7th Annual NCSA Blue Waters Symposium,
Sunriver, Oregon, June 03-06, 2019

Thermal Multiphase Modeling of Defect Formation Mechanisms and Electromagnetic Force Effects in Continuous Steel Casting

Illinois General Project:
Multiphysics Modeling of Steel Continuous Casting

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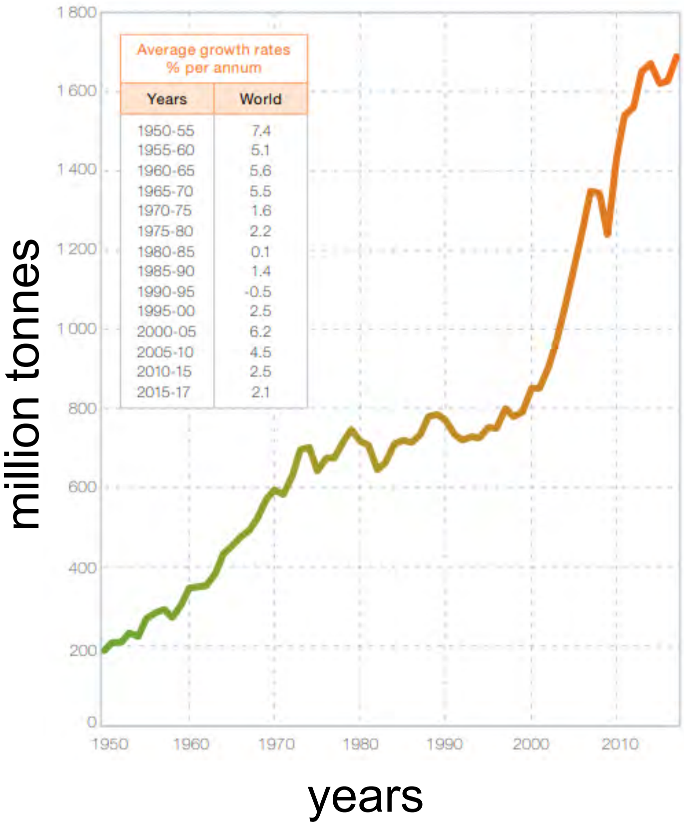
- National Science Foundation (Grant Nos. 18-08731 and 13-00907)

Recent Publications Acknowledging Blue Waters (2018-2019)

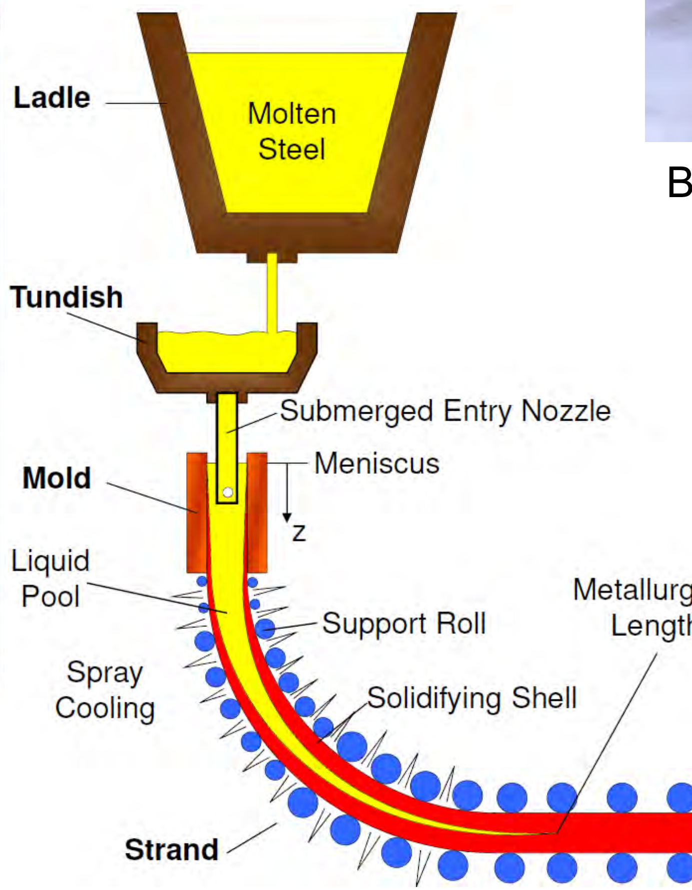
1) Brian G. Thomas, Seong-Mook Cho, Surya Pratap Vanka, Seid Koric, Ahmed Taha, Hyunjin. Yang, and Matthew Zappulla: “Multiphase Turbulent Flow Modeling of Gas Injection into Molten Metal to Minimize Surface Defects in Continuous-Cast Steel”, Blue Waters Annual Report 2018, ed. B. Jewett and C. Watkins, National Center for Supercomputing Applications (NCSA), University of Illinois, Urbana, IL, 2018, pp. 118-119.
2) 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.
3) Matthew L. S. Zappulla and Brian. G. Thomas, "Surface Defect Formation in Steel Continuous Casting", Materials Science Forum, Vol. 941, pp. 112-117, 2018. DOI: 10.4028/www.scientific.net/MSF.941.112
4) Kai Jin, Surya P. Vanka, and Brian G. Thomas, “Large Eddy Simulations of Electromagnetic Braking Effects on Argon Bubble Transport and Capture in a Steel Continuous Casting Mold”, Metallurgical and Materials Transactions B, Vol. 49B (3), pp. 1360-1377, 2018. DOI: 10.1007/s11663-018-1191-1
5) Hyunjin Yang, S.P. Vanka, and B.G. Thomas, “A Hybrid Eulerian-Eulerian Discrete-Phase Model of Turbulent Bubbly Flow”, J. Fluids Eng., Vol. 140 (10), pp. 101202-1-12, 2018 (reprinted from ASME 2017 IMECE2017-70337, Nov. 3-9, 2017, Tampa, FL). [Robert T. Knapp Award, ASME, 2018] DOI: 10.1115/1.4039793
6) Hyunjin Yang, Surya P. Vanka, and Brian G. Thomas, “Modeling of Argon Gas Behavior in Continuous Casting of Steel”, JOM, Vol. 70 (10), pp. 2148-2156, 2018. DOI: 10.1007/s11837-018-2997-7
7) Hyunjin Yang, Surya P. Vanka, and Brian G. Thomas, “Modeling of Argon Gas Behavior in Continuous Casting of Steel”, in CFD Modeling and Simulation in Materials Processing 2018, The Minerals, Metals & Materials Series, Warrendale, PA, pp. 119-131, 2018.
8) 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.
9) 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.
10) 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”, Metallurgical and Materials Transactions B, Vol. 50B (1), pp. 52-76, 2019. DOI: 10.1007/s11663-018-1439-9
11) Seong-Mook Cho and Brian G. Thomas, “Modeling of Transient Behavior of Top-Surface Slag/Molten Steel Interface in Continuous Slab Casting”, Proceeding of 8th International Conference on Modeling and Simulation of Metallurgical Processes in Steelmaking (STEELSIM 2019), Toronto, Ont., Canada, August 13-15, 2019, Assoc. Iron Steel Technology, Warrendale, PA.
12) Matthew L. S. Zappulla, Seong-Mook Cho, and Brian G. Thomas, “Visualization of Steel Continuous Casting Including a New Integral Method for Post-Processing Temperature Data”, Steel Research International, Vol. 90, 1800540 (pp. 1-11), 2019. DOI: 10.1002/srin.201800540
13) Matthew L. S. Zappulla, Seid Koric, Seong-Mook Cho, Hyoung-Jun Lee, Seon-Hyo Kim, and Brian G. Thomas, “Multiphysics modeling of continuous casting of stainless steel”, Journal of Materials Processing Technology, 2019, Under Review.
14) Brian G. Thomas, Seong-Mook Cho, Hyunjin. Yang, Surya Pratap Vanka, Matthew Zappulla, Seid Koric, and Ahmed Taha: “Turbulent Multiphase Thermal Flow Modeling of Defect Formation Mechanisms and Electromagnetic Force Effects in Continuous Steel Casting”, Blue Waters Annual Report 2019, Submitted.
15) CCC Annual Reports, August, 2019, pending

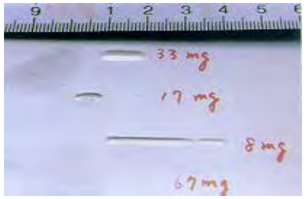
Introduction: Continuous Steel Casting



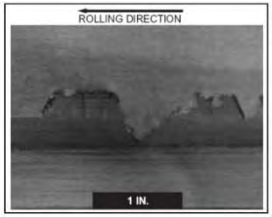
Years	World
1950-55	7.4
1955-60	5.1
1960-65	5.6
1965-70	5.5
1970-75	1.6
1975-80	2.2
1980-85	0.1
1985-90	1.4
1990-95	-0.5
1995-00	2.5
2000-05	6.2
2005-10	4.5
2010-15	2.5
2015-17	2.1

World Steel production





Blister (coil)



Sliver (coil)

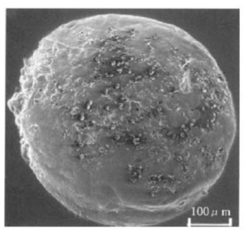
Depression (slab)

Longitudinal crack (slab)

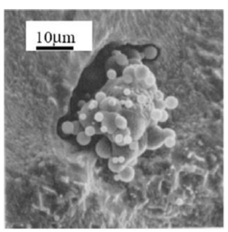
- Over **96% of steel** in the world is continuous cast*, so: even **small improvements** have **tremendous impact**.

