CCC ANNUAL REPORT

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Effect of EMBr onTransient Turbulent Flow in CC using DNS models and Ga-In-Sn Benchmark Measurements

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Acknowledgements

- Continuous Casting Consortium Members (ABB, Mittal, Baosteel, Tata Steel, Magnesita Refractories, Nucor Steel, Nippon Steel, POSTECH, POSCO, SSAB, ANSYS-Fluent)
- K. Timmel, G. Gerbeth, et. al., FZD Research, Dresden, Germany (measurements)
- Aaron Shinn and graduate students at Metals Processing Simulation Lab (GPU models).

Objectives

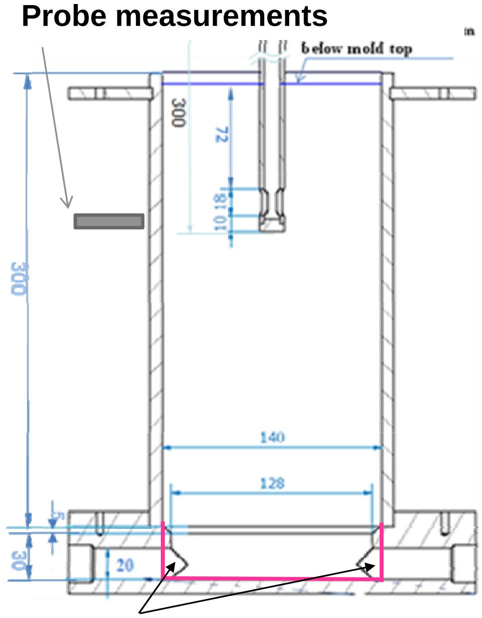
- Model development and testing of CFD codes
  - Extended GPU based CFD code (CU-FLOW) for magnetohydrodynamic (MHD) formulations, turbulent kinetic energy and vorticity budget calculations
  - Direct numerical simulations (DNS) in MHD and non-MHD channel and square duct flows
  - Tested various RANS models (k-ε and Reynolds stress) with MHD effects in channel and square duct flows
- Application of models to understand turbulent flows and steel quality issues in continuous casting processes
  - Compare 6 different methods to quantify transient turbulent flows in the nozzle and mold of a realistic GaInSn model of a typical CC process
  - Investigate effect of electromagnetic braking (EMBr) on turbulent flows in a CC process using GaInSn model to help design better ruler brake systems

Liquid metal GaInAs physical model

(FZD, Dresden, Germany, G. Gerbeth et al, 2010)

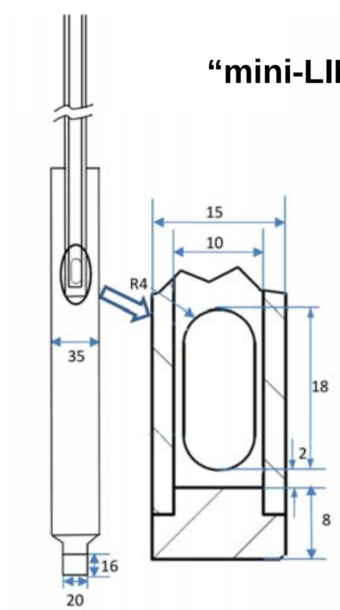
UDV (Ultrasonic Doppler Velocimeter)

Probe measurements



Regions approximated in LES model

"mini-LIMMCAST"



Timmel, Gerbeth et al, EPM-09, Dresden, Germany.

Computational analysis

Rajneesh Chaudhary, C. Ji, BG Thomas, CCC, UIUC

RANS (RKE and SKE):

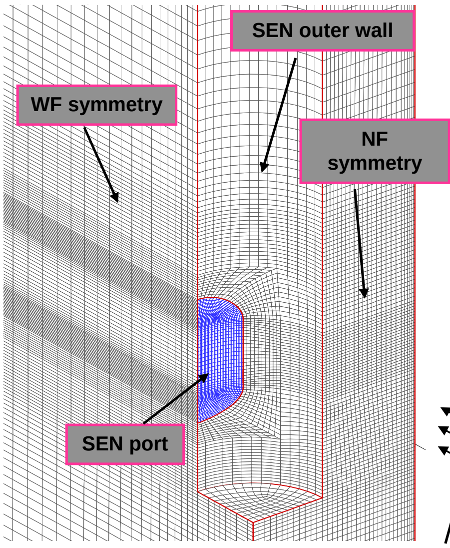
- **Quarter domain in RANS**

~0.61 million hexa cells

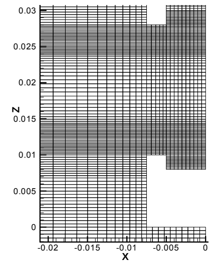
LES:

Full domain in LES

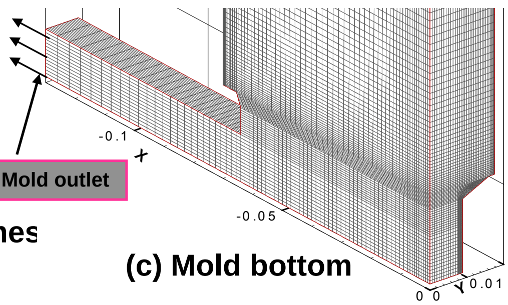
~1.33 million cells



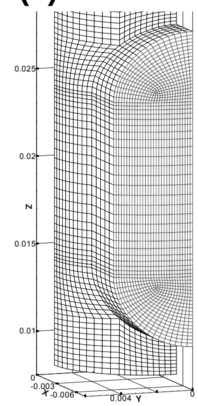
(a) Isometric view of mold mes close to SEN port



(b) Near SEN



(c) Mold bottom



(d) port

Computational Models Evaluated (RANS)

- RANS (SKE and RKE):
  - Steady-state segregated solver
  - Semi-Implicit Pressure Linked Equations (SIMPLE) method for pressure-velocity coupling
  - 2nd order upwind scheme for convection terms
  - Unscaled residuals were reduced below 1.0x10^{-04} to stagnant values.
  - Execution time: **~8 hrs** with parallel FLUENT (6-cores parallel FLUENT on 2.66GHz Xeon 8MB RAM)

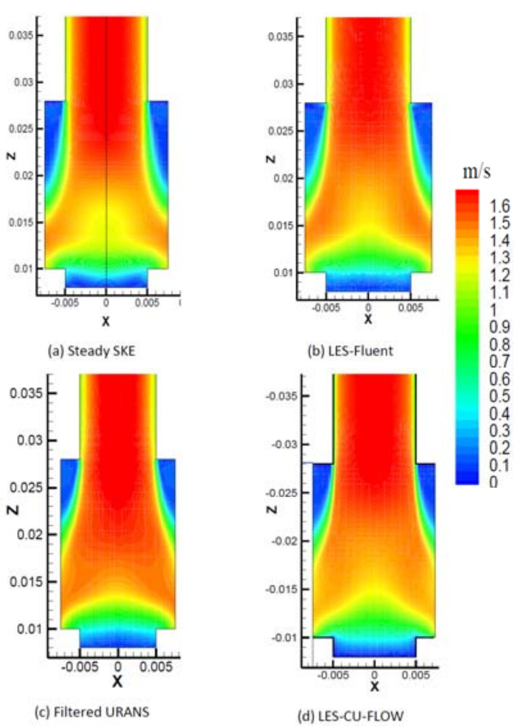
- Filtered URANS(unsteady filtered SKE):
  - Unsteady 2nd order implicit time update
  - Implicit Fractional Step Method (I-FSM) for pressure-velocity coupling
  - 2nd order upwind scheme for convection terms
  - Correction in eddy viscosity is implemented using user defined functions.
  - unscaled residuals decreased by 1000X each time step.
  - 31s simulation, (timestep, Δt=0.004 sec) after initial transient (~20s)
  - Execution time: **~100 hrs** (3-cores)

Computational Models Evaluated (LES)

- LES (Fluent):
  - Unsteady 2nd order implicit time update
  - Implicit Fractional Step Method (I-FSM) for pressure-velocity coupling
  - 2nd order central differencing scheme for convection terms
  - unscaled residuals decreased by 1000X each time step.
  - 21.5s simulation, (timestep, Δt=0.0002 sec) after initial transient (~23s)
  - Execution time: **~67 days**

