A final report for Blue Waters Illinois General Project Allocations

Multiphysics Modeling of Steel Continuous Casting

1. PI and Co-PIs/ Collaborators

PI: **Brian G. Thomas** bgthomas@illinois.edu; bgthomas@mines.edu; (217)333-6919; (303)273-3309 (ph)
Research Professor, and C. J. Gauthier Professor Emeritus,
Department of Mechanical Science & Engineering, University of Illinois at Urbana-Champaign (UIUC)
Also: Professor, Department of Mechanical Engineering, Colorado School of Mines (CSM)

Co-PIs / Collaborators (alphabetical order):
Cho, Seong-Mook (Research Assistant Professor)
seongmookcho1@mines.edu; (217)244-2859;
Department of Mechanical Engineering, CSM
Koric, Seid (Technical Assistant Director at NCSA, and Associate Research Professor of Engineering at UIUC) skoric@illinois.edu; (217) 265-8410;
NCSA, UIUC
Taha, Ahmed (Technical Program Manager at NCSA)
taha@illinois.edu; (217) 244-3008;
NCSA, UIUC
Vanka, S.P. (Emeritus Professor of Mechanical Engineering)
spvanka@illinois.edu; (217) 244-8388
Department of Mechanical Science & Engineering, UIUC
Vellakal Chidambara, Kumaraswamy Madhu (Research Programmer at NCSA)
vcmadhu@illinois.edu; (217) 300-0251
NCSA, UIUC
Yang, Hyunjin (Ph.D. Student)
hyang69@illinois.edu; (217) 244-2859;
Department of Mechanical Science & Engineering, UIUC
Zappulla, Matthew (Ph.D. Candidate)
Zappulla@mines.edu; (303)273-3309;
Department of Mechanical Engineering, CSM

Corresponding author: Brian G. Thomas bgthomas@illinois.edu; bgthomas@mines.edu

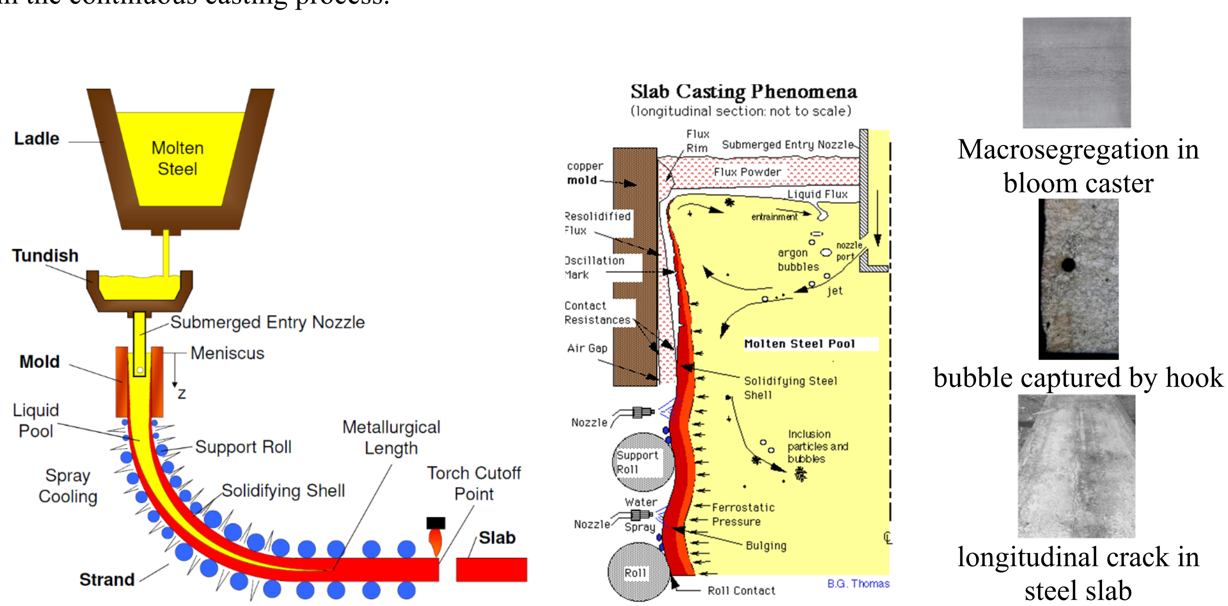
2. Executive summary (150 words)

This project aims to develop computationally-intensive and accurate multiphysics models using the multi-GPU based in-house code, CUFLOW and the commercial software programs, ANSYS-Fluent and Abaqus on Blue Waters (BW), to accurately simulate and scienfically understand trasient multiphysics phenomena in continuous steel casting, and to find practical ways to improve the process, which can impact greatly on the steel industry. The models, validated via lab experiments and plant measurements, have achieved speed-up breakthroughs on BW-XE and -XK nodes, which enables both higher resoultion and more simulations. A new hybrid mutiphase flow model has been developed to calculate arogn-gas behavior and bubble size distribution in a caster. In addition, transient flow, argon bubble transport and capture, and superheat distribution have been quantified with and without magnetic fileds, by applying LES, RANS, coupled with DPM and magnetic-induction MHD models. Finally, transient thermal-stress behavior of the solidifying steel shell has been simulated.

