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LES of Turbulent Flow in GaInSn Model of Continuous Casting Process with and without EMBr using GPU based in-house CFD code

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Objective

- To investigate turbulent flows and effect of magnetic field on turbulence in GaInSn model of continuous casting process.
  - Turbulent flow model:
    - Large Eddy Simulation (LES) performed using GPU based CFD code
    - Constant Smagorinsky / WALE Sub-Grid Scale (SGS) model for SGS viscosity
    - Electric potential method for MHD calculations
  - Measurements:
    - Velocity measurements performed using Ultrasonic Doppler Velocimetry (UDV) in a small scale liquid metal (GaInSn) model of continuous casting process (available at FZD, Dresden, Germany [1-2])
- Analyze different magnetic field configurations and look for optimization
  - No EMBr (LES + measurements)
  - Single-ruler EMBr (LES + measurements)
  - Double-ruler EMBr, new SEN designs (only computations)
- To analyze transient flow features of the turbulent flow in the nozzle and mold of the GaInSn model with and without EMBr.

LES and MHD model equations

Filtered continuity and Navier-Stokes (N-S) equations

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \quad \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \bar{u}_i}{\partial x_j}\right) - \frac{\partial \tau_{ij}}{\partial x_j} + \bar{F}_i$$

Sub-Grid Stresses

$$\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j$$

Eddy viscosity model for Sub-Grid Stresses

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\nu_s \bar{S}_{ij} \qquad \text{where, } \bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$$

Wall-Adapting Local Eddy-viscosity (WALE) SGS model: (gives correct near wall asymptotic behavior (y^3) of SGS viscosity close to wall without any damping function)

$$\nu_s = L_s^2 \frac{\left(S_{ij}^d S_{ij}^d\right)^{3/2}}{\left(\bar{S}_{ij}\bar{S}_{ij}\right)^{5/2} + \left(S_{ij}^d S_{ij}^d\right)^{5/4}}$$

$$L_s = C_w \Delta, \qquad \Delta = \left(\Delta x \Delta y \Delta z\right)^{1/3}$$

$$S_{ij}^d = \frac{1}{2}\left(\bar{g}_{ij}^2 + \bar{g}_{ji}^2\right) - \frac{1}{3}\delta_{ij}\bar{g}_{kk}^2, \quad \bar{g}_{ij} = \frac{\partial \bar{u}_i}{\partial x_j},$$

$$C_w = 0.325, \quad \delta_{ij} = 1, \text{ if i=j, else } \delta_{ij} = 0$$

Constant Smagorinsky SGS model:

$$\nu_s = L_s^2 \left|\bar{S}\right|, \quad \left|\bar{S}\right| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}},$$

$$L_s = C_s \Delta, \qquad C_s = 0.1,$$

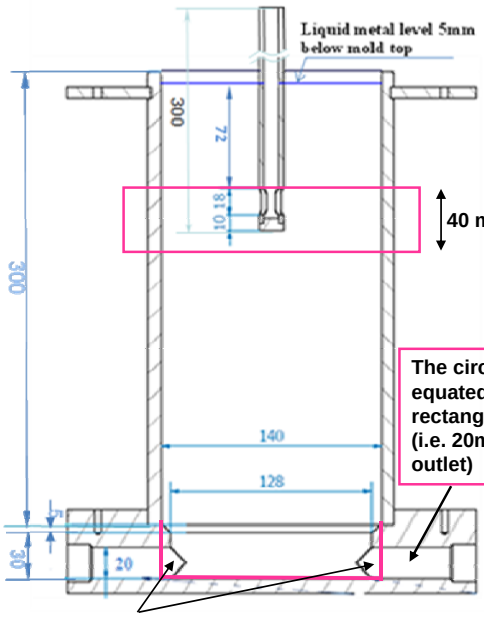
Δx, Δy, and Δz are the grid spacing in x, y and z directions.

MHD equations:

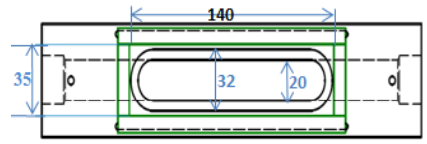
$$\nabla^2 \bar{\phi} = \nabla \cdot \left(\vec{\bar{v}} \times \vec{B}_0\right), \quad \vec{\bar{J}} = -\nabla \bar{\phi} + \vec{\bar{v}} \times \vec{B}_0, \quad \vec{\bar{F}} = \vec{\bar{J}} \times \vec{B}_0 : \text{ Lorentz force}$$

More details on the formulation of LES are given in [3], [4] and [5].

