

# Effect of EMBR on Transient Mold Flow with DNS Modeling and Ga-In-Sn Benchmark Measurements

Ramnik Singh  
(MSME Student)

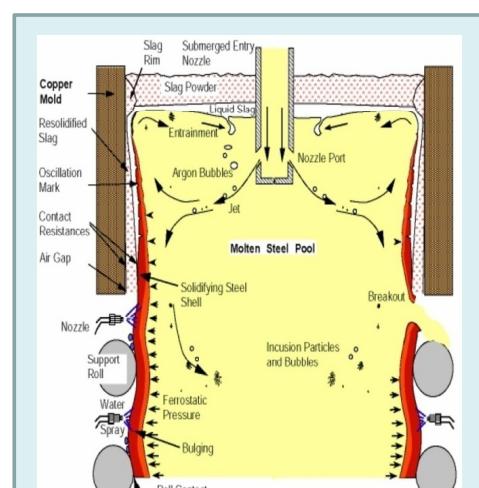
Work performed under NSF Grant CMMI 11-30882



*Department of Mechanical Science and Engineering*  
University of Illinois at Urbana-Champaign

## Importance of Mold Flow

- Turbulent flow in the mold is responsible for most CC defects
- Effects of surface velocity and turbulence:
  - Too high : Slag emulsification
  - Too low : Meniscus freezing and hook formation
  - Too turbulent : Surface defects due to level fluctuations
- Other issues with turbulent flow:
  - Inclusions and gas are carried deep into the strand
  - Longitudinal cracks starting at meniscus and breakouts



Schematic of the continuous casting mold

- Develop an accurate computational model of turbulent liquid metal flow in continuous steel casting, using Direct Numerical Simulations(DNS) and high performance GPUs
- Study the effects of Electromagnetic Braking (EMBr) on flow in the mold region
- Validate the computational model against data in actual steel plants
- Optimize EMBr for actual plant nozzle geometries and operating conditions in order to reduce defects

- Develop CU-FLOW to incorporate solid regions of high conductivity to enable mold flow simulations with **solidifying steel shell**
- **Validate** the model with conducting walls against measurements from experiments performed on the scaled **mini-LIMMCAST mold** model at FZD
- Study mold flow patterns with different EMBR configurations in **actual steel plant geometries** with the solidifying steel shell

Mass Conservation Equation

$$\nabla \cdot \vec{v} = 0$$

Momentum Conservation Equation

$$\rho \left( \frac{\partial \vec{v}}{\partial t} + \nabla \cdot (\vec{v} \vec{v}) \right) = -\nabla p + \mu \nabla \cdot \nabla \vec{v} + \vec{j} \times \vec{B}$$

### MHD Equations- Electric potential method

Charge Conservation Equation

$$\nabla \cdot \vec{j} = 0$$

Current Density Equation

Derived using Ohm's law with assumption  
that  $Re_M << 1$  for liquid metal flows

$$\vec{j} = \sigma(-\nabla \varphi + \vec{v} \times \vec{B})$$

Poisson's equation

for electric potential

(with variable conductivity)

$$\nabla \cdot \sigma \nabla \varphi = \nabla \cdot \sigma (\vec{v} \times \vec{B})$$

