**Blue Waters Annual Report 2016 – Research Summary Submission**
**Due: June 3, 2016**

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**Title:**
Transient Two-Phase Flow and Electro-Magnetic Field Effect in Steel Continuous Casting

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**Subject:** Physics & Engineering (Fluids)

**Number of images:** 3 images

**Executive Summary**

This project aims to advance current state-of-the-art computationally-intensive models of multiphase phenomena including turbulent fluid flow, particle transport, and MagnetoHydroDynamics (MHD) in the continuous casting of steel, and further, to apply those models to get practical insights to understand the transient flow phenomena related to defect formations and to improve this important commercial process. In this report, a transient two-phase Large-Eddy-Simulation model of molten steel-argon gas flow was applied to investigate anisotropic turbulent flow in the caster, with and without a double-ruler electro-magnetic field. The model calculations have been validated with plant measurements, and applied to understand the mechanism of the flow variations, which are important to surface defect formation in the final product. In addition, the effects of the magnetic field on the flow stability in the caster have been quantified with different process parameters.

## Introduction

Continuous casting is used to manufacture over 95 % of steel in the world [1]. Molten steel flows from a tundish, through a slide gate control valve, and down a vertical bifurcated nozzle into the mold, as shown in Figure 1. Once in the mold, molten steel solidifies against the water-cooled copper mold walls to form a solid shell. Transient fluid-flow phenomena in the mold are very important to quality and defects in the final product. Abnormal surface flow aggravates level fluctuations, shear instability of the molten slag/steel interface, and vortex formation near the SEN, which leads to mold slag entrainment. These detrimental flow phenomena in the mold become more complex with argon gas, which is injected into the nozzle to prevent the nozzle clogging. Furthermore, the argon gas bubbles may become entrapped into the solidifying steel shell, to form other defects. To stabilize and optimize the transient fluid flow in the mold, electro-magnetic fields are often applied, especially at high casting speed [2-4].

In the present work, Large Eddy Simulations of multiphase flow are performed to quantify the transient behavior of molten steel-argon gas flow in the nozzle and mold during nominally-steady continuous casting of steel slabs. The model has been validated with plant measurements and applied to investigate the mechanism of multiphase flow stability, argon-bubble entrapment into the steel shell and effects of double-ruler Electro-Magnetic Braking (EMBr) on the transient flow variations for different process conditions.

## Methods & Results

To calculate transient flow of molten steel and argon gas in the nozzle and mold, a three-dimensional finite-volume LES model coupled with Discrete Phase Model (DPM) for particle tracking has been developed, considering the interaction between the molten steel flow and argon bubble motion. This model was implemented into a special multi-license version of ANSYS Fluent on Blue Waters (BW).

Time-averaged and instantaneous flow patterns in the nozzle and mold are shown in Figure 2 [3]. The asymmetrically-positioned slide gate middle plate, with its open area near the Outside Radius (OR) side, produces swirl flows in the nozzle well bottom, alternating chaotically between clockwise and counter-clockwise rotation. Instantaneous mold flow patterns show up-and-down wobbling of the jet in the mold, which produces different impingement points on the NF. When the nozzle flow from the slide gate flips sides down the nozzle (Figure 2a), it produces counter-clockwise swirl exiting the ports, impinges downwards on the narrow faces, and results in slow surface flow in the mold. When the nozzle flow goes straight down to produce clockwise swirl exiting the port, the accompanying faster jet bends upwards, impinges the NF horizontally, and produces 50% faster surface flow (Figure 3a).

Time-averaged and instantaneous profiles of surface velocity magnitude predicted by the LES model are compared with nail board measurements in Figure 3 (b). Each line shows surface velocity magnitude profiles across the mold width at the center-plane 10mm below the interface between the molten steel and liquid mold flux layers. Symbols with error bars present time averages and standard deviations of 10 nail-dipping tests at each measurement location [4]. The model predictions of the average velocity profile, and its time and spatial variations, all agree with the measurements. This confirms that the LES-DPM model on BW is an accurate tool to predict complex mold-flow phenomena including multiphase effects.

Related work coupling turbulent flow with DPM to model bubble transport and capture, based on local force balances on argon-gas bubbles at the solidification front, has revealed that biased flow across the mold surface can aggravate bubble capture [5].

The effect of double-ruler Electro-Magnetic Braking (EMBr) was added to the LES-DPM model by implementing the magnetic induction MHD equations. The EMBr in the current work has one peak centered across the mold above the port and the other centered below the nozzle port. With EMBr, swirl direction flipping occurs more frequently, flow asymmetries are reduced, turbulence from jet wobbling is reduced, and thus surface velocity fluctuations are smaller [3]. Furthermore, an efficient multi-GPU based code, CUFLOW, was used to perform LES to investigate the effects of several SEN depths and double-ruler EMBr strengths [6], in order to suggest the best choice of operating conditions to control surface flow.