3. Description of research activities and results

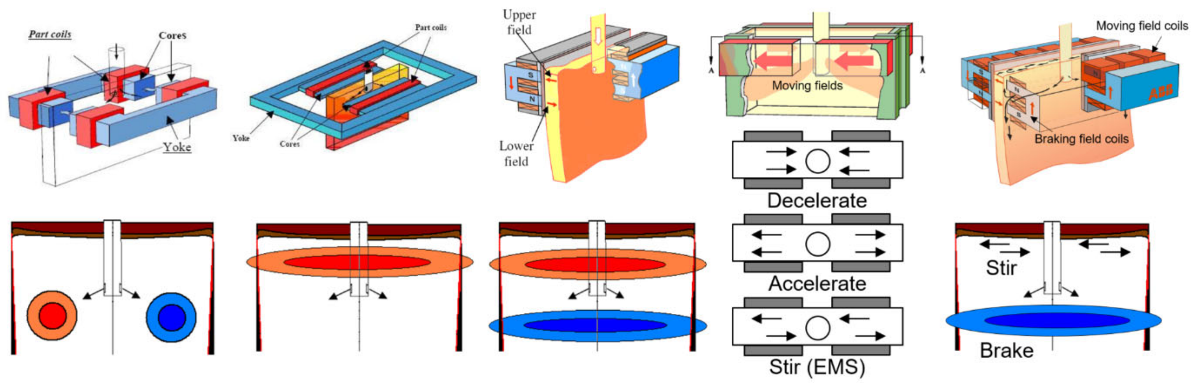
3.1. Key Challenges

Continuous casting is used to manufacture over 96% of steel in the world [1] and many defects in final steel products from this process are related to complex multiphysics phenomena, including turbulent multiphase flow, particle transport and capture, MagnetoHydroDynamics (MHD), heat transfer, solidification, and thermal-mechanical behavior, as shown in Fig.3.1-1. To control these complex phenomena and reduce the defects, many effors have been made to optimize process design and operating conditions, including nozzle design (size, angle, shape), mold dimensions (thickness, width, aspect ratio), casting speed, argon gas injection (flow rate, bubble size, injection location), and electromagnetic systems (Fig. 3.1-2). Especially, application of moving magnetic (Fig.3.1-2(d)) or combined (Fig.3.1-2(e)) fields, recently developed, is expected to make significant improvements in effectiveness, efficiency, and quality in the continuous casting process.



(a) (b) (c)

Fig. 3.1-1. Schematics of (a) steel continuous casting [2] and (b) CC slab-mold phenomena [2], and (c) defects in steel products [3,4].



(a) Local EMBr (b) Ruler EMBr (c) Double-ruler EMBr (d) Moving fields (e) Combined

Fig. 3.1-2. Types of electro-magnetic mold flow control systems showing hardware (top) and field shape (below). [5]

This project has investigated many different phenomena in the nozzle, mold, and strand regions of the steel continuous caster. Firstly, a new hybrid multiphase flow model [6,7] has been developed by coupling an Euelrian-Euelrian model for the gas fraction with the Discrete Phase Model (DPM) for bubble tracking, to simulate argon bubble behavior including bubble and gas pocket formation, breakup, coalescense, and accumulation. This model enables more realistic prediction of argon bubble size distribution in nozzle and mold during continuous steel casting, which is unable to be measured in lab-scale physical water models or in the real caster. Secondly, particle transport and capture into the solidifying steel shell with and without a static magnetic field by double-ruler Electro-Magnetic Braking (EMBr) has been calculated by applying Large Eddy Simulations (LES) coupled with the DPM and a electric potential MHD model and C-code based User-Defined Functions (UDFs) for the particle capture criterion [8,9], and the models have been validated via pleant measurements. Thus, more accurate size and location of the particles captured into the steel shell can be predicted, compared to the simple capture models used in previous work. Thirdly, the effects of moving magnetic fields applied by Electro-Magnetic Level Stabilizer (EMLS) and Mold Electro-Magnetic Stirrer (MEMS) on jet wobbling, argon bubble transport, surface velocity and level, and superheat distribution are investigated with transient simulations using LES, Reynolds Averaged Navier-Stokes (RANS)-based standard k-ε model, DPM, and MHD models. Finally, thermal stress behavior of stainless steel shell in a slab casting mold is quantified to predict depression and crack formation during the casting process.

To facilitate easy technology transfer, widely-used commercial software tools (ANSYS FLUENT HPC and ABAQUS) have been used to supplement our multi-GPU-based in-house CUFLOW code. Both software packages have efficient implementations on the Blue Waters system, with promising scale-up for our specific numerical methodologies, which we are exploiting, with the help of experts on both codes (both in-house co-PIs, and collaborators at the software companies). Furthermore, several researchers in NCSA have collaborated on this project over the several years of this multifaceted project.

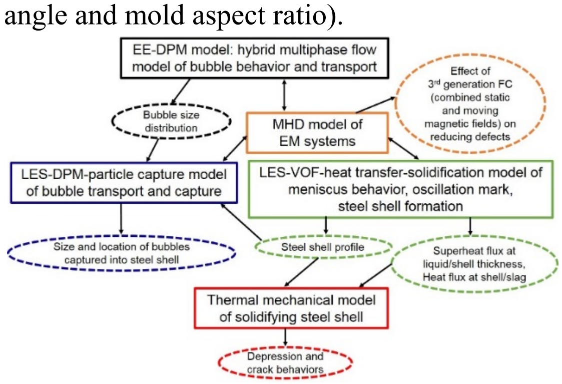
This project is supported by the Continuous Casting Consortium (UIUC) and the Continuous Casting Center (CSM), which between both institutions, is currently supported by 10 member companies in the steel industry who provide funding, experimental measurements (for model validation), and who allow free sharing of the research results with each other and with the public via publication in archival journals and conference proceedings.

This work is also supported by two active NSF GOALI grants: CMMI-13-00907 (GOALI: Operational Reconfigurability of Constrained Moving-Boundary Processes through Agile Motion Planning with Application to Steel Continuous Casting), and CMMI 18-08731 (GOALI: Turbulent Flow Modeling of Gas Injection to Minimize Surface Defects in Continuous-Cast Steel). The latter NSF project expects advanced high-performance computing to be a major component of the work, so the Blue Waters computational resource is very beneficial for this project.

3.2. Why it Matters

The continuous casting process is difficult to study with lab scale model experiments and plant experiments, owing to the hostile environment of the molten steel and the many governing process variables including thermal properties of steel and slag, process geometries, and process conditions. Thus, development of accurate, but computationally-intensive, multiphysics models to simulate the complex defect formation mechanisms is an ideal tool in studying and improving this process. This will enable understating of the defect formation mechanisms, and reduction of the defects by optimizing the process design and operating conditions, more efficient than conducting long, expensive, extremely limited trials in lab scale model and steel plant. Even small improvements in continuous casting processes can have huge impact on steel industries. This huge saving in this process will be greatly effective in development of steel industries and other related industries such as automobile and ship manufacturing, and construction.

The multiphysics models, explained in previous Section 3.1, are strongly interrelated as shown in Fig, 3.1-3. The predicted bubble size distribution from the hybrid multiphase flow model of complex interactions between bubbles, can be used as an input data for the particle tranport and capture model simulations. In addition, the validated particle capture model is available to be coupled with an MHD model, which enables quantification of the effect of electromagnetic forces on surface/internal defect formation due particle capture phenomena. Finally, thermal-mechanical behavior of the solidifying steel shell in the mold can be simulated and quantified using steel shell profile, superheat flux at liquid/solid steel interface, and heat flux in steel shell/slag gap which are calculated from the heat transfer-solidification model of meniscus behavior, oscillation mark, and steel shell formation. The complex physical phenomena, which include transient fluid flow, MHD, particle (bubble, inclusion) transport and capture, liquid mold flux/molten steel interface variations, heat transfer, solidification, and thermal stress in the steel shell, have been simulated by applying the models to investigate surface/internal defects including bubble, alumina, and slag capture defects, depression, and crack formation. Based on these simulations, safe operating windows in the continuous casting process are being found, based on performing parametric studies of the process parameters including EMBr, EMLS, EMS current strength, Submerged Entry Nozzle (SEN) depth, caster dimensions (SEN port angle and mold aspect ratio).