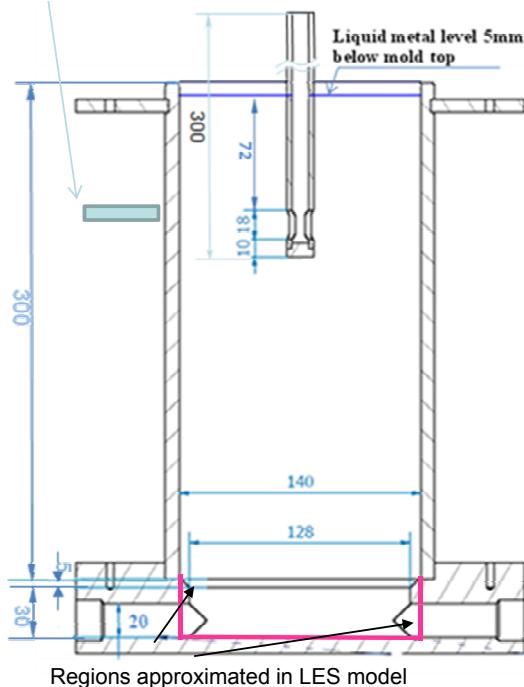
Lorentz Force Equation

$$\vec{F}_L = \vec{j} \times \vec{B}$$

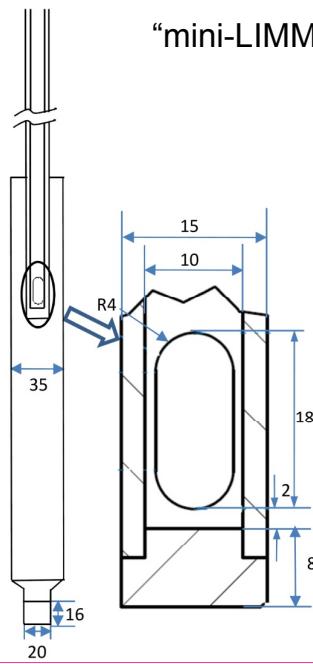
## Numerical Method

- **Finite Volume Method (FVM)** with **fractional step method** for pressure-velocity coupling with explicit formulation of convection and diffusion terms in momentum equations
- Convection and diffusion terms are discretized using **second order central differencing** scheme in space
- **WALE SGS model** is used for modeling filtered scales
- Time integration is done using explicit second order **Adams-Bashforth scheme**
- **Geometric Multigrid solver** is used for Pressure Poisson and Electric Potential Poisson Equations
- Lorentz force is added as an explicit source term in momentum equations
- All the equations (incompressible-MHD flow) have been solved on Graphic Processing Unit (GPU) [<sup>4</sup>Shinn et al. and Chaudhary et al.]

UDV (Ultrasonic Doppler Velocimeter)  
Probe measurements



"mini-LIMMCAST"



<sup>1</sup>Timmel et al,  
EPM-09, Dresden, Germany.

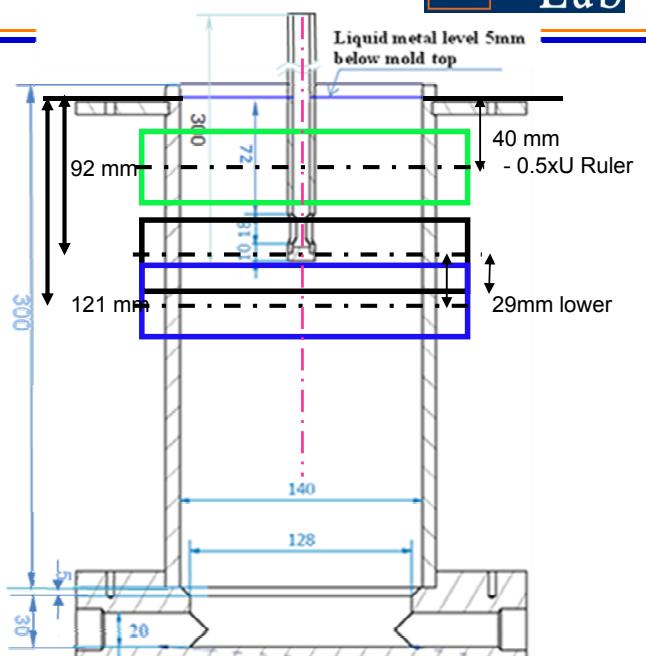
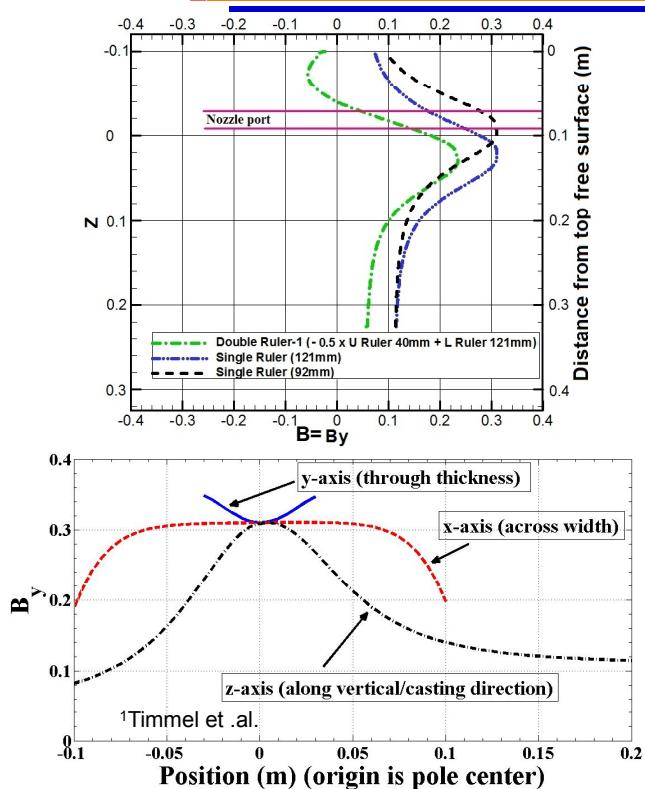
• CFD Lab

