Continuous Casting Consortium

Blue Water Symposium,
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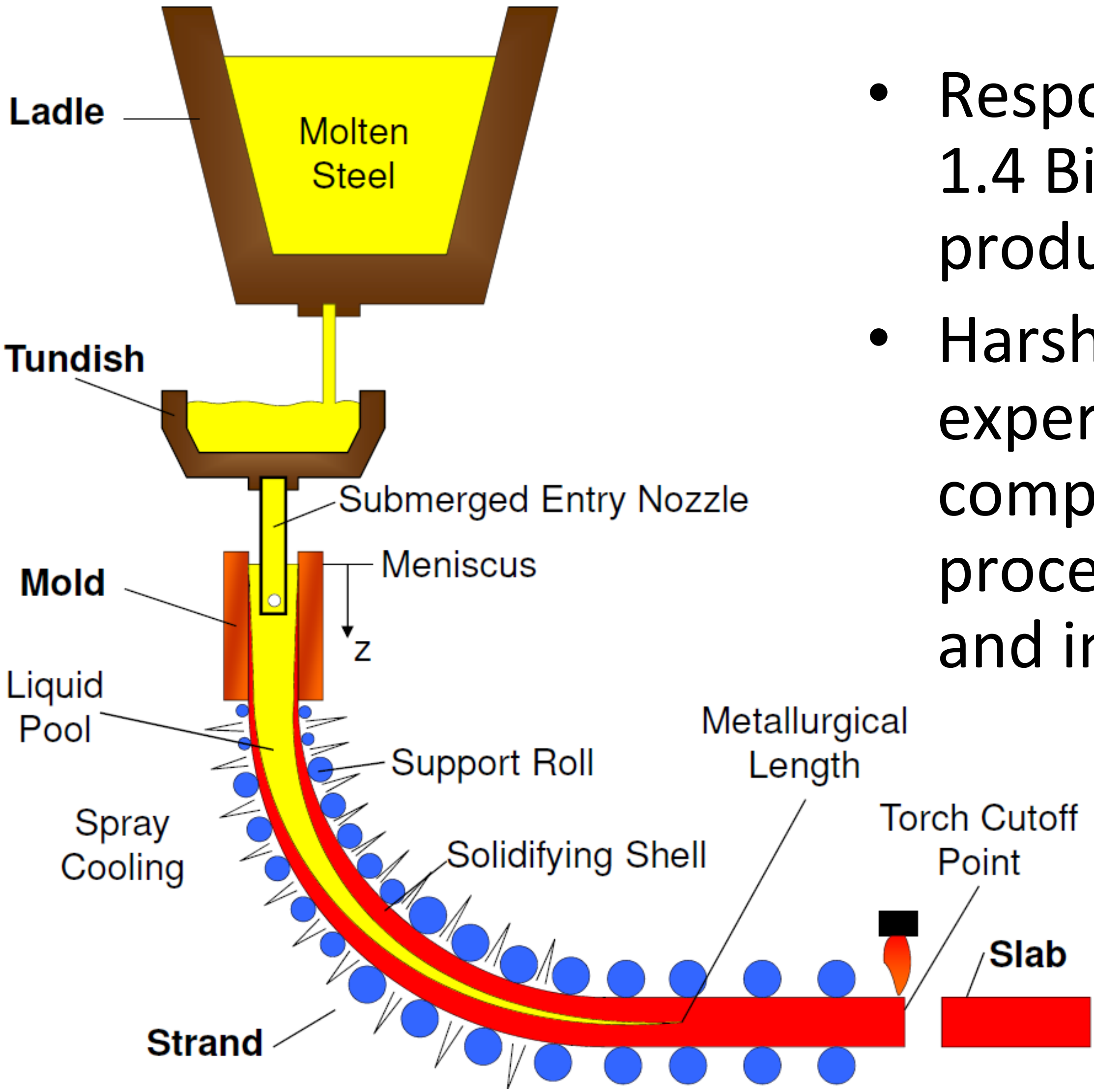
Preliminary Evaluation of ABAQUS, FLUENT, and in-house GPU code Performance on Blue Waters

B. G. Thomas[1], L. C. Hibbeler[1], K. Jin[1], S. Koric[2], R. Liu[1], A. Taha[2]

1- UIUC/MechSE   2- NCSA

Continuous Casting of Steel



- Responsible for >95% of the 1.4 Billion tonnes of steel produced every year
- Harsh environment makes experiments difficult; computer models allow process to be understood and improved

Continuous Casting Models

Phenomena:

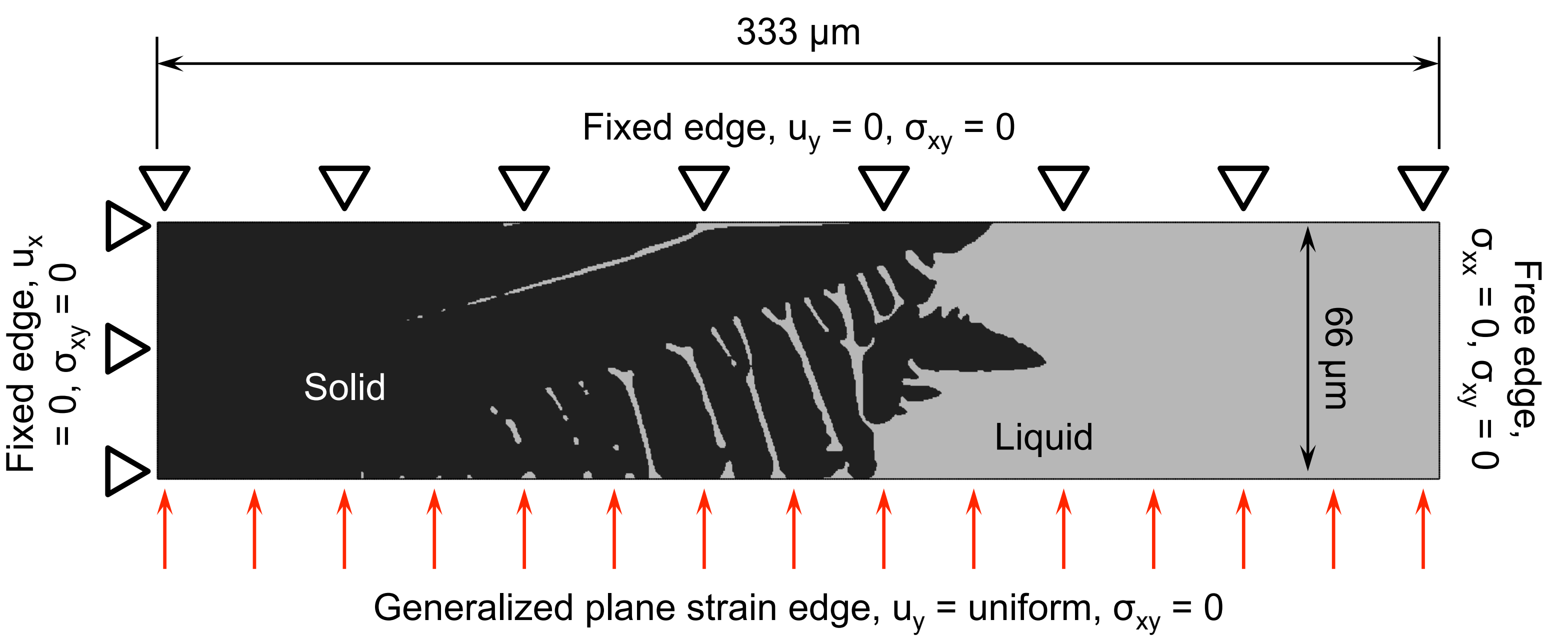
- **Heat transfer** governs steel solidification
- Multiphase turbulent **fluid flow** controls inclusion defects, surface quality, and affects steel solidification
- Shell and mold **deformation and stress** control distortion, crack defects and other quality problems