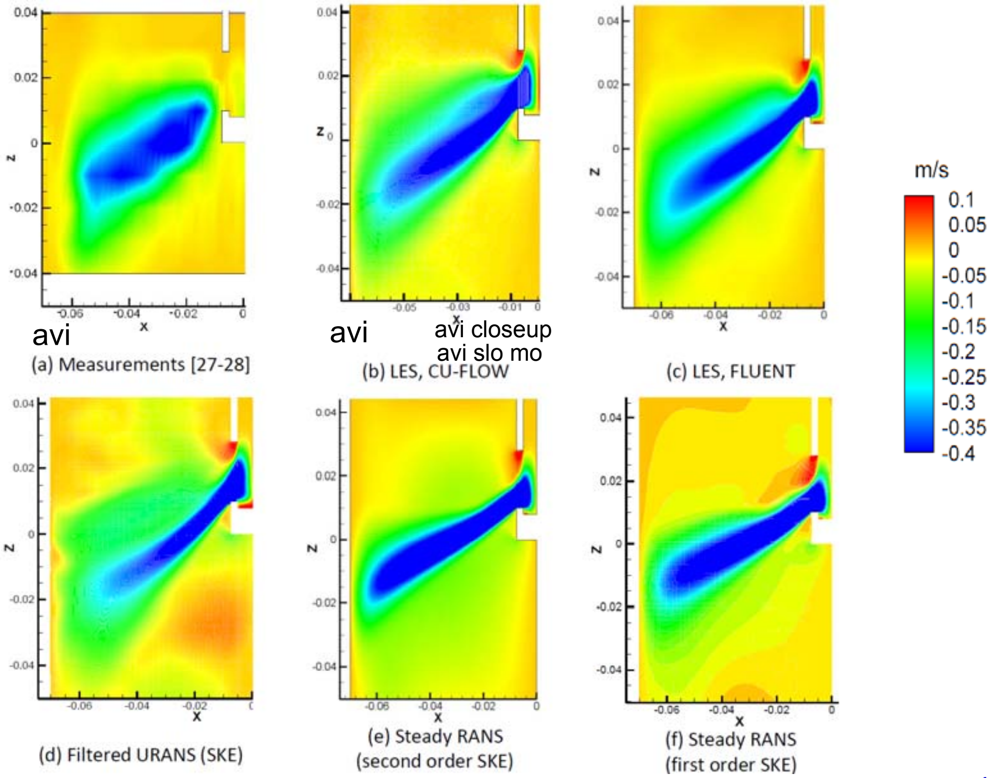
- LES (CU-UIFLOW) GPU Code
  - Unsteady 2nd order explicit time integration (Adams-Bashforth)
  - Implicit Fractional Step Method (I-FSM) for pressure-velocity coupling
  - 2nd order central differencing scheme for convection terms
  - Geometric multigrid solver (incompressible MHD; explicit Lorentz source)
  - Executes on Graphics Processing Unit (video card)
  - ~20s simulation, (timestep, Δt=0.0002 sec) after initial transient (~20s)
  - Execution time: **~14 days**
  - 5X less time on ~5X finer mesh (>**25X faster than Fluent**)

Comparison of average velocity magnitude at nozzle mid-plane and jet characteristics



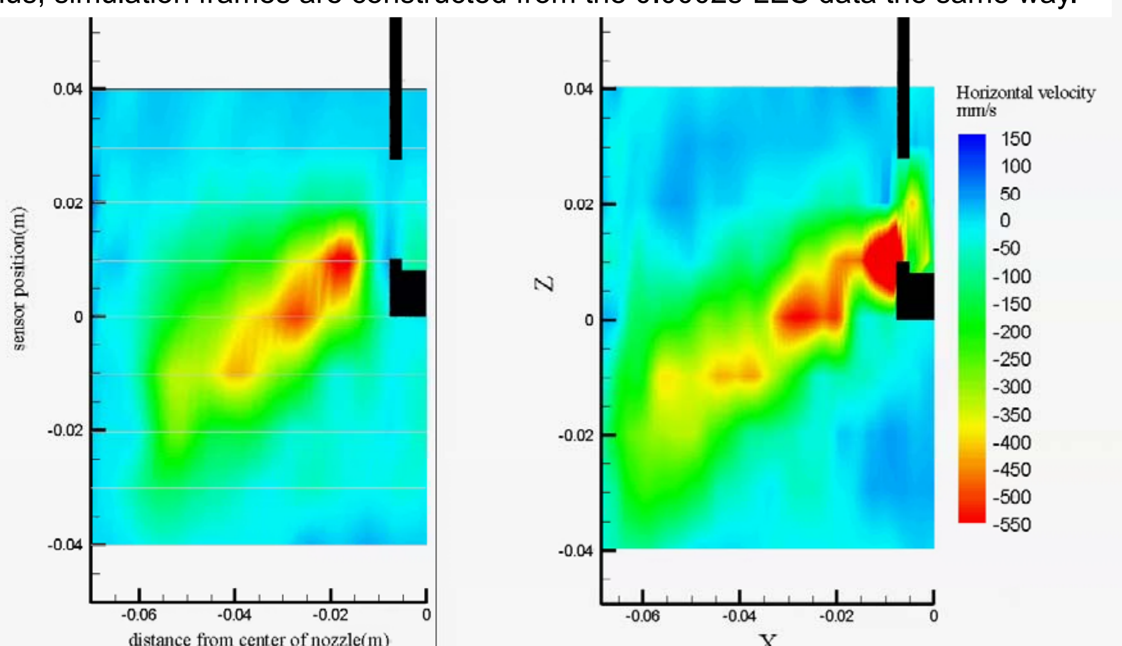
Properties	Steady SKE model	LES model (FLUENT)	Filtered URANS (SKE)
	Left port	Left port	Left port
Weighted average nozzle port velocity in x-direction(outward)(m/s)	0.816	0.71	0.577
Weighted average nozzle port velocity in y-direction(horizontal)(m/s)	0.073	0.108	0.0932
Weighted average nozzle port velocity in z-direction(downward)(m/s)	0.52	0.565	0.543
Weighted average nozzle port turbulent kinetic energy (m^2/s^2)	0.084	0.142	0.0847
Weighted average nozzle port turbulent kinetic energy dissipation rate (m^2/s^3)	15.5	---	15.8
Vertical jet angle (degree)	32.5	38.5	43.3
Horizontal jet angle (degree)	0	0	0
Horizontal spread (half) angle (degree)	5.1	8.6	9.2
Average jet speed (m/s)	0.97	0.91	0.8
Back-flow zone (%)	34.0	25.1	17.6

Comparison of models
(average horizontal velocity at mid plane)



Comparison of realistic movies of horizontal velocity in half mold between measurement and LES

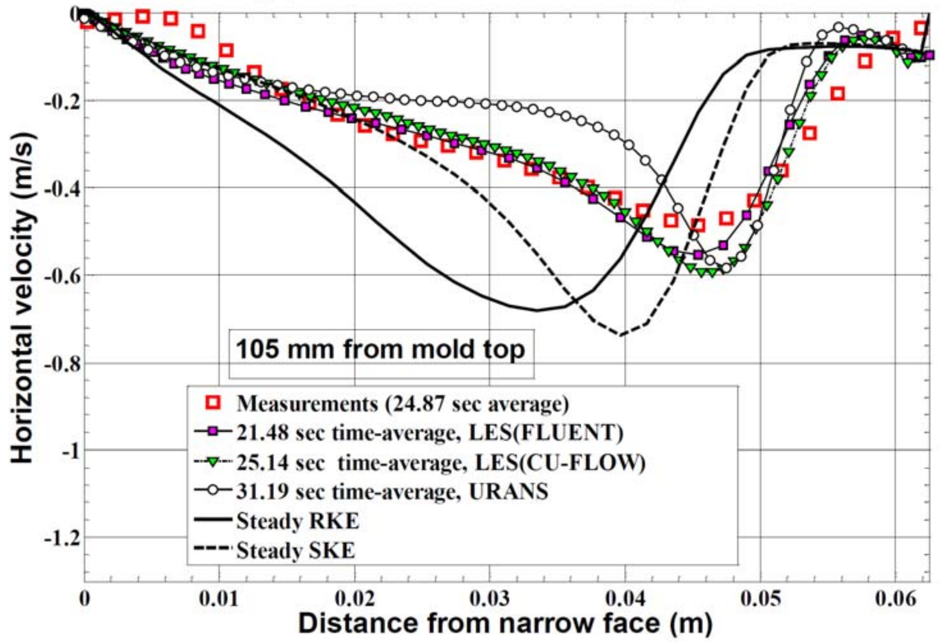
The sensor measured every 0.2s, with averaging occurring over 15ms in each frame
Thus, simulation frames are constructed from the 0.0002s-LES data the same way.