• Metals Processing Simulation Lab

• Ramnik Singh

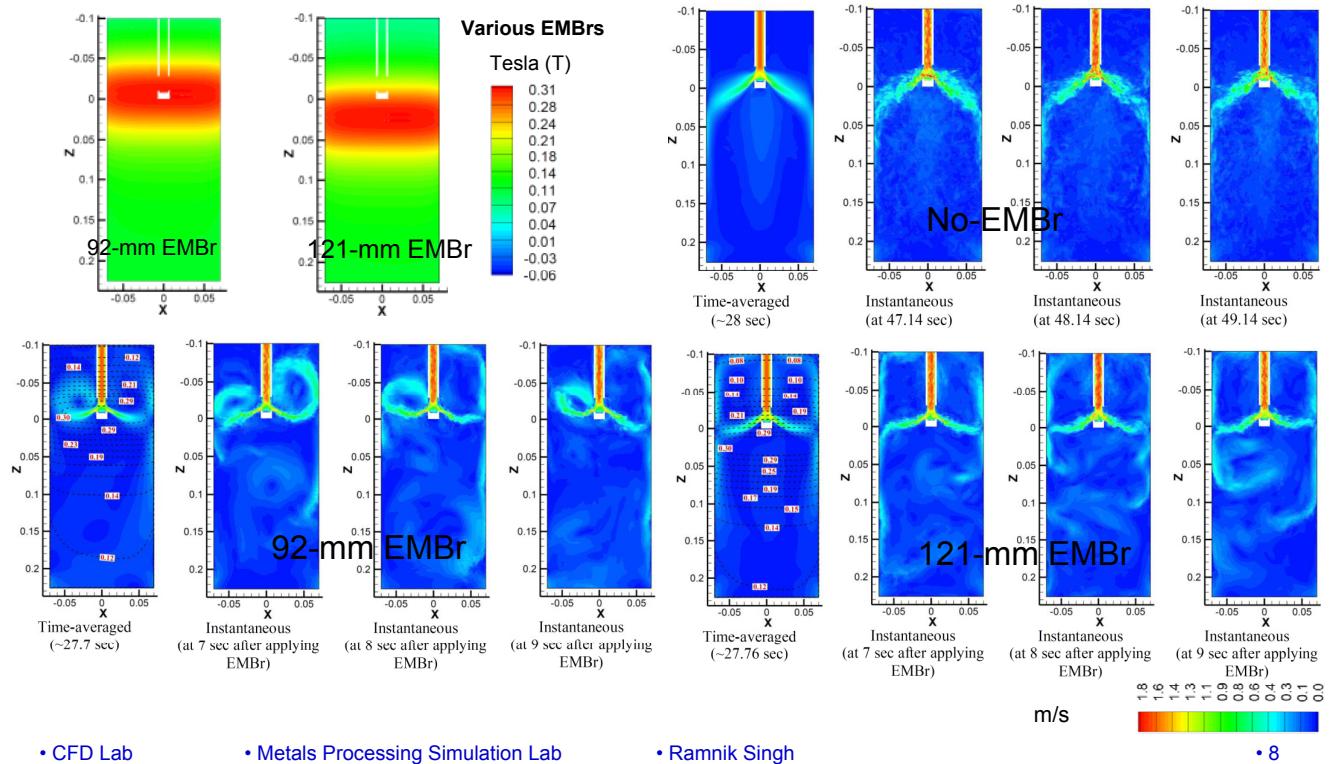
• 6

## Configurations of the EMBR

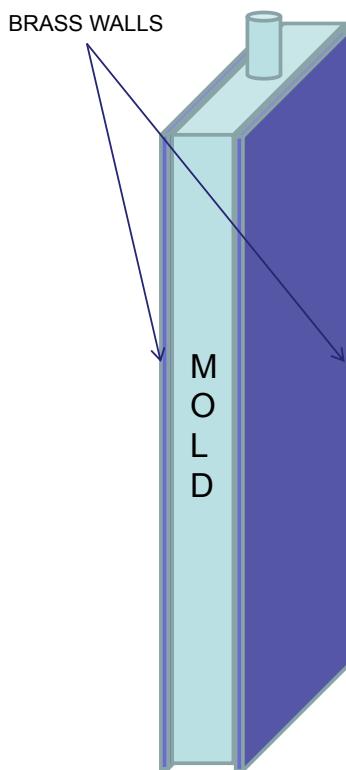


92-mm single-ruler (across nozzle)  
121-mm single-ruler (below nozzle)  
Double-ruler (0.5\*40mm + 121mm)

Work published in paper by <sup>2</sup>Chaudhary et al , Feb 2012



## Dresden Mold With Conducting Plates on Wide Faces



- The plexi-glass walls are replaced by brass walls
- Dimensions and other features remain exactly the previous geometry.

