Study of Transient Fluid Flow in Continuous Casting of Steel Using LES Models

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Objectives

- Develop realistic, efficient method for transient flow in continuous casting mold calculations
- Compare LES and K-ε in Fluent and in-house codes (LES3D and CART3D)
- Apply models to test problem (with measurements available, 0.4-scale LTV water model)
- Investigate effect of true nozzle inlet condition, side-to-side asymmetry and open bottom on transient flow in mold region
- Use best transient model to improve casting process (ultimate objective)

0.4-Scale LTV Water Model with PIV Measurement

Previous Work *(0.4-scale LTV water model)*

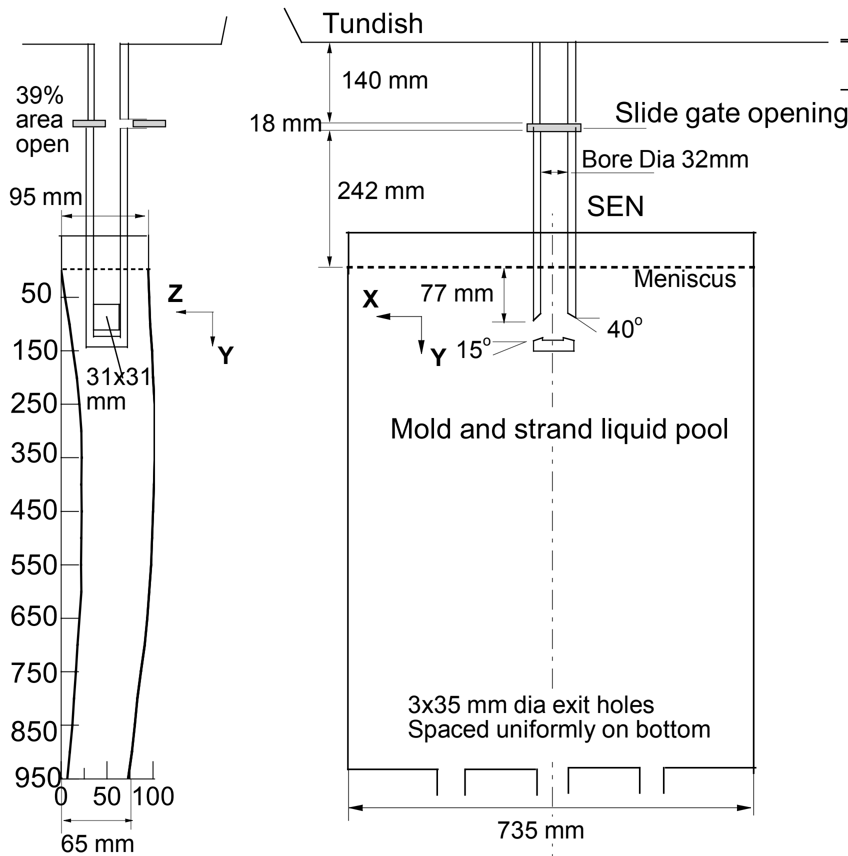
- Two-phase fluid flow in continuous casting nozzles using k-ε model (Hua Bai);
- Two-phase flow in molds using k-ε model (Tiebiao Shi)
- Simulation (using LES3D) of transient flow in 0.4 scale water model with inlet generated from

  -i) a fully developed duct using LES (Sivaraj Sivaramakrishman)

  -ii) a simplified nozzle simulation using LES (Q. Yuan)
- PIV measurements in nozzle and mold

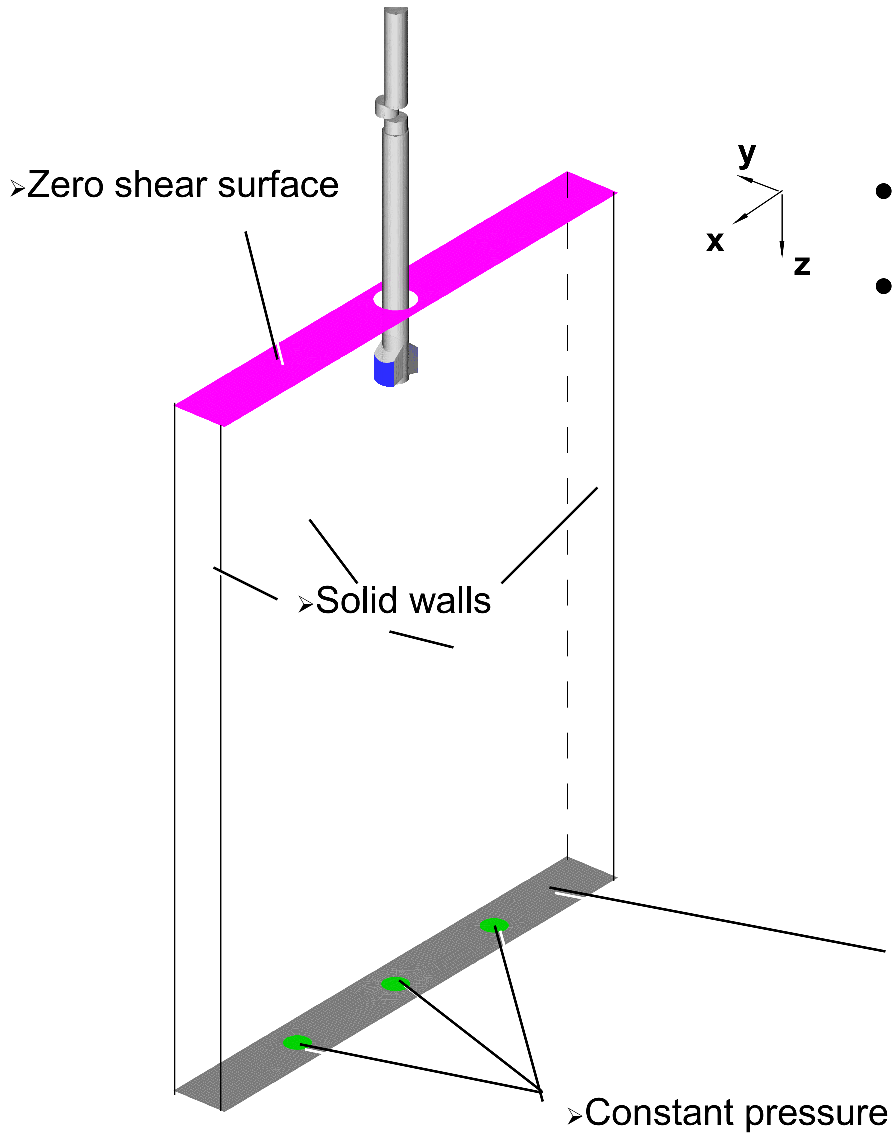
- no side-to-side asymmetry
- mold inlet condition not precise

Dimensions and Conditions(0.4-scale LTV water model)



Dimensions/Conditions	Value
Slide-gate orientation	90°
Slide-gate opening, linear fraction	52%
(Area Fraction)	(40%)
SEN bore diameter	32mm
SEN submergence depth	77 ± 3mm
Port Height × Width	32mm × 31mm
Port thickness	11mm
Port angle, lower edge	15° down
Port angle, upper edge	40° down
Bottom well recess depth	4.8mm
Water model height	950mm
Water model width	735mm
Water model thickness	80 mm ± 15 mm
Inlet volumetric flow rate through each port	3.53×10^{-4} m^3/s
Averaged inlet jet angle at port	30°
Liquid density	1.0×10^{3} kg/m^3
Liquid material dynamic viscosity	0.001 Pa-s
Gas injection	0%

Schematics of Computation Domain



- Nozzle simulation (Fluent: k-ε)
- Mold simulation

  - Fluent: k-ε and LES:

    half mold and both sides simulation with outlet holes at bottom

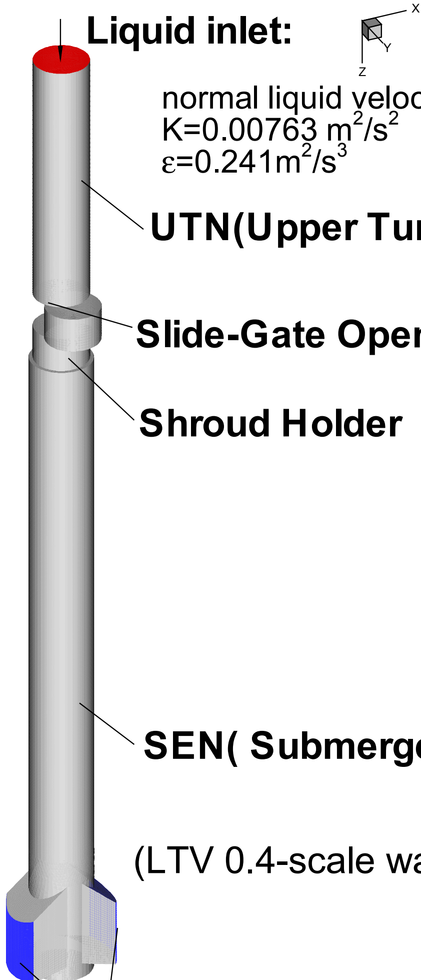
  - Fluent LES:

    both sides simulation with open bottom

➢Solid wall except outlet being three holes;

➢P=constant for open bottom simulation.

