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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Recent Publications Acknowledging Blue Waters (2018-2019)

15. CCC Annual Reports, August, 2019, pending
Over **96% of steel** in the world is continuous cast*, so: even **small improvements** have **tremendous impact**.

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** Brian G. Thomas, ccc.Illinois.edu
Introduction: Defect-Related Phenomena in Continuous Steel Casting

- 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

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

<table>
<thead>
<tr>
<th>PC - 4GPU Workstation</th>
<th>Blue Waters Supercomputer</th>
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<tbody>
<tr>
<td># of Nodes</td>
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<tr>
<td>Node CPU</td>
<td>Xeon E5-2650v2 Ivy Bridge, 2.60 GHz, 8 cores</td>
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<tr>
<td>GPU/Node</td>
<td>4 × Nvidia Tesla C2075, 4 × 5 GB, 575 MHz</td>
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</tbody>
</table>

<Configuration of 4 GPU workstation>

<Configuration of BW nodes showing 2 nodes>
Ground-Breaking Speed-Up on Blue Waters

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

<CUFLOW on Blue Waters XK Node>  <ANSYS FLUENT HPC on Blue Waters XE Node>
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 entrainment and entrapment**
- CFD / VOF model: fluid flow & liquid slag/molten steel interface motion
  - Entrapped slag region near meniscus
  - Entrained slag-droplet size
- Particle capture models: slag inclusion & bubble capture at steel shell front
  - Location and size of captured particles

**Initial solidification defect**
- Turbulent Flow / Heat transfer model
  - Temperature distribution
  - Superheat transport profile at steel shell front

**Argon gas bubble defect**
- EEDPM model: hybrid multiphase flow model of bubble behavior and size
  - Bubble size distribution
- MHD models of EM systems
  - Effects of static or moving magnetic fields on defect formation

**Depression and crack**
- Thermal-mechanical model with phase-specific constitutive equations
  - Deformed shape and stress profile with phase transformation

**EM force effects**
Slag Defect Formation: LES coupled with VOF

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

<Jet wobbling>

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

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

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

### Region 3 analysis window

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<tr>
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<th>$d_{32}$ (mm)</th>
<th>$\sigma_b$ (mm)</th>
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<tr>
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<tr>
<td>Predicted</td>
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<td>0.64</td>
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### Region 6 analysis window

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<tbody>
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<tr>
<td>Predicted</td>
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<td>0.71</td>
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</table>

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

- **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>**

- **Gas pocket formation**

- **Bubbles in nozzle and mold**

- **<EEDPM validation with low-melting alloy model>**

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

Initial-Solidification Defect Formation: RANS Standard k-\(\varepsilon\) Model Coupled with Heat Transfer Model

Note: abnormal low temperature

Defects associated with low temperature near meniscus

Effects of Electromagnetic Stirring: Magnetic-Induction MHD Model

More uniform superheat transport with M-EMS

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

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: $3000 \times$ faster
  - Multi-GPU based in-house code, CUFLOW on BW XK node: $40 \times$ 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