**Why Blue Waters**

Multiphase flow simulations in the continuous caster were enabled by Blue Waters, including the large domain volume (eg. 0.2 m X 1.6m X 4.6m) and fine mesh (eg. ~22 million cells) needed to properly capture and resolve the turbulent flow. Specifically, the Fluent-14.5 HPC software on Blue Waters ran 3357 times faster than on an ordinary work station PC (Dell T7600: Intel ® Xeon ® CPU E5-2603 @ 1.80GHz, RAM 40.0 GB, using 6 cores) with 1120 cores (70 XE nodes).

**Next Generation Work**

A validated two-dimensional thermal-fluid model of solidification phenomena at the slag/molten steel interface near the meniscus region [7], will be extended into the full 3-dimensional LES mold discussed here, to investigate how anisotropic multiphase flow variations affect initial solidification, with and without magnetic fields.

**References**

[1] *Steel Statistical Yearbook 2014*. (World Steel Association, Brussels, Belgium, 2014)

[2] Singh, R., B. G. Thomas, and S. P. Vanka, Large Eddy Simulations of Double-Ruler Electromagnetic Field Effect on Transient Flow During Continuous Casting. *Metallurgical and Materials Transactions B*, Vol. 45B (2014), pp.1098-1115.

[3] Cho, S-M., B G. Thomas, and S-H. Kim, Transient Two-Phase Flow in Slide-Gate Nozzle and Mold of Continuous Steel Slab Casting with and without Double-Ruler Electro-Magnetic Braking. *Metallurgical and Materials Transactions B*, 2016, accepted.

[4] Cho, S-M., S-H. Kim, and B. G. Thomas, Transient Fluid Flow during Steady Continuous Casting of Steel Slabs: Part I. Measurements and Modeling of Two-phase Flow. *ISIJ Int*, Vol. 54, No. 4 (2014), pp. 845-854.

[5] Jin, K., B.G. Thomas, and X. Ruan, Modeling and Measurements of Multiphase Flow and Bubble Entrapment in Steel Continuous Casting. *Metallurgical and Materials Transactions B*, Vol. 47B, No. 1 (2016), pp. 548-565. DOI: 10.1007/s11663-015-0525-5

[6] Jin, K., S. P. Vanka, B.G. Thomas, and X. Ruan, Large Eddy Simulations of the Effects of Double-Ruler Electromagnetic Braking and Nozzle Submergence Depth on Molten Steel Flow in a Commercial Continuous Casting Mold. *TMS Annual Meeting*, CFD Modeling and Simulation in Materials Processing Symposium, Nashville, TN, Mar. 14-18, 2016, TMS, Warrendale, PA, 2016, pp. 159-166.

[7] Yan, X., A. Jonayat, B. G. Thomas, Thermal-Fluid Model of Meniscus Behavior during Mold Oscillation in Steel Continuous Casting, *TMS Annual Meeting*, Nashville, TN, Mar. 14-18, 2016, TMS, Warrendale, PA, 2016, pp. 181-186

**Publications**

- Jin, K., B.G. Thomas, and X. Ruan, Modeling and Measurements of Multiphase Flow and Bubble Entrapment in Steel Continuous Casting. *Metallurgical and Materials Transactions B*, Vol. 47B, No. 1 (2016), pp. 548-565. DOI: 10.1007/s11663-015-0525-5
- Cho, S-M., B G. Thomas, and S-H. Kim, Transient Two-Phase Flow in Slide-Gate Nozzle and Mold of Continuous Steel Slab Casting with and without Double-Ruler Electro-Magnetic Braking. *Metallurgical and Materials Transactions B*, 2016, accepted.
- Jin, Kai, Surya P. Vanka, Brian G. Thomas, and Xiaoming Ruan, Large Eddy Simulations of the Effects of Double-Ruler Electromagnetic Braking and Nozzle Submergence Depth on Molten Steel Flow in a Commercial Continuous Casting Mold. *TMS Annual Meeting*, CFD Modeling and Simulation in Materials Processing Symposium, Nashville, TN, Mar. 14-18, 2016, TMS, Warrendale, PA, 2016, pp. 159-166.
- Jin K., S. P. Vanka, R. K. Agarwal and B.G. Thomas, GPU Accelerated Simulations of Three-Dimensional Flow of Power-law Fluids in a Driven Cube. *Journal of Fluids Engineering*, submitted and is under review.
- Jin K., P. Kumar , S. P. Vanka and B.G. Thomas, Rise of an argon bubble in liquid steel in the presence of a transverse magnetic field. *Physics of Fluids*, submitted and is under review.