0.4-Scale LTV Nozzle Computation Domain



Liquid inlet:

normal liquid velocity=1.148m/s
$K=0.00763\ m^2/s^2$
$\varepsilon=0.241 m^2/s^3$

UTN(Upper Tundish Nozzle)

Slide-Gate Opening

Shroud Holder

SEN(Submerged Engry Nozzle)

(LTV 0.4-scale water model nozzle)

Nozzle ports

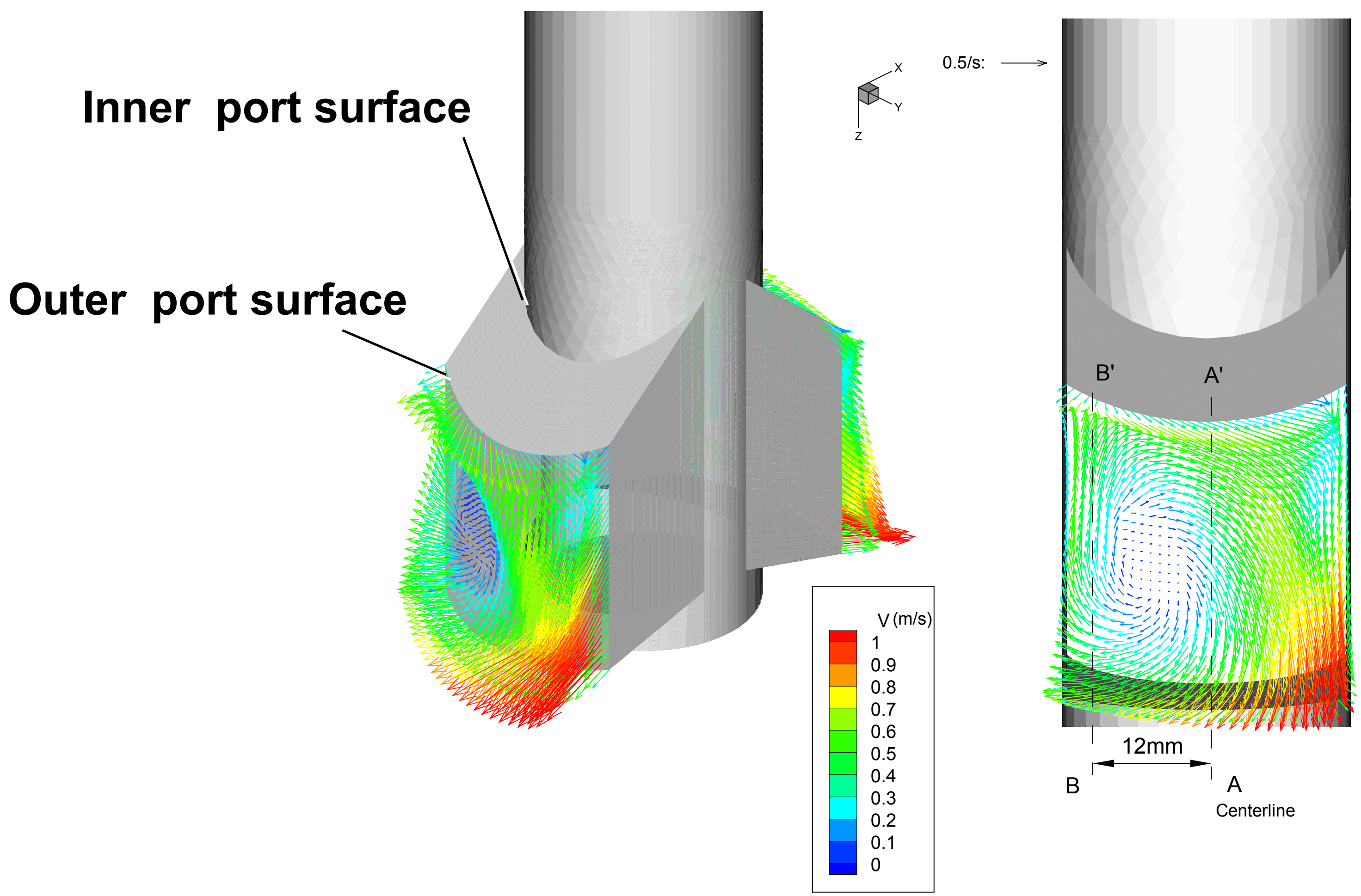
pressure = constant
zero normal gradient for velocities, K and ε.

Slide-gate orientation	90°
Slide-gate opening, linear fraction ofthe opening distance	52%
SEN bore diameter	32mm
Port Height $\times$ Width	32mm $\times$ 31mm
Port thickness	11mm
Port angle, lower edge	15° down
Port angle, upper edge	40° down
Bottom well recess depth	4.8mm
Inlet volumetric flow rate through each port	$7.09\times10^{-4}\ m^3/s$
Casting speed (top thickness)	10.2mm/s (0.611m/min)
Liquid density	1000 kg/m^3
Liquid material dynamic viscosity	0.001 Pa-s
Gas injection	0%

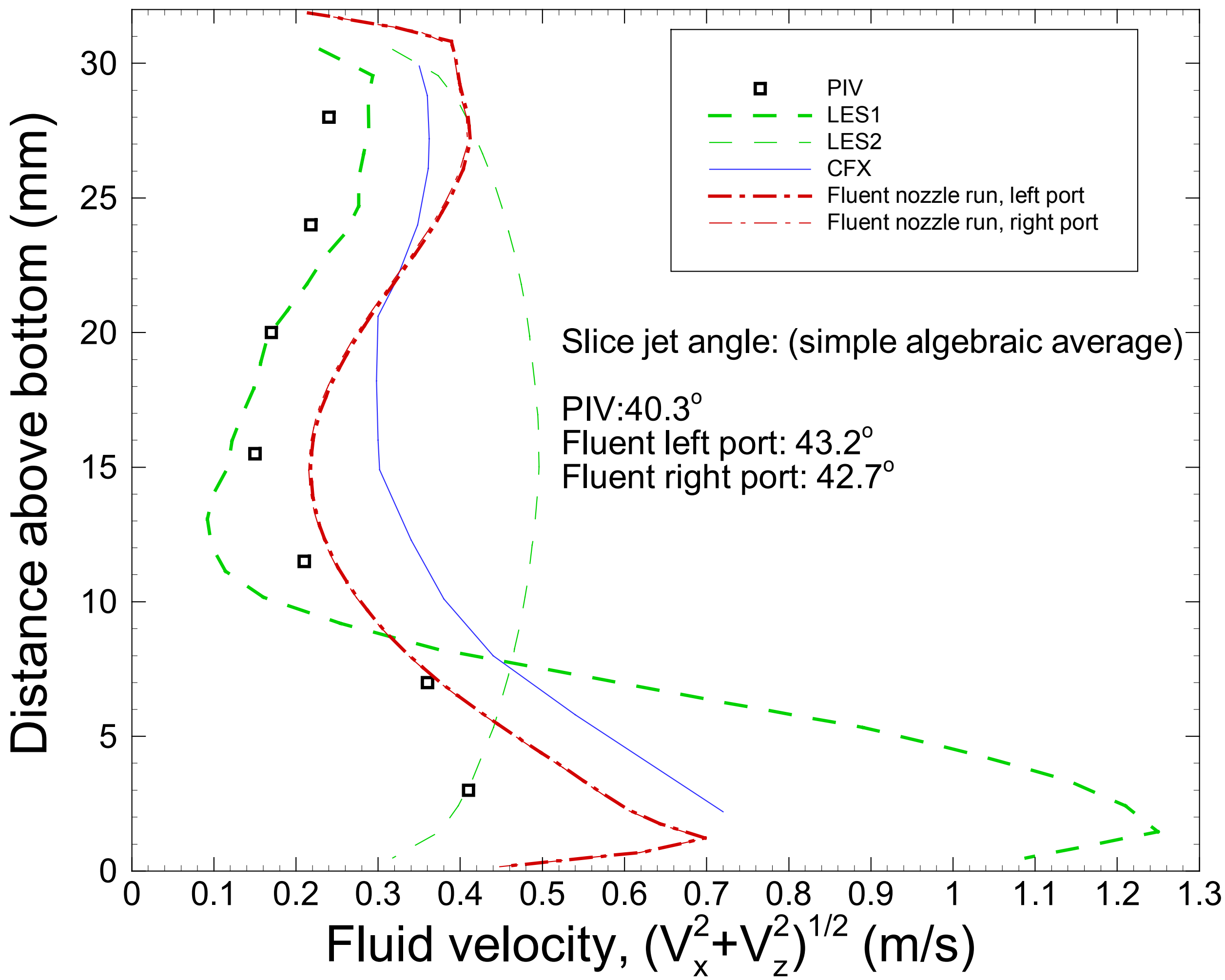
Nozzle Simulation

- 3D steady time-averaged Navior-Stokes equations (186,519 cells)
- Standard K-ε turbulent viscosity model
- Fluent 5.5.14 (Finite Volume Method)
- Integrated using iterative solver (Algebraic Multi-Grid Method) for 4500 iterations (36 CPU hours on PIII 750MHz PC)
- Second order accuracy
- Residual $\leq 1.6 \times 10^{-6}$ (continuity)
- Converging strategy: under-relaxation factors are 0.2 (pressure), 0.4 (momentum) and 0.2(K and ε).

Velocity Field at Nozzle Port Outer Surface

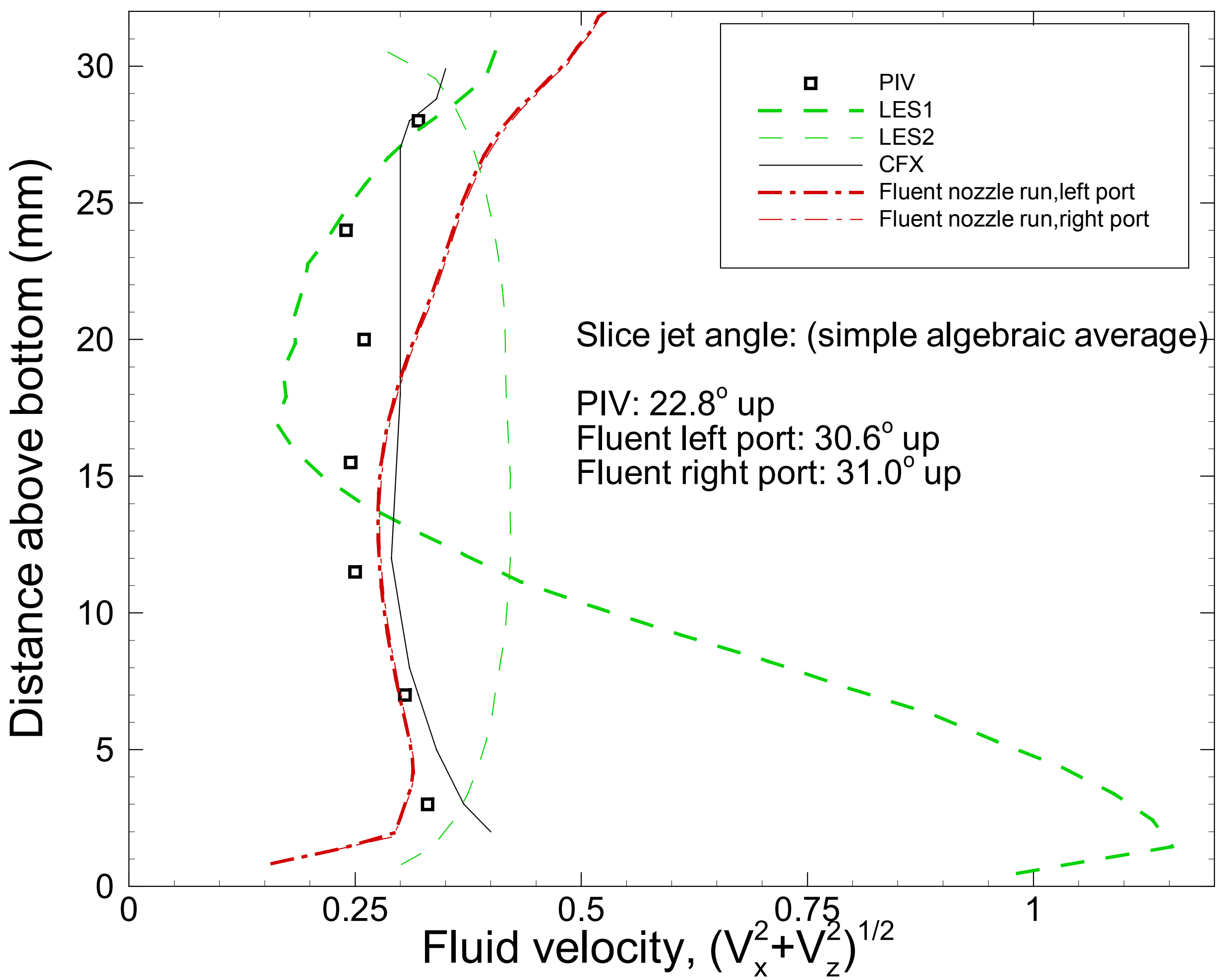


Comparison with PIV (along center line A-A', outer surface)