Measurements (~125 frames)
(~0.2 sec time interval ~25 sec movie - Real time)

LES (~43 frames)
(~0.2sec time interval 15ms avg) (~8 sec movie)

Comparison of Computer Simulations with Liquid-Metal Model Measurements



(b) at 105 mm from mold top

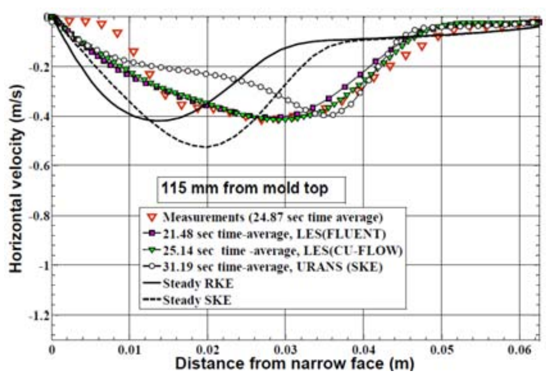
Comparison with horizontal velocity measurements

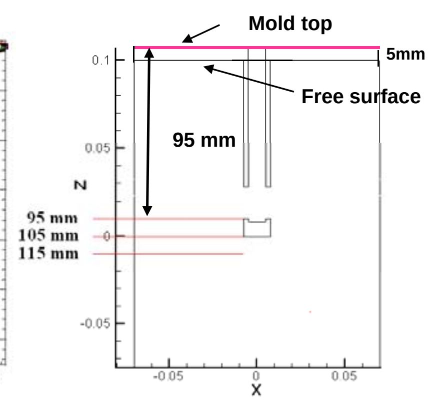
(at 95, 105 and 115 mm from mold top)

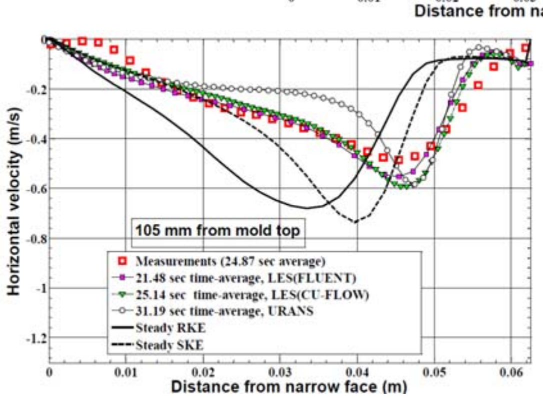
LES outperformed RANS models.

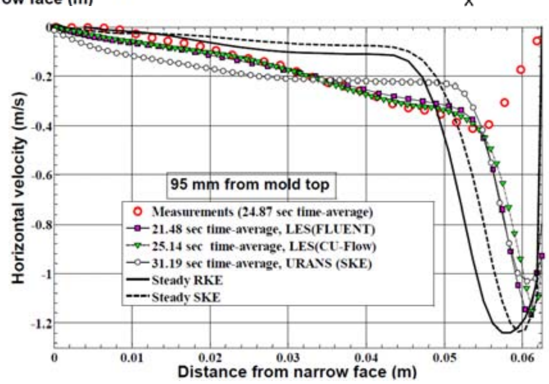
Filtered URANS performed in between LES and steady RANS models.

SKE is better than RKE.

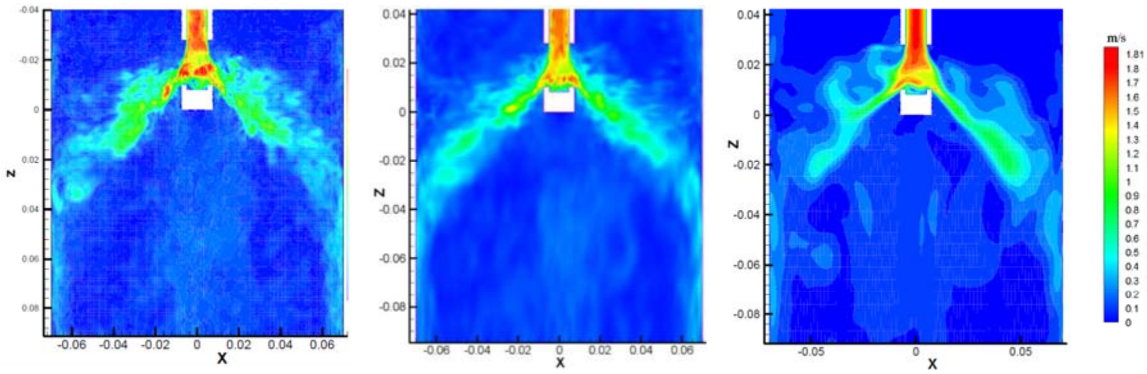








Instantaneous velocity magnitude at mold mid-plane

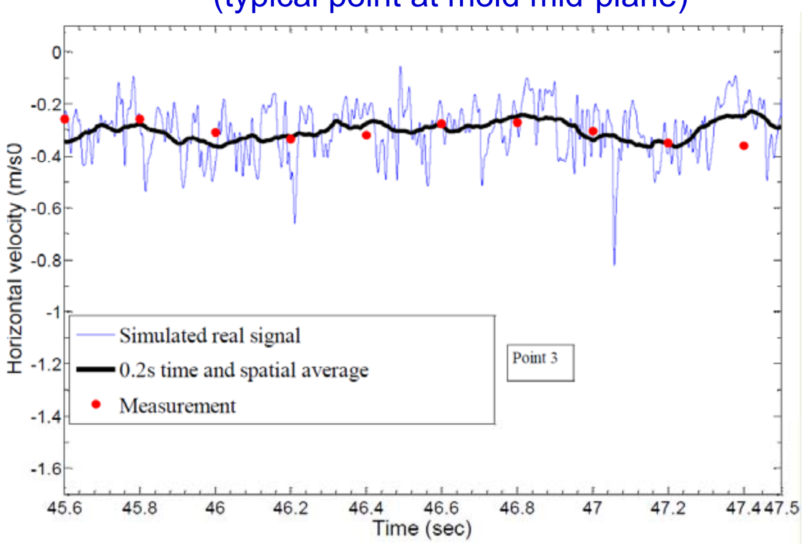


LES CU-FLOW | **LES FLUENT** | **Filtered URANS**

R. Chaudhary, C. Ji, B. G. Thomas, and S. P. Vanka, Transient Turbulent Flow in a Liquid-Metal Model of Continuous Casting, Including Comparison of Six Different Methods, Metallurgical and Materials Transactions B, In-Press, 2011.

Evaluation of Time History Prediction & Measurement

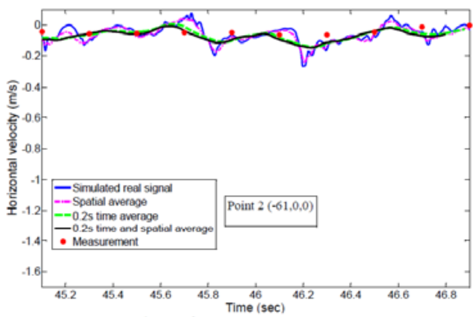
(typical point at mold mid-plane)



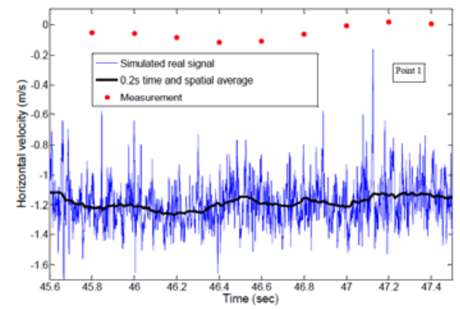
(e) Point-3 (-41, 0, 10)

- Measurements have huge temporal filtering
- Real flows have much larger -frequency changes
-

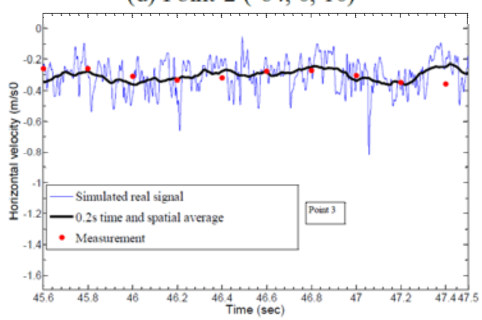
Instantaneous horizontal velocity: comparison between LES and measurements



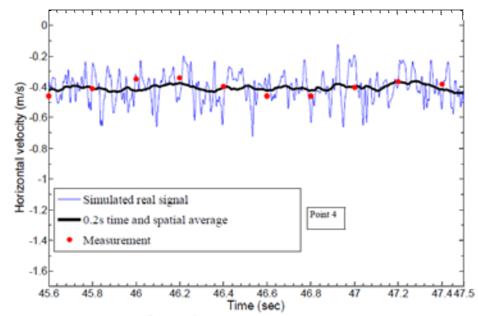
(d) Point-2 (-64, 0, 10)



(c) Point-1 (-8.5, 0, 10)

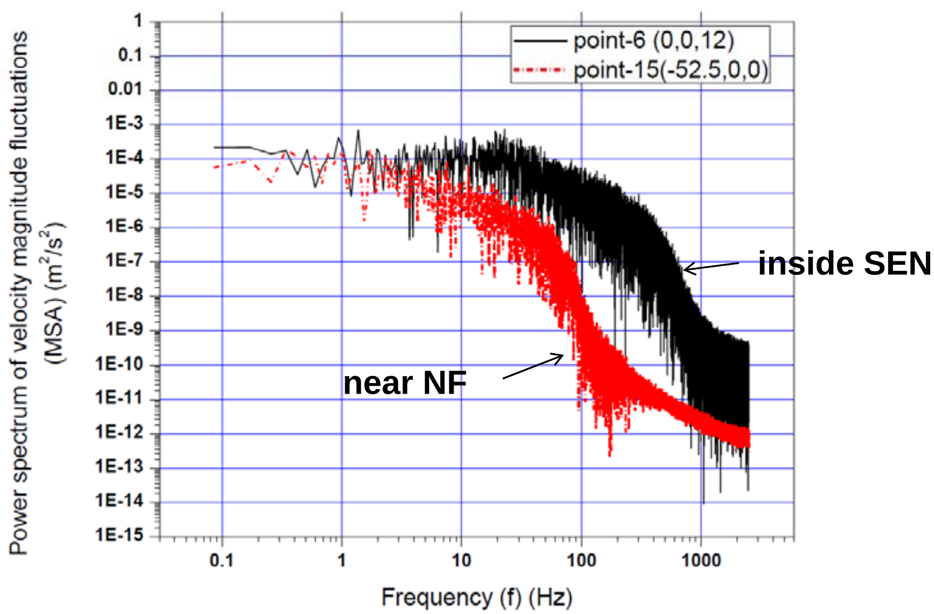


(e) Point-3 (-41, 0, 10)