* World Steel Association. In Steel Statistical Yearbook 2018, World Steel Association: Brussels, Belgium, 2018, pp. 9-12.
** Brian G. Thomas, ccc.Illinois.edu

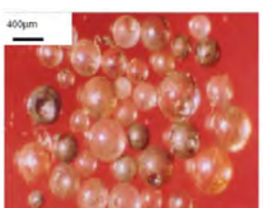
Introduction: Defect-Related Phenomena in Continuous Steel Casting



Bubble with inclusions

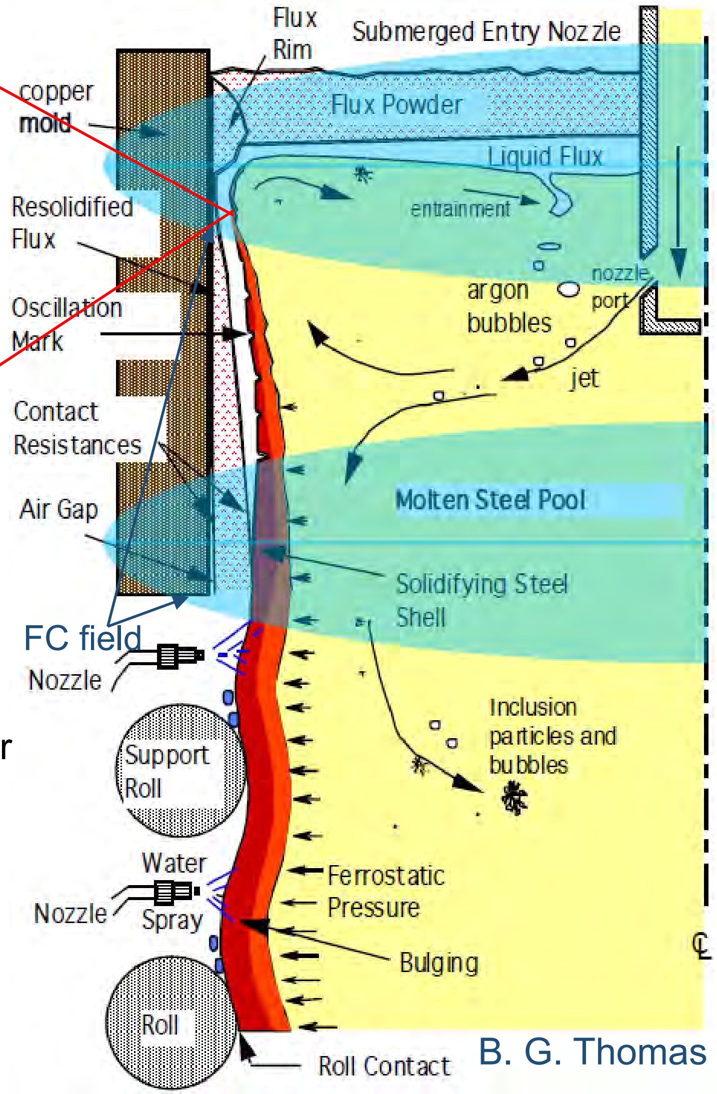


Alumina cluster



Slag inclusions

<Particle capture into steel shell>

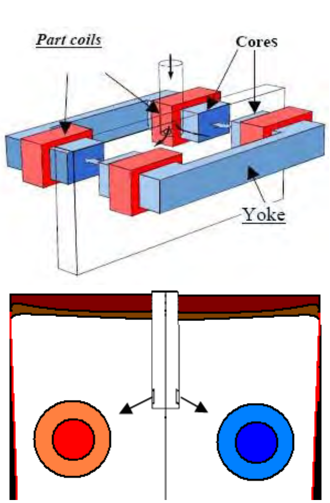


<Schematic of phenomena in mold>

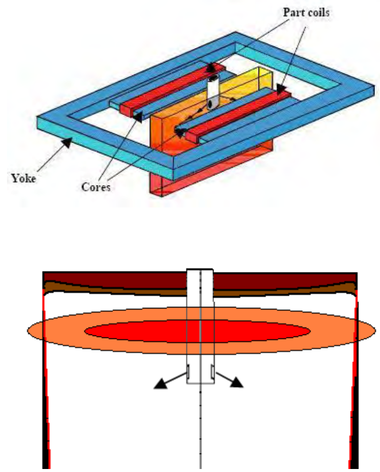
<Surface instability: mold top view>

- Instability at liquid flux/molten steel interface
- Slag entrainment and entrapment
- Particle (slag droplet, alumina, bubble) capture into steel shell
- Nonuniform superheat transport and meniscus freezing
- Deformation & stress in steel shell
- Embrittlement & cracks
- MagnetoHydroDynamics (MHD)

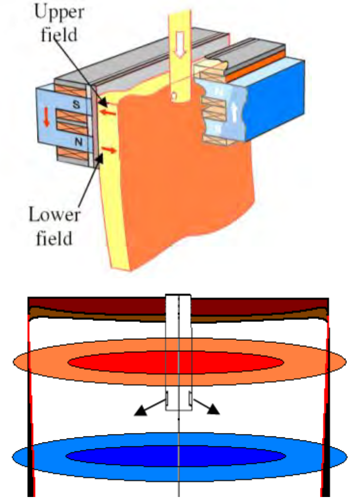
Introduction: Electro-Magnetic (EM) Systems



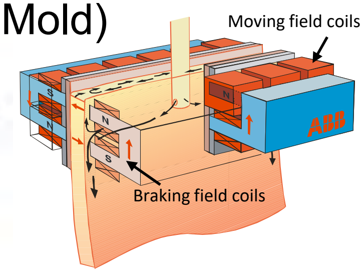
Local EMBr

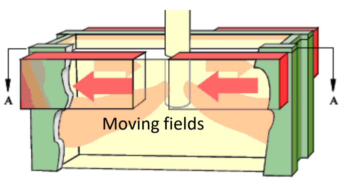


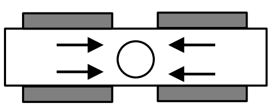
Single-ruler EMBr



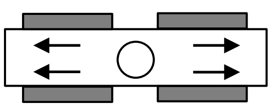
Double-ruler EMBr (Flow Control (FC)-Mold)



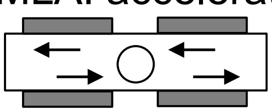




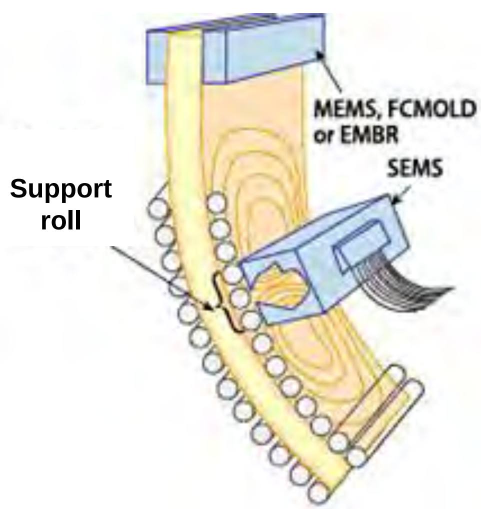
EMLS: decelerate



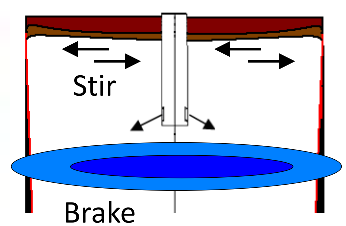
EMLA: accelerate



M-EMS / EMRS: stir



SEMS



Combined fields

- **Magnetic fields (static/moving/combined fields)** greatly alter **molten steel flow** and corresponding **phenomena** in continuous casting*
  - Flow pattern
  - Surface instability
  - Superheat transport and initial solidification
  - Particle transport and capture
  - Grain structure and internal quality
  - Steel composition distribution

*Seong-Mook Cho and Brian G. Thomas: "Electromagnetic Forces in Continuous Casting of Steel Slabs", Metals (Special Issue: Continuous Casting), 2019, Vol. 9, 471 (pp. 1-38), DOI: 10.3390/met9040471.