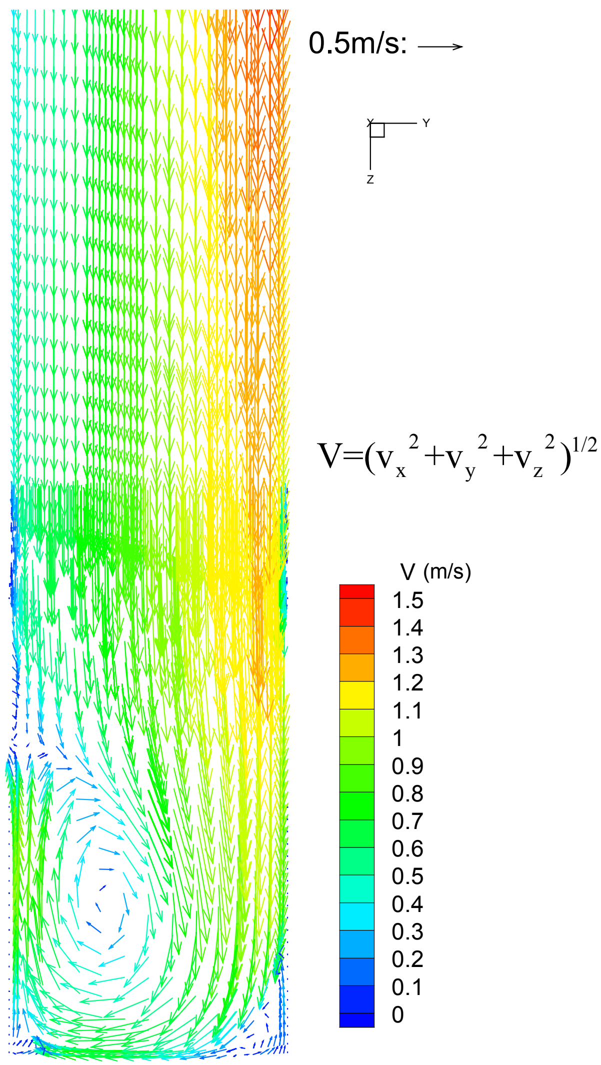
CFX: H Bai, "Argon Bubble Behavior in Slide-Gate Tundish Nozzles during Continuous Casting of Steel Slabs", Ph.D. Thesis, 2001, Univ. of Illinois at Urbana-Champaign.

Comparison with PIV (along B-B', 12mm from A-A', low velocity side)

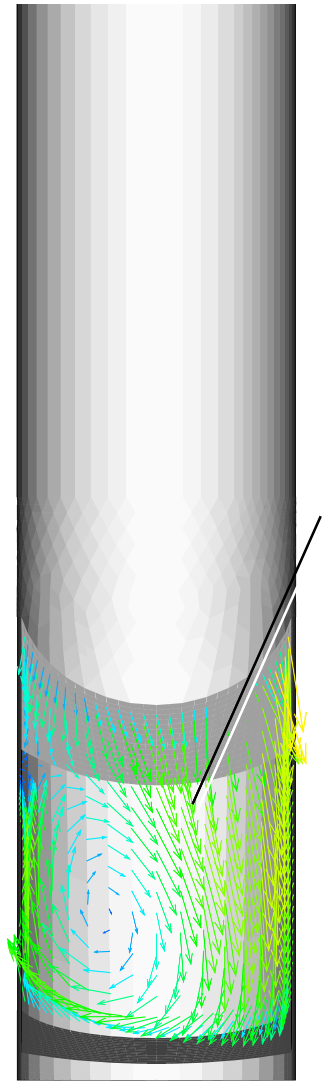


CFX: H Bai, "Argon Bubble Behavior in Slide-Gate Tundish Nozzles during Continuous Casting of Steel Slabs", Ph.D. Thesis, 2001, Univ. of Illinois at Urbana-Champaign.

Velocity Fields Viewing into Nozzle Port



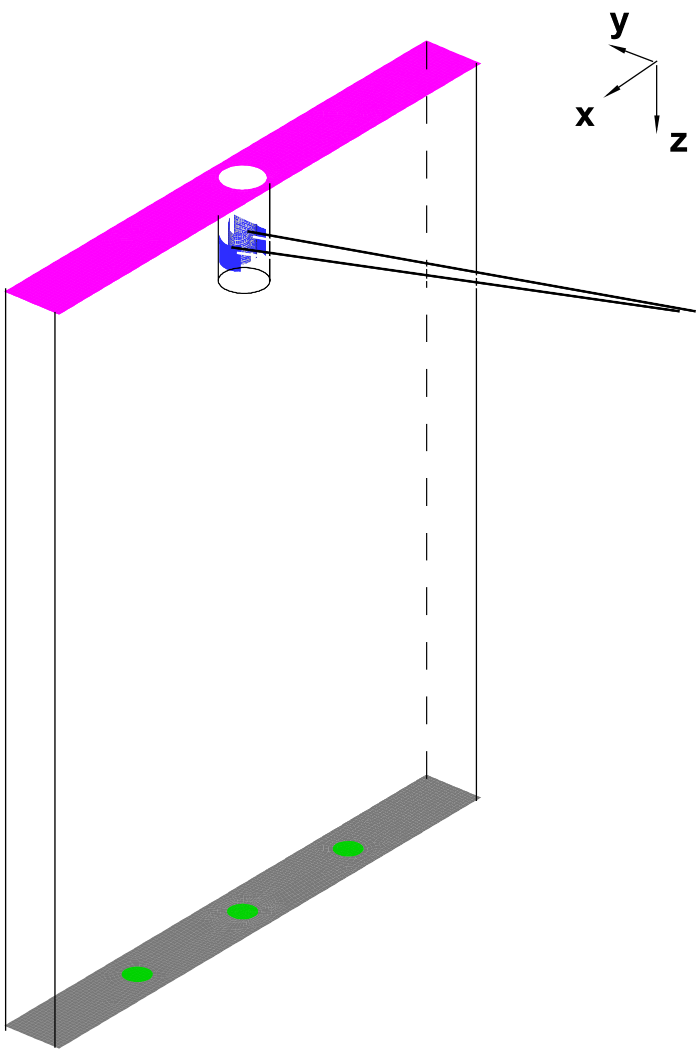
Ceneter plane



Inner port surface

- Cross-stream Velocity field at the nozzle port inner bore surface
- Velocity field here were inputted as the inlet velocities for mold simulation.

Schematics of Mold Flow Geometry



Velocity at the nozzle port (inner surface) obtained from nozzle simulation employed as mold simulation inlet condition.

Mold Flow Simulations

- 3D transient Large Eddy Simulation (LES) with Smagorinsky model and standard steady K-ε model
- Both full mold (450,084 computation cells) and half mold (225,042 computation cells) domain
- 50 hours per flow second on a PIII 750MHz PC with 0.01s time step (full mold simulation)
- Fluent 5.5.14 for K-ε and transient LES
- Residuals: $\leq 5\times10^{-4}$ (continuity,K- ε)

  $\leq 10^{-3}\times$ inlet mass flow rate (continuity, LES)
- Converging Strategy: under-relaxation factors are:

  pressure: 0.7(K- ε) and 0.3 (LES)

  momentum: 0.2 (K- ε) and 0.7 (LES)

  K and ε: 0.8

Governing Equations:

Continuity: $$\frac{\partial \mathrm{v}_i}{\partial x_i} = 0$$

Momentum: $$\frac{D\mathrm{v}_i}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\nu_{eff}\left(\frac{\partial \mathrm{v}_i}{\partial x_j} + \frac{\partial \mathrm{v}_j}{\partial x_i}\right)$$

where

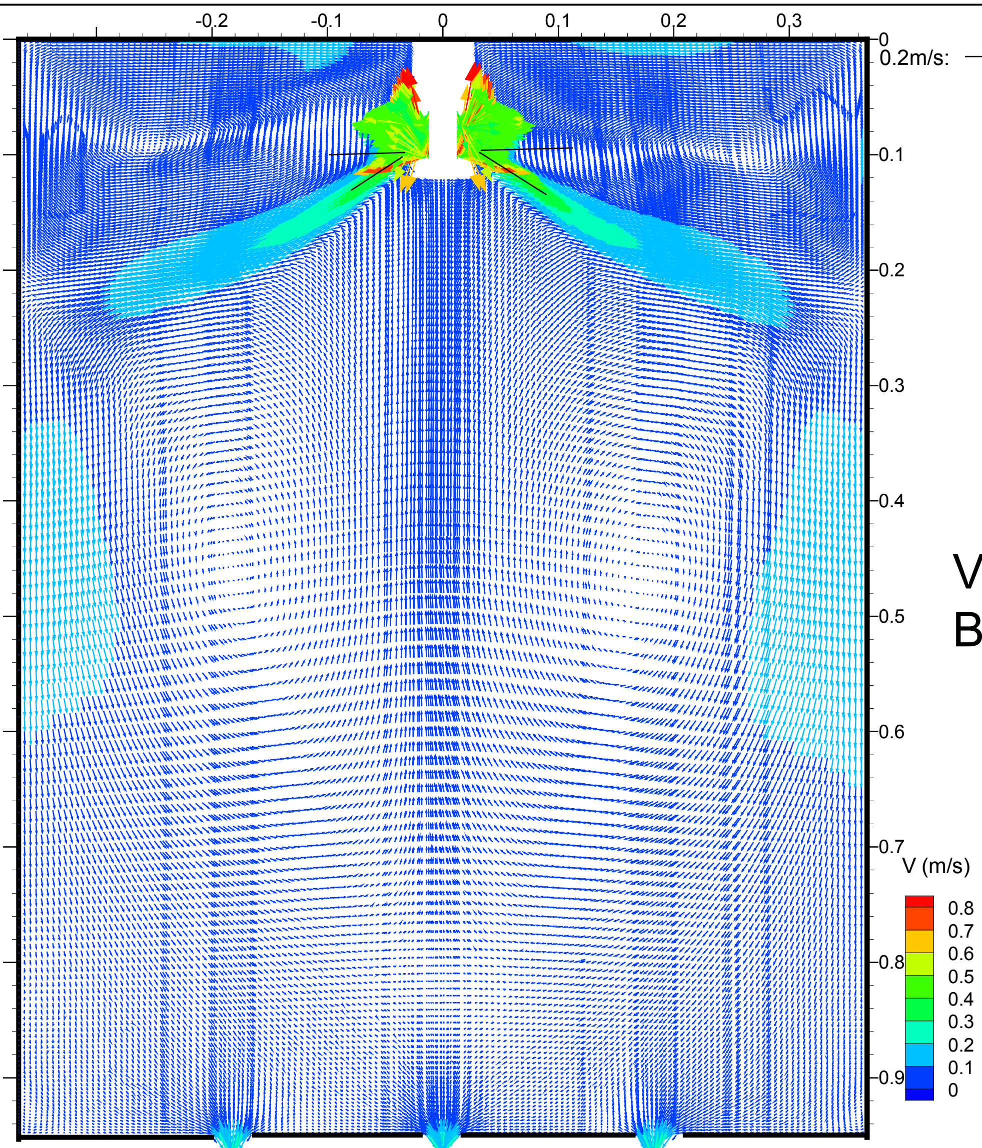
$$\nu_{eff} = \nu_0 + 0.01(\Delta x \Delta y \Delta z)^{2/3}\sqrt{\frac{\partial \mathrm{v}_i}{\partial x_j}\frac{\partial \mathrm{v}_i}{\partial x_j} + \frac{\partial \mathrm{v}_i}{\partial x_j}\frac{\partial \mathrm{v}_j}{\partial x_i}}$$ for LES