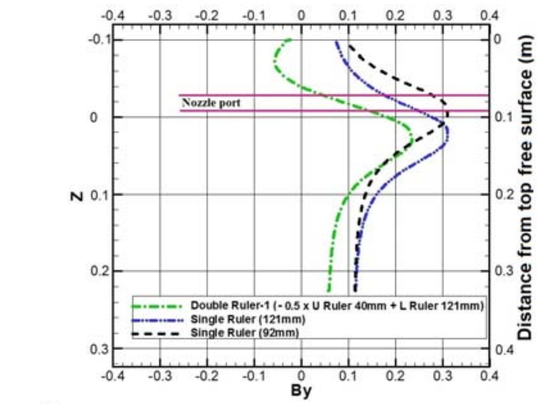
(f) Point-4 (-41, 0, 0)

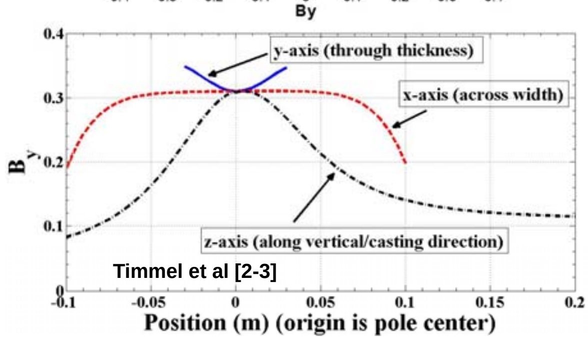
Power Spectrum (Fourier Analysis of Velocity Fluctuations)

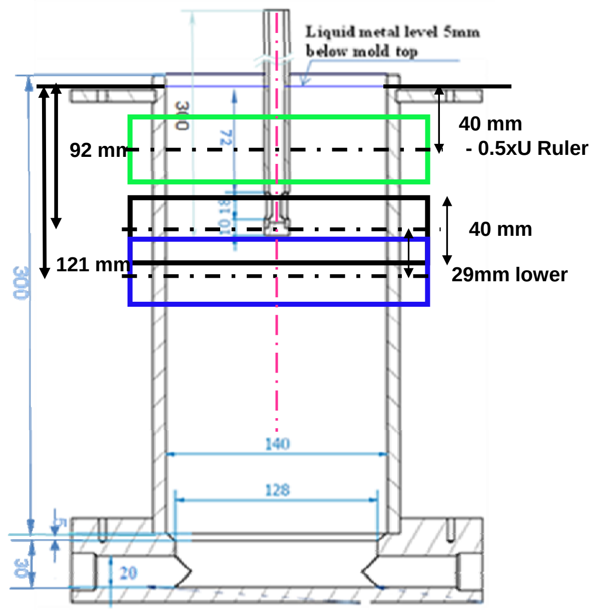


Frequency of turbulent velocity variations is higher near SEN port and jet.

Effect of EMBr







92-mm single-ruler (across nozzle)

121-mm single-ruler (below nozzle)

Double-ruler (0.5*40mm + 121mm)

Direct Numerical Simulation (DNS) Overview: Governing equations for Incompressible MHD flow for low magnetic Reynolds number

Continuity equation: $$\nabla \cdot \vec{v}^* = 0$$

Momentum equations: $$\frac{\partial \vec{v}^*}{\partial t^*} + \nabla^* \cdot \left(\vec{v}^* \vec{v}^*\right) = -\nabla^* p^* + \frac{1}{\mathrm{Re}} \nabla^* \cdot \nabla^* \vec{v}^* + \frac{Ha^2}{\mathrm{Re}} \left(\vec{J}^* \times \vec{B}^*\right)$$

Electric potential method: $$\nabla^{*2} \phi^* = \nabla^* \cdot \left(\vec{v}^* \times \vec{B}_0^*\right)$$ Poisson's equation for electric potential

$$\vec{J}^* = -\nabla^* \phi^* + \vec{v}^* \times \vec{B}_0^*$$ Ohm's law

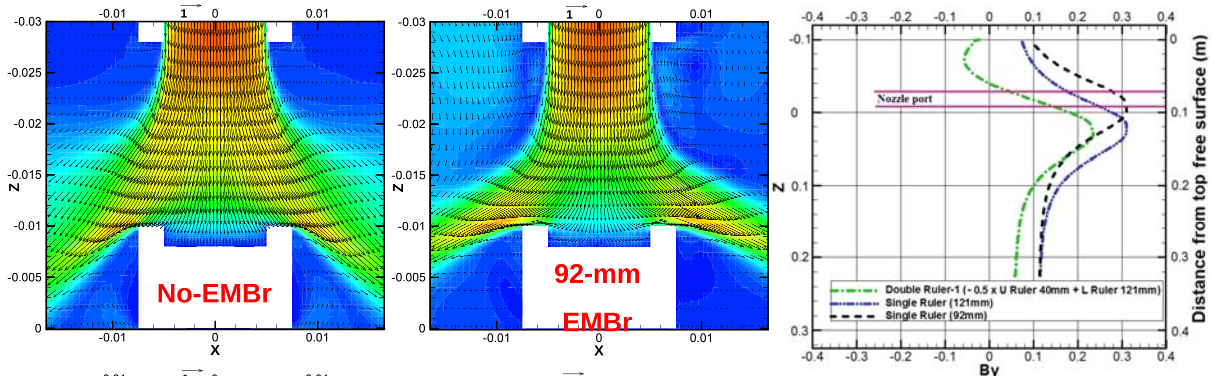
Where: $$\mathrm{Re} = \frac{D_h U_b}{\nu} \qquad Ha = D_h B_0 \sqrt{\frac{\sigma}{\rho \nu}}$$

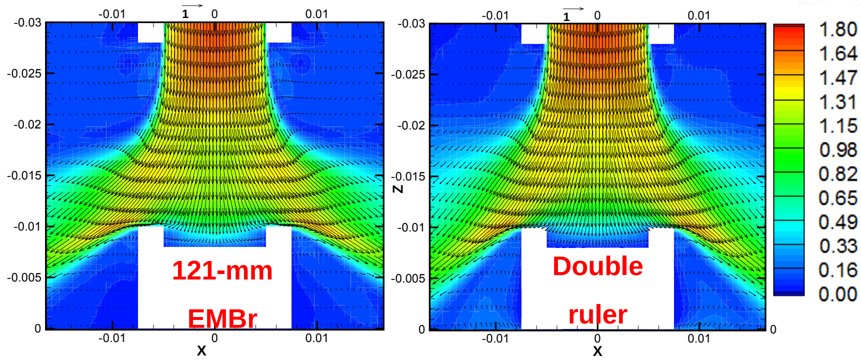
$$\vec{x}^* = \left(x^*, y^*, z^*\right) = \left(\frac{x}{D_h}, \frac{y}{D_h}, \frac{z}{D_h}\right) \qquad t^* = \frac{t}{\left(D_h / U_b\right)} \qquad \vec{v}^* = \left(u^*, v^*, w^*\right) = \left(\frac{u}{U_b}, \frac{v}{U_b}, \frac{w}{U_b}\right)$$

$$p^* = \frac{p}{\rho U_b^2} \qquad \vec{B}_0^* = \left(\frac{B_{0x}}{B_0}, \frac{B_{0y}}{B_0}, \frac{B_{0z}}{B_0}\right) \qquad \phi^* = \frac{\phi}{\left(D_h U_b B_0\right)} \qquad \vec{\nabla}^* = \frac{\partial}{\partial x^*} i + \frac{\partial}{\partial y^*} j + \frac{\partial}{\partial z^*} k$$

Note: conducting steel shell is not in CFD or experiment: differs from steel caster