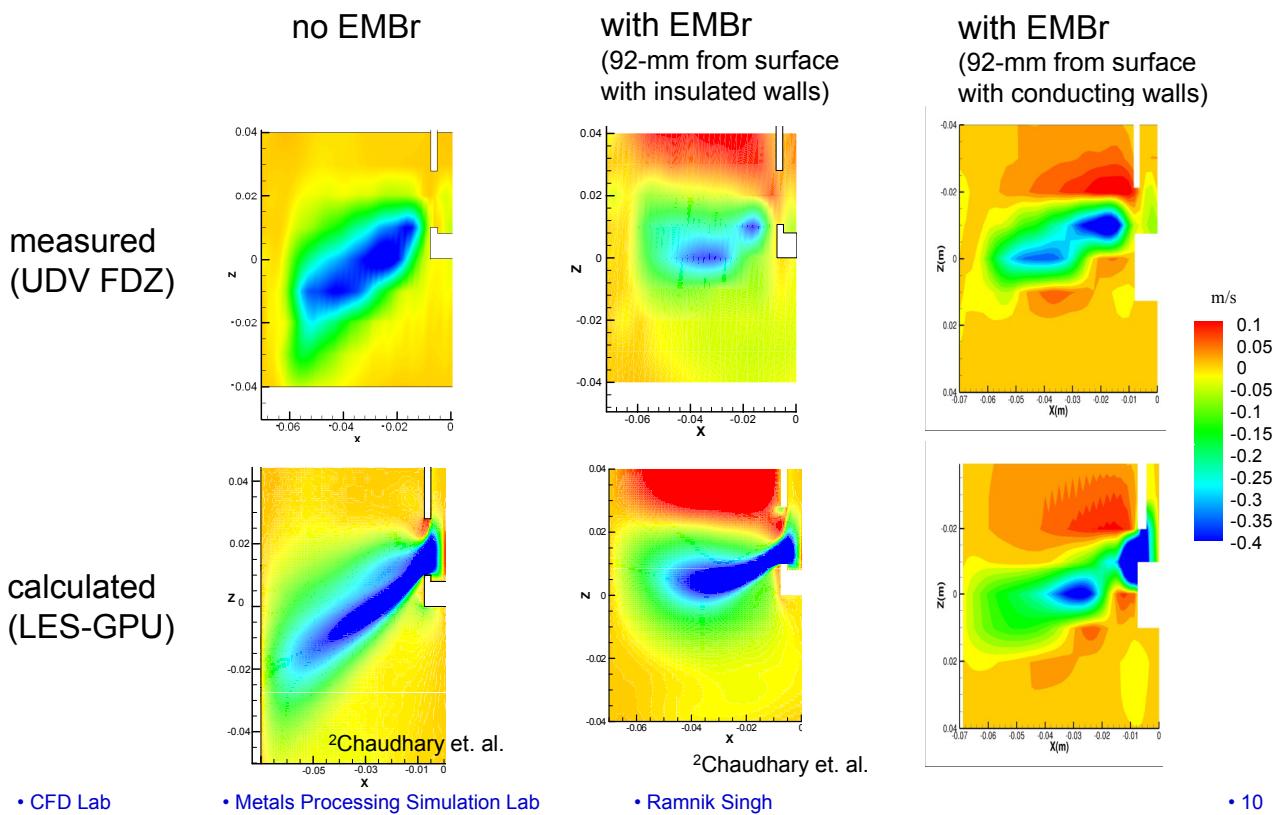
<sup>3</sup>Miao et .al.

Type of Detail	Mini-Limncast Mold	Real Caster Mold
Thickness of Each Plate(t)	0.5mm	5 mm (assumed)
Conducting Wall	Brass Plate	Solidifying Steel
Conductivity of Plate ( $\sigma_{\text{wall}}$ )	$15 \times 10^6 \text{ } \Omega\text{m}$	$0.787 \times 10^6 \text{ } \Omega\text{m}$
Thickness of Mold(L)	35.0 mm	90.0 mm
Conductivity of molten Steel ( $\sigma_{\text{liquid}}$ )	$3.2 \times 10^6 \text{ } \Omega\text{m}$	$0.787 \times 10^6 \text{ } \Omega\text{m}$
Conductivity ratio( $c_w$ )	0.133	0.125

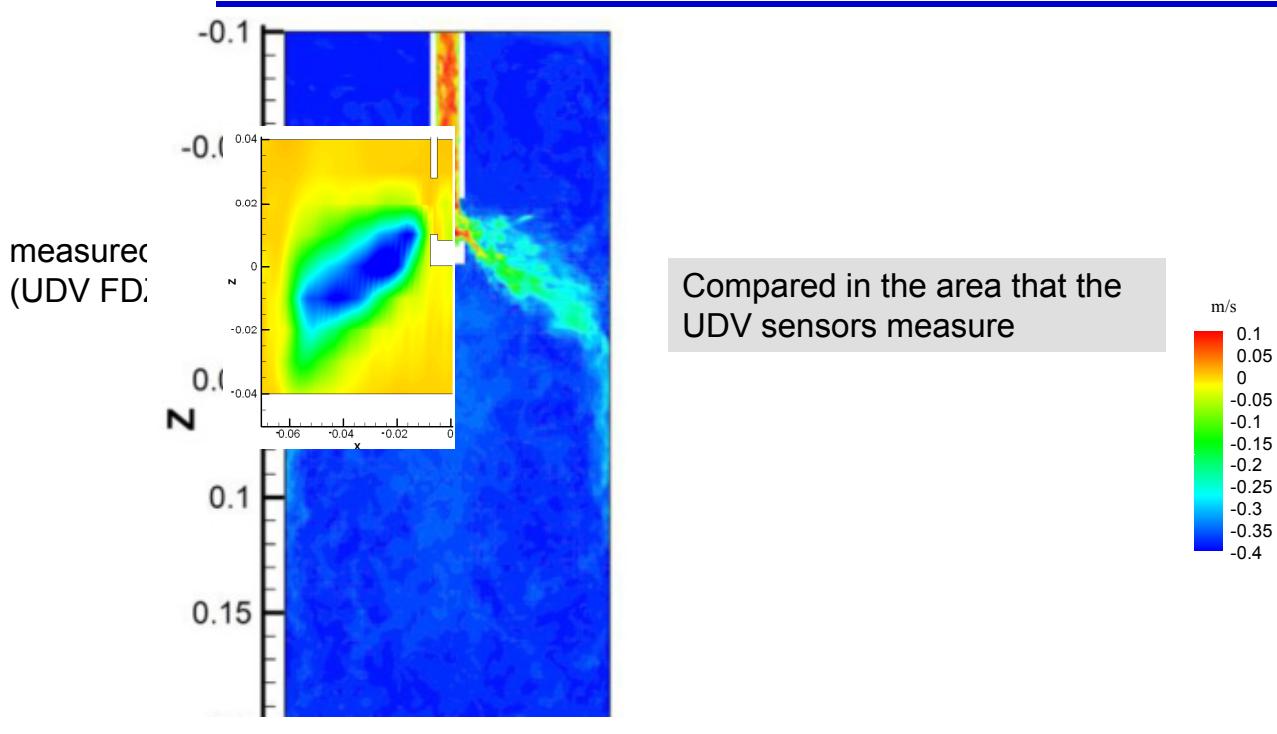
Is this a good scaled model to represent an actual caster?