$$\nu_{eff} = \frac{\mu_{eff}}{\rho} = \frac{\mu_0 + \mu_t}{\rho} = \frac{\mu_0}{\rho} + C_\mu \frac{K}{\varepsilon}$$ for K- ε

tensor subscripts i and j mean x, y and z directions; repeated induces imply summation.

Fluent K- ε Comparison with PIV (both sides 0.4-scale water r

Impinging point:
PIV(0.20m)
Simulation(0.22m)



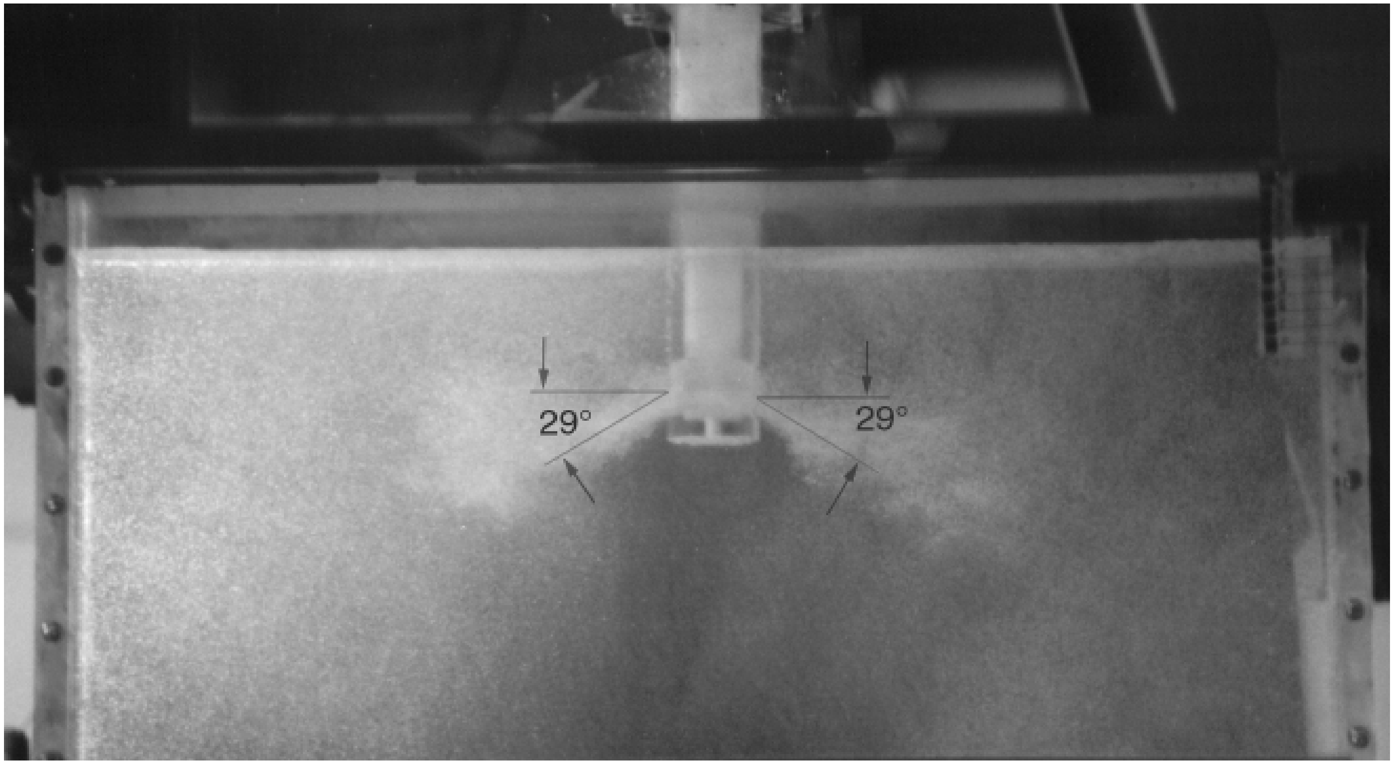
Jet angle

PIV: 29º

Simulation: 28º

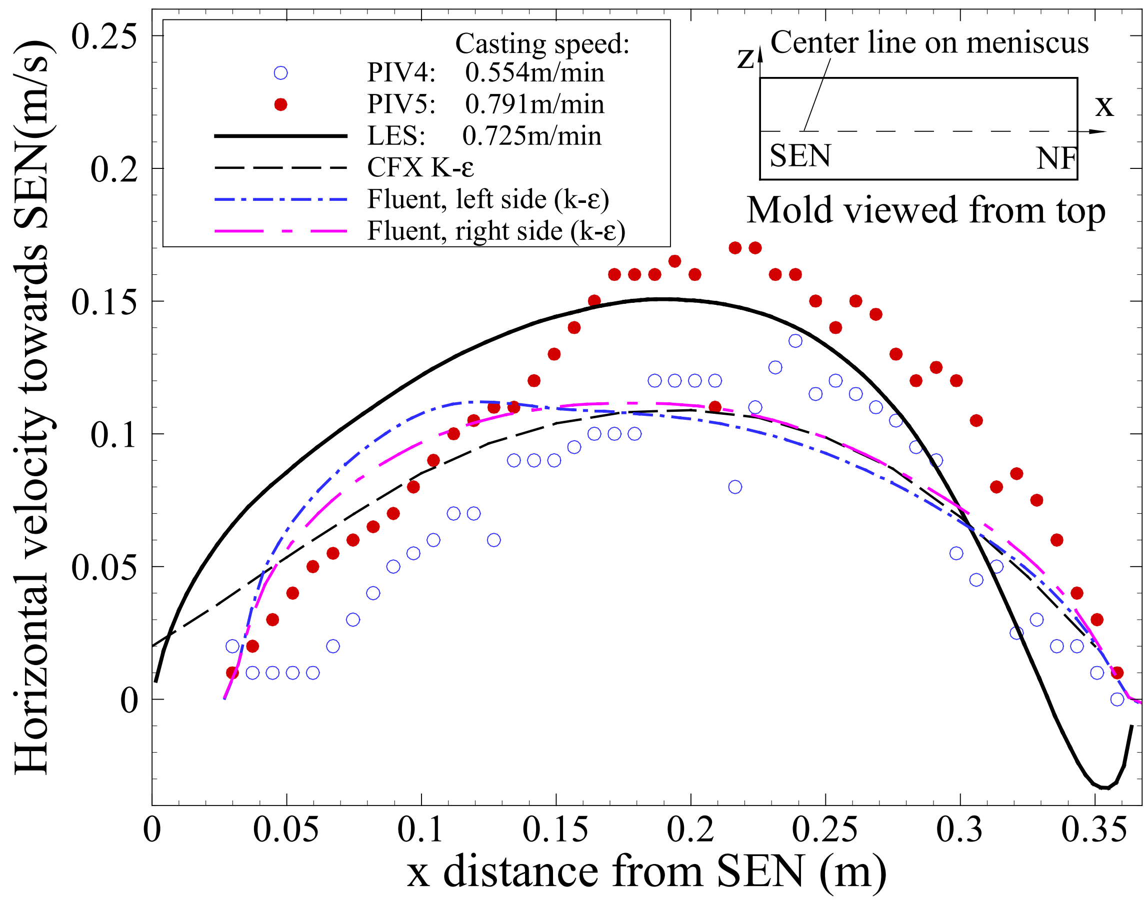
Velocity at centerplane
Between wide faces

Comparison with Experiment



*S. Sivaramakrishnan, "Transient Fluid Flow in the Mold and Heat Transfer Through the Molten Slag layer in Continuous Casting Steel", M.S. Thesis, 2000, Univ. of Illinois at Urbana-Champaign.