EMBr: Time-averaged velocity contours and vectors at nozzle bottom

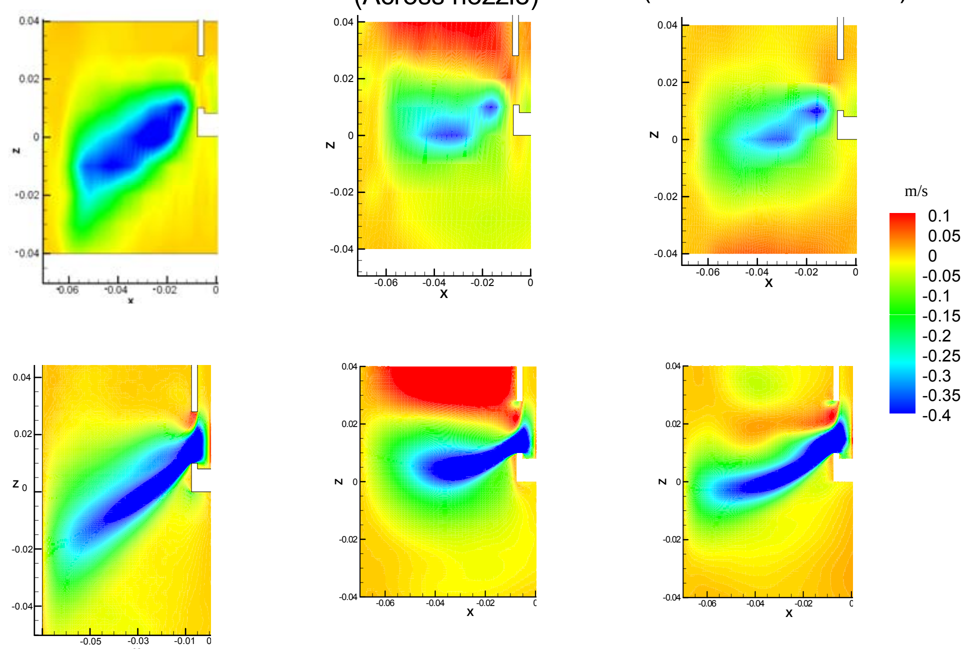




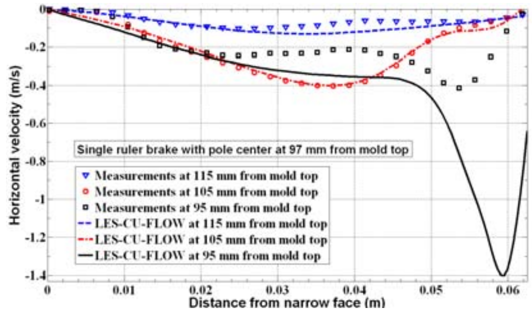
Jet angle becomes less downward as EMBr field across ports increases

Time-averaged flow patterns

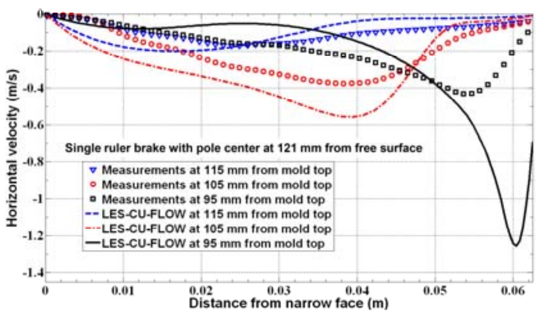
	no EMBr	with EMBr (Across nozzle)	with EMBr (92mm below surface)
measured (UDV FDZ)			
calculated (LES-GPU)			



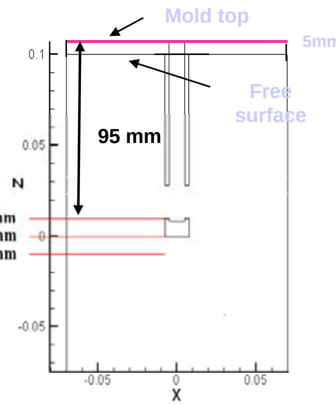
Quantitative comparison of LES-CU-FLOW and UDV measurements (horizontal velocity along 3 lines)



92 mm single-ruler



121 mm single-ruler

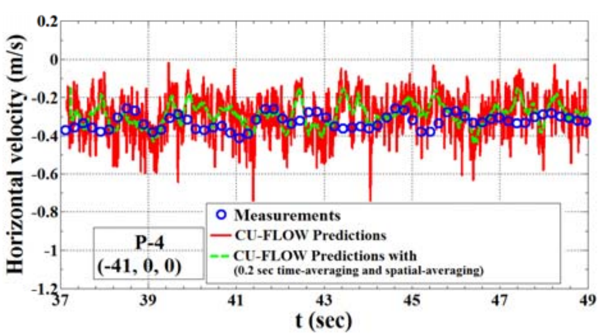


Predictions generally match well

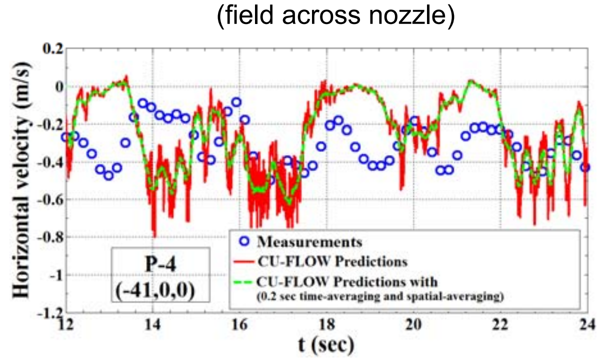
Measurement problems near SEN, NF, and center of jet

Measured (with UDV) and simulated (LES-GPU) (horizontal velocity at mold mid-plane)

no EMBr



with 92-mm EMBr
(field across nozzle)



Instantaneous horizontal velocity at x=33 mm, z=19 mm

Measurements — **Timmel et al, EPM-09, Dresden, Germany.**

CU FLOW model — **(~8 sec time average, timestep 0.00007 sec) (left side)**
Constant Smagorinsky SGS model

Velocity becomes less stable with EMBr field across the nozzle ports

Comparison of velocity histories at 2 points near and far from the ports

Measured (with UDV) and simulated (LES-GPU)

(no EMBr) (with 121-mm EMBr)

Near Port:

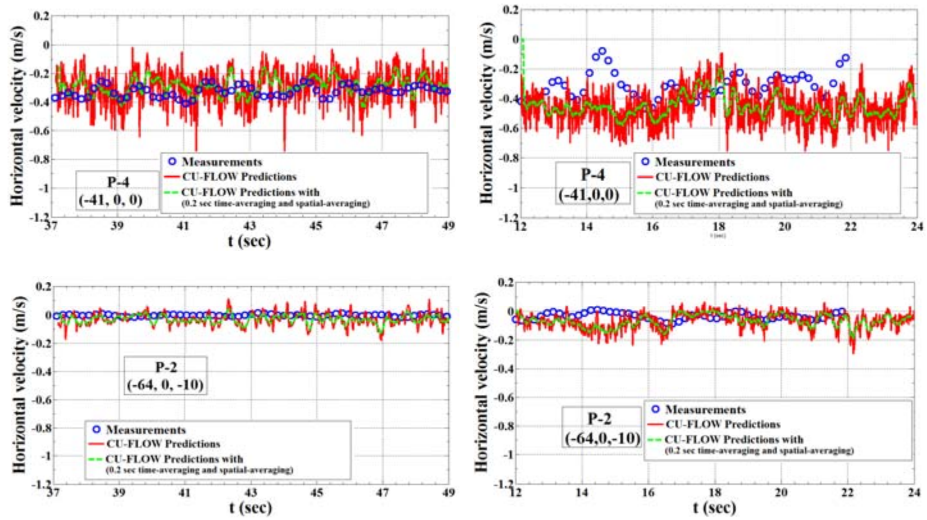
turbulent;

variable v

Near NF:

low-frequency

variations

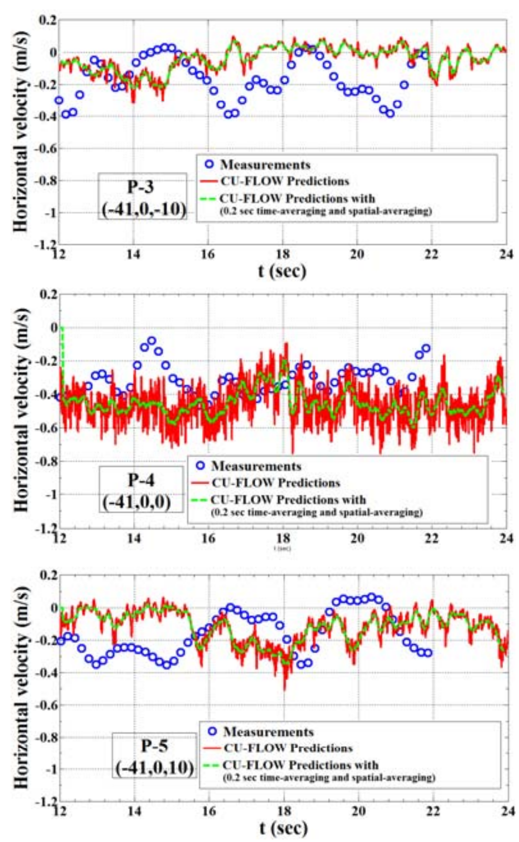


Comparison of velocity histories at 3 points in jet

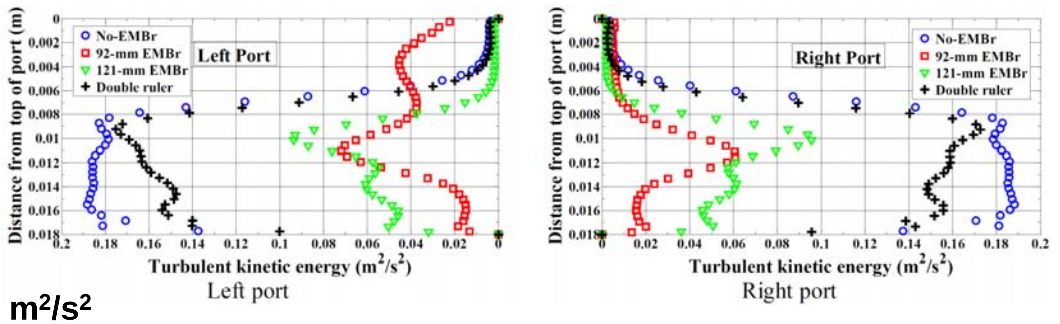
(with 121-mm EMBr)