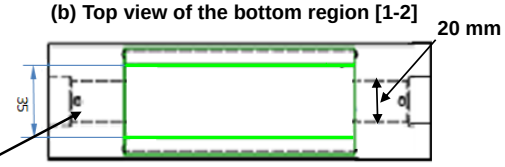
Geometry of GaInSn model of Continuous Casting Process at FZD, Dresden, Germany [1-2]



(a) Front view [1-2]

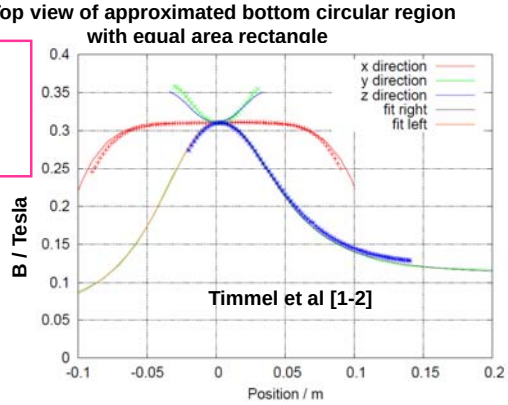


(b) Top view of the bottom region [1-2]

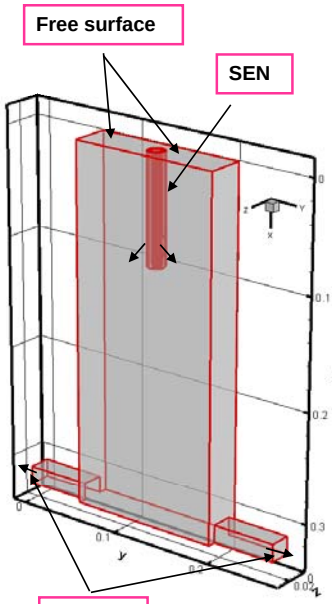


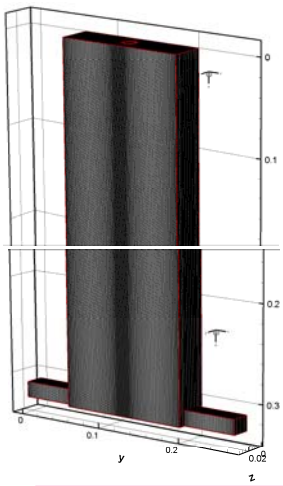
(c) Top view of approximated bottom circular region with equal area rectangle

The circular outlet is equated with equal area rectangular cross-section (i.e. 20mmx16mm each outlet)

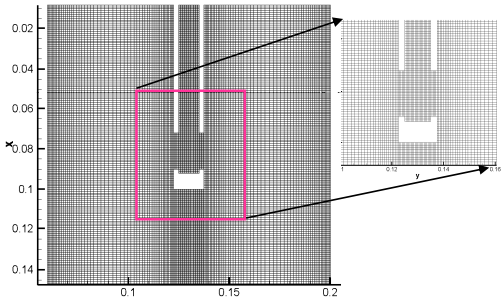


Geometry and mesh created in GPU solver (total ~5.5 million hexa cells)

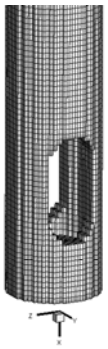




Mesh in whole domain



Mold mid-plane mesh close to SEN



Close up at mesh in SEN

Process parameters

Volume flow rate/ Nozzle inlet velocity	110 *ml/s* / 1.4 *m/s*
Casting speed	**1.35 *m/min***
Mold width	**140 *mm***
Mold thickness	**35 *mm***
Mold length	330 *mm*
Nozzle diameter	10 *mm*
Total nozzle height	300 *mm*
Nozzle port dimension	8*mm*(width)×18*mm*(height) rectangular with top and bottom having 4 *mm* radius chamfered
Nozzle bore diameter (inner/outer)	10*mm*/15*mm*
SEN depth	**72mm**
Density(ρ) (GaInSn, melting point 10.5°C) [6]	6360 kg/m^3
Viscosity(μ) [6]	0.001895 *kg/m s*
Nozzle port angle	0 degree
Shell/gas injection	No/No
EMBr (single ruler)	yes

Boundary conditions for LES

- Fixed laminar plug normal velocity(1.4 m/s) at the inlet
- Wall boundary with no-slip. $(\vec{v} = 0.0)$
- Convective boundary condition for the two outlets [7-8]. $\frac{\partial \vec{v}}{\partial t} + U_{\text{outlet}} \frac{\partial \vec{v}}{\partial n} = 0$ n: boundary normal direction