Comparison of Top Surface Velocity with PIV

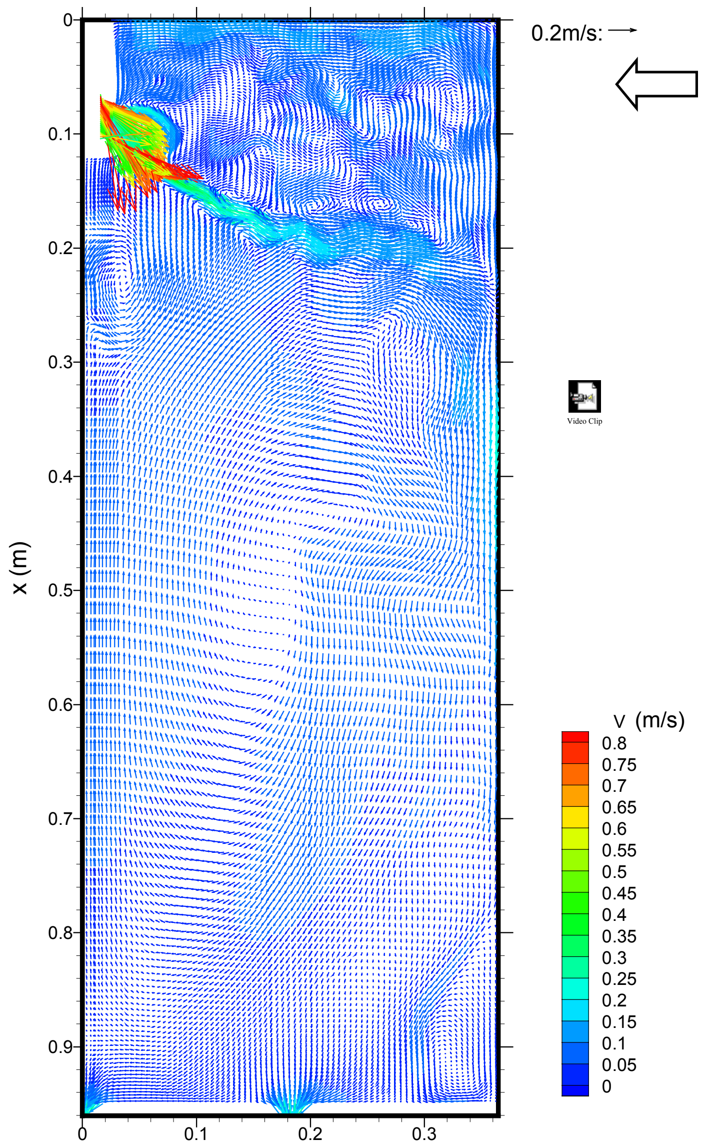


Horizontal velocity along top surface centerline.

Findings:

- K- ε model generates symmetrical flow pattern in mold region
- K- ε model is capable of capturing time-averaged flow field
- Transient K- ε model was not able to capture turbulent transient flow evolution in mold region, likely due to large dissipation.

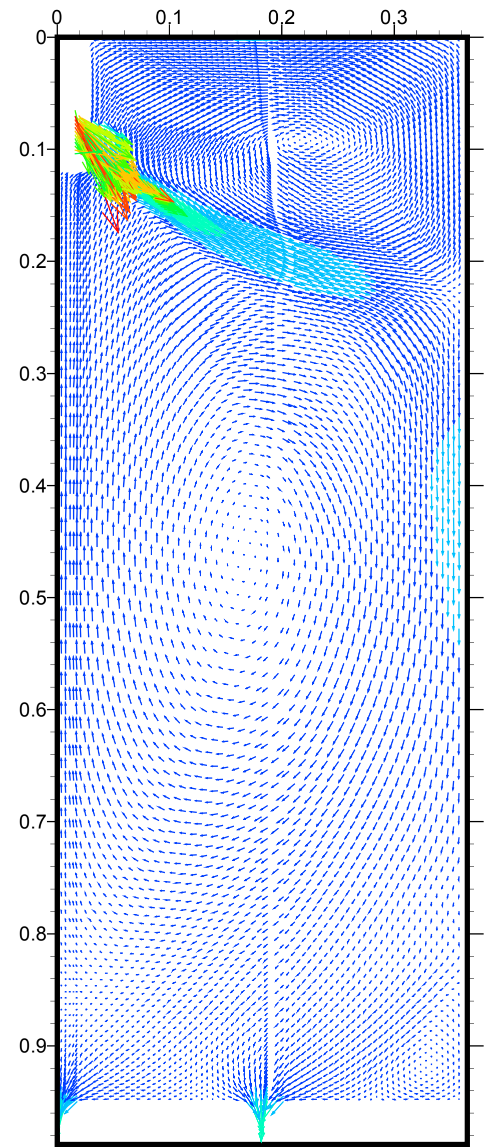
Fluent LES and K- ε (half mold simulation, centerplane)



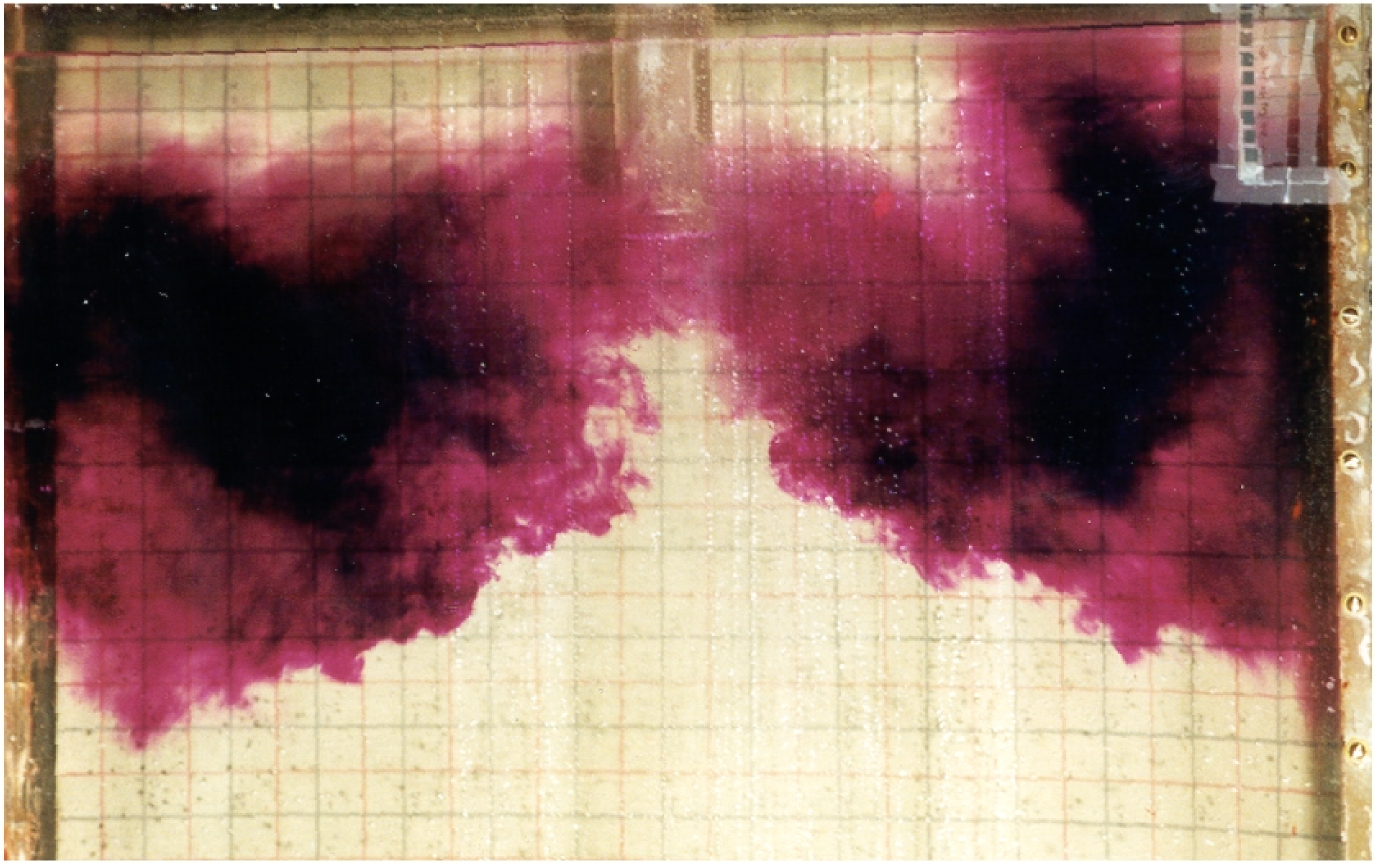
LES:

Staircase jet pattern observed

K- ε

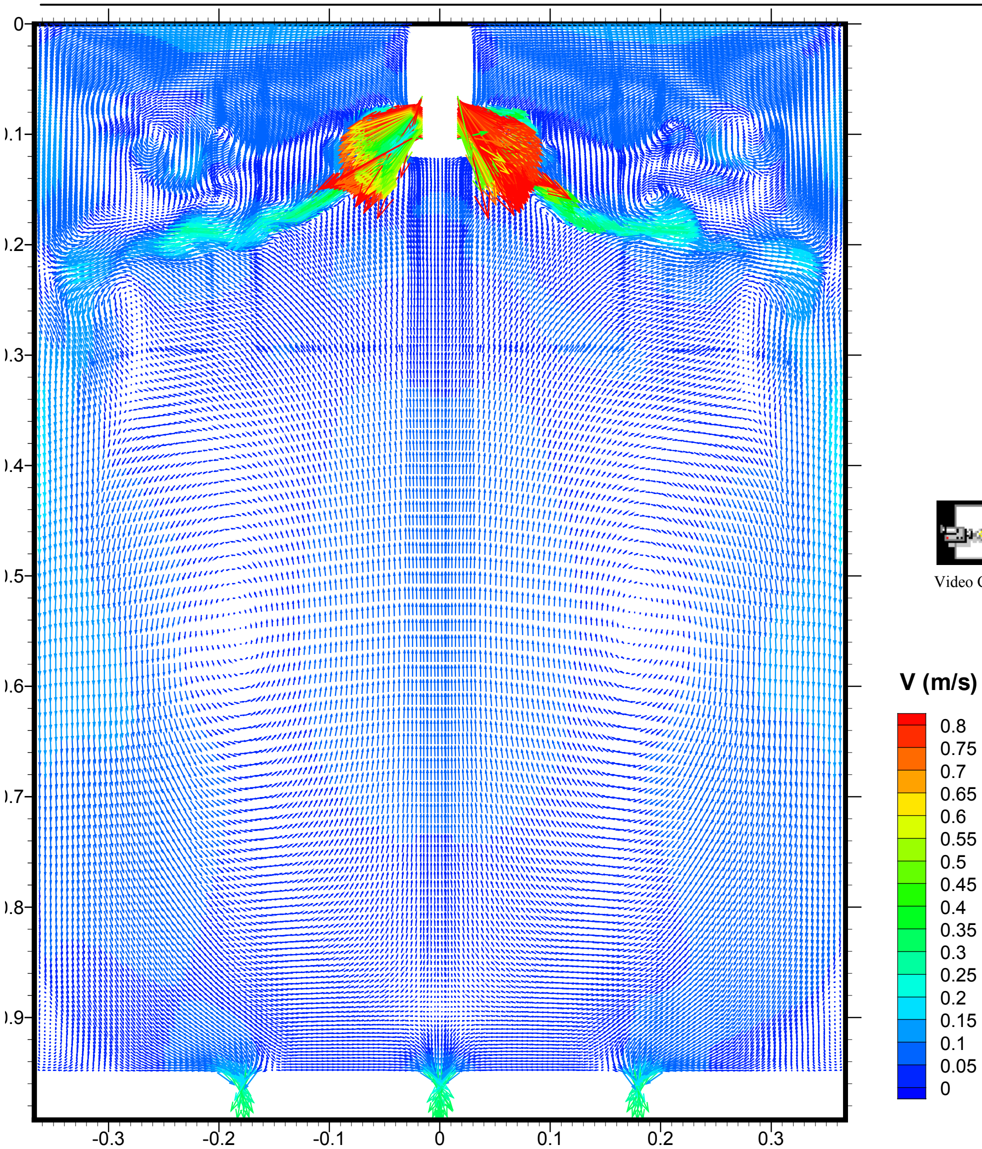


Flow Asymmetry Observed in Experiment



*S. Sivaramakrishnan, “Transient Fluid Flow in the Mold and Heat Transfer Through the Molten Slag layer in Continuous Casting Steel”, M.S. Thesis, 2000, Univ. of Illinois at Urbana-Champaign.