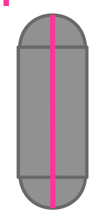
Measured (with UDV) and simulated (LES-GPU) (horizontal velocity at mold mid-plane)

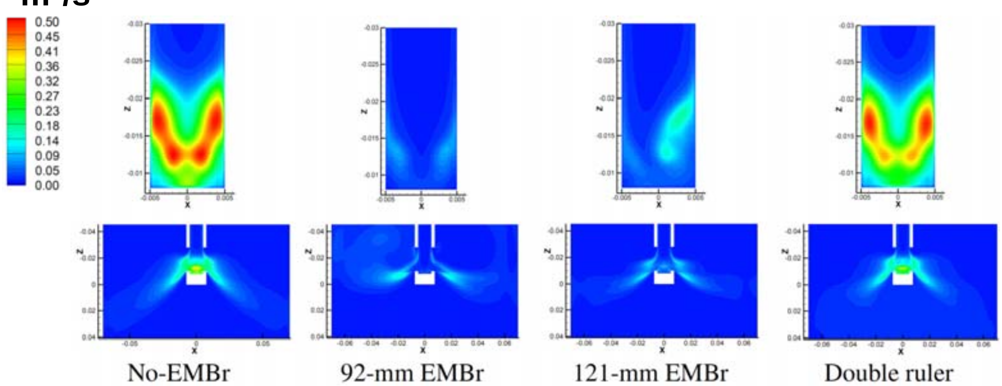
- High frequency turbulent variations in center of jet (P-4)
- Low frequency variations in edges of jet (P-3, P-5)



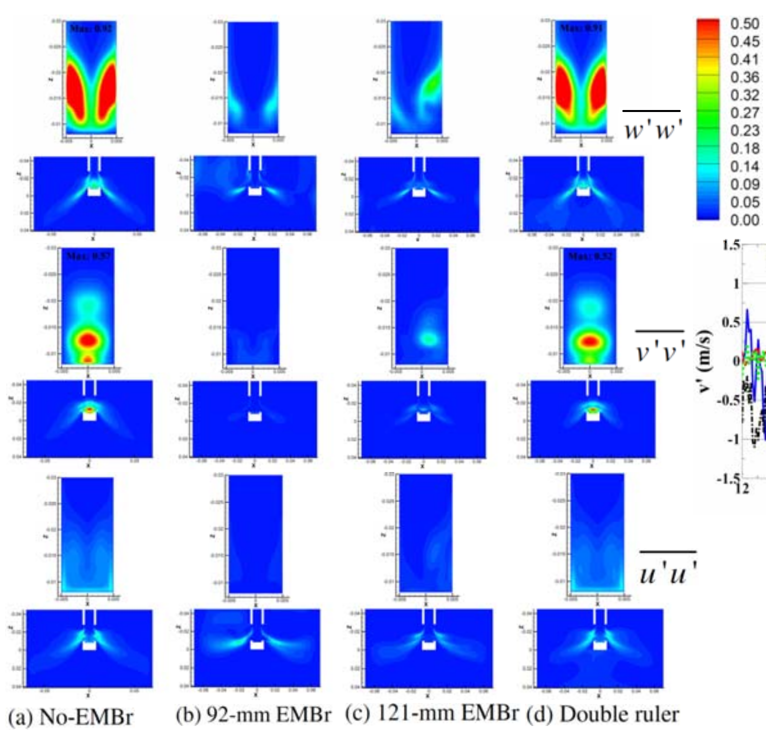
Resolved Turbulent Kinetic Energy at ports, nozzle bottom and in the mold



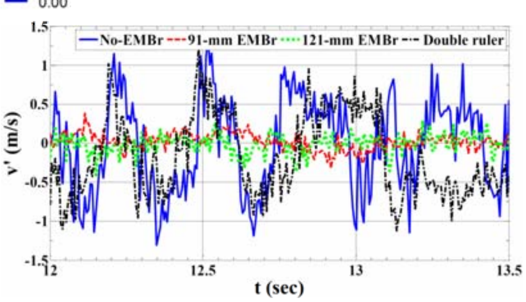




Resolved Reynolds stresses and suppression of nozzle bottom swirl and its alternation

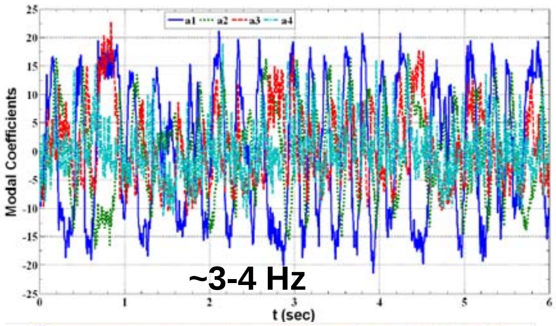


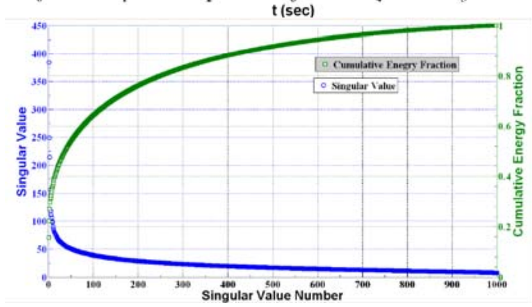
95 mm from mold top at nozzle bottom center

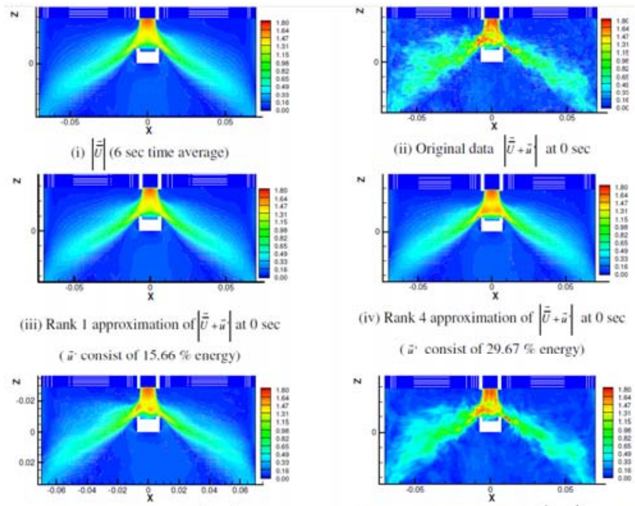


EMBr suppresses swirl and alternating flow

POD Analysis: Modal coefficients, singular values, energy fraction and rank approximation







(i) $\left|\bar{\vec{U}}\right|$ (6 sec time average)

(ii) Original data $\left|\bar{\vec{U}}+\vec{u}'\right|$ at 0 sec

(iii) Rank 1 approximation of $\left|\bar{\vec{U}}+\vec{u}'\right|$ at 0 sec ($\vec{u}'$ consist of 15.66 % energy)

(iv) Rank 4 approximation of $\left|\bar{\vec{U}}+\vec{u}'\right|$ at 0 sec ($\vec{u}'$ consist of 29.67 % energy)

(v) Rank 15 approximation of $\left|\bar{\vec{U}}+\vec{u}'\right|$ at 0 sec ($\vec{u}'$ consist of 40% energy)

(vi) Rank 400 approximation of $\left|\bar{\vec{U}}+\vec{u}'\right|$ at 0 sec ($\vec{u}'$ consist of 88% energy)

$$U'_z = USV^T$$

Singular values $s_1 \geq s_2 \geq s_3 \geq s_4 \ldots . s_q \geq 0$

Temporal coefficients show sine and cosine behavior, signifying back and forth temporal variations in spatial POD modes. (3-4 Hz frequency)

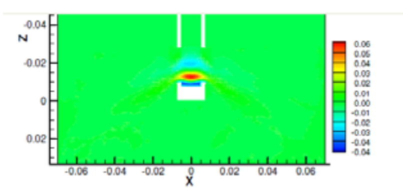
k^th rank approximation

$$s_{k+1} = s_{k+2} \ldots . = s_q = 0$$

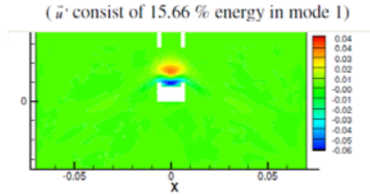
w'