$$c_w = \frac{\sigma_w t_w}{\sigma_l L}$$

# Comparison of Time Averaged Horizontal Velocity

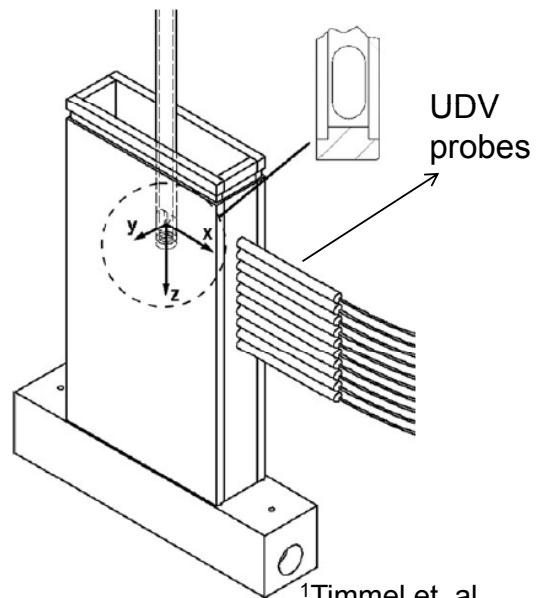


# Comparison of Time Averaged Horizontal Velocity-Continued



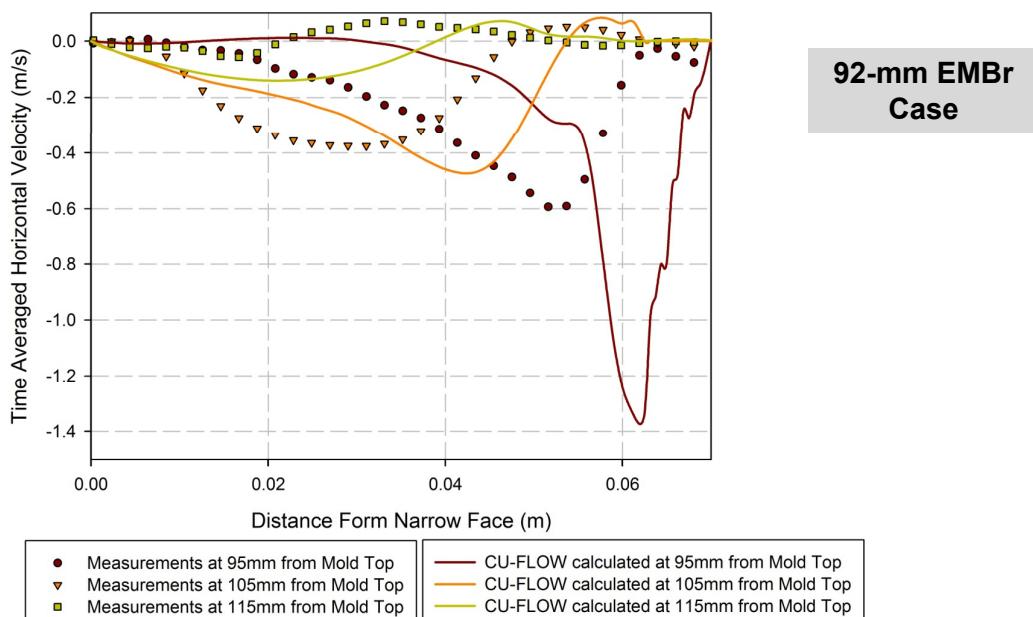
Why does the contour of horizontal velocity look different in the results from Chaudhary et. al. paper?

- The experiment uses UDV sensors to measure the horizontal velocity
- 10 such sensors are placed along the casting direction on the narrow face
- The simulation provides continuous field of a variable but the measurements represent data which is spatially averaged on few points in the region of interest.