Models:

- Stress analysis (Lagrangian FEM) – ABAQUS
- Fluid flow (Eulerian FDM) – FLUENT
  - CUFLOW (inhouse code)

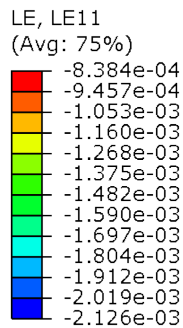
Microscale Deformation Analysis

- ``Hot tearing'' and porosity defects lead to low-quality steel, or worse, a breakout
- Governed by coupled, microscale heat transfer, mass transfer, fluid flow, and solid deformation at the solidification front

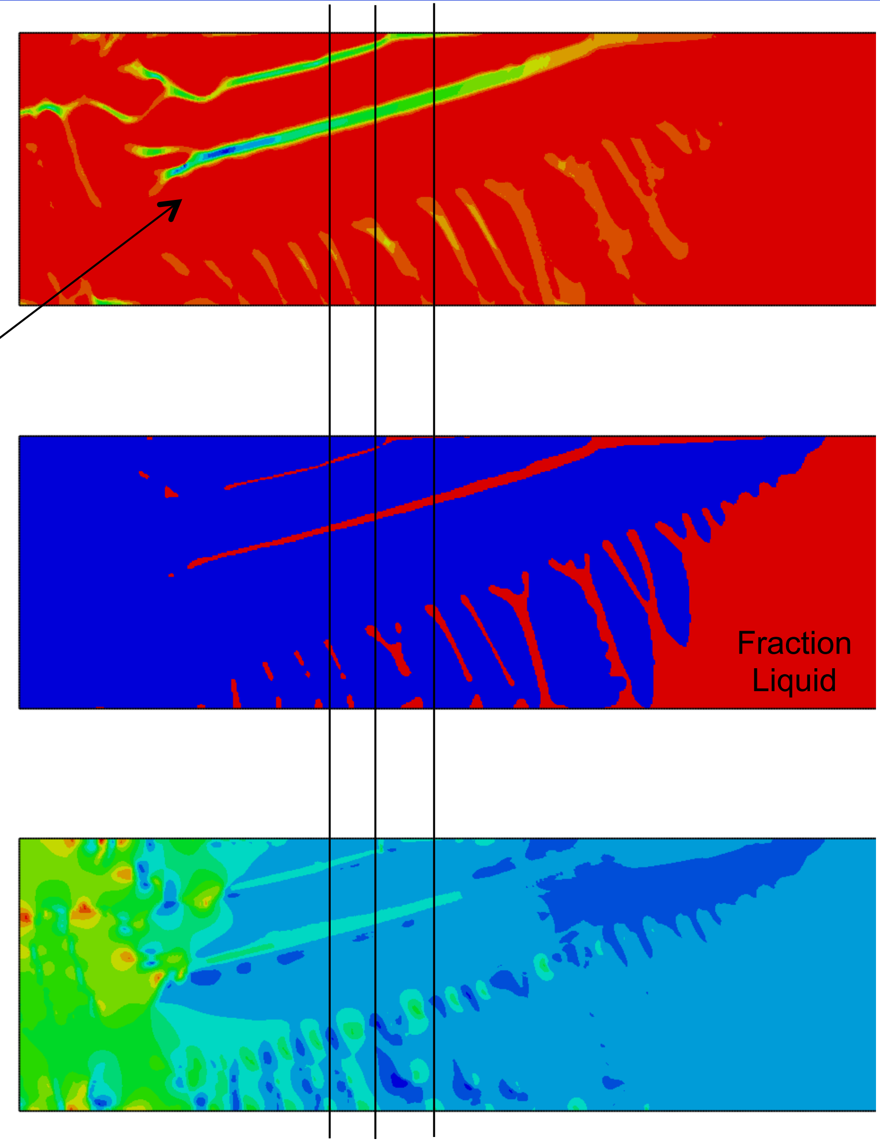


Microscale Deformation with ABAQUS

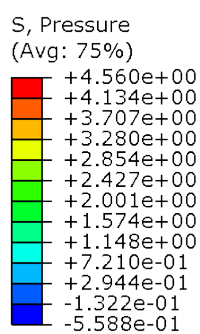
Total strain in vertical direction



- Strain concentrations in liquid regions
  - Most motion occurs in liquid
- Peak negative pressure in roots of secondary arms
  - Insufficient feeding can lead to porosity