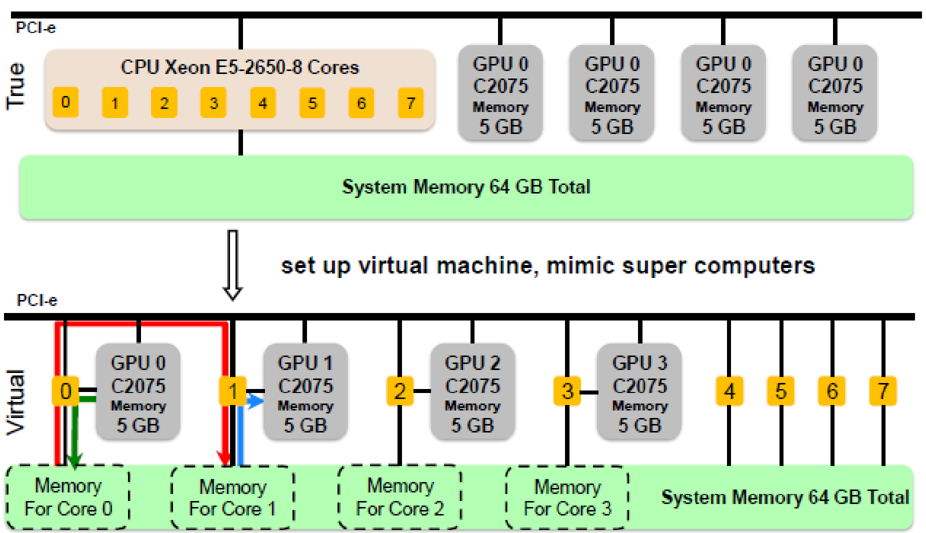
Thermal Multiphase Models on Blue Waters

- **Why computational modeling**:
  - Experiments and measurements to quantify phenomena are extremely limited due to harsh environment and huge size of process, and many process parameters.
- **Why Blue Waters**
  - Many coupled governing equations need to be solved for multiphysics simulations.
  - High-resolution (micrometer-length scale and millisecond-time) prediction to capture defect formation in huge domain.
  - Numerous cases to be calculated simultaneously with different process conditions, for parametric studies essential to optimize this complex process.
- **Applied models: ANSYS FLUENT HPC (commercial CFD code)** and **CUFLOW (multi-GPU based in-house code)**
  - Turbulence models: Large Eddy Simulation (LES), Reynolds-Averaged Navier-Stokes (RANS) models (standard k-ε and Shear Stress Transport (SST) k-ω)
  - Secondary phase models: Volume Of Fluid (VOF), Eulerian-Eulerian (EE) model, Lagrangian Discrete Phase Model (DPM), EE-DPM Hybrid model.
  - Particle capture model (calculates local force balance on each particle at solidification front).
  - Heat transfer model.
  - MagnetoHydroDynamics (MHD) model: electric-potential and magnetic-induction methods.

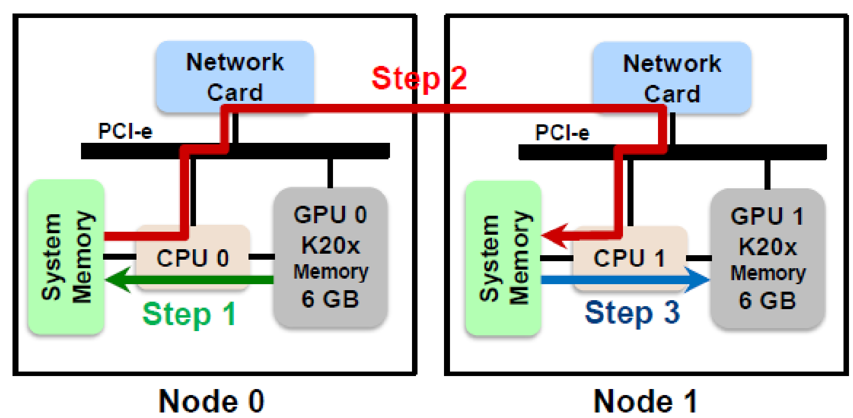
CUFLOW Configuration

- Two versions of CUFLOW, CPU and GPU versions, tested
  - CPU version, run on multi-CPU PC: data compunication through MPI
  - GPU version, run on multi-GPU PC and multi-CPU&GPU pair supercomputer (eg. Blue Waters)

	PC - 4GPU Workstation	Blue Waters Supercomputer
#of Nodes	1	4224
Node CPU	Xeon E5-2650v2 Ivy Bridge, 2.60 GHz, 8 cores	AMD 6276, 2.3 GHz, 16 cores
GPU/Node	4 × Nvidia Tesla C2075, 4 × **5 GB**, 575 MHz	1 × Nvidia Tesla K20x, 1 × **6 GB**, 732 MHz



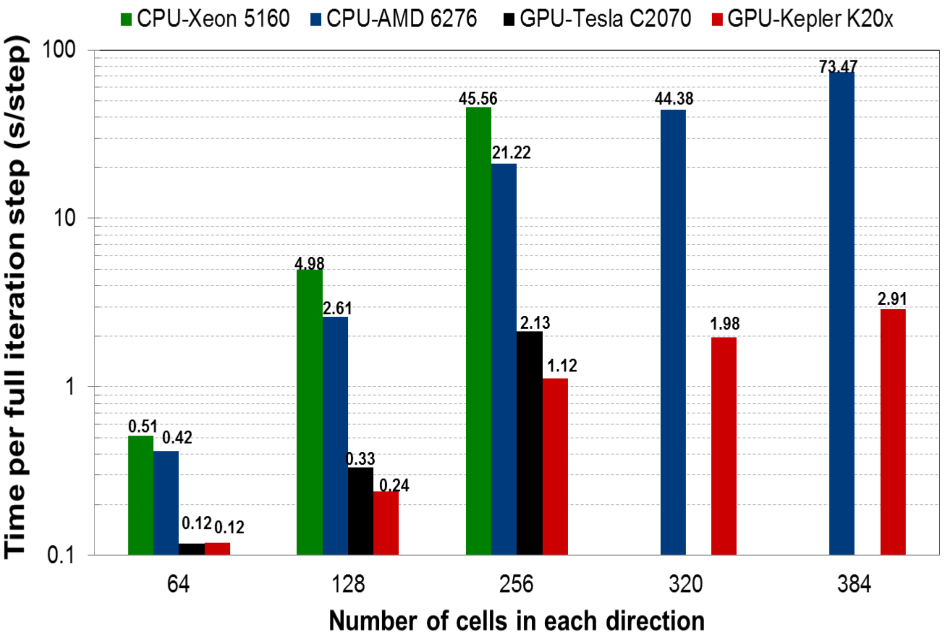
<Configuration of 4 GPU workstation>

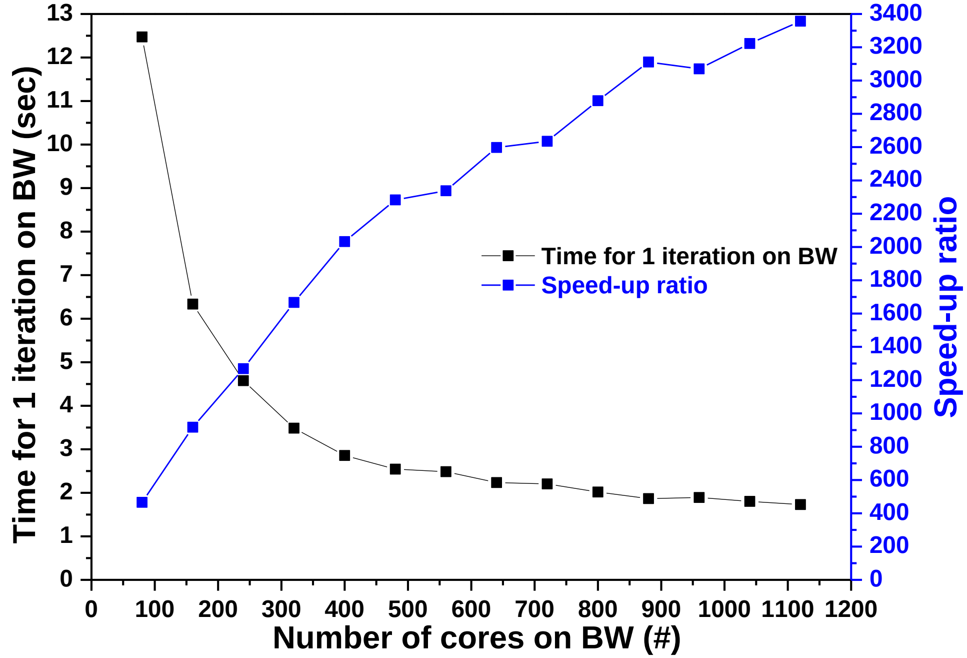


Three Steps: cudaMemcpy(…), MPI_Send(…) and MPI_Recv(…), cudaMemcpy(…)

