, a classic double-roll pattern is observed for these conditions, with transient unbalanced behavior, and side-to-side flow oscillations, especially in the lower recirculation regions. The three snapshots show how flow from the jets that emerge from the bifurcated nozzle ports impinge upon the narrow faces at fluctuating heights and times, creating unbalanced flow. These flow oscillations are more common in wider molds, and have been reported in previous research [15]. For the conditions here, they have a period of ~16s, which matches previous findings [15]. This oscillating flow causes asymmetric flow across the top surface. Flow through the narrow gap between the SEN and the wideface causes vortices, observed in Fig. 8 c), which could entrain mold slag and cause internal defects [16].



a) 25sec b) 30sec d) 35sec

Fig. 8. Contour plots of instantaneous velocity magnitude from LES simulations [13]

The model calculations were compared with two rows of nailboard measurements taken at the commercial caster and matched reasonably well, both quantitatively and qualitatively. Fig. 9 shows the velocity profile across the top surface which is highest (over 0.5m/s) between the submerged entry nozzle and the narrow face, where velocities are lowest. The simulated velocity profile generally agrees with the velocities based on the nailboard measurements from Eq. (1). In addition, the range of instantaneous velocity profiles of +/- ~0.1m/s agrees with measured range of several repeated plant measurements. Fig. 10 a) shows that the flow is directed mainly from the narrow face towards the central nozzle. Again, both the direction and variations of the transient model agree with the directions observed in the nailboard measurements.

The free surface level profile was also measured from the solidified lumps and compared with the model predictions in Fig. 10 b). The heights of the two rows of solidified lumps were averaged to estimate the surface level profile along the centerline. The measured and the predicted surface level profiles match very closely if the measured profile is rotated. Pivoting about the center handle of the nail board to raise one end 10mm and lower the other end by 10mm could easily have been introduced while dipping the nail board manually into the mold. Even without considering this rotation, the trend of higher level on the narrow face, and lowest level midway between the SEN and NF is both predicted and measured, and agrees with previous work [17]. Furthermore, the variations of over 15mm in surface height are significant for the formation of defects.

Having been validated, the model can be applied in parametric studies to investigate quantitatively, the flow conditions produced for different casting conditions and nozzle geometries. Such recent studies include investigation of the effects on transient flow of sudden stopper-rod movements [10], stopper-rod dithering [18], argon gas injection [19], and electromagnetic braking [12, 14].

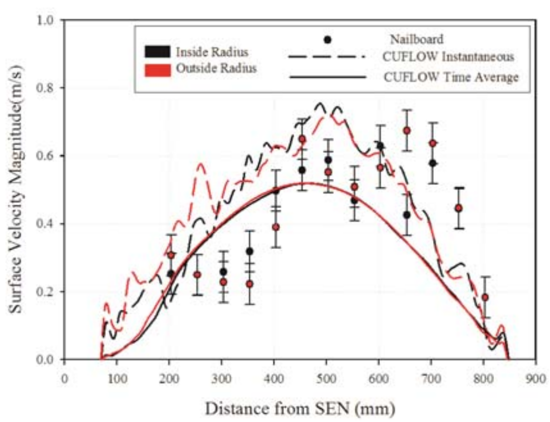


Fig. 9. Comparison of measured and calculated surface velocity magnitude on the two rows of nails on the nail board [14]

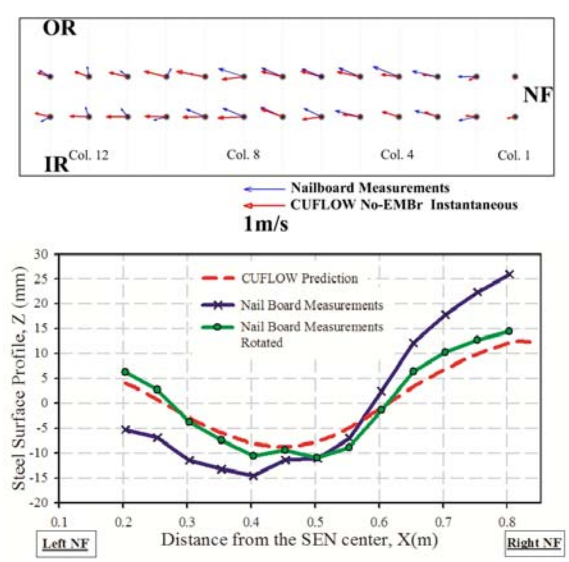


Fig. 10. Comparison of measured and calculated surface velocities (top) and instantaneous surface level profile (bottom)

5. Conclusions

This work has presented several examples of using computational models, laboratory, and plant experiments together to gain new insight into steel continuous casting. The DHHT test may experience nonuniform temperature gradients and fluid flow that differs from the real process, and should be taken into account when extracting fundamental property measurements from the results. When evaluated using a model equation presented here, nailboard tests can accurately measure surface velocity in molten metal flowing beneath slag and powder layers. Large eddy simulations of turbulent flow in the mold using a highly-refined grid have been validated by nailboard measurements and applied to reveal significant flow oscillations during nominally-steady state continuous casting conditions. These transient oscillations are more important than the steady-state flow pattern itself in causing quality problems. Turbulent flow models validated by nailboard measurements are being used in many other recent parametric investigations.

This work exemplifies a general methodology of how computational models can be applied to improve understanding of laboratory and plant experiments. Lab experiments are often very different from the real process they aim to illuminate. Computational models can account for these differences. If properly developed, models can capture the governing phenomena in the lab experiments. Calibration of the model, by adjusting the fundamental property parameters inside the model in order to match with the lab measurements, is often the best way to measure material properties. A critical step of model development is comparison with both lab and plant measurements. Although measurements in the plant are often difficult and peripheral, they are valuable by enabling model validation. After a rigorous validation procedure, a fundamentally-based computational model can be applied to gain new insights into the real process, accurately predicting behavior which often cannot be measured or obtained in any other way.

Acknowledgments

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