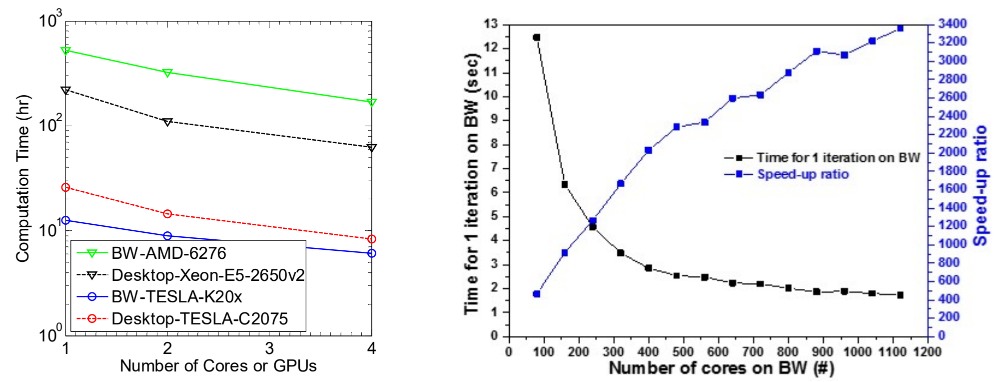


Fig, 3.1-3. Flow chart for multiphysics models.

3.3. Why Blue Waters

Development of accurate multiphysics models of steel continuous casting, for more detailed, accurate understanding of defect formation mechanisms and improvement of the process, requires great computational resources. Specifically, to capture the complex and interrelated phenomena in a large domain size (~ 2 m^3), some of which involve sub-millimeter spacial resolution, and macro-scale flow phenomena (up to a minute) requires many computational cells (~100 million), and many time steps, owing to the very small time-step size (smaller than ~10^{-4} sec). In the current works, this has been enabled by great speed-up breakthrough with good scaling on Blue Waters has been achieved.

The multi-GPU in-house CUFLOW codes [10-12] has achieved a good parallel scalability on Blue Waters XK nodes, showing only 48 hours of wall-clock time for 30 seconds of fully developed LES-MHD flow in 14-million cells domain as shown in Fig. 3.3-1(a). Furthermore, LES coupled with VOF to simulate transient liquid mold flux/molten steel interface motion and the shear flow patterns in 10 mm-thickness slag layer and 2 mm-thick slag gap between the mold hot plate and steel shell in the continuous casting mold, which requires a very huge domain volume (eg. ~2 m^3) consisting of total 20 million cells, which is refined (down to ~0.5 mm cell length) with time step size (~0.0005 sec), shows speedup of over 3000X with Fluent [13,14] HPC on the Blue Waters supercomputer with 70 XE nodes as shown in Fig. 3.3-1(b), compared to an ordinary work station PC (Dell T7600: Intel ® Xeon ® CPU E5-2603 @ 1.80GHz, RAM 72.0 GB, using 6 cores). Furthermore, numerous cases (over 15 cases) have been achieved simultaneously to investigate various process conditions, which has enabled a parametric study, essential to optimize this complex process. Thus, the parallel supercomputing environment on Blue Waters is greatly contributing to more accurately quantifying the complicated multiphysics phenomena with high resolution and more practical investigation considering the numerous cases simultaneously, in order to improving understanding of defect formation in this complex commercial process for numerous process conditions.



(a) (b)

Fig. 3.3-1. Speedup breakthrough of (a) CUFLOW and (b) ANSYS Fluent calculations on Blue Waters, relative to a lab workstation.

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3.4. Accomplishments

Significant accomplishments have been made since May, 2017 on several aspects of this multifaceted project. This report summarizes a few of the new results accomplished since last year in Sections 3.4.1 and 3.4.2. In addition, a list of other accomplishments (journal publications, reports, and presentations) are given in Section 4.

Note: The results shown in Sections 3.4.1 and 3.4.2 are not yet published, so should be considered confidential. The authors cordially request you to share these sections only with the Blue Waters team and the National Science Foundation. The authors will inform the Blue Waters team when these results become publicly available.

3.4.1. Effect of Electro-Magnetic Level Stabilizer (EMLS) Moving Magnetic Field on Transient Flow, Surface Level, and Argon Bubble Distribution in Mold during Continuous Casting of Steel

Seong-Mook Cho (Co-PI) and Brian G. Thomas (PI),
seogmookcho1@mines.edu (Seong-Mook Cho) and bgthomas@illinois.edu (Brian G. Thomas)

Executive Summary

Effect of moving magnetic field applied by Electro-Magnetic Level Stabilizer (EMLS) on transient fluid flow, argon bubble transport, and surface velocity and level in the mold during steady continuous slab casting is investigated using Large Eddy Simulations (LES) with magnetic induction MagnetoHydroDynamics (MHD) model. Mold flow patterns, surface velocity, surface level, their variations, and argon bubble distribution in the mold with and without EMLS are quantified with the LES-MHD model, and compared with corresponding plant measurements. EMLS reduces up-and-down jet

wobbling and the jet flow is deflected downward by strong electromagnetic forces induced near the narrow face. Thus, the jet flow deflected downward by EMLS has a longer path towards the mold top surface. In addition, the moving forces continuously brake the flow in the mold. Finally, surface velocity and level are more stable and less argon bubbles reside near the steel shell, due to the weaker jet with EMLS. Furthermore, the LES models shows a good agreement with the measurements of the surface velocity, surface level profiles, and their fluctuations from the nail board dipping tests in the real plant.

Introduction

Molten steel flows from a tundish, through a vertical bifurcated nozzle, into the mold. 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. Especially, abnormal surface flow causes severe level fluctuations [1], shear instability of the molten slag/steel interface, and vortex formation near the SEN, which leads to mold slag entrainment into the molten steel pool, resulting in surface defects in the steel product.