Pressure stress



Negative pressure means material in tension

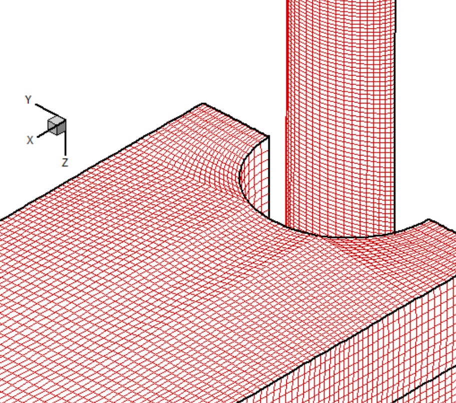
Computation Details

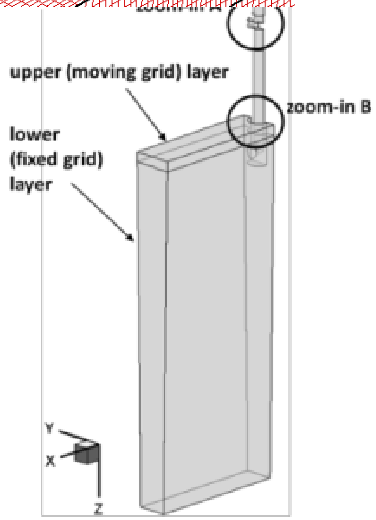
- ``Small'' domain has 2.26 MDOF
- One global FEM Newton iteration = 0.57 Tflop

Threads	CPU Time (s)	Average CPU time per thread (s)	Wall Clock Time Required for 1 sec simulation (Day)
32	15	0.47	6.80
64	9	0.14	5.25
128	6	0.05	5.50
256	4	0.02	5.50

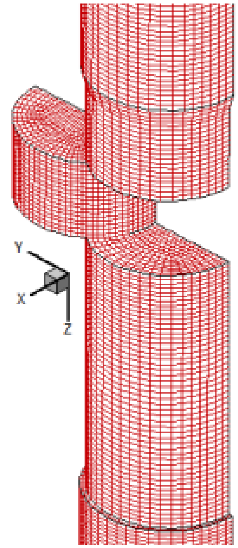
- Direct solver is limited by communication after 64 threads – need a better algorithm
  - ABAQUS/Explicit IS better, but cannot read in multiple fields