**Images and Captions**

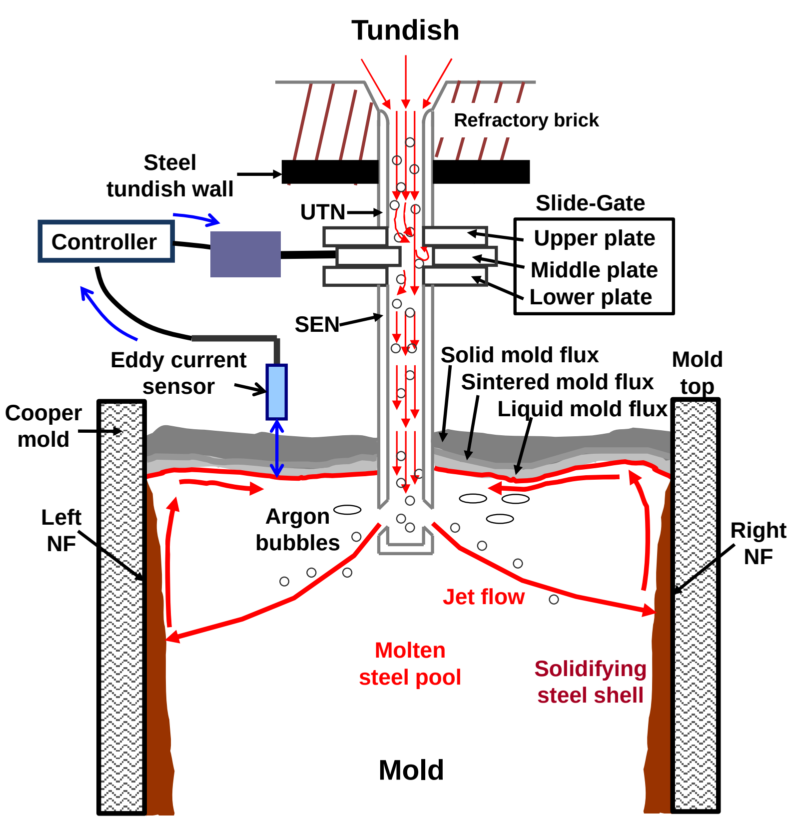


FIGURE 1: Schematic of the continuous steel slab-casting process

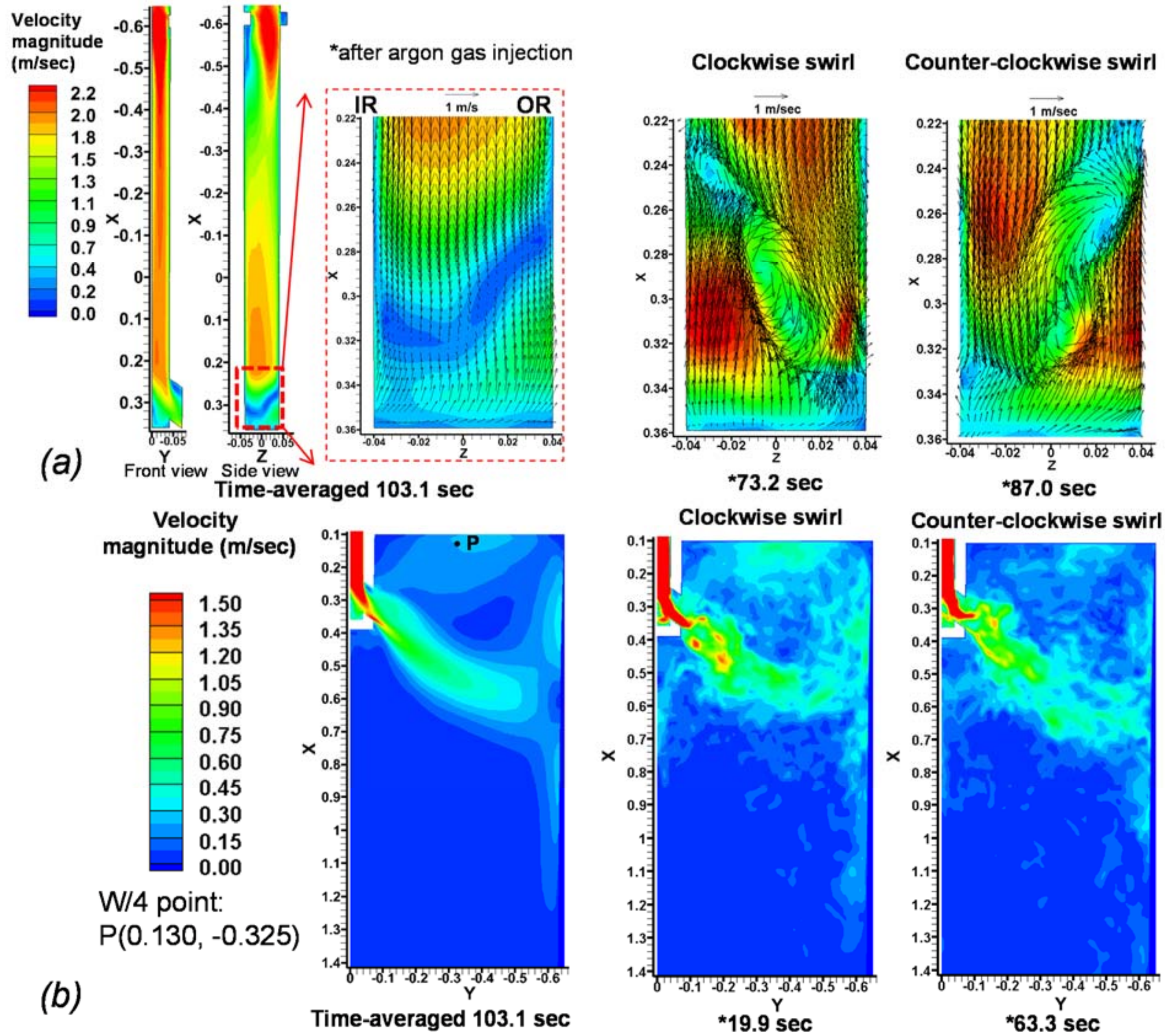


FIGURE 2: Time-averaged and instantaneous flow patterns in (a) nozzle and (b) mold