To control the transient fluid flow to avoid defects during continuous casting of steel slabs, many efforts have been made to optimize nozzle geometries and caster operating conditions including casting speed, submergence depth of the nozzle, mold width, argon gas injection, and Electro-Magnetic Forces (EMF), with the aim to achieve stable mold flow under nominally steady-state operation conditions. Application of a magnetic field to stabilize steel flow is an attractive method because the induced forces intrinsically adjust to flow variations. The field strength distribution depends on the magnet position(s), coil windings, and current. Electromagnetic systems are classified according to the type of field: static (DC current) or moving field (usually AC current). Static systems include local [2], single-ruler, and double-ruler (FC-Mold) Electro-Magnetic Braking (EMBr) [3-6]. Moving systems include Electro-Magnetic Level Stabilizer (EMLS), Electro-Magnetic Level Accelerator (EMLA), and Electro-Magnetic Rotating Stirrer (EMRS).

In the present work, Large Eddy Simulations have been validated with plant measurements and then applied to quantify the transient behavior of molten steel flow in the nozzle and mold with and without EMLS during nominally-steady continuous casting of steel slabs. Mold flow pattern, surface velocity, surface level, and especially their variations are compared between EMLS off and on cases, to obtain deeper insights into the effect of EMLS on steel quality.

Methods & Results

To calculate transient flow of molten steel in the nozzle and mold with and with EMLS, a three-dimensional finite-volume LES model coupled with a magnetic induction MHD model has been developed, considering mass/momentum sink to account for solidification of the molten steel by applying a C-code based User-Defined Function (UDF). This model was implemented a special High-Performance Computing (HPC) license version of the commercial CFD code ANSYS Fluent on the Blue Waters XE node. The model domain including tundish bottom, stopper-rod, nozzle, mold, strand, and steel shell regions consists of ~ 5 million hexahedral cells. To quantify transient surface level profiles in the mold, the calculated pressure profiles at the interface between liquid mold flux and molten steel at the mold top surface were used [7].

Fig. 3.4.1-1 shows the external moving magnetic field applied by EMLS at the center middle plane and 6 locations across mold width and along the casting direction in the mold. This moving magnetic field has two frequencies: 1 Hz (alternating current in each local magnet) and 2 Hz (phase shift between magnets to induce flow in a circular motion around the mold). Time-averaged flow patterns and turbulent kinetic energy in the mold both with and without EMLS are shown in **Fig. 3.4.1-2**. Both cases show a classic double-roll pattern in the mold. With no EMLS, the instantaneous mold flow patterns show up-and-down wobbling of the jets, which varies the impingement points on the NF. EMLS reduces the jet wobbling and makes the jet flow deflect downward due to the strong electromagnetic forces induced near the narrow face. Thus, the mold flow is slightly downward and turbulent kinetic energy of the fluid flow in the mold is generally reduced with EMLS. The change of the jet behavior also affects argon gas distribution in the mold, as shown in **Fig. 3.4.1-3.** The weaker jet makes less bubbles reside near the steel shell with EMLS. This could decrease bubble capture into the steel shell in the mold cavity.

Time-averaged and instantaneous profiles of surface velocity magnitude predicted by the LES model are compared with the nail board measurements in **Fig. 3.4.1-4**. 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. The model predictions of the average velocity profile, and its time and spatial variations, all agree with the measurements. This confirms that the LES-MHD model on BW is an accurate tool to predict complex mold-flow phenomena including EMLS effects. As expected from the mold flow patterns with EMLS, surface flow is slower showing less fluctuations, especially near the NF. Furthermore, EMLS makes the surface level flatter with less fluctuations near the NF. However, level fluctuations near the SEN are greater with EMLS, as shown in **Fig. 3.4.1-5**. The LES coupled with MHD model on BW shows good agreement with the measurements of both surface velocity, level, and their fluctuations. The discrepancy of the level variations near the SEN is likely due to short modeling time (~40 sec), which is insufficient to capture low-frequency fluctuations caused by surface level oscillation between the narrow faces. Longer calculating time would be needed to improve the model predictions of the transient surface behavior. Future work will also study heat transfer and particle entrapment, to better understand EMLS effects on steel quality, and how to optimize EMLS.

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Images and Captions

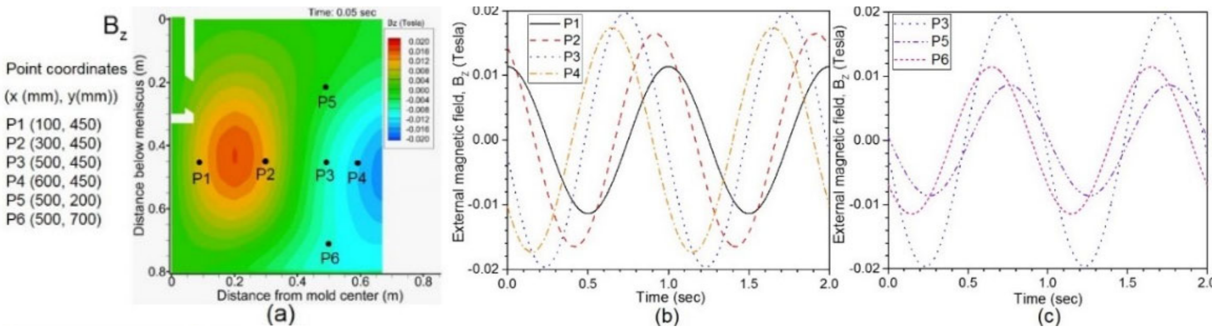


Fig. 3.4.1-1. External moving magnetic field by with EMLS: (a) instantaneous field at the center middle plane and (b) local EMLS fields (b) across mold width, (c) in casting direction