<Configuration of BW nodes showing 2 nodes>

Ground-Breaking Speed-Up on Blue Waters





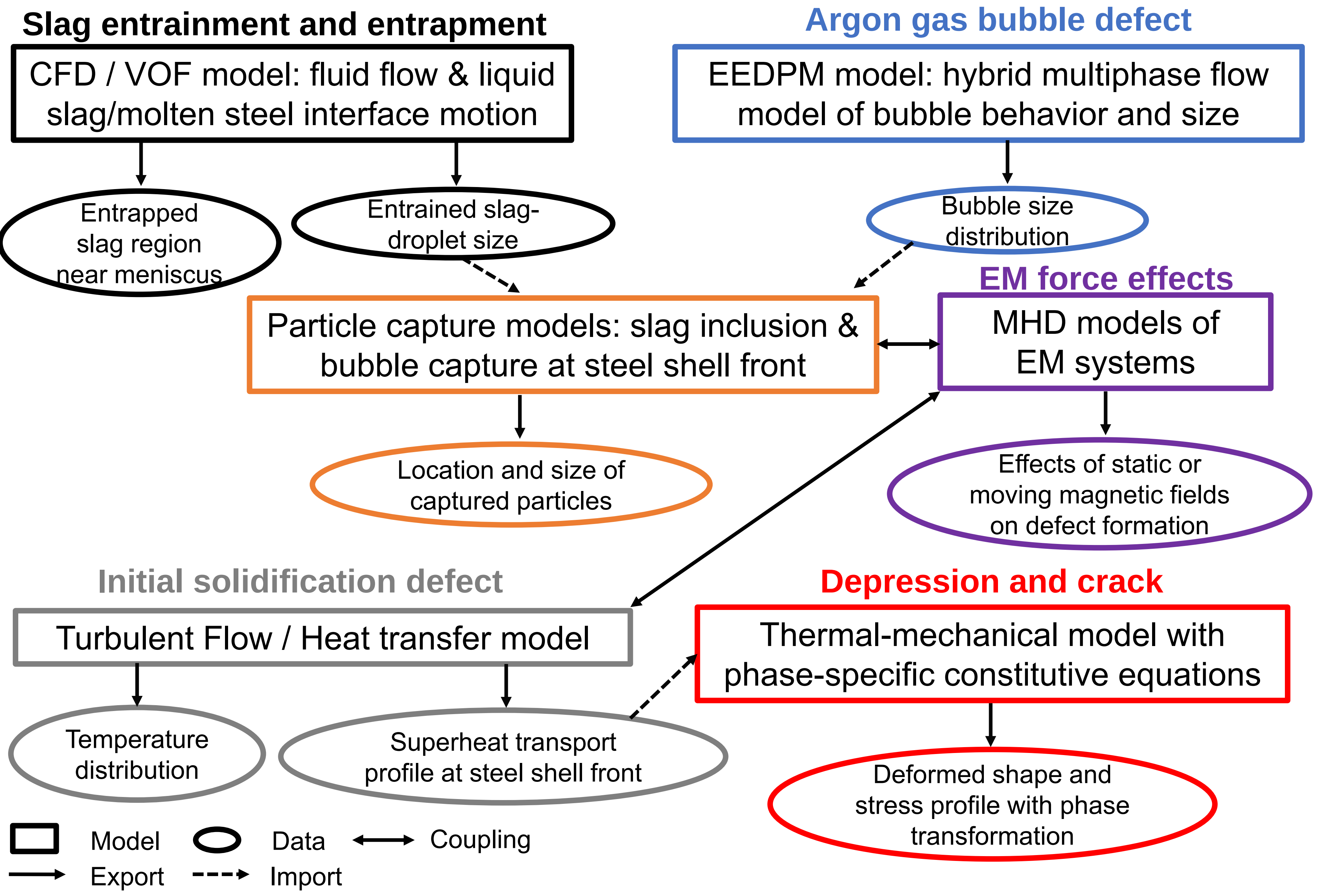
<CUFLOW on Blue Waters XK Node> <ANSYS FLUENT HPC on Blue Waters XE Node>

- **Multi-GPU based in-house code CUFLOW** on Blue Waters **XK node**, which has K20x GPU as co-processors: **×40 speed up**
- **ANSYS-Fluent HPC** on Blue Waters **XE node: ×3000 speed up**

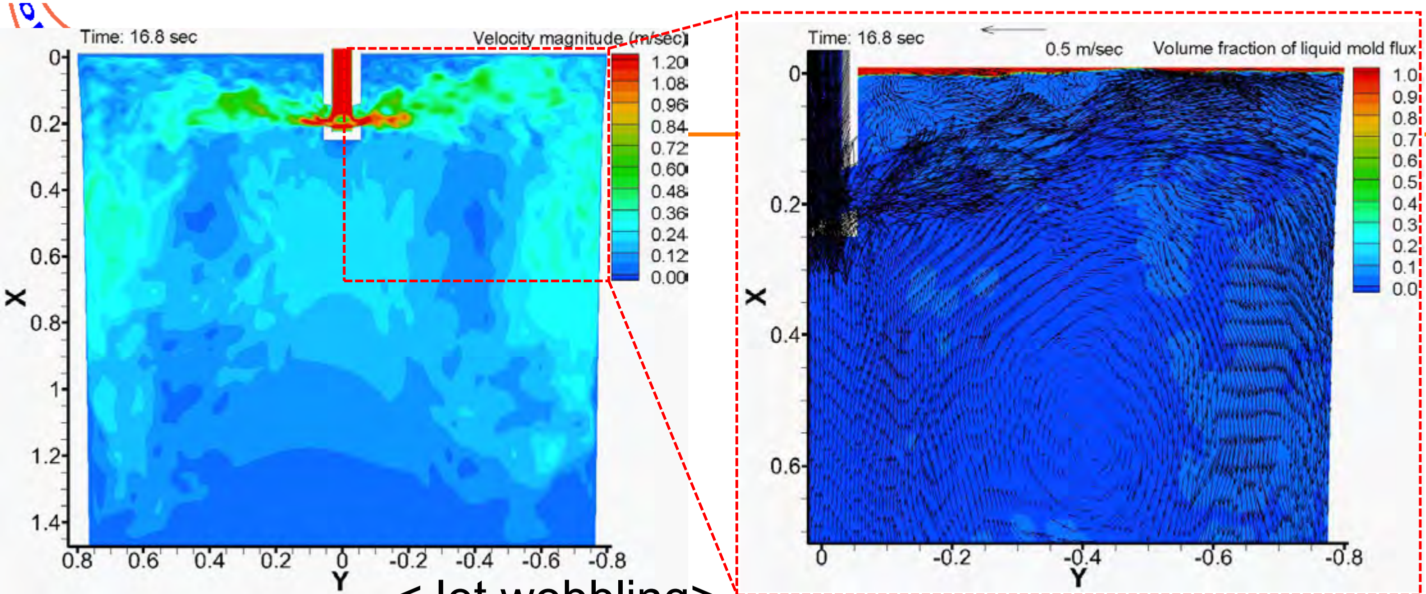
Recent Research on CC with Blue Waters

- **Objectives**
  - To develop accurate, high-resolution turbulent multiphase thermal flow models of defect formation mechanisms and electromagnetic force effects in continuous steel casting.
  - To get insights into defect formation mechanisms: slag inclusion, bubble defect, initial solidification (meniscus freezing and hook), depression and crack.
  - To provide practical strategies of EM systems operation to reduce defects.
- **Projects:**
  - Top surface interface variation effect on slag defect formation: LES-VOF
  - Bubble behavior and size distribution: EE-DPM hybrid multiphase model
  - Argon bubble transport and capture with Electro-Magnetic Braking (EMBr): LES-DPM-Particle capture-electric potential MHD model
  - Initial-solidification defect formation: RANS standard k-ε model coupled with heat transfer model
  - Effects of electromagnetic stirring: magnetic-induction MHD Model
  - Depression and crack formation: Multiphysics model (thermal turbulent flow & thermal mechanical behavior)