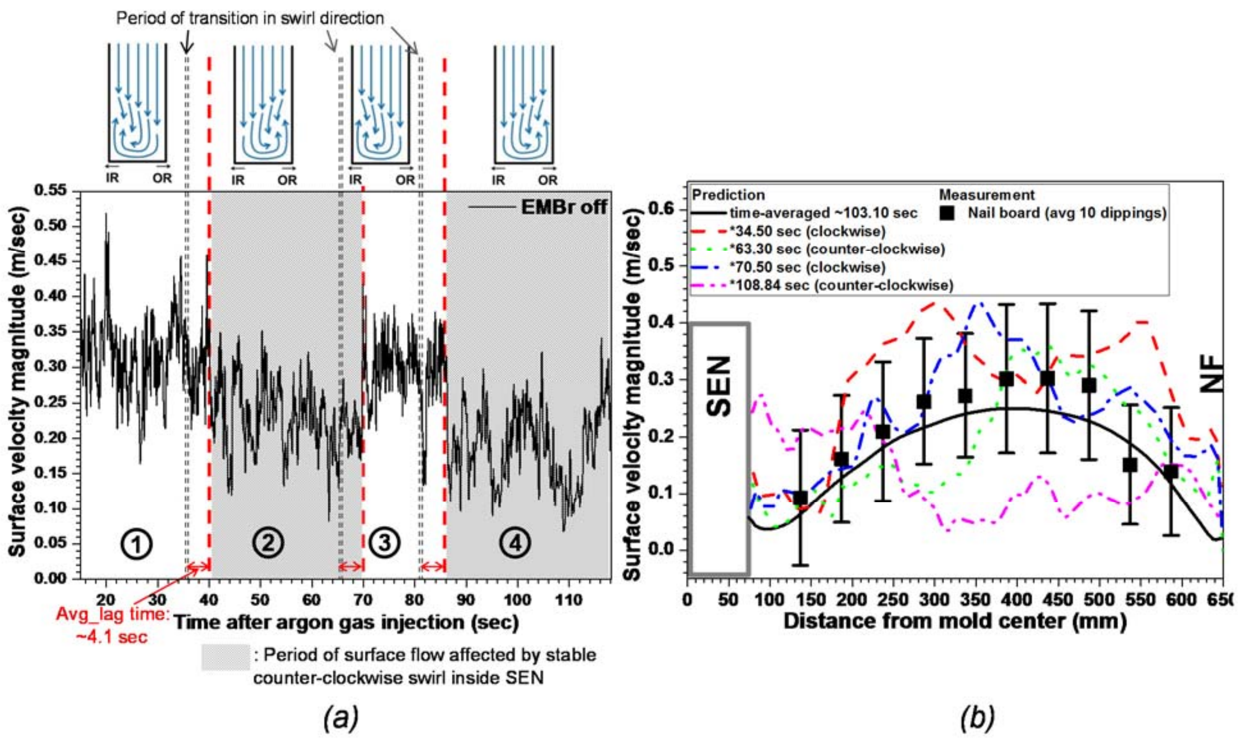


FIGURE 3: (a) Instantaneous surface velocity magnitude at W/4 point and (b) comparison of predicted surface velocity profiles with plant nail-board measurements