Turbulent Fluid Flow with FLUENT

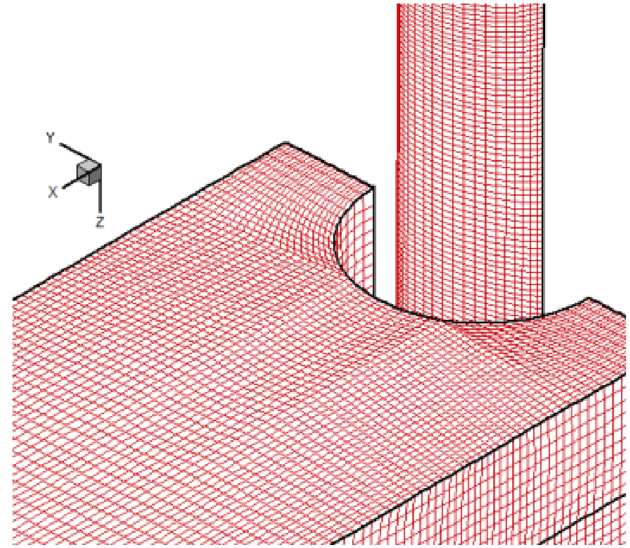




(a) Domain geometry

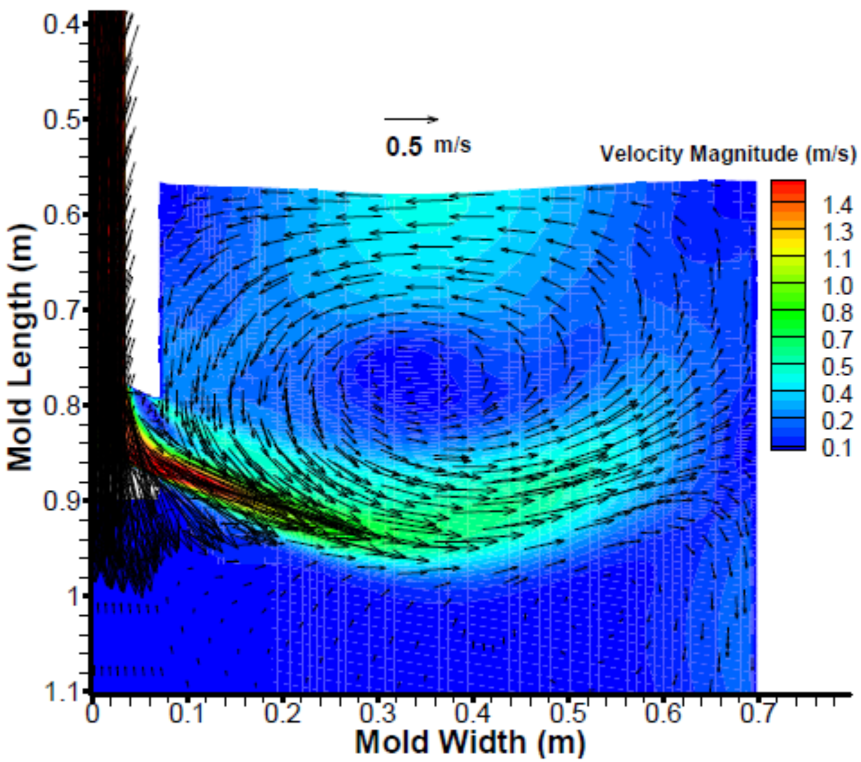


(b) Mesh in region A

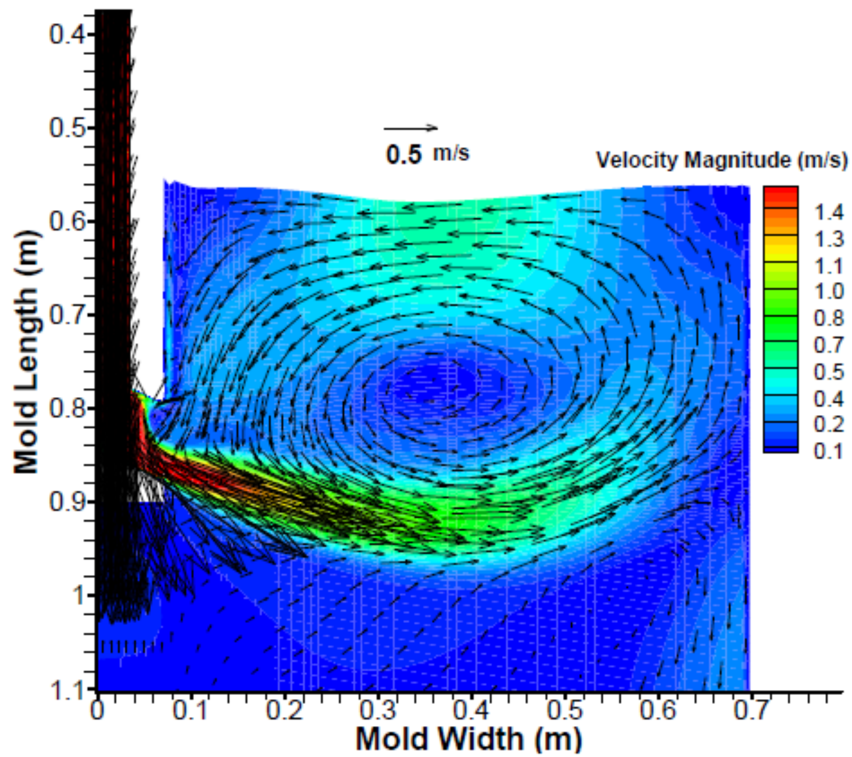


(c) Mesh closeup in region B

Fluid Flow with Free Surface



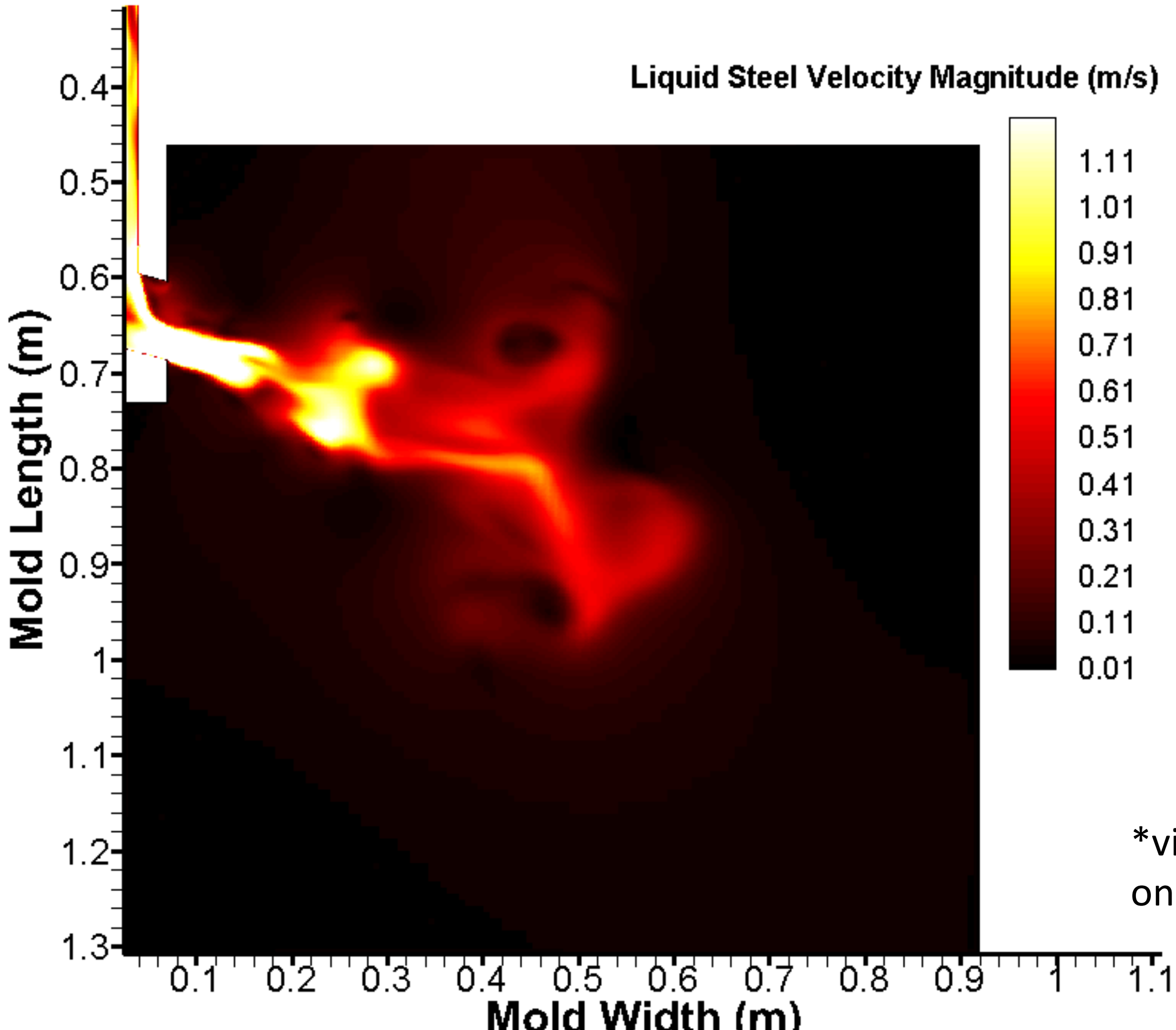
Steel only



Steel and argon

DES Simulated Transient Flow Pattern (quasi-steady state)