Flow Chart of Modeling Methodology

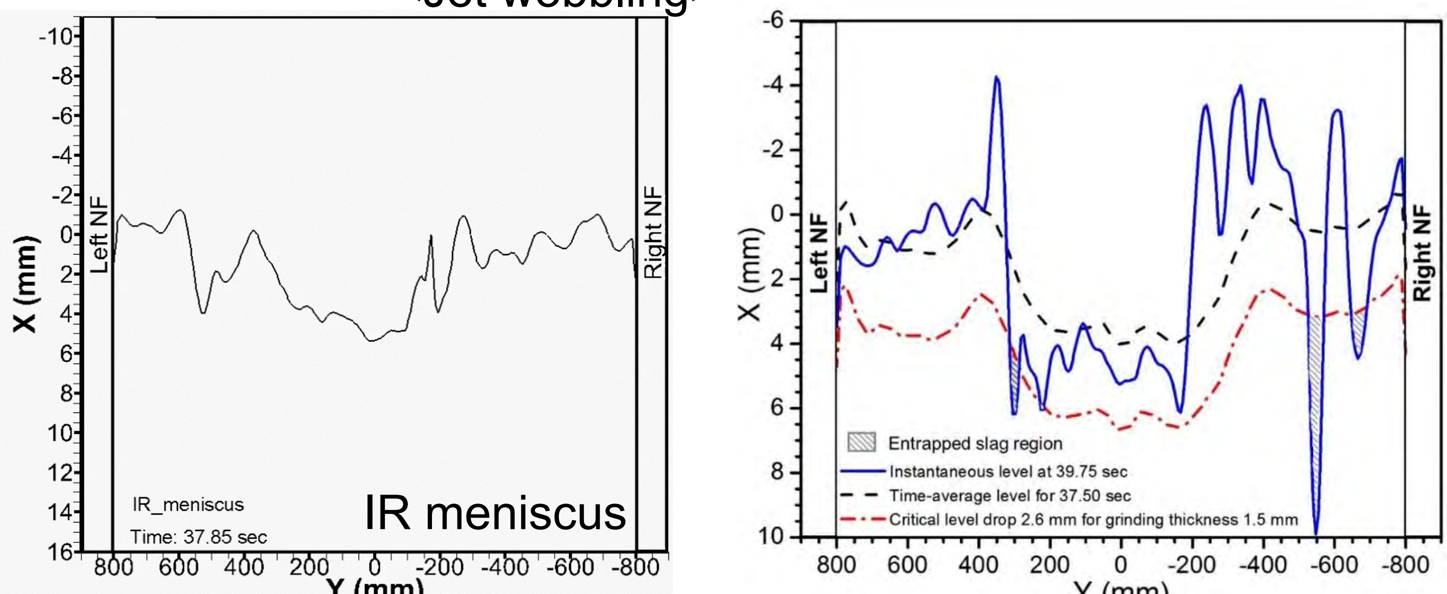


Slag Defect Formation: LES coupled with VOF



<Jet wobbling>

- Severe **jet wobbling**
- **Slag entrapment** due to sudden **level drops**
- **Steel reoxidation** due to **open slag eye** with **severe surface instability**

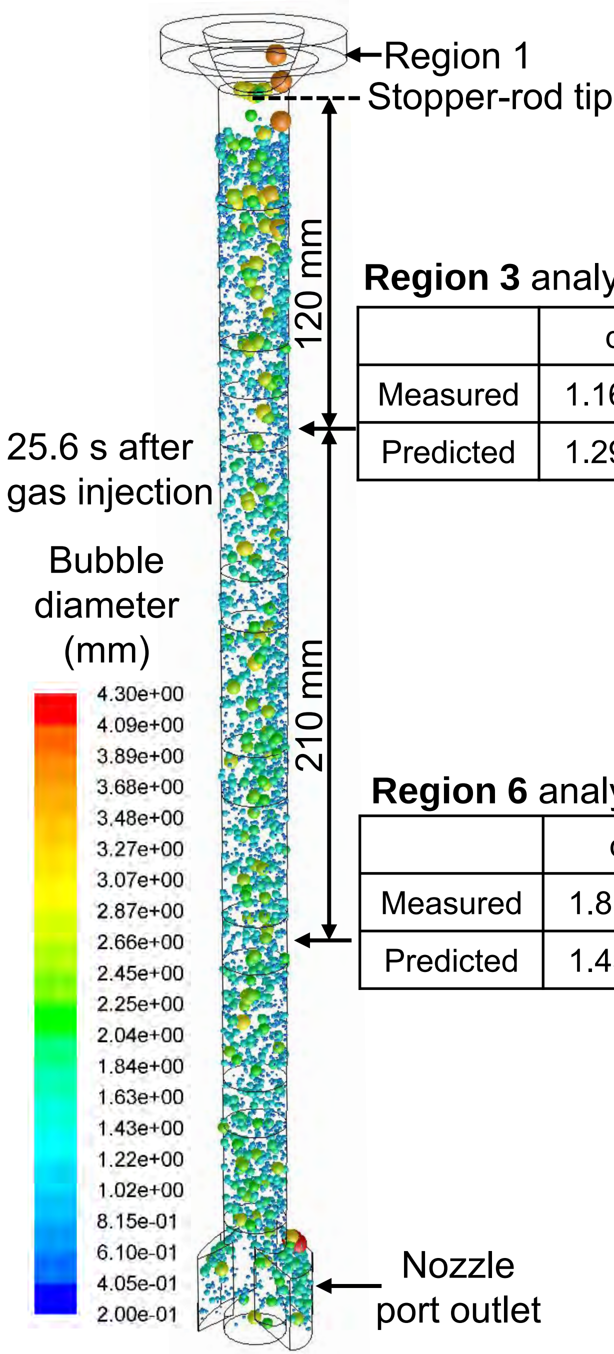


<Liquid slag/molten steel interface instability and slag entrapment>

<Slag defects>

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”, Metallurgical and Materials Transactions B, Vol. 50B (1), pp. 52-76, 2019. DOI: 10.1007/s11663-018-1439-9

Bubble Behavior and Size Distributions: EE-DPM Validation with Water Model

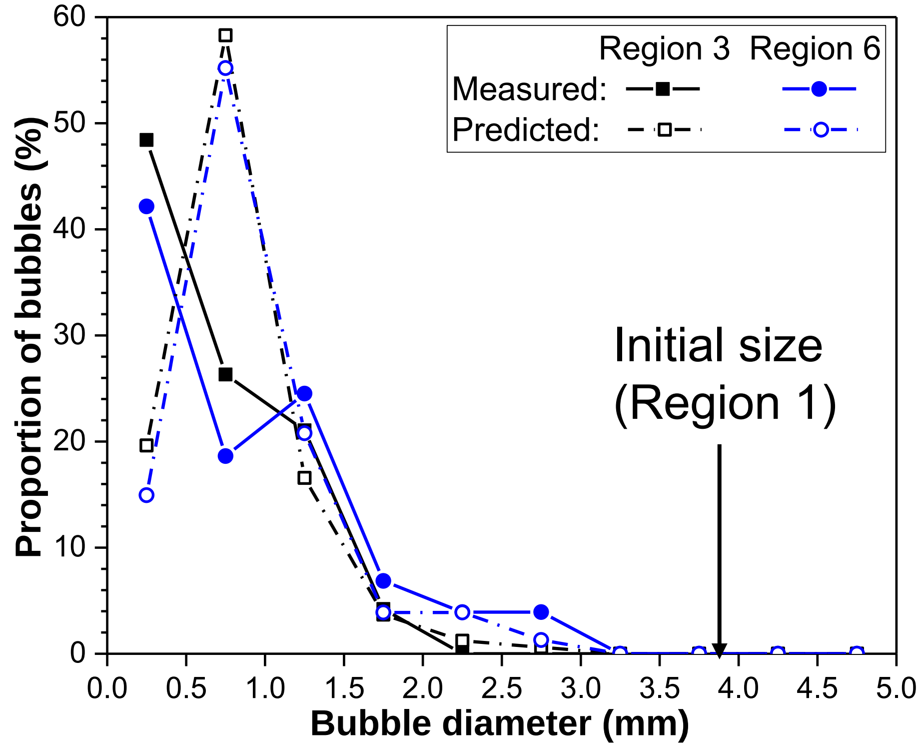


Region 3 analysis window

	d_{32}	σ_b
Measured	1.16 mm	0.67 mm
Predicted	1.29 mm	0.64 mm

Region 6 analysis window

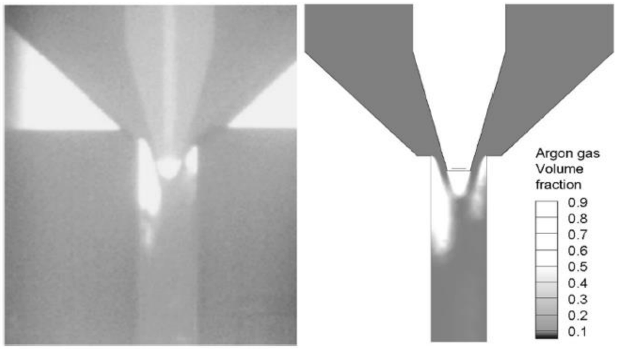
	d_{32}	σ_b
Measured	1.81 mm	1.17 mm
Predicted	1.43 mm	0.71 mm



- **EE-DPM** reasonably simulates **bubble breakup** and **coalescence**.
- Generally **matches measured size distributions.**

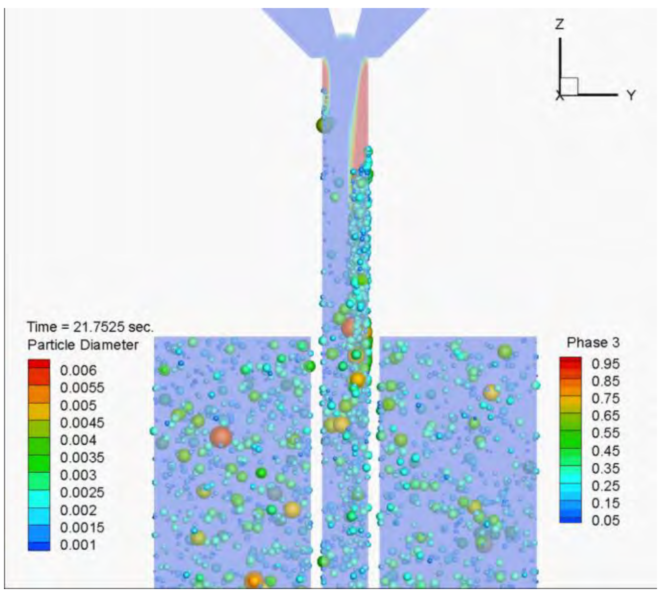
Seong-Mook Cho and Brian G. Thomas, "1) LES Modeling of Slag Entrainment and Entrapment and 2) Nozzle Flow Model Validation with Measurements of Pressure-Drop and Bubble-Size Distribution", CCC Annual Report, 2018.