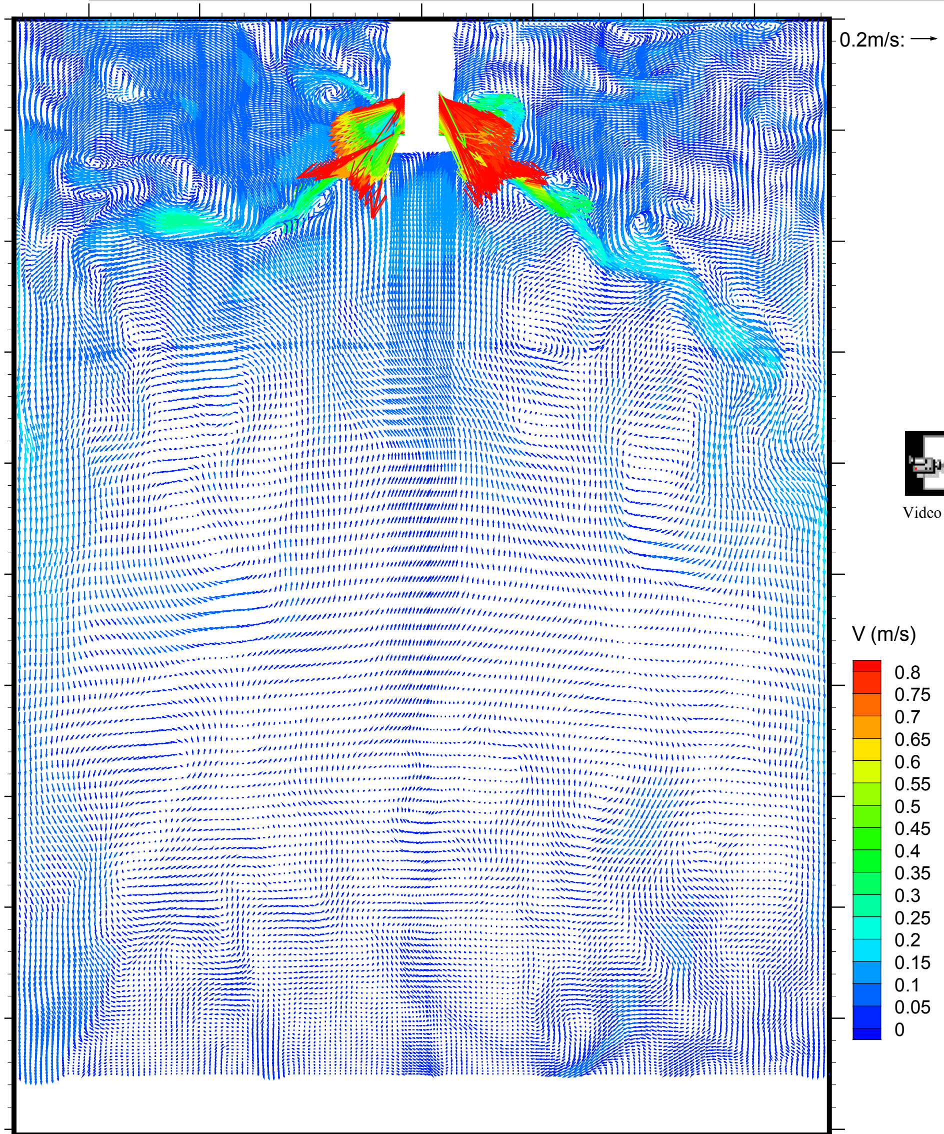
Fluent-LES (both sides simulation with outlet holes)



Video Clip

Typical instantaneous flow pattern

Fluent-LES (both sides simulation with open bottom)

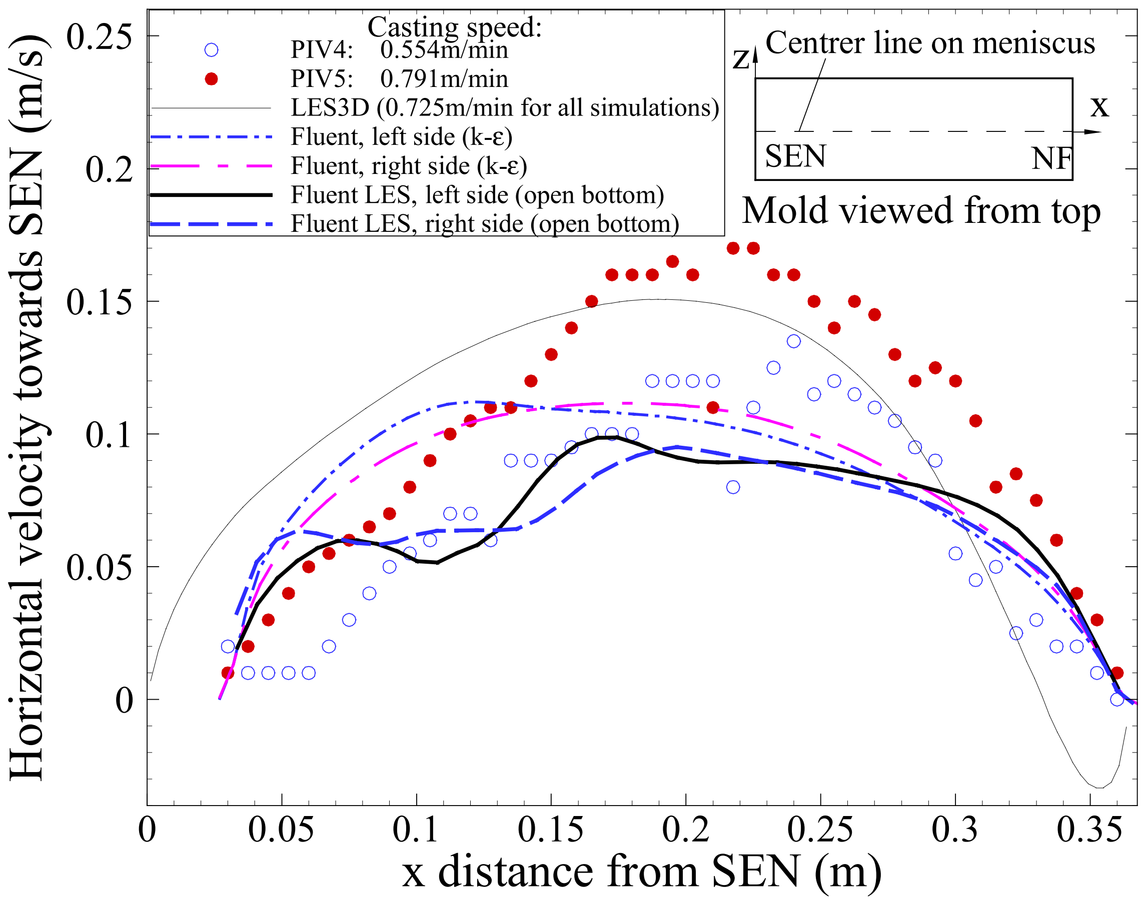


Video Clip

Observations:

Obvious asymmetry between two sides were observed.

Comparison of Fluent LES, K- ε, PIV and LES3D



Time-Averaging Duration

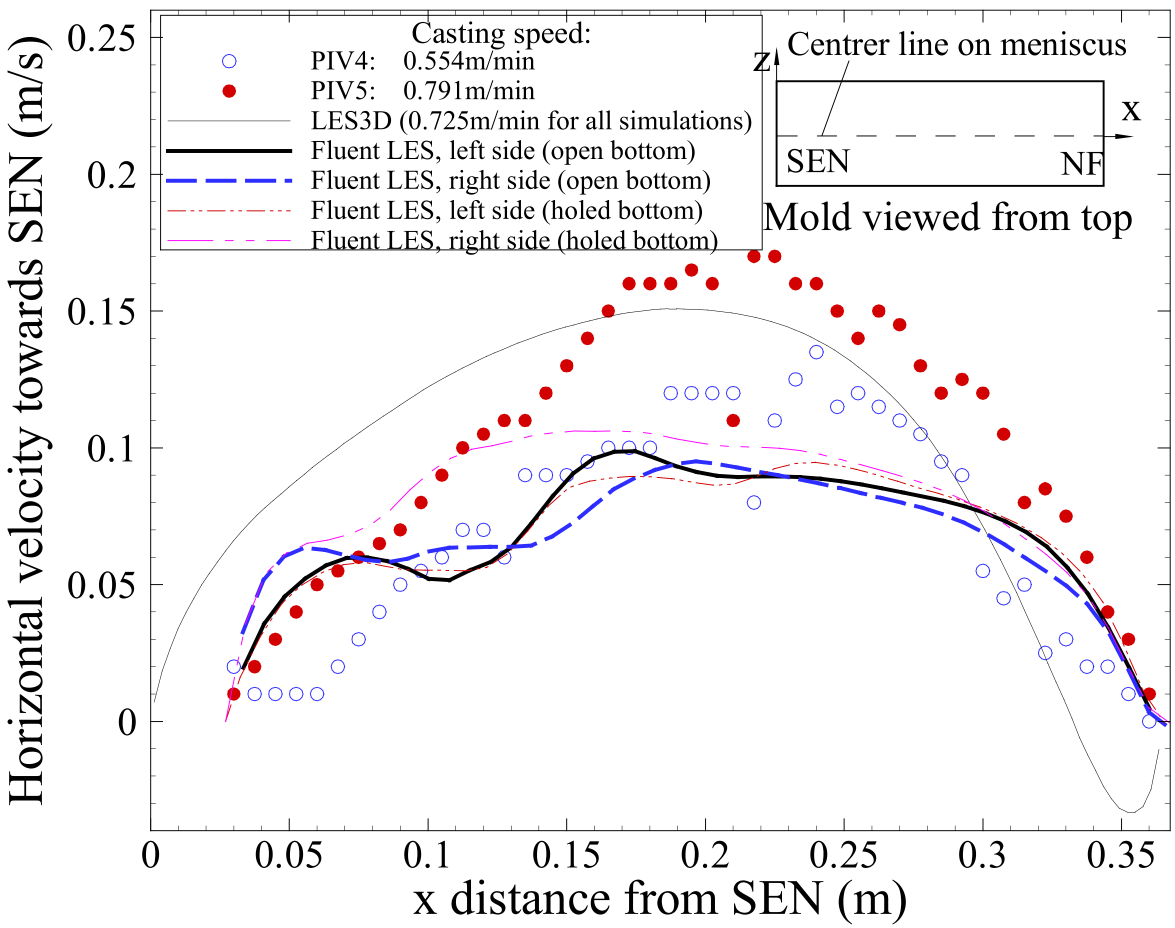
LES3D: 45 s

Fluent LES (open bottom) 8.6s

PIV: ~ 30 min over a set of measurement

Horizontal velocity along top surface centerline.