Significant proper orthogonal modes

no EMBr

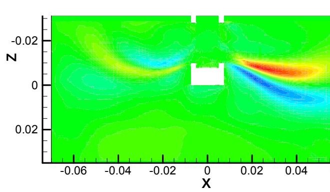


(i) mode 1 for v' ($\vec{u}'$ consist of 15.66 % energy in mode 1)



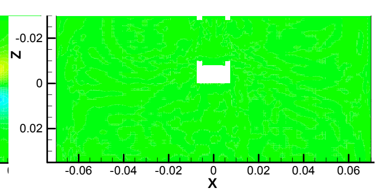
(ii) mode 2 for v' ($\vec{u}'$ consist of 6.58 % energy in mode 2)

with 92-mm EMBr

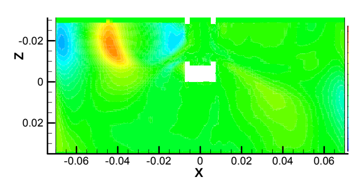


mode 1 for u'

(23% of energy)



mode 1 for v'



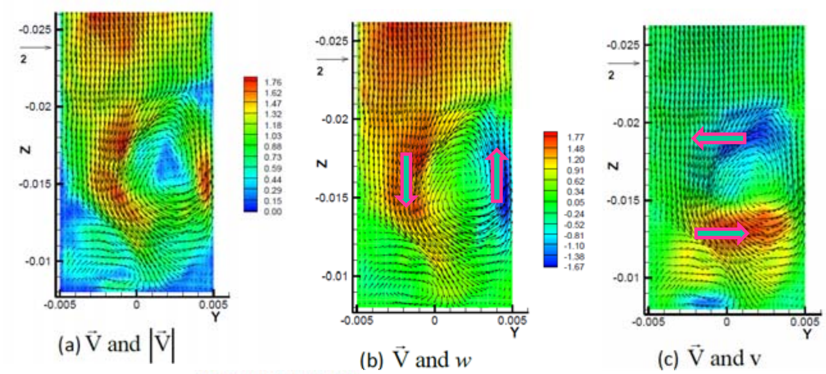
(iv) mode 2(7.66% of energy):

Proper orthogonal decomposition (POD) of instantaneous velocity fluctuation data using single value decomposition (SVD) done with a MATLAB code.

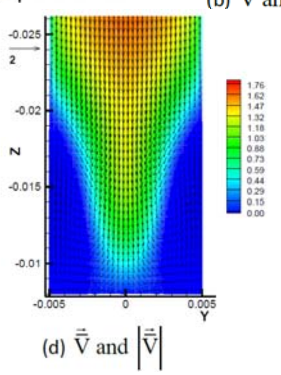
No-EMBr: the most significant modes involve swirl inside the nozzle

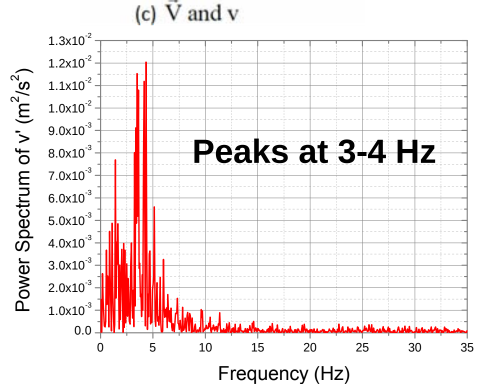
With-EMBr : suppresses v' components and shows strong modes in upper recirculation zone.

No-EMBr: Instantaneous and time average velocity at nozzle bottom

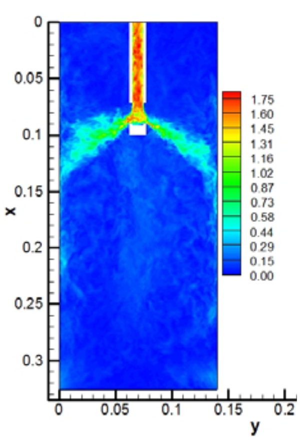


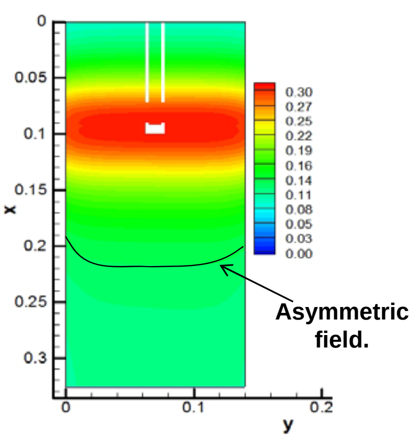
Front-back swirl

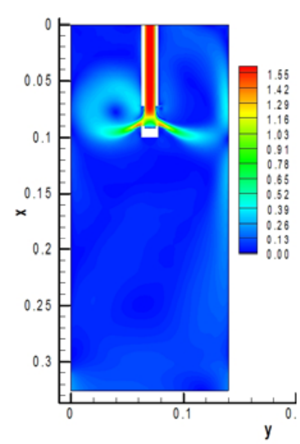




Effect of 92-mm single ruler EMBr on turbulent flow in continuous casting (centered across nozzle 92mm below meniscus)







closeup

whole mold

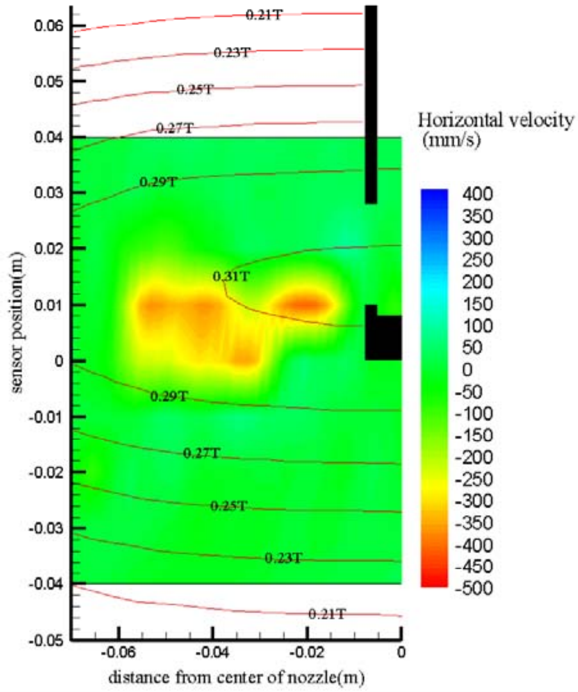
(no MHD correction in SGS viscosity

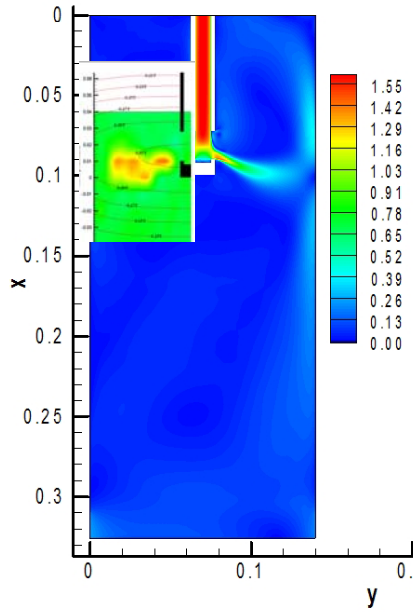
Flow starts laminarizing in lower and upper rolls: dominance of low frequency fluctuations.

For poorly-designed EMBr location, a small right-left asymmetry in magnetic field causes huge right-left asymmetry in turbulent flow due to the dominance of large scales.