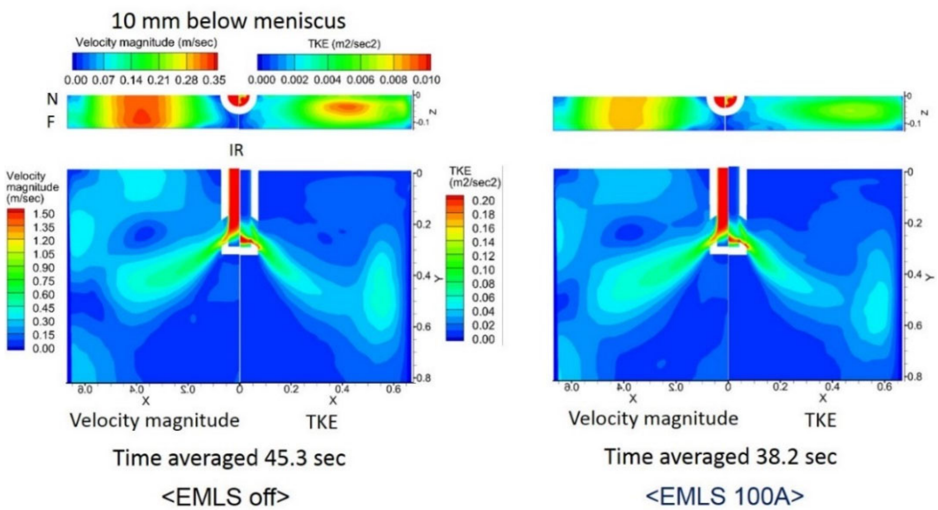
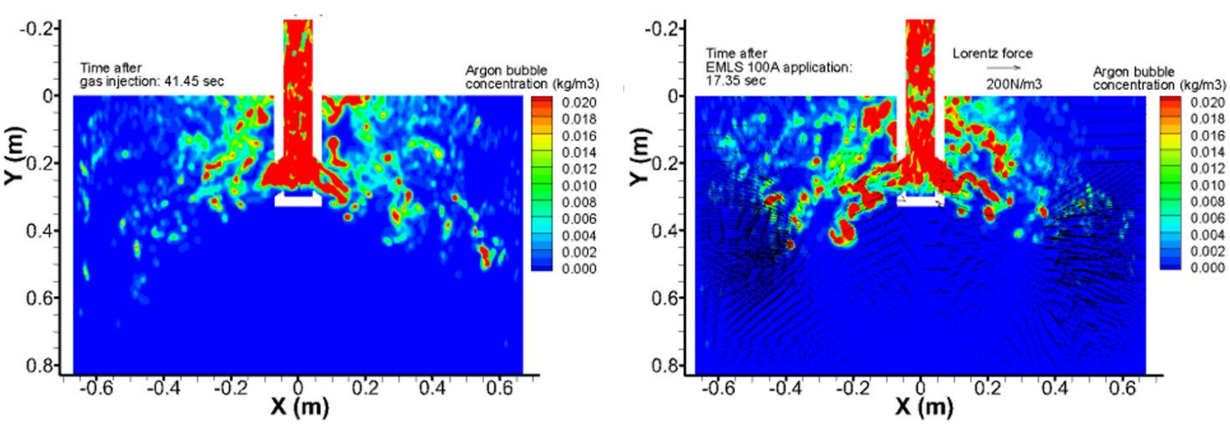


Fig. 3.4.1-2. Time-averaged flow patterns and turbulent kinetic energy in the mold with and without EMLS



(a) (b)

Fig. 3.4.1-3. Instantaneous argon bubble distributions (a) without and (b) with EMLS 100A

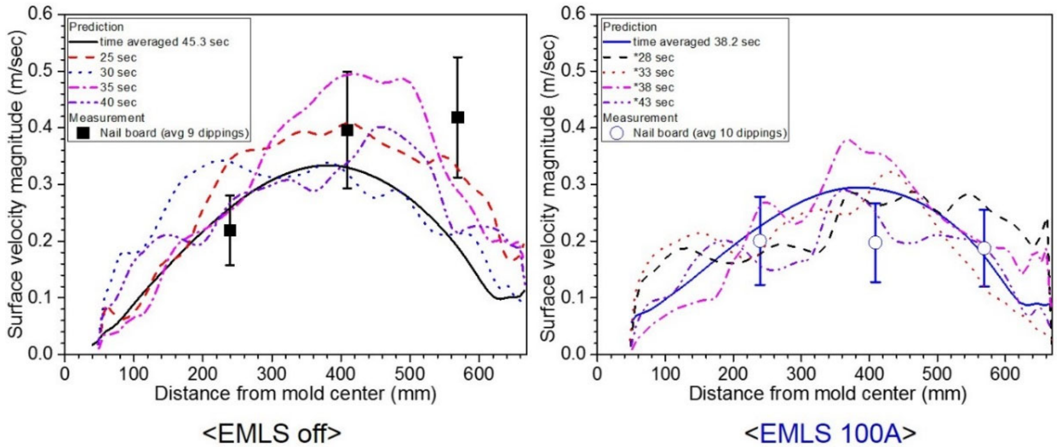


Fig. 3.4.1-4. Model validation: comparison of surface velocity between EMLS off and on

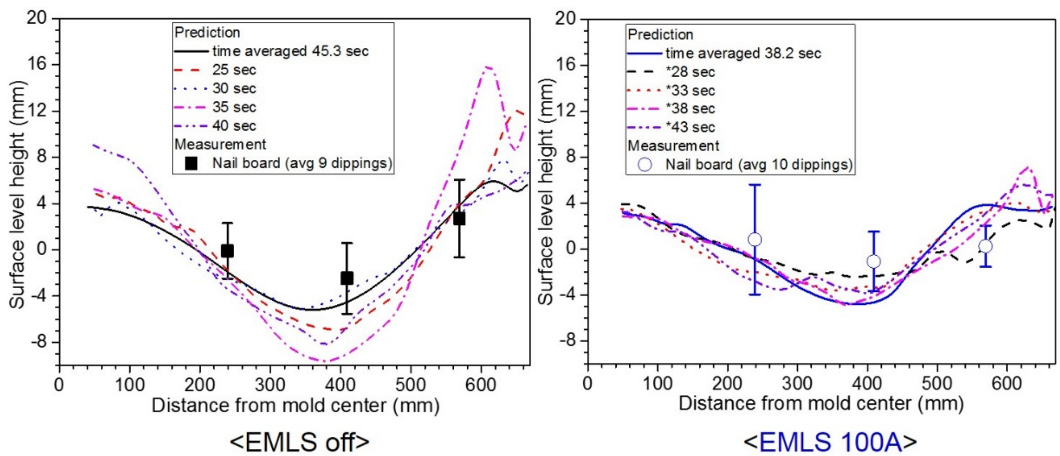


Fig. 3.4.1-5. Model validation: comparison of surface level with (left) and without (right) EMLS

3.4.2. Flow Pattern and Superheat Distribution in Mold with Mold Electro-Magnetic Stirrer (MEMS) during Continuous Casting of Thick Steel Slabs

Seong-Mook Cho (Co-PI) and Brian G. Thomas (PI)
seogmookcho1@mines.edu (Seong-Mook Cho) and bgthomas@illinois.edu (Brian G. Thomas)

Executive Summary

A Reynolds-Averaged Navier-Stokes (RANS) model using the standard k-ε model is applied together with a heat transfer model and the magnetic induction MagnetoHydroDynamics (MHD) model to investigate the effect of Mold Electro-Magnetic Stirring (MEMS) on the fluid flow pattern, temperature distribution, and superheat distribution during the continuous casting of thick slabs. MEMS generates magnetic field peaks which move around the mold wide faces, mainly along the thickness and width directions in the mold, making a rotating flow pattern. This causes an increase of flow velocity and more

uniform temperature near the steel shell in the mold. Finally, MEMS makes superheat flux delivery into the steel shell more uniform in the mold region.