- Center plane velocity distribution*



*video simulation performed on Dell workstation

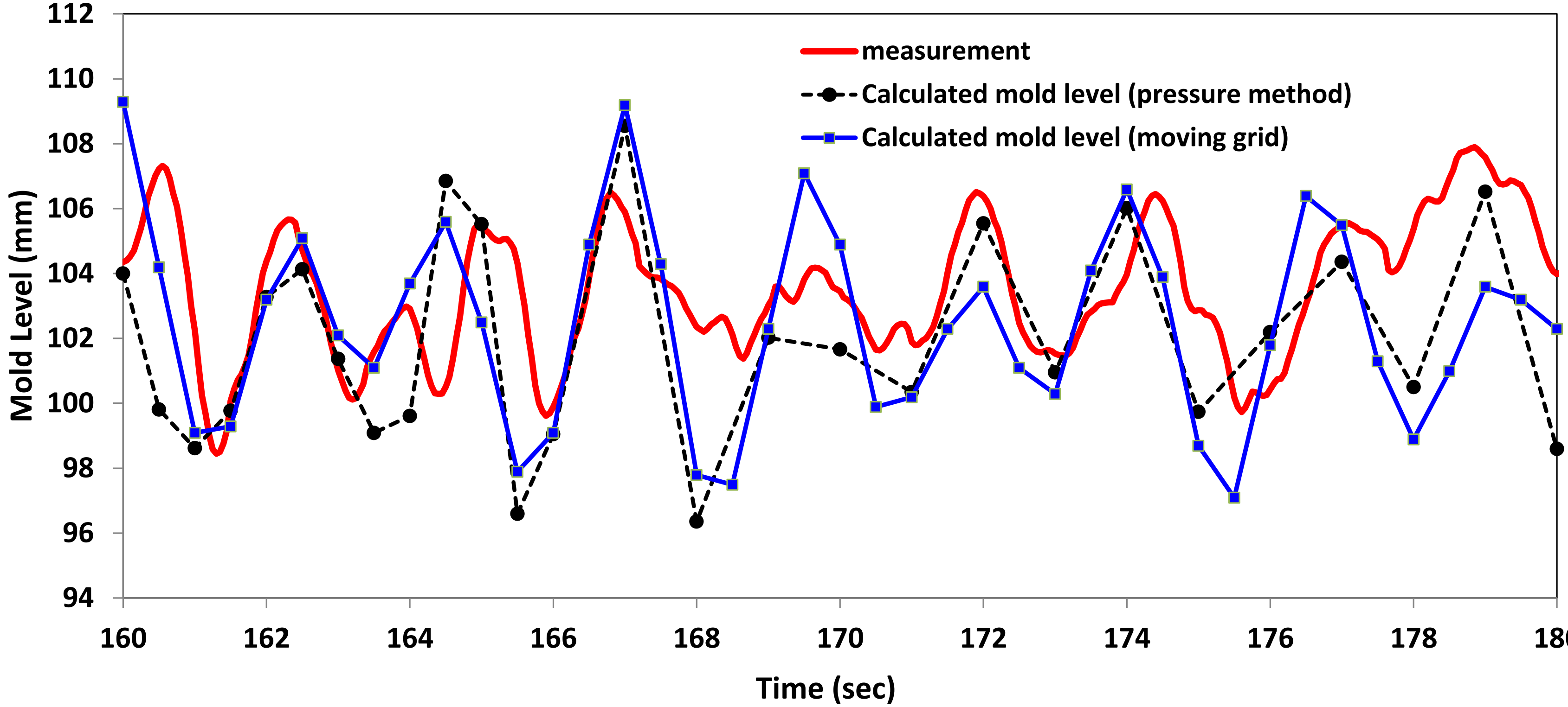
Comparison of Simulated and Measured Mold Level

Pressure method:

$$\Delta h = \frac{p - p_0}{\rho_L g}$$

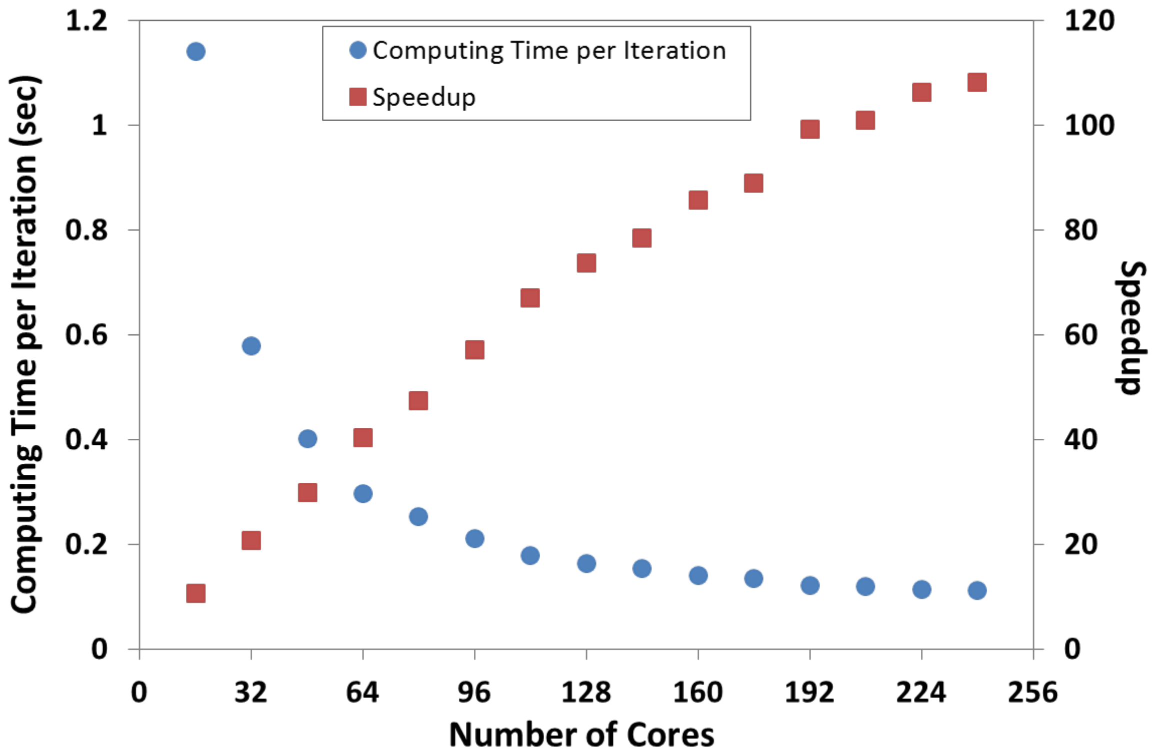
p_0 is the static pressure at starting time (160 sec in current case)

Pressure at quarter mold point at meniscus is used in current calculation



- Results from both methods match reasonably well with measured mold level

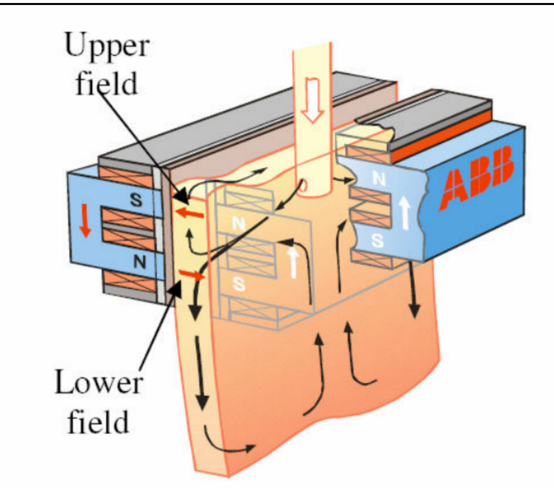
FLUENT Speedup on Blue Waters



Speedup relative to 1-core on high-end workstation*

*Performance with simple pressure-based top surface level: Almost no speedup with moving-grid free surface method