Bubble Behavior and Size Distributions: EE-DPM Validation with Low-Melting Alloy Experiments and Model Application to Real Caster



Measured Predicted

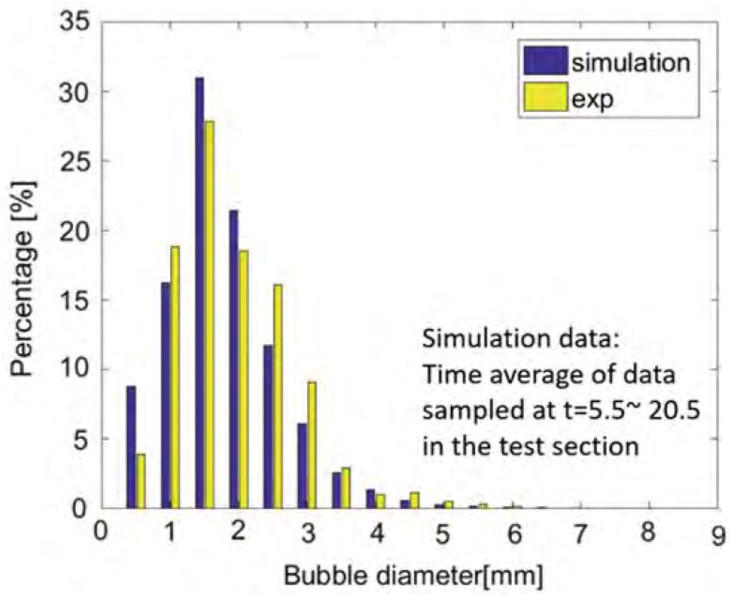
Gas pocket formation



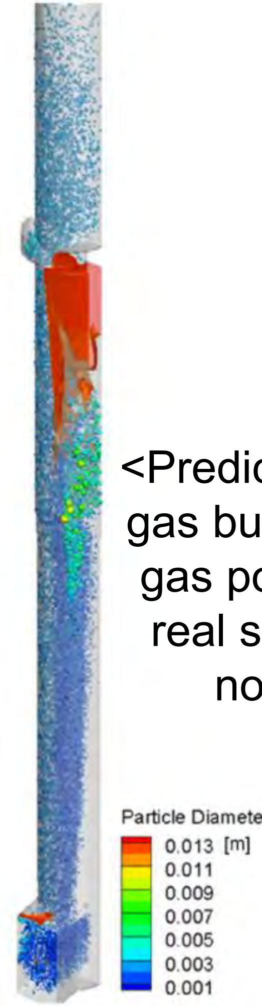
Bubbles in nozzle and mold

<EEDPM validation with low-melting alloy model>

- **Validated EEDPM** is applied to **real caster** case



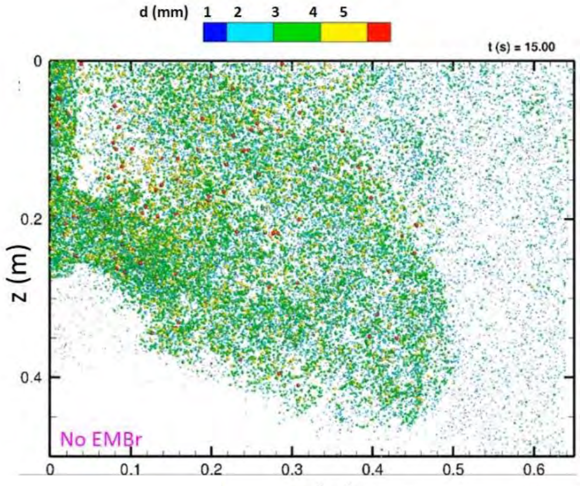
Comparison of predicted bubble size distribution with measurements



<Predicted argon gas bubbles and gas pocket in a real slide-gate nozzle>

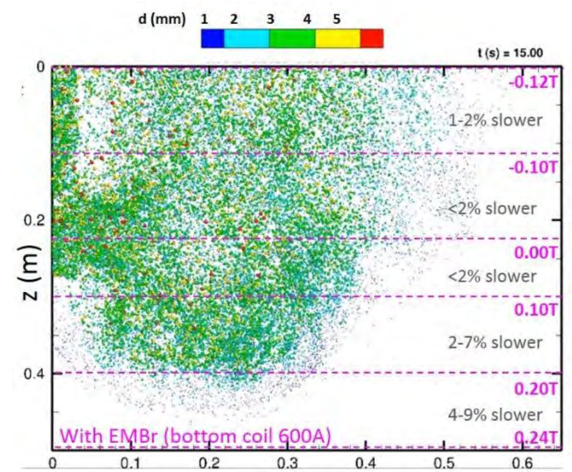
-Hyunjin Yang, Surya P. Vanka, and Brian G. Thomas, “Modeling of Argon Gas Behavior in Continuous Casting of Steel”, JOM, Vol. 70 (10), pp. 2148-2156, 2018. DOI: 10.1007/s11837-018-2997-7
-Hyunjin Yang, Surya P. Vanka, and Brian G. Thomas, “Modeling of Argon Gas Behavior in Continuous Casting of Steel”, in CFD Modeling and Simulation in Materials Processing 2018, The Minerals, Metals & Materials Series, Warrendale, PA, pp. 119-131, 2018.

Bubble Defect Formation: LES coupled with DPM, Particle Capture Model, and MHD



SEN NF

<EMBr off>



SEN NF

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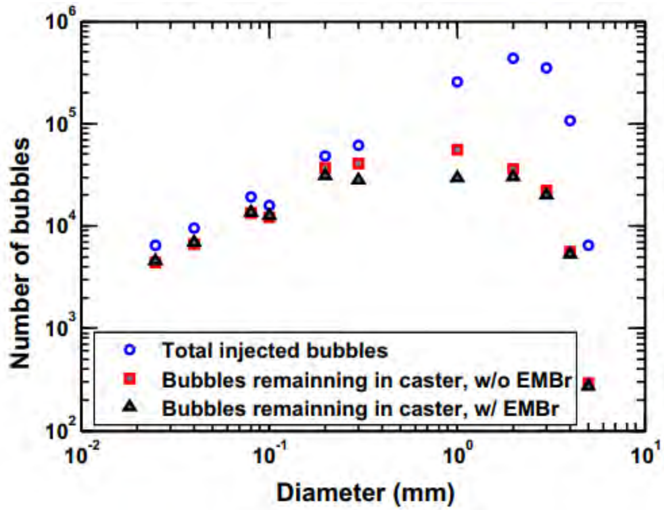
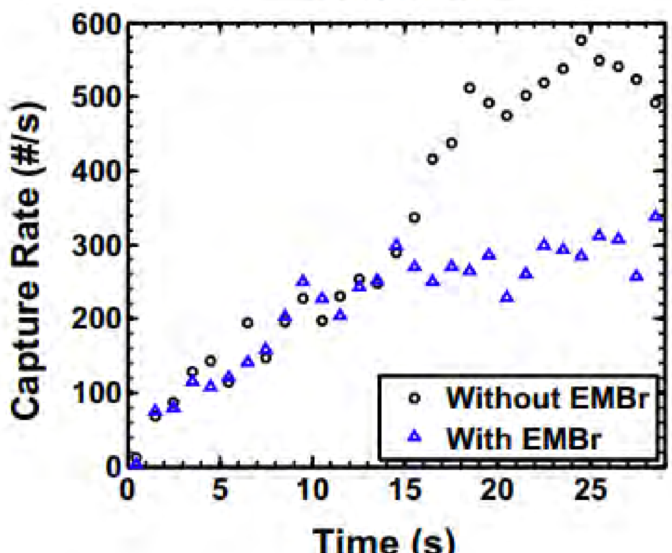