Introduction

Meniscus freezing and hook formation [1,2], due to insufficient superheat into the steel shell during the initial solidification near the mold top surface, are well known to cause critical surface defects in final steel products. To reduce defects related to superheat distribution at steel shell front and temperature distribution near the meniscus, many efforts have been made to optimize nozzle design (nozzle port angle, area, shape, etc) and process conditions (depth of Submerged Entry Nozzle (SEN), casting speed, argon gas injection, etc). However, these parameters should be needed to be optimized for each casting conditions. Thus, application of Electro-Magnetic (EM) systems to the casting mold is a very attractive method to control fluid flow, temperature, and superheat in the mold, because their induced forces intrinsically adjust to flow variations.

This work applies Reynolds-Averaged Navier-Stokes (RANS) model using the standard k-ε turbulence model, coupled with a heat transfer model, and the magnetic induction MagnetoHydroDynamics (MHD) model equations, to predict the time-averaged flow pattern, temperature distribution, and superheat distribution at the shell solidification front in a thick slab mold with / without Mold Electro-Magnetic Stirrer (MEMS), during steady continuous casting.

Methods & Results

To investigate the effect of MEMS on the flow pattern, temperature, and superheat distribution at the steel shell front in a thick-slab mold with and without MEMS during steady continuous casting, a 3-dimensional RANS based fluid-flow model, with the standard k-ε model, coupled with a heat transfer model and magnetic induction MHD model was implemented into a special High-Performance Computing (HPC) license version of the commercial CFD code ANSYS Fluent on the Blue Waters XE node. Furthermore, the model was coupled with various User-Defined Functions (UDF) to consider thermal properties of steel and mass/momentum sink of the molten steel due to the solidification [3-5].

Results for the MEMS-off case are shown in **Fig. 3.4.2-1**. More flow exits the slightly larger ports towards the narrow face, than towards the wide face. However, the shorter path of the flow towards the wide face, leads to higher velocity and higher temperature in the upper mold region (~300 mm below meniscus) on the wide face. At the same time, superheat is unable to reach the region near the chamfered corner, as shown in the dashed red box in Fig. A-2-1. The MEMS location, 330 mm below the meniscus, makes a rotating magnetic field around the central region of the mold. Time-variations of the field components (B_X, B_Z) with a local frequency of 1.1 Hz are shown in **Fig. 3.4.2-2**, along the thickness and width directions in the mold produce a moving field with a phase frequency of ~3 Hz, around the perimeter of the mold. With MEMS, the surface flow velocity increases (surface velocity appears to be in a safe window of operation: F-value [6]: 3 ~ 5; surface velocity: 0.2 ~ 0.4 m/sec). Superheat flux at the shell front becomes more uniform due to the rotating flow in the mold. Finally, MEMS increases superheat flux to the corners, making the superheat flux more uniform at the shell front in the mold region, by rotating flow around the perimeter of the mold as shown in **Fig. 3.4.2-3**. With MEMS, the surface flow becomes faster (0.4 m/s) and temperature becomes more uniform after ~5 sec. So, hook formation near the corners might be a problem during the initial 10s of operation, when the corners are colder, EMS is off, (first 5s) and flow is transient.

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Images and Captions

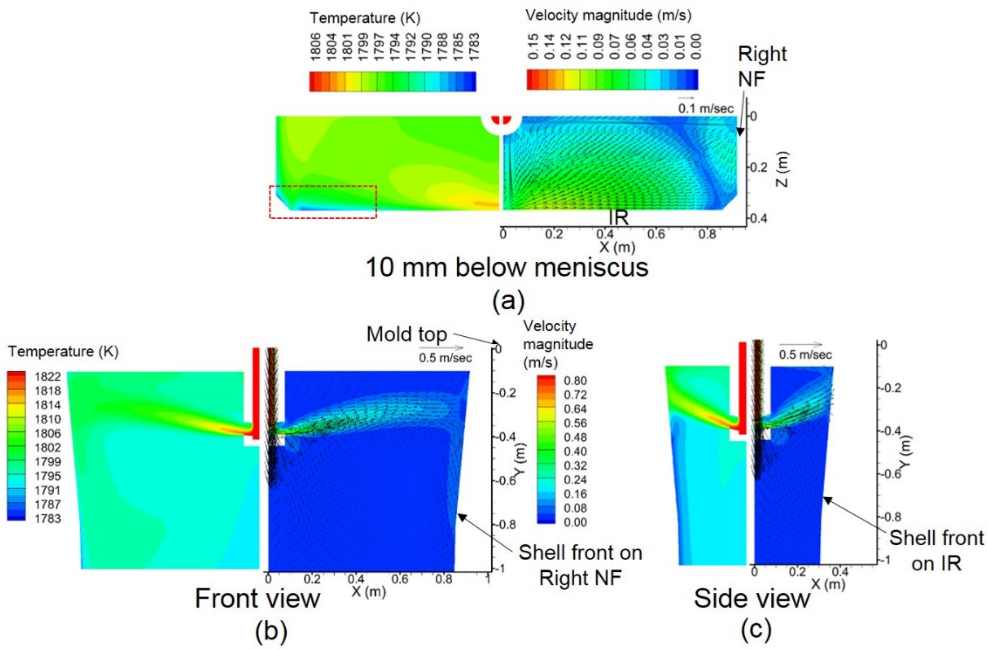


Fig. 3.4.2-1. Time-averaged flow patterns and temperature distribution in the mold without MEMS