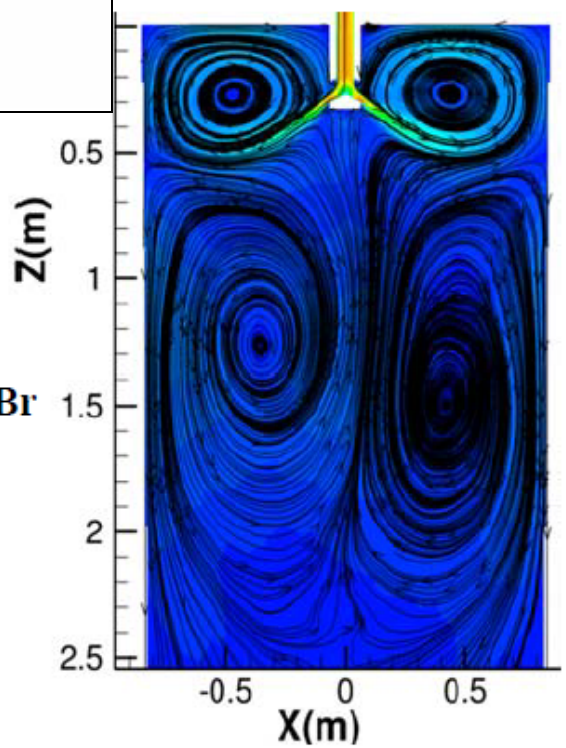
Fluid Flow with MHD (CUFLOW – in-house GPU code)



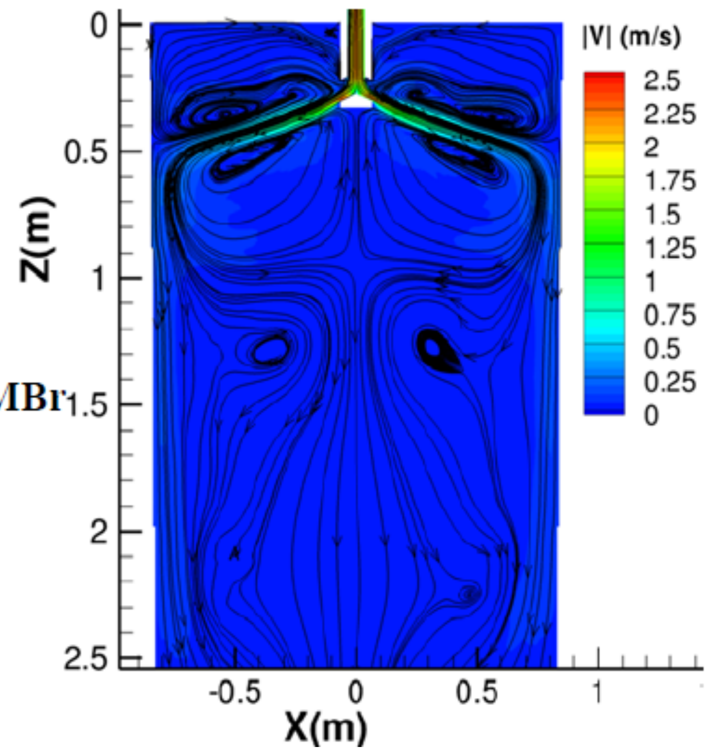
- Magnetic field can greatly change flow, with potential to improve quality in commercial CC process
- Difficult to study except by computational modeling

Time-averaged Flow patterns:

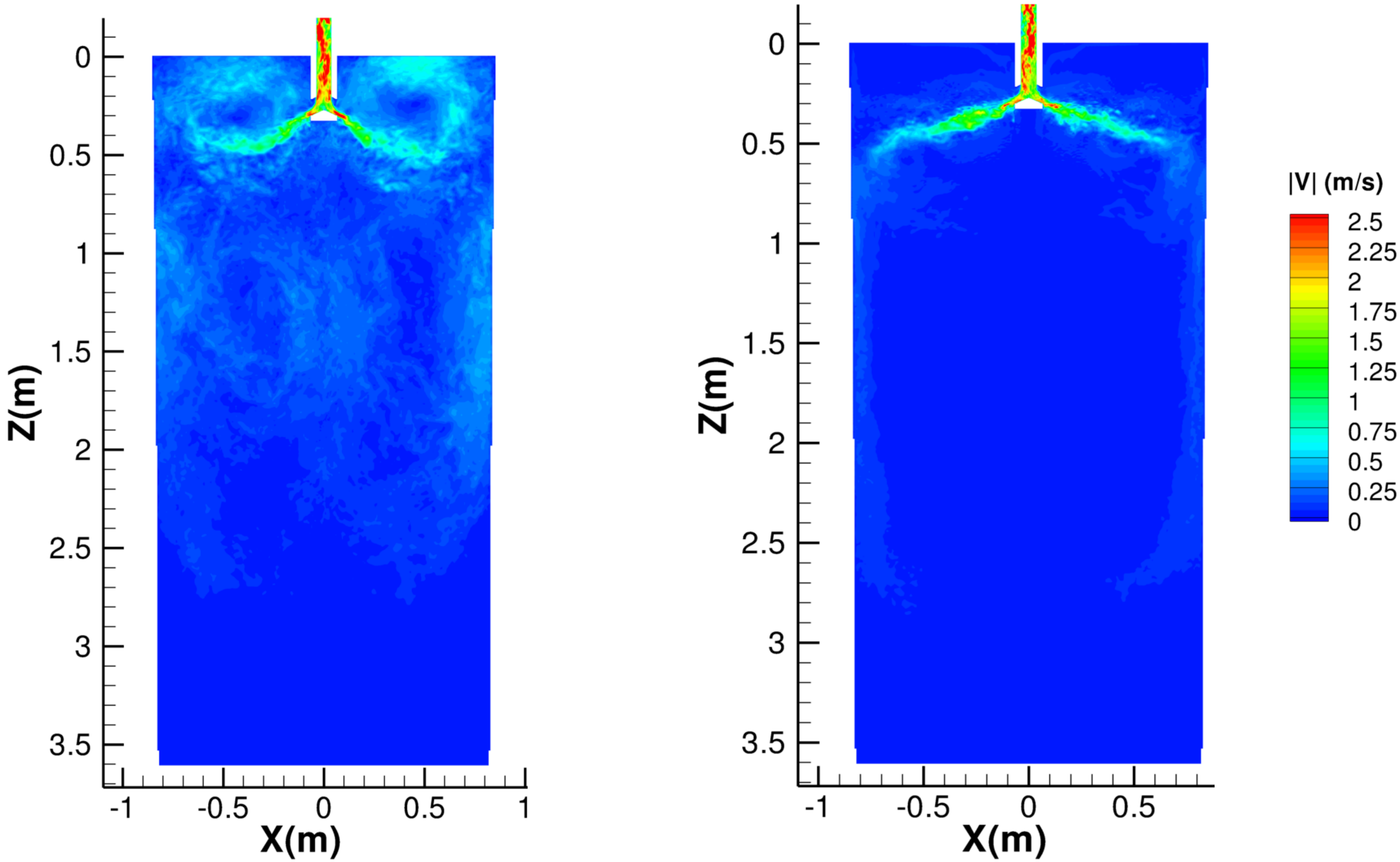
No-EMBr



EMBr

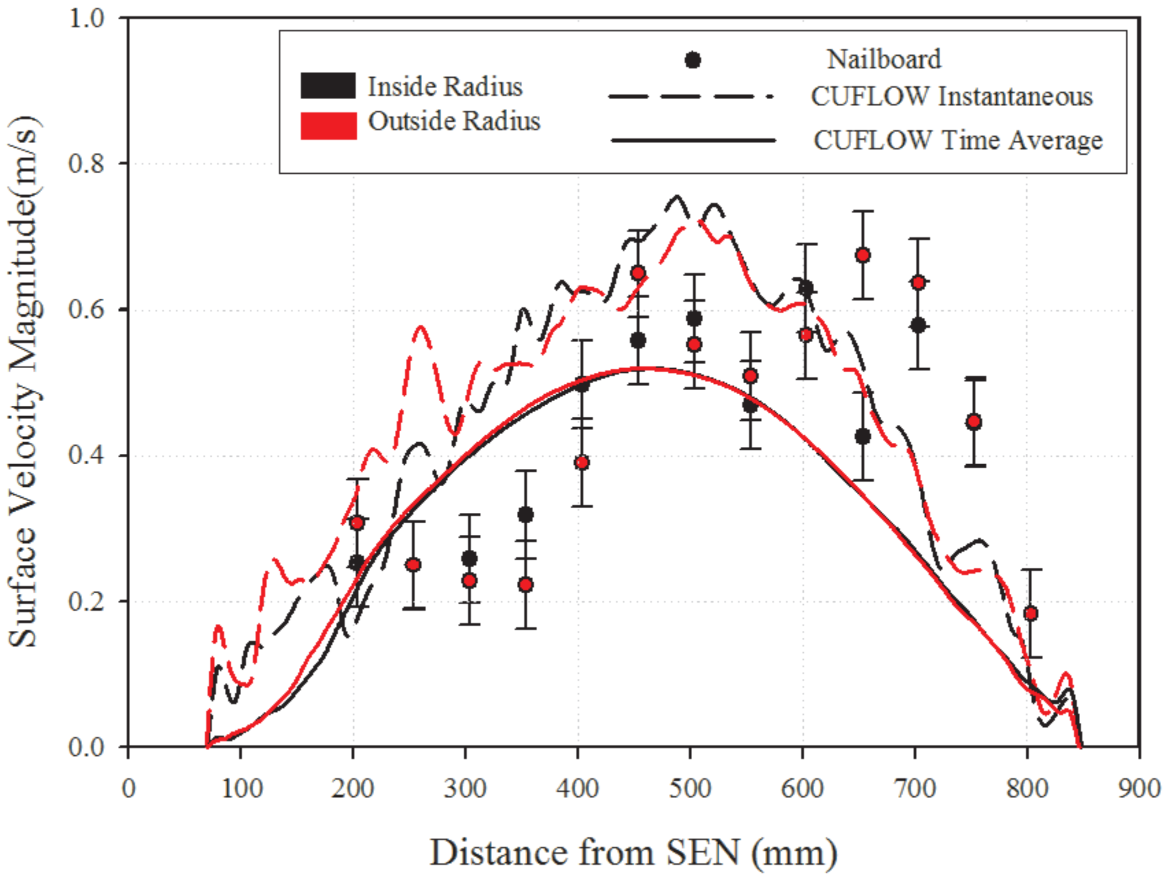


Instantaneous Results



No-EMBr **EMBr**

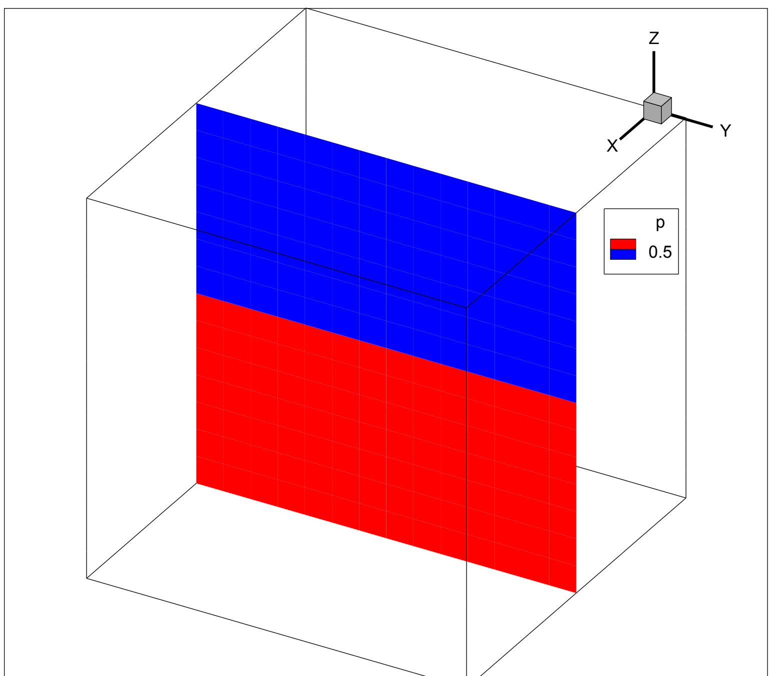
Comparison with Nail Board Measurements Top surface Velocity