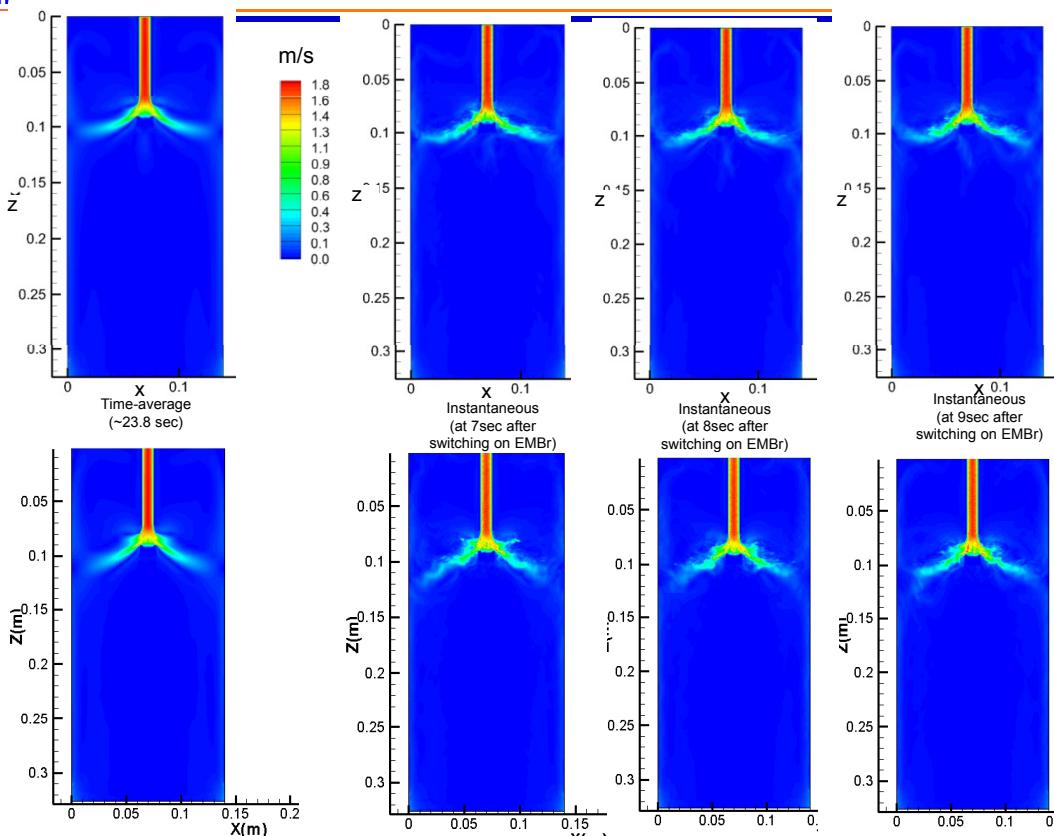
<sup>1</sup>Timmel et. al.

The results for the conducting wall case were extracted on lines corresponding to the sensor positions.

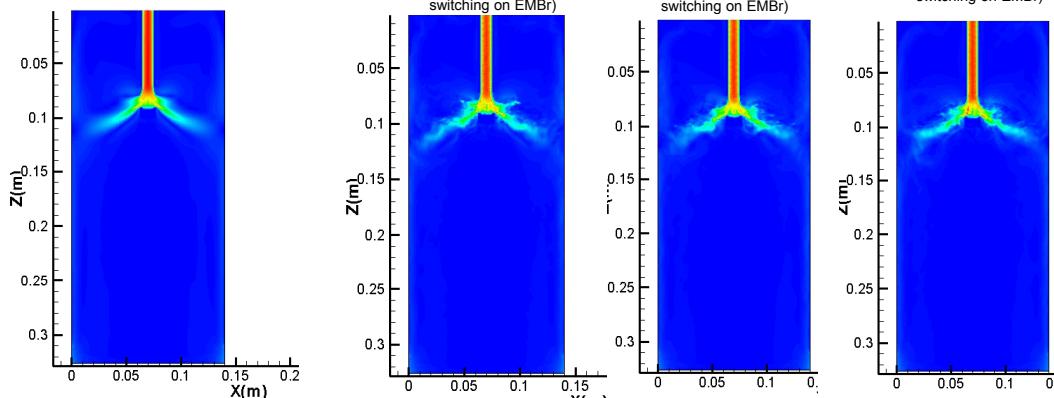


## Effect of single type EMBR on turbulent flow in continuous casting (Contours of velocity magnitude)

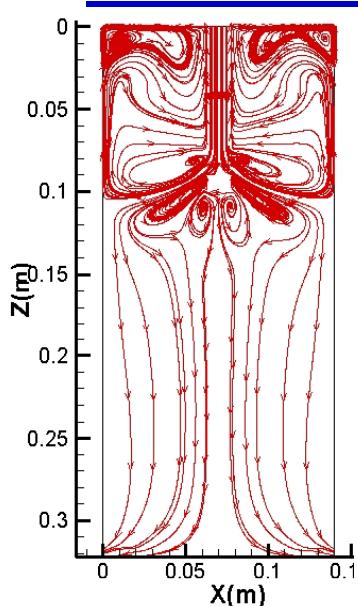
92-mm  
EMBr  
(Conducting  
Wall)