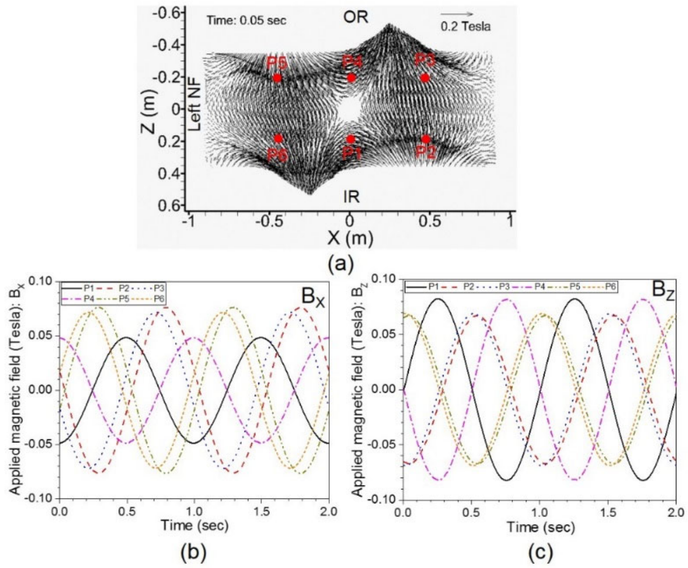


Fig. 3.4.2-2. External moving magnetic field by MEMS: (a) instantaneous field at the horizontal plane 330 mm below the meniscus and (b) local MEMS fields of B_x, (c) B_z

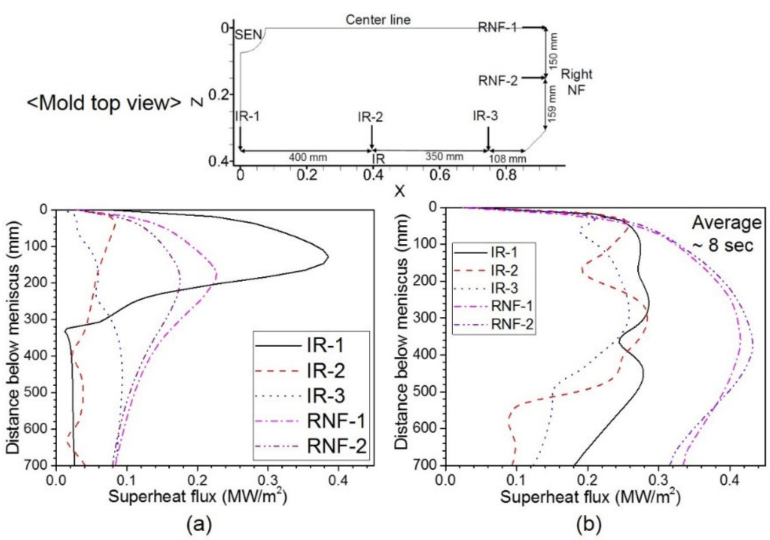


Fig. 3.4.2-3. Superheat flux distribution at steel shell front (a) without and (b) with MEMS

3.4.3. Other Accomplishments from the Blue Waters Project Last Year (2017-2018).

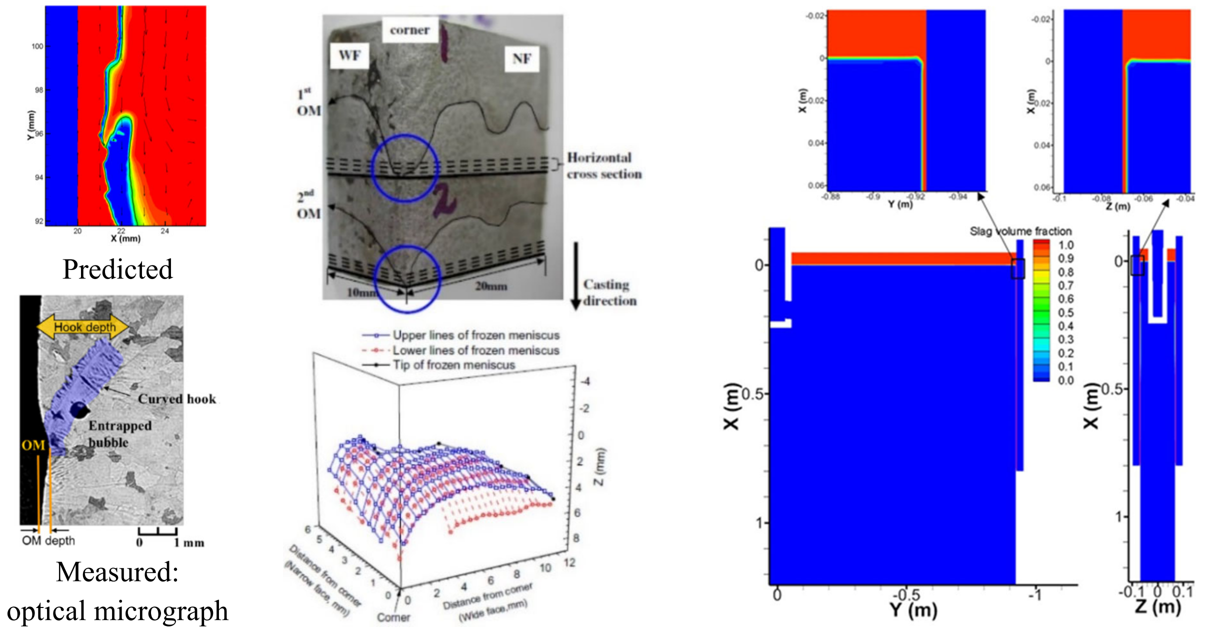
Seventeen publications in archival journals, reports, and conference presentations based on simulations using Blue Waters have been achieved in 2017-2018, and several more publications are currently in preparation, expected in 2018. Please see our list of publications in Section 4.

3.5. Next Generation Work

The mold region where the steel shell first starts to solidify is called the meniscus region due to its shape. In addition, hook-shaped steel shell tips sometimes form during the initial solidification in the meniscus region which travel down with the shell and capture particles which end up in the final product [1-3]. Thermal flow and solidification in the meniscus region is affected by the mold plate oscillation, surface tension, and the slag layer on top of the steel pool [4,5], and the incoming molten-steel jet from the nozzle ports, as revealed in our previous BW project achievements. Specifically, the steel shell where the jet flow impinges can be remelted by superheat delivered along with the jet flow, resulting in severe shell erosion and even breakouts. Previous studies with a two-dimensional domain conducted on a lab PC shows that a very fine mesh (~50 μm cell thickness) is needed to capture the shape of solidified steel shell tip and the gap (oscillation mark) between steel shell and the mold [4,5].