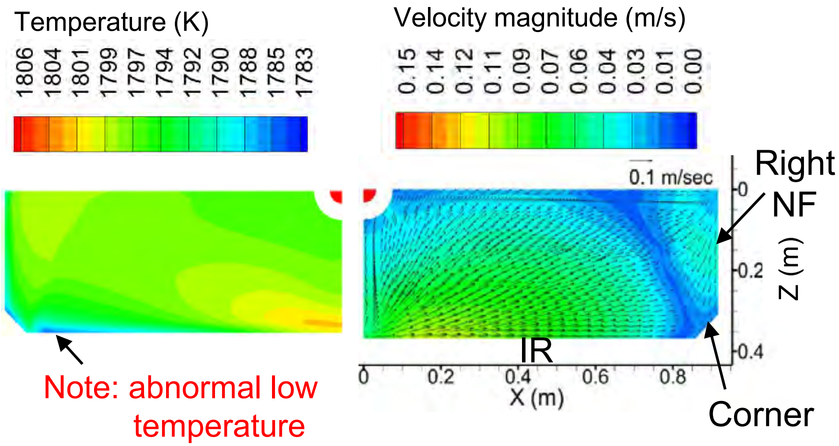
More floatation



Less capture

Kai Jin, Surya P. Vanka, and Brian G. Thomas, "Large Eddy Simulations of Electromagnetic Braking Effects on Argon Bubble Transport and Capture in a Steel Continuous Casting Mold", Metallurgical and Materials Transactions B, Vol. 49B (3), pp. 1360-1377, 2018. DOI: 10.1007/s11663-018-1191-1

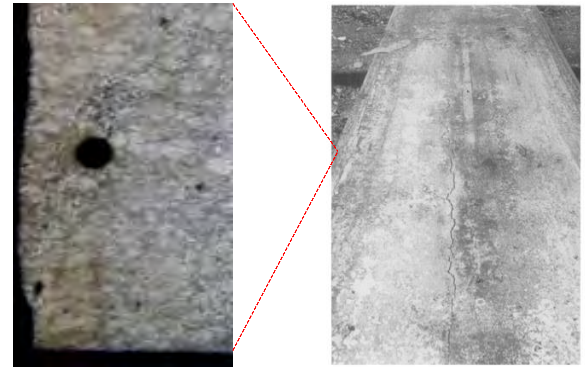
Initial-Solidification Defect Formation: RANS Standard k-ε Model Coupled with Heat Transfer Model



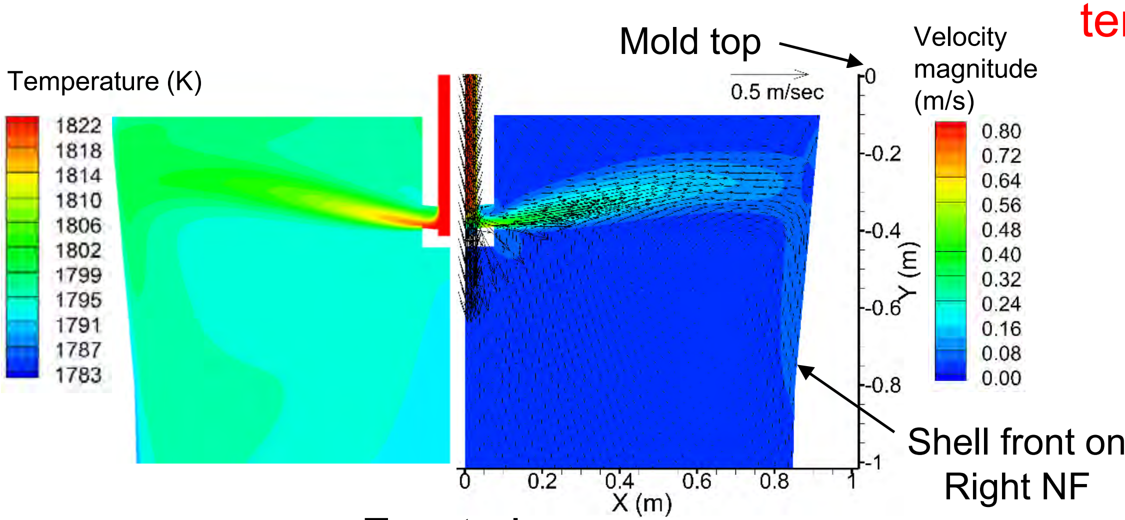
Top Surface (10 mm below meniscus)

small bubble captured by subsurface hook

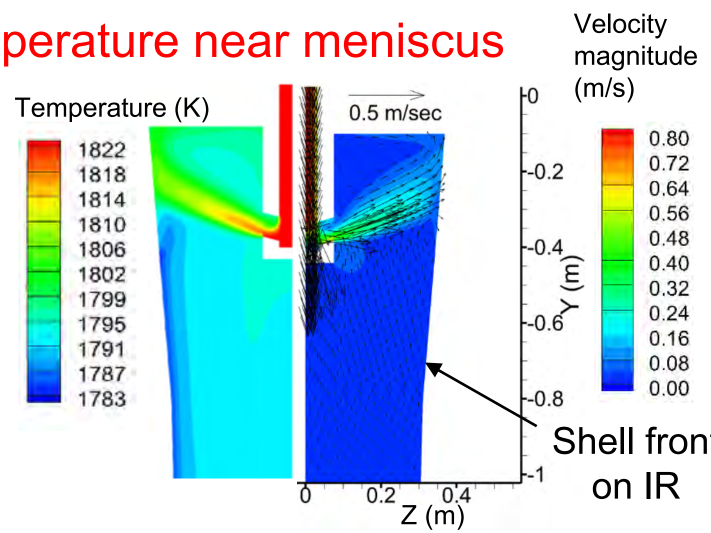
longitudinal crack along steel slab surface



Defects associated with low temperature near meniscus



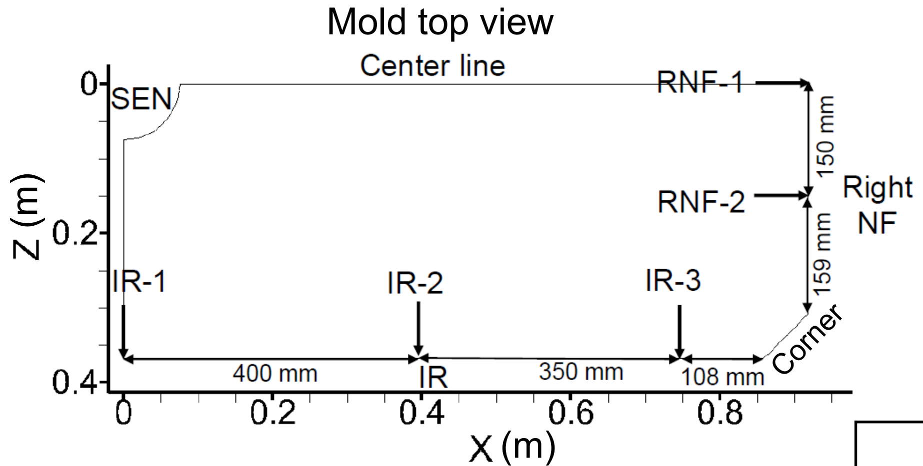
Front view



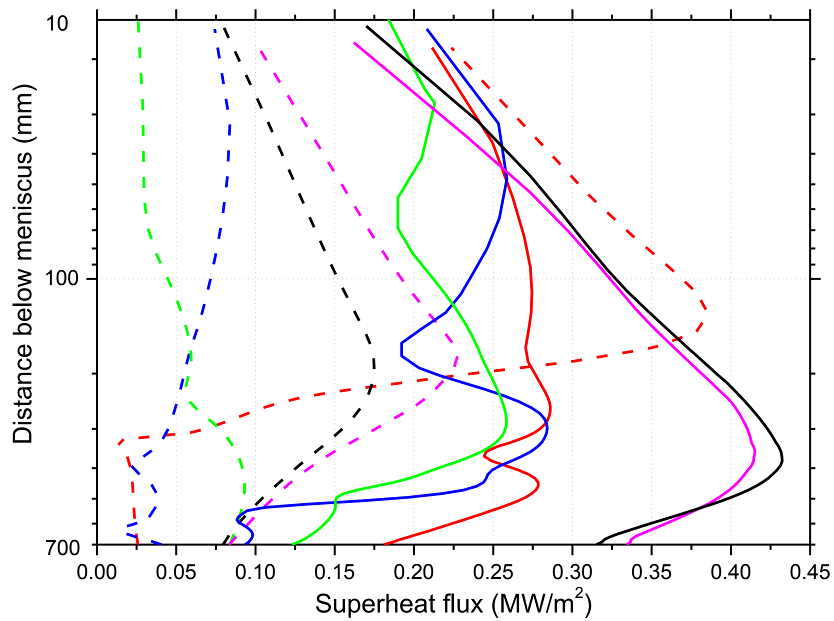
Side view

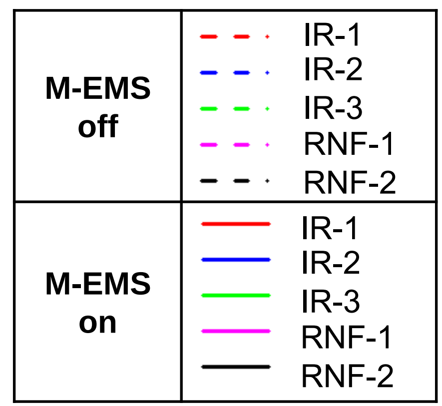
Brian G. Thomas, Seong-Mook Cho, Hyunjin. Yang, Surya Pratap Vanka, Matthew Zappulla, Seid Koric, and Ahmed Taha: "Turbulent Multiphase Thermal Flow Modeling of Defect Formation Mechanisms and Electromagnetic Force Effects in Continuous Steel Casting", Blue Waters Annual Report 2019, Submitted.