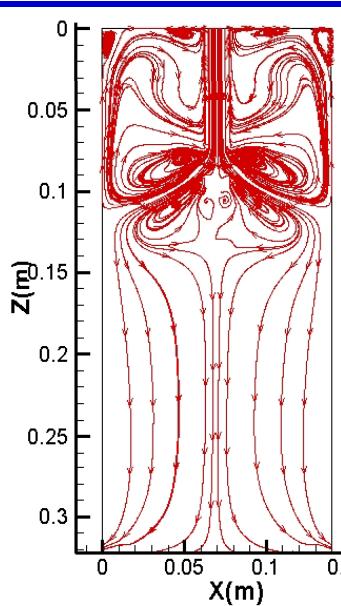
121-mm  
EMBr  
(Conducting  
Wall)



## Effect of single type EMBR on turbulent flow in continuous casting (Streamlines of Mean Flow)

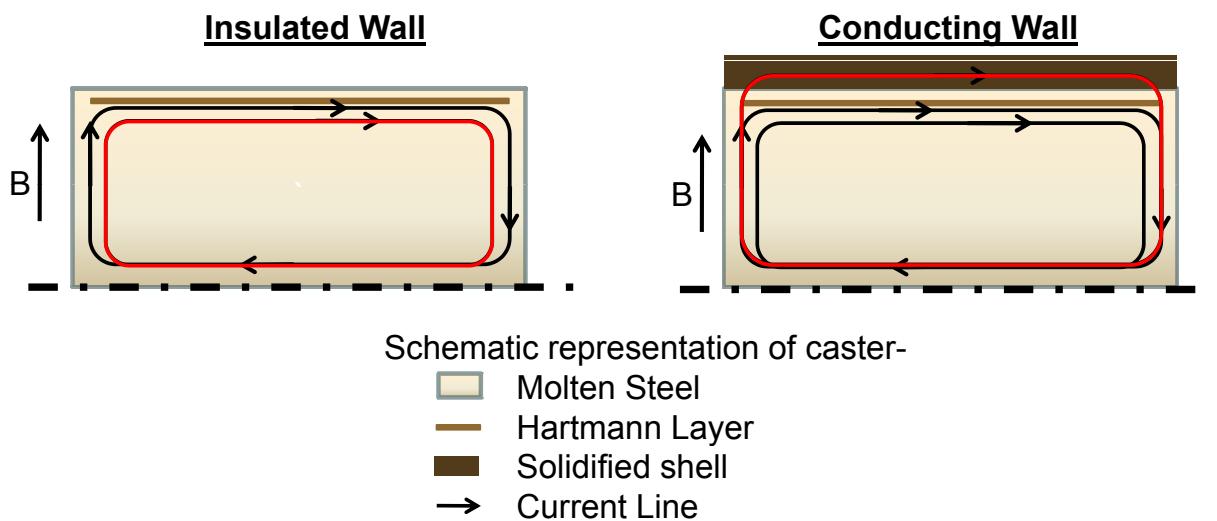


92-mm EMBR  
(Conducting Wall)



121-mm EMBR  
(Conducting Wall)

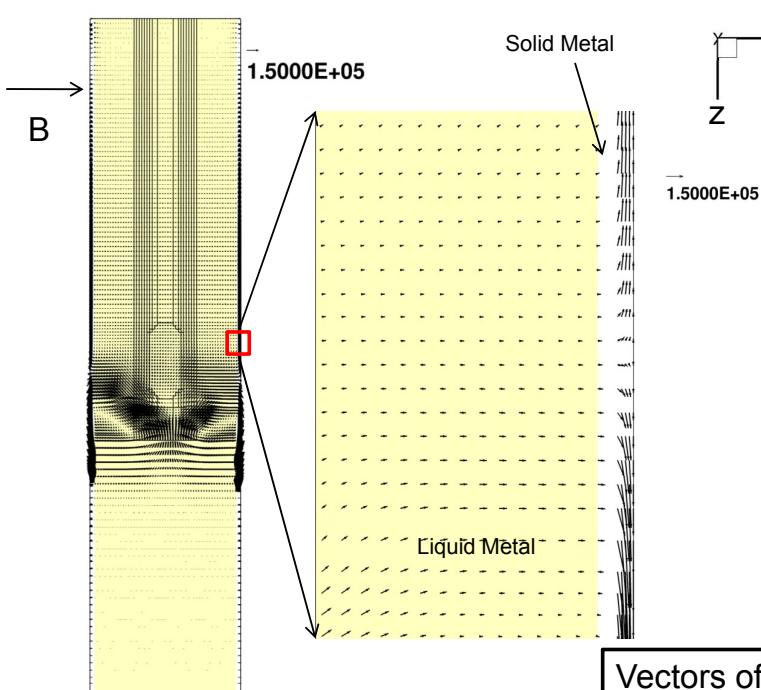
# Why would the conducting plate change the flow pattern?