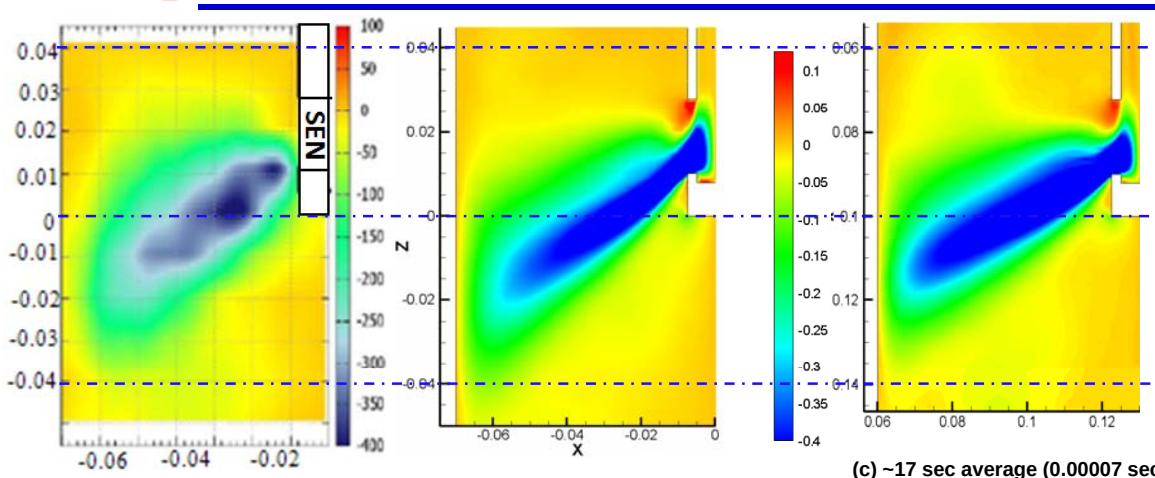
  U_{outlet} : instantaneous boundary normal velocity (area average)

- All boundaries were considered insulated for current density.(i.e. $J_n = 0 \Rightarrow \frac{\partial \bar{\phi}}{\partial n} = 0$)

Numerical method

- Finite Volume Method (FVM) with fraction step method for pressure-velocity coupling with explicit formulation of convection and implicit diffusion terms in momentum equations.
- Convection and diffusion terms discretized using second order central differencing scheme in space.
- Time integration achieved through explicit second order Adams-Bashforth scheme for convection terms and second order Crank-Nicolson implicit scheme for viscous terms.
- Geometric Multigrid solver is used for Pressure Poisson and Electric Potential Poisson Equations.
- Lorentz force is calculated and added as explicit source term in momentum equations.
- All the equations (incompressible-MHD flow) have been solved on an extension of CU-FLOW (a Graphic Processing Unit (GPU) based fluid flow solver (Shinn & Vanka [9]) with MHD module, vorticity and TKE budgets routines (Chaudhary et al [4]) .
- This GPU based code is 15-20 times faster than a single core 3.2 GHz CPU.

Comparison of horizontal velocity in non-EMBr case



(a) ~25 sec average (~0.2 sec time interval) (UDV measurements) [1-2]

(b) 21.48 sec average (0.0002 sec time interval) (WALE SGS model)

(LES using FLUENT, ~1.3 million mesh)

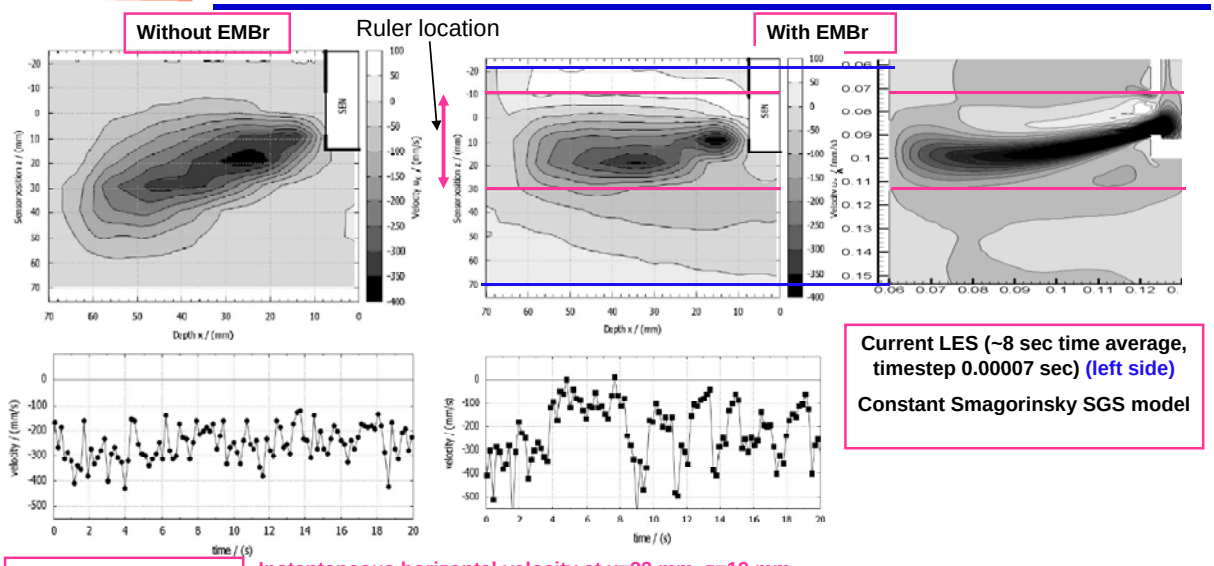
(c) ~17 sec average (0.00007 sec time interval) (Constant Smagorinsky model SGS model)