Effects of Electromagnetic Stirring: Magnetic-Induction MHD Model



- More **uniform superheat transport** with M-EMS





<Superheat flux profiles at steel shell front>

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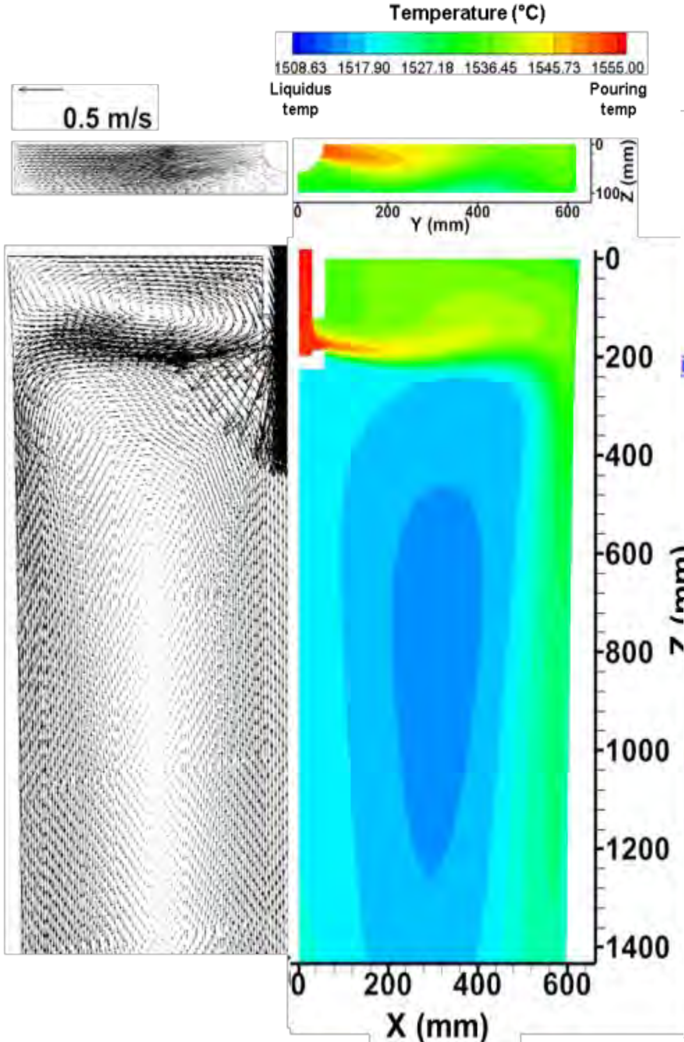
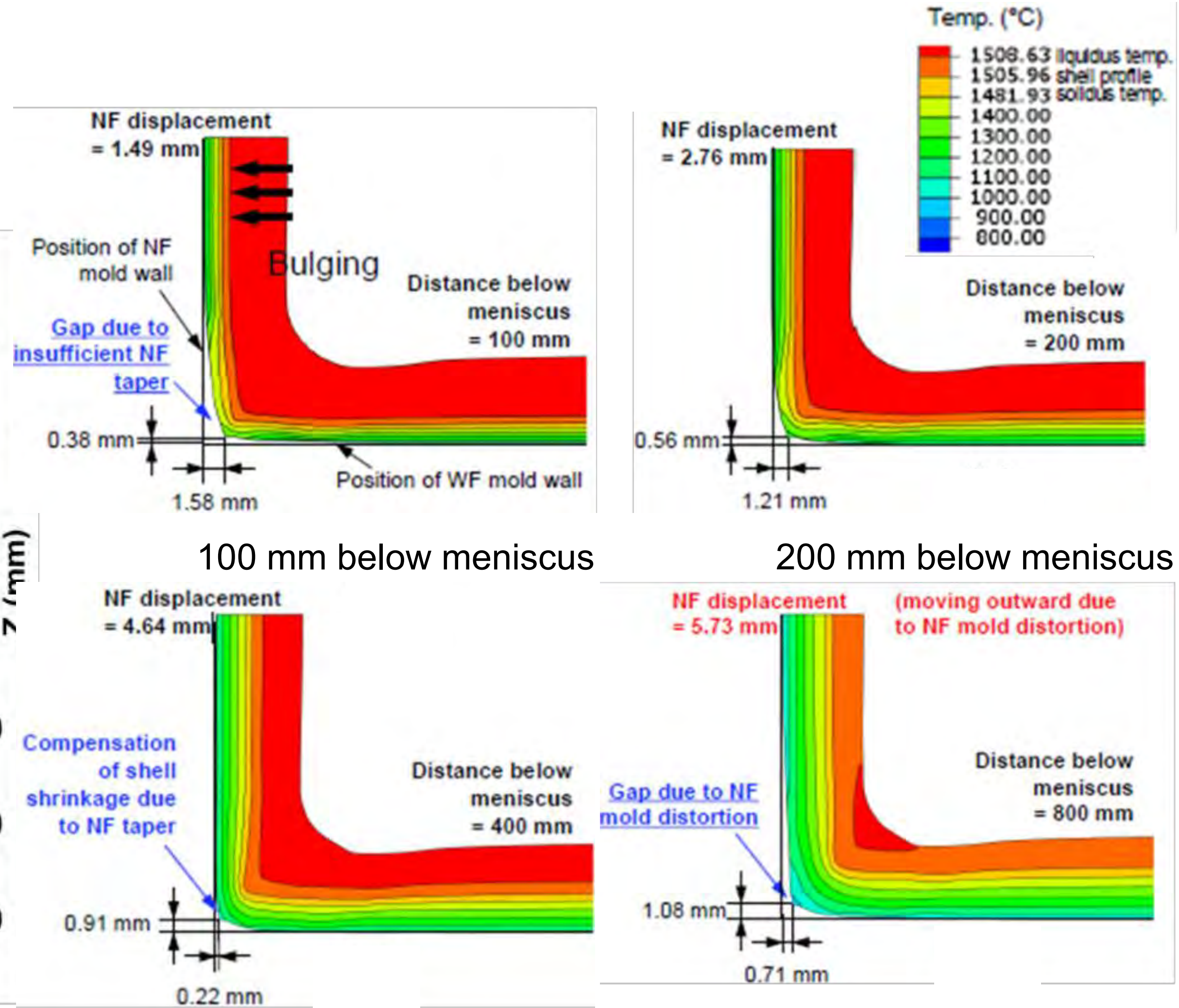
Depression and Crack Formation: Multiphysics Model (Thermal Turbulent Flow & Thermal Mechanical Behavior)



<Thermal turbulent molten-steel flow in mold>



<Deformed shell shape with temperature contours>

Matthew L. S. Zappulla, Seid Koric, Seong-Mook Cho, Hyoung-Jun Lee, Seon-Hyo Kim, and Brian G. Thomas, "Multiphysics modeling of continuous casting of stainless steel", Journal of Materials Processing Technology, 2019, Under Review.

Summary

- **Speed-up breakthrough** on **Blue Waters parallel supercomputing** for **high-resolution simulations** (millisecond-time scale and micrometer-length scale) for **continuous steel casting**
  - **ANSYS Fluent HPC** on **BW XE node: 3000×** faster
  - **Multi-GPU based in-house code**, **CUFLOW** on **BW XK node**: **40×** faster

- Various multiphase simulations of **defect formation mechanisms** and **electromagnetic force effects**
  - **Surface instability, slag entrainment and entrapment:** LES-VOF
  - **Argon bubble behavior** and **size distributions:** hybrid multiphase EE-DPM model
  - **Particle capture defect** with **EMBr:** LES-DPM-particle capture-electric potential MHD
  - **Initial solidification defect:** RANS standard k-ε coupled with heat transfer model
  - Effects of **electromagnetic stirring**: magnetic induction MHD model
  - **Depression** and **crack**: turbulent thermal flow-thermal mechanical behavior