The validated 2-D thermal-fluid model to simulate solidification phenomena at the slag/molten steel interface near the meniscus region [4,5], will be applied to much larger 3-D huge-volume domain (including nozzle, mold, and strand regions) as shown in Fig. **3.5-1 (c),** to consider further-detailed effects of anisotropic jet flow variations on the solidification and simulate more deeper hook and oscillation mark in the corner region which were observed from our previous optical micrograph studies (Fig. **3.5-1** (b)). This complex domain will be carefully blocked to generate high resolution (cell length: ~50 μm) structured hexahedral cells with reasonable cell skewness and aspect ratio (lower than 5). The blocked-out domain with assigned cell pacing on each line of the blocks, will be volume-meshed on the special high memory Blue Waters XE node, with aid of Dr. Taha, NCSA. The domain is expected to have an ultra-fine mesh consisting of over ~ 100 million hexahedral cells. The high-resolution and –quality meshed domain will be built and run in Fluent on the distributed parallel XE nodes, employing the LES model for anisotropic turbulence, the Volume Of Fluid (VOF) model for liquid mold flux/molten steel interface motion and slag entrapment, a solidification model for steel shell solidification, and several c-code based User-Defined Functions (UDFs) for various process conditions and material thermal properties. Furthermore, a species transport model will be implemented, to simulate macrosegregation defects in the mold region, especially near the hook formation region at the meniscus. This modeling calculation is not feasible to be achieved without the Blue Waters computation resources. Based on new understanding found from these comprehensive model simulations on Blue Waters, we plan to gain deeper insight into the relation between the transient thermal multiphase flow phenomena, solidification and slag defects during continuous steel casting.

This work is enabling a better prediction of particle capture into the steel shell. As investigated from our previous plant measurement studies, the hook can capture particles including bubble, alumina, and slag droplet more and easier than normal shape steel shell. This result will be used for other model calculations as an input data. More details of this next work are prepared in our recent proposal for Blue Waters Illinois Allocation General Project which was already submitted on September 15, 2018.



(a) (b) (c)

Fig. 3.5-1. (a) Comparison of initial solidification between 2-D prediction and measurement [4], (b) measured oscillation marks and hooks in slag/steel corner regions [3], and (c) 3-D steel/slag domain (22 million cells) covering the corner region

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4. List of publications, data sets associated with this work

1) B. G. Thomas, S-M. Cho, S. P. Vanka, H. Yang, M. Zappulla, A. Taha, and S. Koric: "Transient Multiphase Flow Phenomena and Defect Formation in Steel Continuous Casting", Blue Waters Annual Report book, 2017, ed. B. Jewett, University of Illinois, Urbana, IL, 2017, pp. 160-161.
2) K. Jin, S. P. Vanka, and B. G. Thomas: "Large Eddy Simulations of Electromagnetic Braking Effects on Argon Bubble Transport and Capture in a Steel Continuous Casting Mold", Met. Mat. Tran. B, 2018, DOI: 10.1007/s11663-018-1191-1.
3) H. Yang, S. P. Vanka, and B. G. Thomas: "Hybrid Eulerian-Eulerian Discrete-Phase Model of Turbulent Bubbly Flow", Proc. of ASME IMECE 2017-70337, 2017.
4) H. Yang, S. P. Vanka, and B. G. Thomas: "Modeling of Argon Gas Behavior in Continuous Casting of Steel", Proc. of TMS 2018, 2018.

5) S-M. Cho, B. G. Thomas, S-H. Kim, S-W. Han, and Y-J. Kim: "Effect of EMLS Moving Magnetic Field on Transient Slab-Mold Flow", CCC Annual Report, 2017
6) H-S. Kim, S-M. Cho, S-H. Kim, and B. G. Thomas: "Mold Flow and Shell Growth in Large-Section Bloom Casting using CON1D", CCC Annual Report, 2017
7) H. Yang, S. P. Vanka, and B. G. Thomas: "Hybrid Model of Multiphase Flow Including Gas Pockets, Gas Bubbles, Breakup and Coalescence", CCC Annual Report, 2017.
8) Matthew L.S. Zappulla and Brian G. Thomas: "Thermal-Mechanical Model of Depression Formation in Steel Continuous Casting", TMS Annual. Meet. Suppl. Proc., San Diego, CA, 2017, p. 501
9) Matthew L.S. Zappulla and Brian G Thomas: "Surface Defect Formation in Steel Continuous Casting", THERMEC' 2018, Paris, France, 2018.
10) Brian G. Thomas, Seong-Mook Cho, Surya Pratap Vanka, Seid Koric, Ahmed Taha, Hyunjin. Yang, and Matthew Zappulla, "Multiphase Turbulent Flow Modeling of Gas Injection into Molten Metal to Minimize Surface Defects in Continuous-Cast Steel", Blue Waters Annual Report 2018, National Center for Supercomputing Applications (NCSA), University of Illinois, Urbana, IL, 2018, Submitted.
11) Seong-Mook Cho and Brian G. Thomas: "Multiphysics Modeling of Steel Continuous Casting: Multiphase Turbulent Flow Modeling of Steel Continuous Casting with Electro-Magnetic Systems to Minimize Surface Defects", 6th National Center for Supercomputing Applications (NCSA) Blue Waters Symposium, Sunriver, Oregon, USA, June 04-07, 2018.
12) Seong-Mook Cho, Brian G. Thomas, and Seon-Hyo Kim: "Effect of Nozzle Port Angle on Transient Flow and Surface Slag Behavior during Continuous Steel-Slab Casting", Met. Mat. Tran. B, 2018, in press.
13) Seong-Mook Cho and Brian G. Thomas: "1) LES Modeling of Slag Entrainment and Entrapment and 2) Nozzle Flow Model Validation with Measurements of Pressure-Drop and Bubble-Size Distribution", CCC Annual Report, 2018.
14) Matthew L. S. Zappulla and Brian G. Thomas: "Modeling and Online Monitoring with Fiber-Bragg Sensors of Surface Defect Formation during Solidification in the Mold", CCC Annual Report, 2018.
15) Matthew L. S. Zappulla, Seid Koric, Seong-Mook Cho, Hyoung-Jun Lee, Seon-Hyo Kim, and Brian G. Thomas: "Multi-Physics Modeling of Visco-Plastic Behavior of Solidifying Stainless Steel Shell during the Continuous Casting Process", Journal of Materials Processing Technology, 2018, In preparation.
16) Matthew L. S. Zappulla and Brian G. Thomas: "Improving Steel Armor-Plate Quality by Advanced Computational Models of the Continuous Slab-Casting Process", DoD Steels Summit, Bethesda, MD, October 2018, poster accepted.
17) Matthew L. S. Zappulla, Seong-Mook Cho, and Brian G. Thomas: "Visualization of Steel Continuous Casting Models for Process Understanding", Steel Research International, 2018, Under Review.

And, several more publications based on simulations using Blue Waters are in preparation, with publication expected in 2018.