LES using in-house GPU code, ~5.5 million mesh)

1. All matched closely.

2. WALE model has shown better predictions (especially the jet angle and spread) and therefore WALE model is being used in future runs.

Measured [1] (using UDV) and predicted (LES) horizontal velocity at mold mid-plane (with and without EMBr)



Current LES (~8 sec time average, timestep 0.00007 sec) (left side)

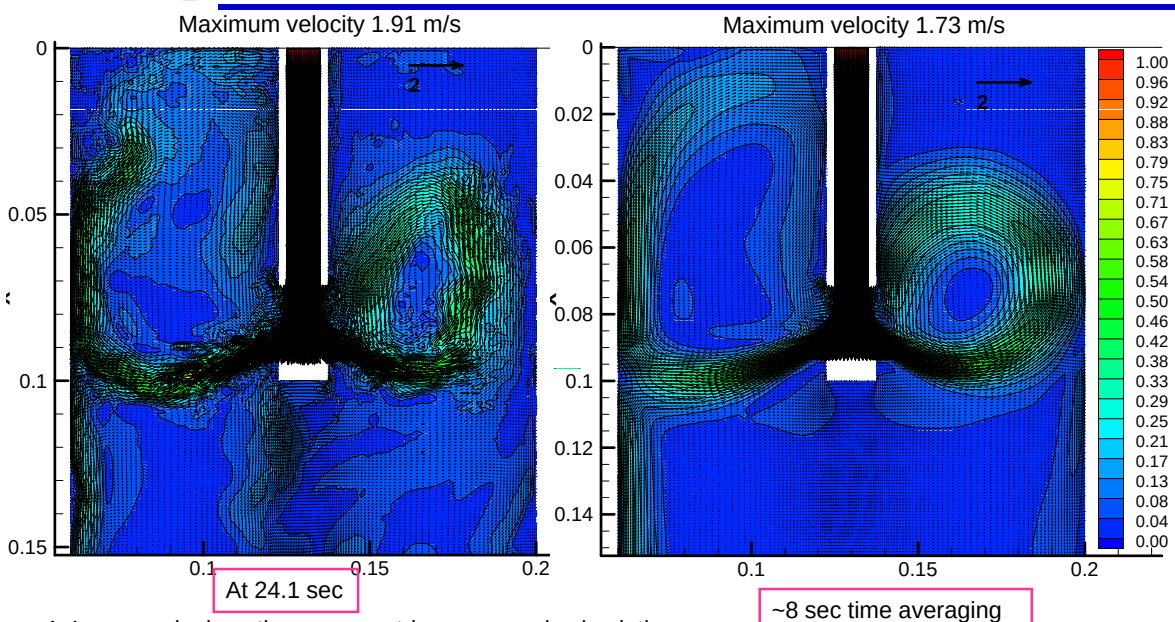
Constant Smagorinsky SGS model

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

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

1. Jet bends upward with single ruler EMBr.
2. EMBr generates large scale, non-isotropic velocity fluctuations.

Predicted instantaneous and time average velocity magnitude at mold mid-plane



1. Large scale, long time asymmetries are seen in simulations.
2. These findings are consistent with measurements.
3. Need more time averaging to confirm the asymmetry.

Conclusions and Future Work

- LES predictions of horizontal velocity from GPU code matched closely with LES (using FLUENT) and with the measurements.
- WALE SGS model gives better predictions and therefore is being used for future in GPU code.
- Measurements suggested large scale, anisotropic fluctuations caused by EMBr [1].
- This finding is reinforced by simulations and velocities in ~8 sec time average suggested right and left asymmetry in the mold.
- More time is required with LES (WALE model) to confirm this asymmetry.
- More configurations (such as double ruler, new SEN designs, and different locations of magnetic fields) are being considered for future work.

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[3] R. Chaudhary, C. Ji, and B. G. Thomas, Assessment of LES and RANS turbulence models with measurements in liquid metal GaInSn model of continuous casting process, CCC 2010 report, MechSE, UIUC.

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