Comparison of Measured & Simulated Transient Flow with EMBr

avi

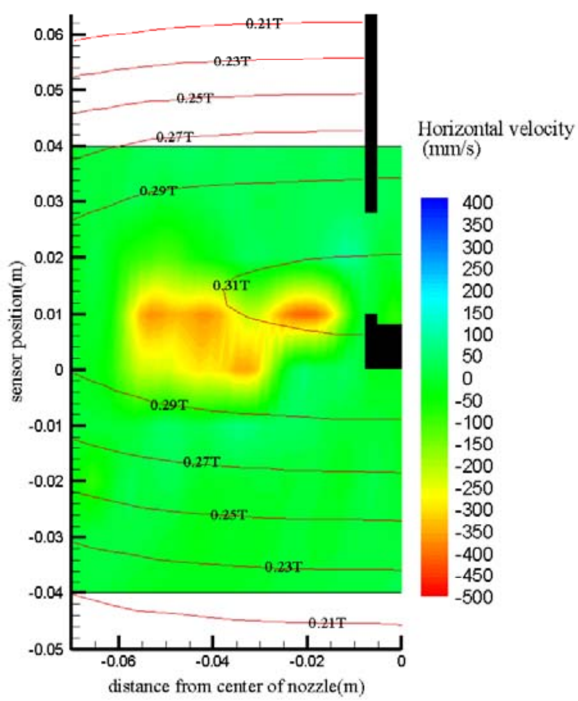


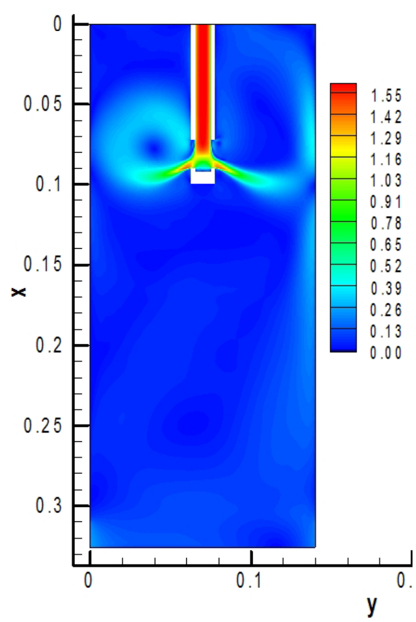


GPU LES model; 11s

Comparison of Measured & Simulated Transient Flow with EMBr

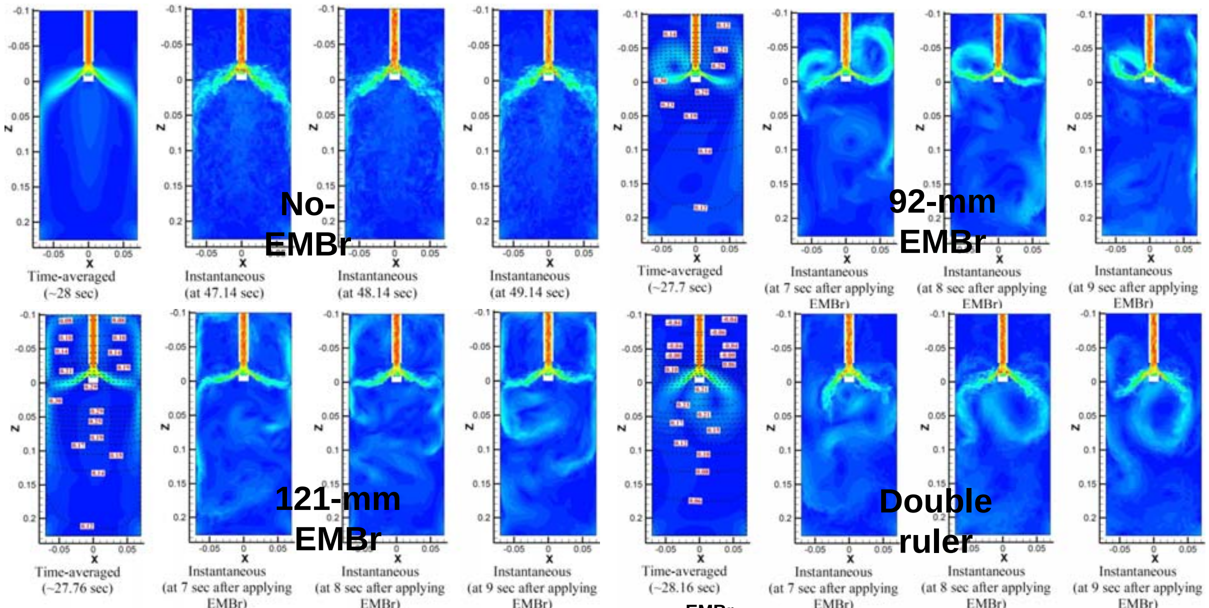
avi

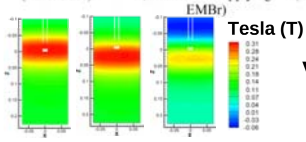




GPU LES model; 11s

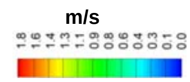
Effect of single/double ruler type EMBr on turbulent flow in continuous casting (velocity magnitude and magnetic field)





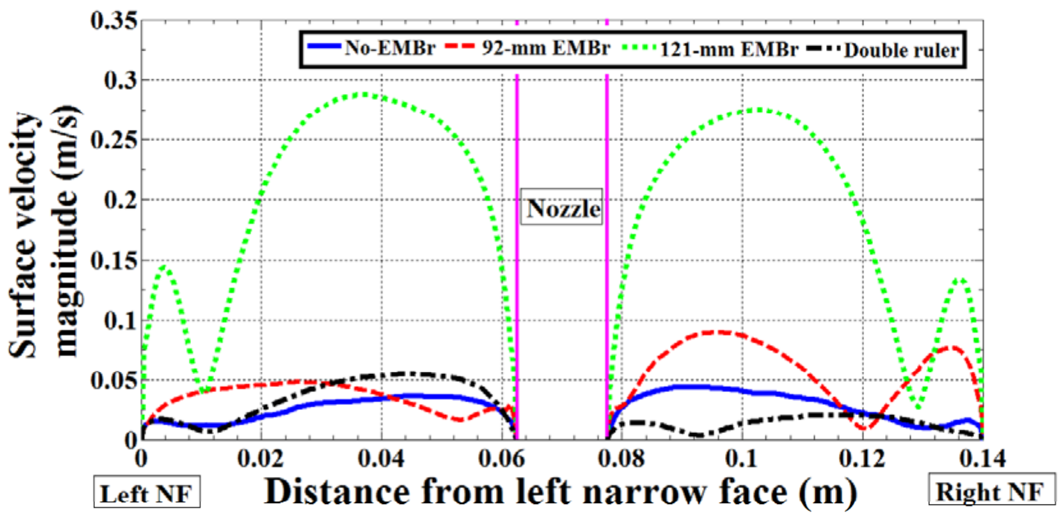
Various EMBrs

EMBr:
1. Flow laminarizes. (92-mm case is very sensitive to asymmetry)
2. Dominance of low frequency fluctuations.
3. Tendency towards 2-d turbulence
4. Vortical structures with their axis aligned with magnetic field.
5. Magnetic field asymmetry fueled by large scale structures.



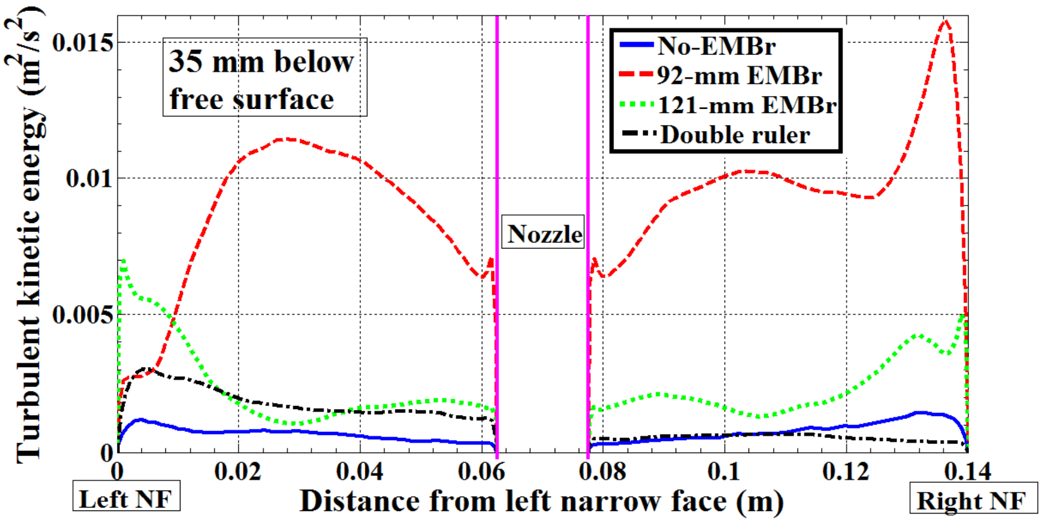
Continuous Casting Consortium

Effect of EMBr on Surface Velocity



Single Ruler-EMBr below the nozzle (121-mm) increases surface velocity, as desired to avoid quality problems due to meniscus freezing

Turbulence near Top Surface



Single Ruler-EMBr across the nozzle (92-mm) increases surface turbulence, likely causing level fluctuations due to the unstable flow. 121-mm EMBr has lower turbulence, even with higher surface velocity

Conclusions

- All codes can capture time-average behavior, but RANS models (eg. K-e) are less accurate and have trouble with transient flow. (Jet is too thin – less spread - and mold velocities are too high)
- The UIUC GPU-LES code is a very accurate tool to simulate fluid flow in Continuous Casting with EMBr
- Fluent-LES is also reasonable but is > 25X slower.
- Filtered URANS performed between LES and steady RANS.
- Measurements are not perfectly accurate either: (too slow close to SEN, and add both spatial and temporal filtering.

- Need to include steel shell into EMBr flow problems in future work. (Lack of conducting shell makes flow less stable)

- Do not operate EMBr over the outlet ports. (makes flow less stable).
- Watch SEN submergence to keep the ports out of the field region
- Stability problems appear worse at very deep submergence. Surface flow too fast at shallow submergence: need to optimize submergence.