Open Bottom Effects On Top Surface Velocity



Time-Averaging Duration

LES3D: 45 s

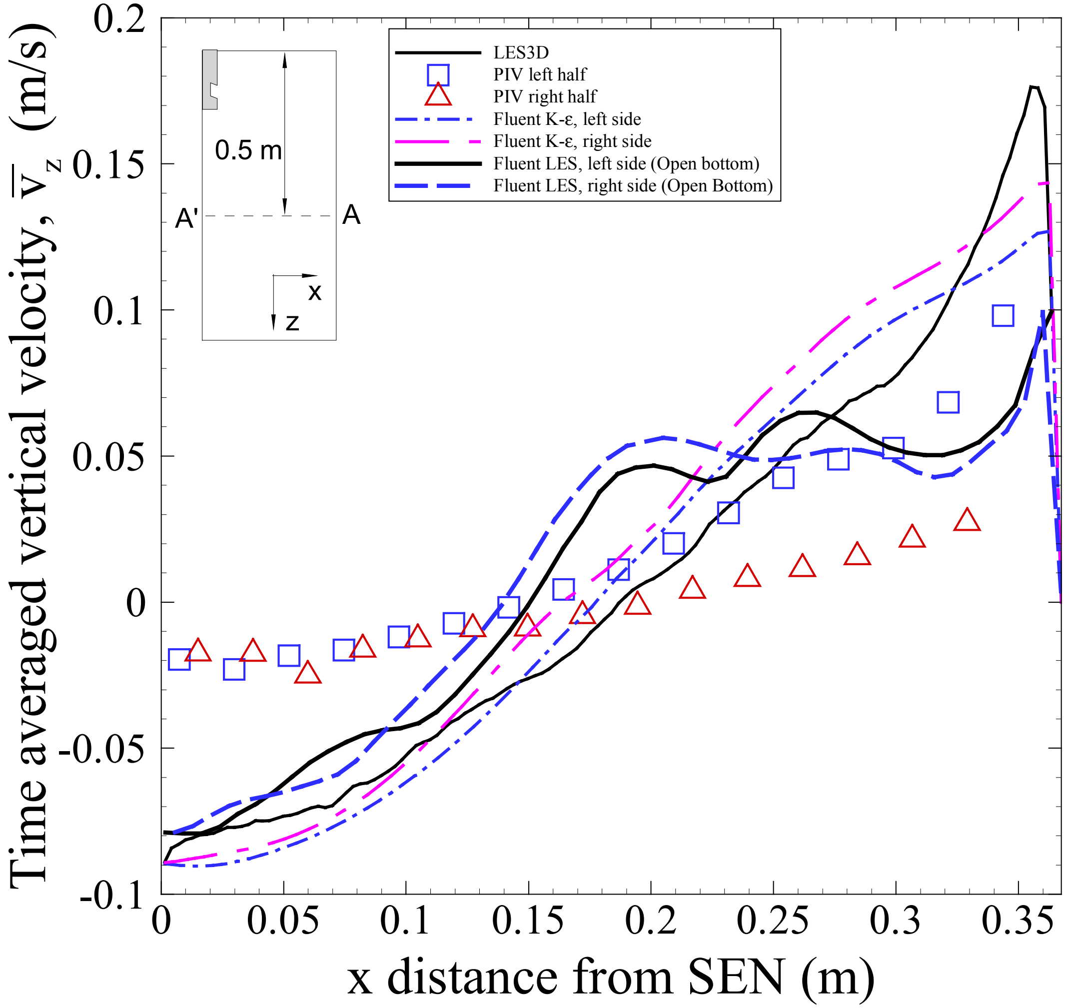
Fluent LES (open bottom) 8.6s

Fluent LES (holed outlets) 10.3s

PIV: ~ 30 min over a set of measurement

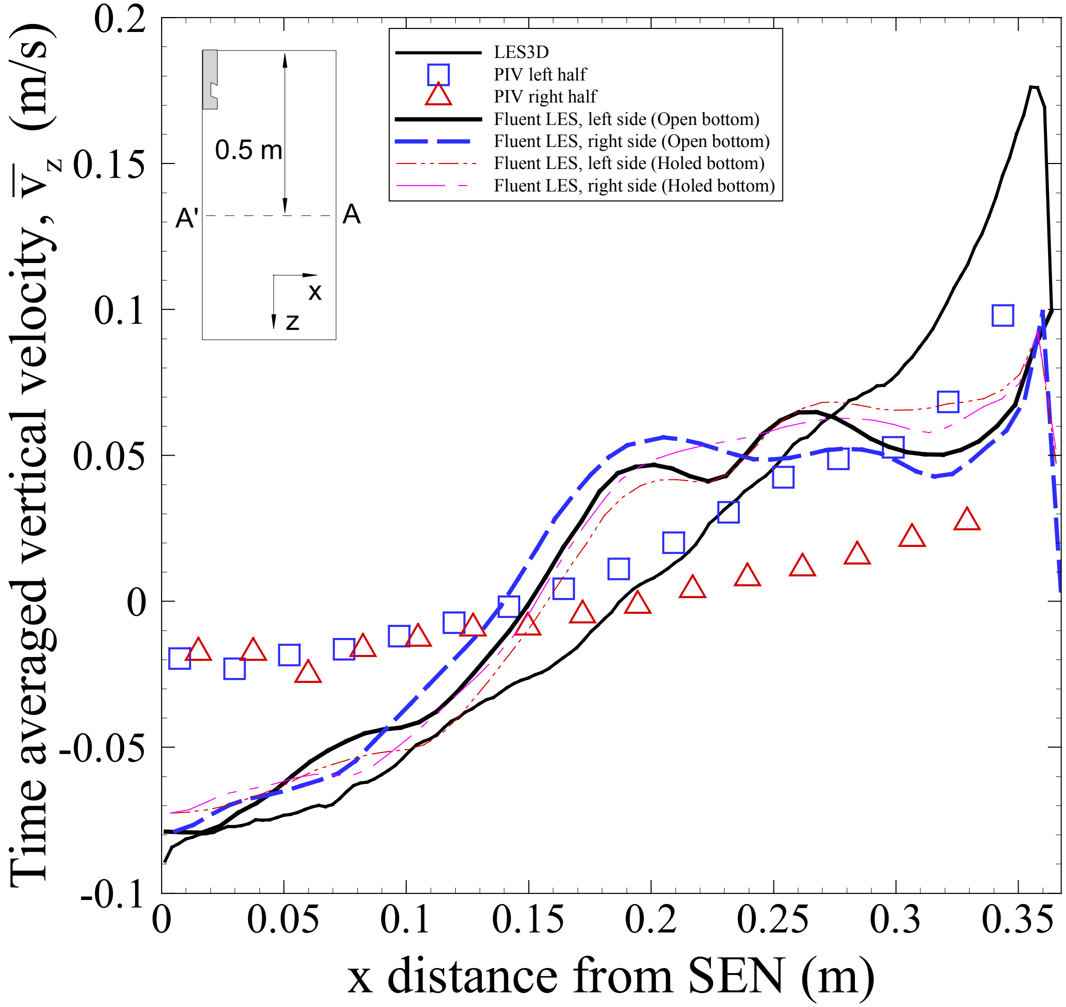
Horizontal velocity along top surface centerline.

Comparison of Fluent LES, K- ε, PIV and LES3D



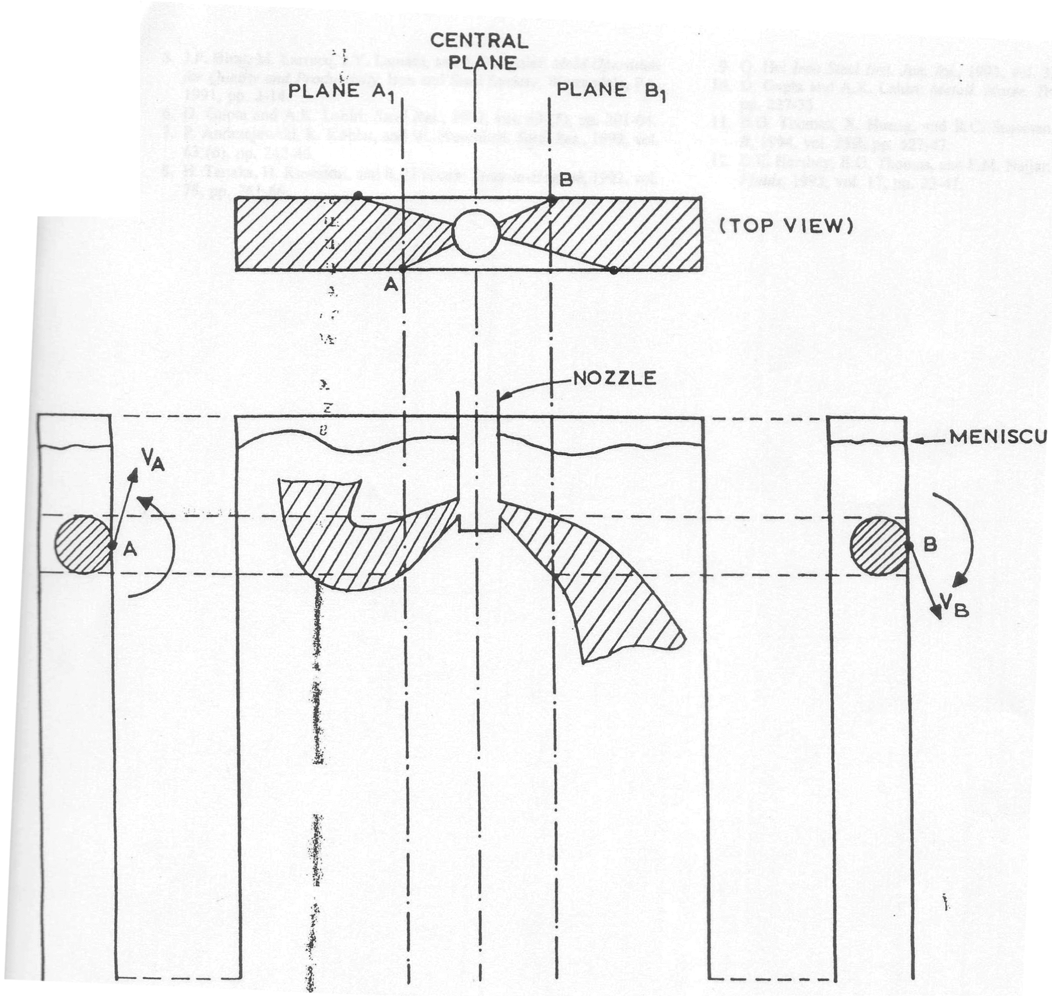
Vertical velocity along horizontal line 0.5 m below top surface at centerplane.