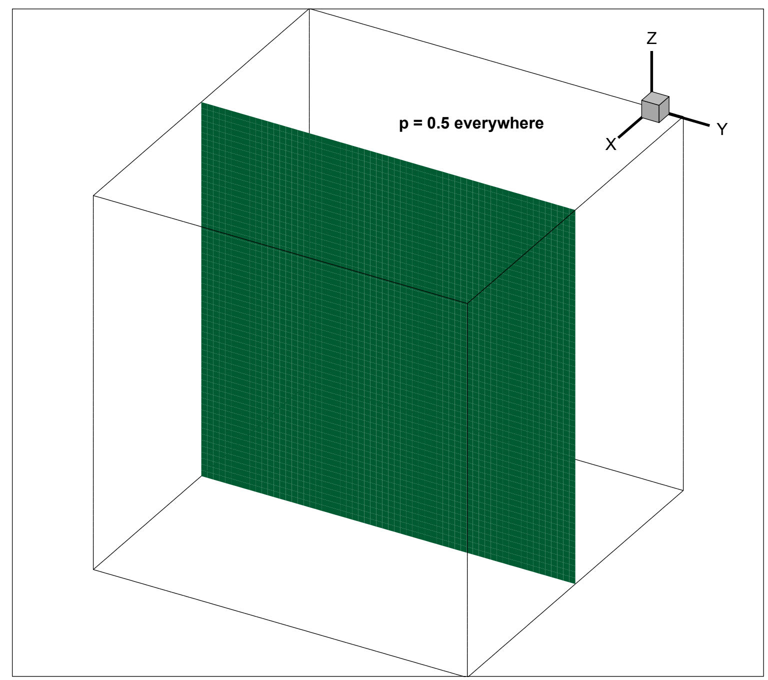


- Measured velocity high near NF.
- Calculated velocity maximum midway between the NF and SEN.
- Maximum of measured velocity quantitatively match the calculated velocity during the phase with stronger surface flow

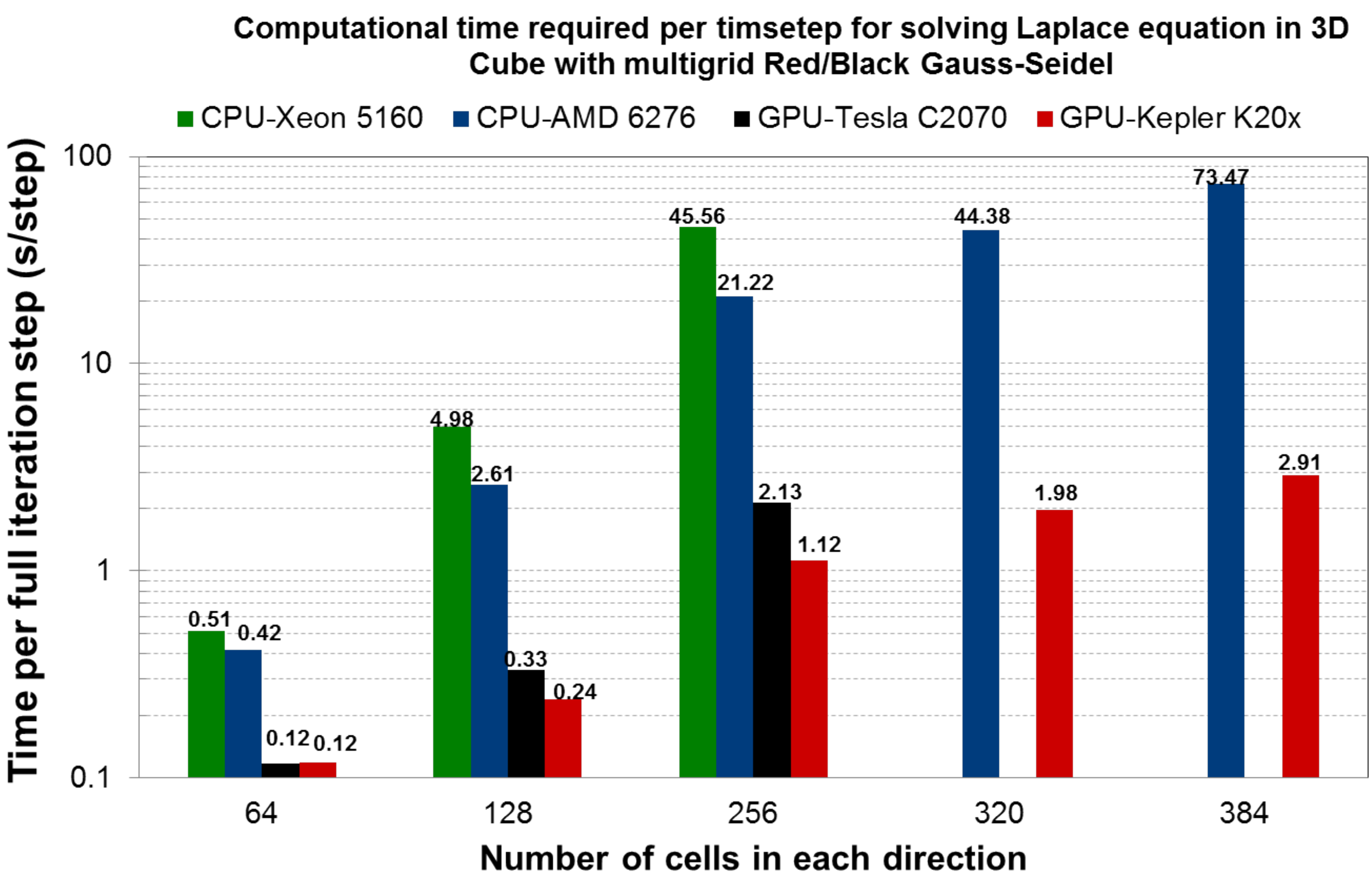
3D Heat Conduction Test Problem

- Multigrid V-cycle with red-black SOR on cube domain
- PPE solver in CUFLOW code on BW





CPU and GPU comparisons



3D Conduction Test Problem Conclusions

- BW CPU (AMD 6276) is ~2X faster than our desktop CPU (Xeon 5160)
- BW GPU (Kepler K20x) is ~1.5X faster than our desktop GPU (Fermi Tesla C2070)
- BW GPU code is 20-30 times faster than the CPU code. The advantage of GPU is greater with more grid points
- CUFLOW must be extended to multiple processors to take advantage of Blue Waters

3D Conduction Test Problem Conclusions

- AMD 6276 in BW CPU is twice as fast as our desktop s CPU (Xeon 5160)
- BW GPU (Kepler K20x) is about 1.5x fast as our Fermi Tesla C2070
- On BW the GPU code is 20-30 times faster than the CPU code. The advantage of GPU is greater with more grid points

- Blue Waters supercomputing resource greatly augments modeling capability for CC research.

Conclusions

- Blue Waters supercomputing resource greatly augments modeling capability for CC research.
- Commercial codes (extended with user subroutines) can perform well on Blue Waters, if care is taken in problem setup.
  - Speed-up of ~100X for ~200 CPU processors for FLUENT with fixed grid
  - Little speedup for FLUENT with moving grid, or for ABAQUS Implicit
- Speed-up of ~25X on GPU relative to CPU (for CUFLOW)

Acknowledgments

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Tata Steel, Goodrich, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech/Posco, SSAB, ANSYS-Fluent)
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