The return current passes through a region of low resistivity, thus it prefers:

- the bulk flow region in the insulated wall case
- the solidified shell in the conducting wall case

## Comparison of Insulated and Conducting wall 92mm cases- Current Density

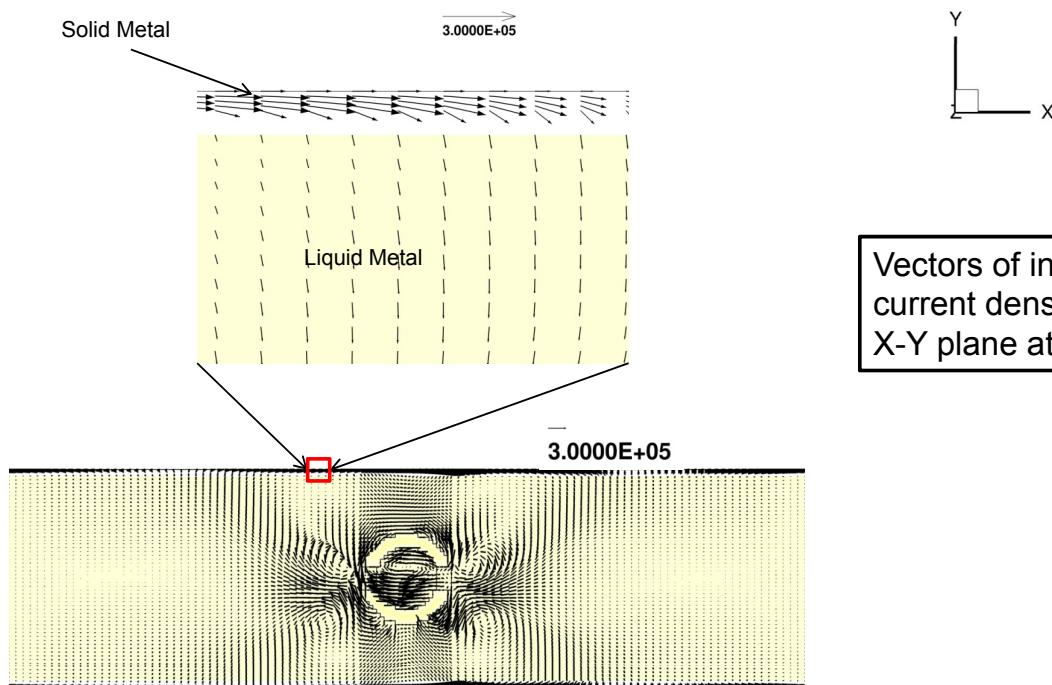


○ The current density is higher in the bulk volume only near the nozzle area

○ Most of the return current takes the path through the conducting plates

○ The Lorentz force which is the cross product of current and applied Magnetic field ( $= J \times B$ ) thus becomes focused on the jet region

Vectors of induced current density in the Y-Z plane at  $x=0.045\text{m}$



# Conclusions

- The results from CU-FLOW simulations match well with the experiments and the LES predicts the transient and mean flow behavior accurately
- The destabilization effect of the magnetic field in case the insulated mold is inhibited and the jets becomes stable in presence of the conducting wall even for the case with the EMBR field on the nozzle
- The low and high frequency fluctuations are damped in the conducting wall cases whereas only the high frequency fluctuations are damped with insulated mold
- The current paths are greatly affected by the conducting wall which intensifies the Lorentz force in the Jet regions
- A grid independence study should be performed to specifically study the effect of the grid density in the conducting wall
- Accurate modeling, in case of the mini-LIMMCAST test case, is required to predict the flow behavior because of the sudden jump in conductivities between liquid metal alloy and the brass wall (~5 times higher)

# References

1. K. Timmel, S. Eckert, G. Gerbeth, Experimental investigation of the flow in a continuous-casting mold under the influence of a transverse, direct current magnetic field, Metall. Mat. Trans. B, DOI: 10.1007/s11663-010-9458-1.
2. R. Chaudhary, B. G. Thomas, S. P. Vanka, Effect of electromagnetic ruler Braking (EMBr) on transient turbulent flow in continuous slab casting using large eddy simulations, Metall. Mat. Trans. B, DOI: 10.1007/s11663-012-9634-6.
3. X. Miao, K. Timmel, D. Lucas, Z. Ren, S. Eckert, G. Gerbeth, Effect of an electromagnetic brake on the turbulent melt flow in a continuous-casting mold, Metall. Mat. Trans. B, DOI: 10.1007/s11663-012-9472-0.
4. R. Chaudhary, A. F. Shinn, S.P. Vanka, B.G. Thomas, Direct numerical simulations of transverse and spanwise magnetic field effect on turbulent flow in a 2:1 aspect ratio rectangular duct, Computers and Fluids, DOI: 10.1016/j.comfluids.2011.08.002.

# Acknowledgements

- National Science Foundation Grant CMMI 11-30882
- Continuous Casting Consortium Members  
(ABB, ArcelorMittal, Baosteel, Tata Steel, Goodrich, Magnesita Refractories, Nucor Steel, Nippon Steel, Postech/Posco, SSAB, ANSYS-Fluent)
- Prof. S.P. Vanka, CFD Lab UIUC
- Prof. B.G. Thomas, Metal Processing Simulation Lab
- National Center for Supercomputing Applications (NCSA) at UIUC – “Forge” cluster

# Questions?



• CFD Lab

• Metals Processing Simulation Lab

• Ramnik Singh

• 22

# Thank You