Open Bottom Effects On Middle Region



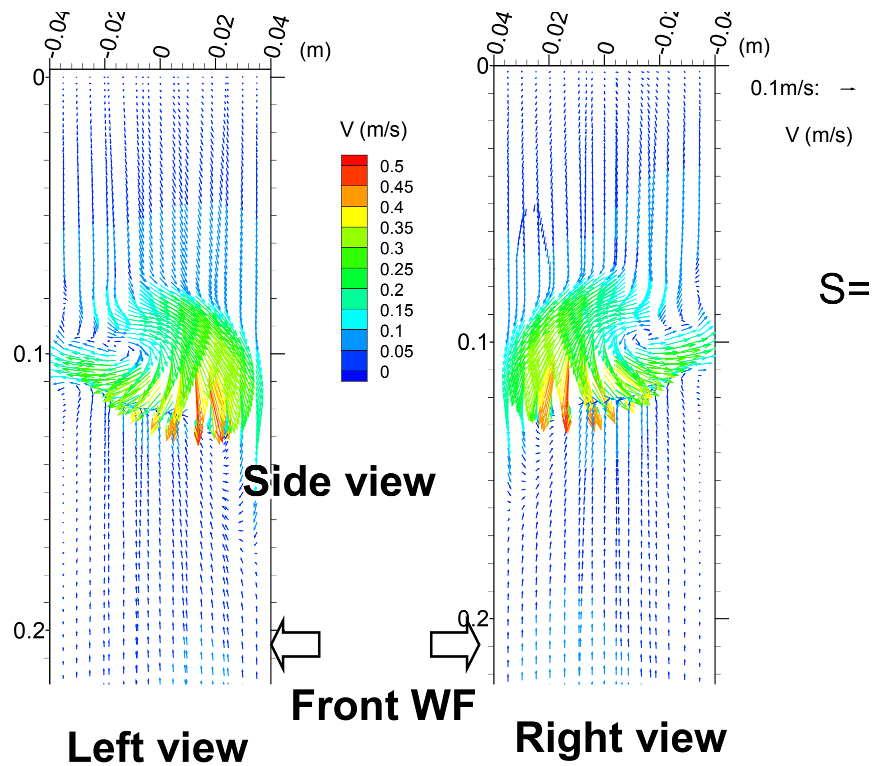
Vertical velocity along horizontal line 0.5 m below top surface at centerplane.

Where Does Jet First Impinges Wide Face?

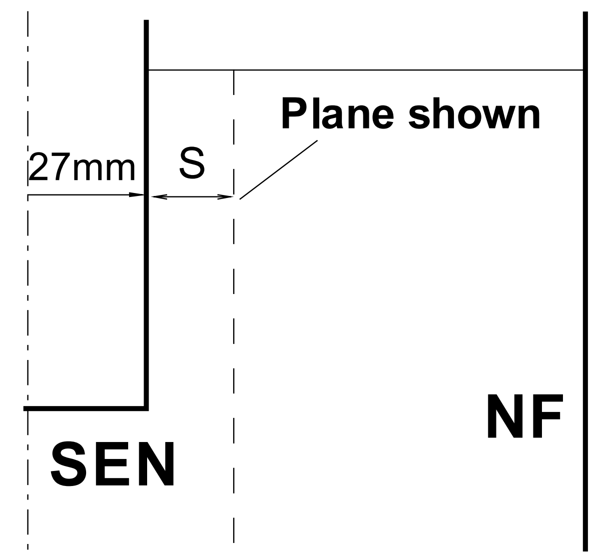


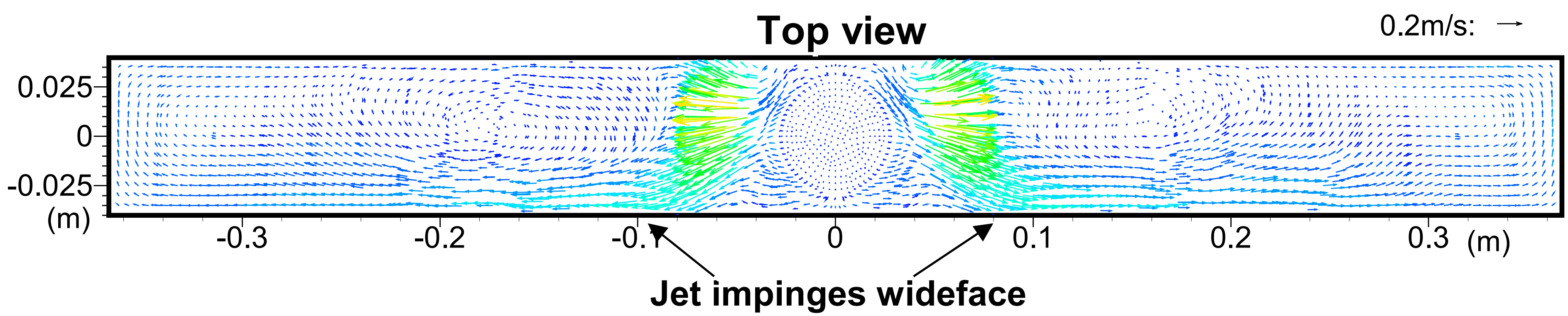
From: “A Water Model Study of the Flow Asymmetry Inside a Continuous Slab Casting Mold”, D. Gupta And A. K. Lahiri, Metallurgical and Materials Transactions B, Vol. 27B, Oct 1996, pp. 757-764.

Simulated Jet Impinging Wide Faces

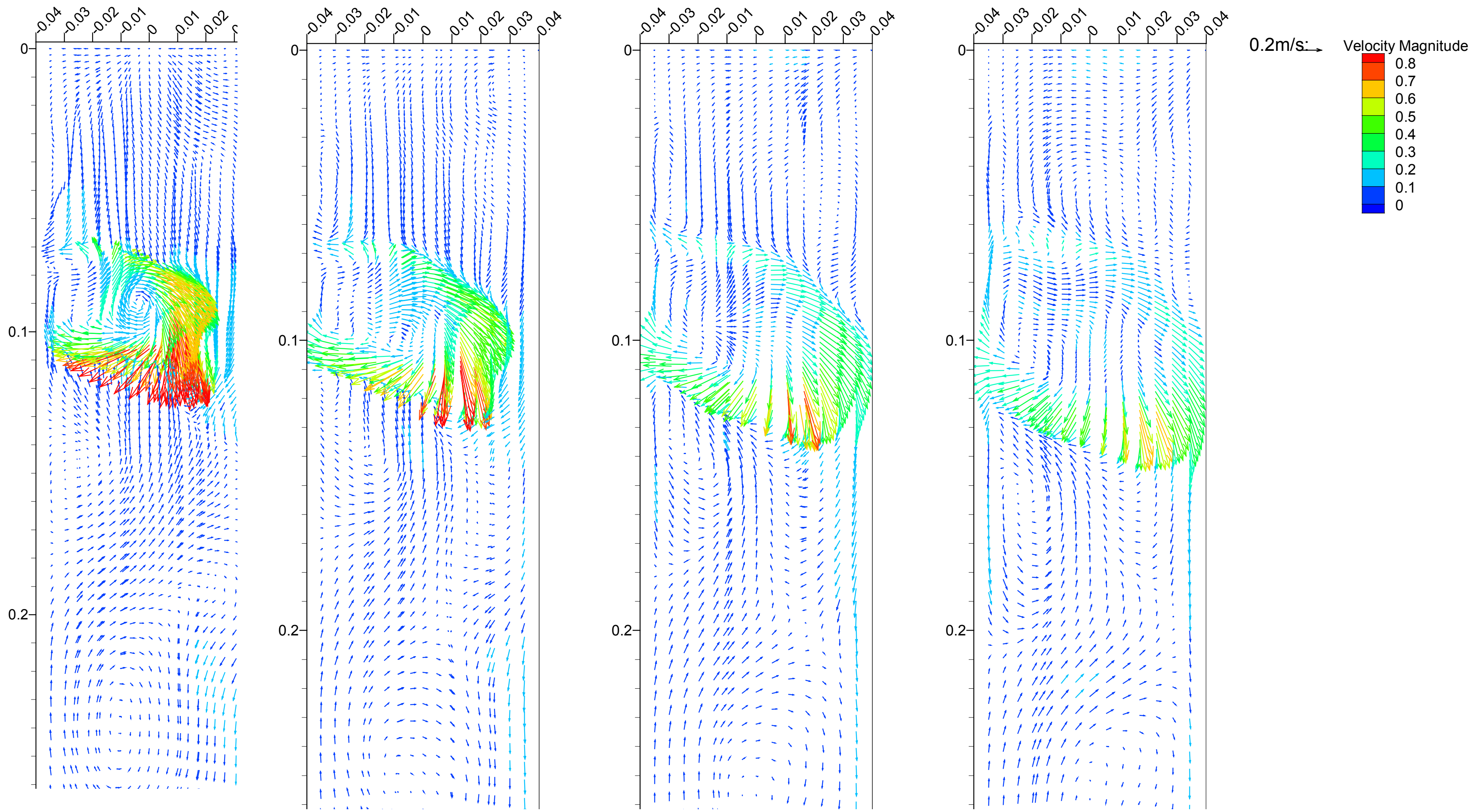


S=13mm





Simulated Typical Motion of Swirl Along Jet: (LES)



S=3mm S=13mm S=23mm S=33mm

Conclusions

- LES simulation is capable of capturing jet asymmetry associated with the nature of the turbulent flow in mold region
- LES results reasonable agree with PIV
- k-ε Model is capable of accurately capturing time-averaged flow field
- Transient k-ε was not able to capture transient flow evolution in caster mold region
- Experiment found asymmetry exists in transient flow exiting nozzle, likely due to turbulence nature of nozzle flow, or asymmetry of nozzle geometry, which was not captured by traditional K- ε by nature.

Future Work

- Large Eddy Simulation of Transient Flow in Full Scale Steel Caster Nozzle and Mold Region (Open Bottom)
- Transient Inclusion Transport in Steel Caster Mold Region