Transient Fluid Flow and Inclusion Motion in the Mold Using LES Models

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Objectives

Compare / Validate

- **Mathematical models and experiments**

Investigate

- **Transient flow structures**
- **Influence of inflow on flow**
- **Particle transport and removal**

in mold region

Flow Investigation Models

- Steady K-ε computational models (CFX)

    - nozzle (H. Bai)

    - mold (T. Shi)

- DNS (Direct Numerical Simulations, S. Sivaramakrishnan)
- LES (Large Eddy Simulations, present work)
- PIV (Particle Image Velocimetry) water models

Governing Equations – LES Flow Model

- Fluid flow

$$\frac{\partial \mathrm{v}_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{D\mathrm{v}_i}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\nu_{eff}\left(\frac{\partial \mathrm{v}_i}{\partial x_j} + \frac{\partial \mathrm{v}_j}{\partial x_i}\right) \qquad (2)$$

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

(Smagorinsky sub-grid viscosity model)

- Particle transport

$$\mathrm{v}_{p,i} = \frac{dx_{p,i}}{dt} \qquad (4)$$

$$\frac{d\mathrm{v}_{p,i}}{dt} = \frac{18\rho\nu_0}{\rho_p d_p^{\,2}}\left(1+0.15\mathrm{Re}^{0.687}\right)\left(\mathrm{v}_i - \mathrm{v}_{p,i}\right) + (1-\frac{\rho}{\rho_p})\vec{g} \qquad (5)$$

$$\mathrm{Re} = \frac{\left|\mathrm{v}_{p,i} - \mathrm{v}_i\right| d_p}{\nu_0} \qquad (6)$$

Subscript: i – x, y, z directions

p – particle

none - fluid

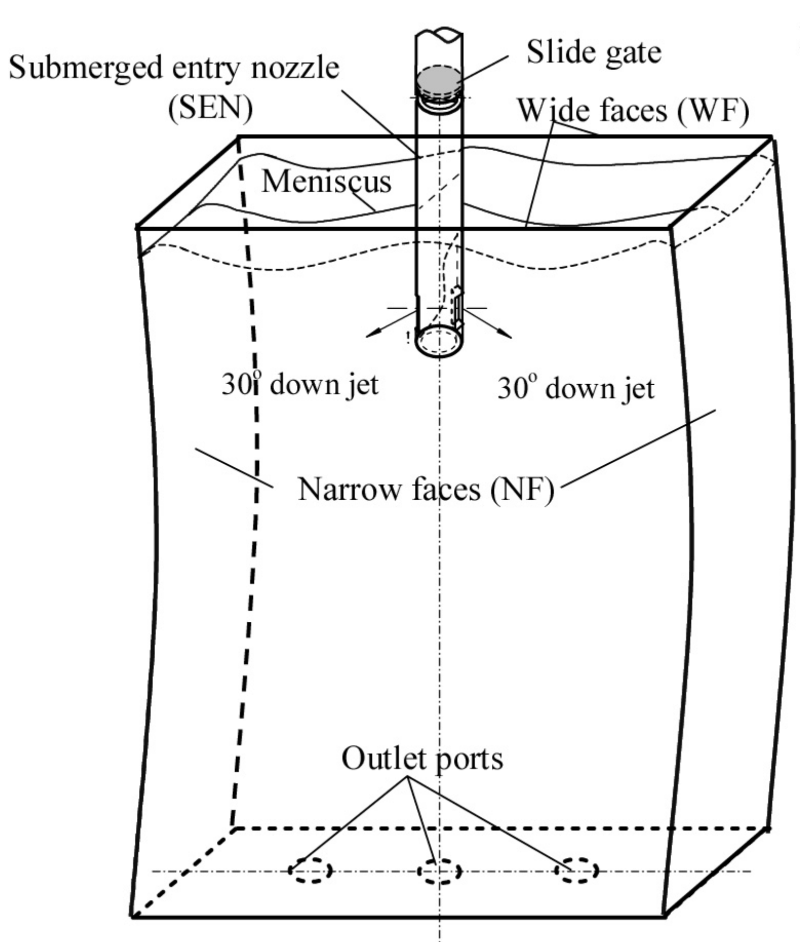
Computational Details

- Three dimensional unsteady Navier-Stokes Equation
- Second order accuracy in time and space for fluid flow
- Fourth order Runge-Kutta method used for particle transport
- Smagorinsky sub-grid viscosity model
- Computation mesh consists of 1.4 and 1.5 million nodes

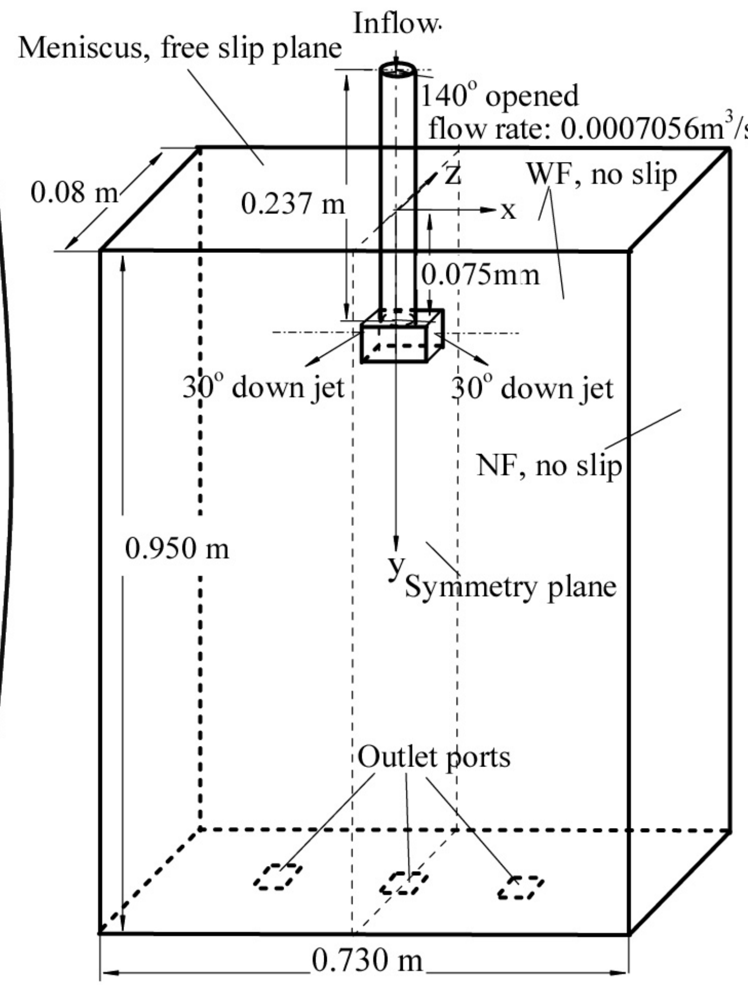
  (128x169x64 and 128x184x64 nodes in x,y and z directions) for full-scale and 0.4-scale water models respectively
- Fluid flow computation takes 19.2 CPUs per time step or 39 days for 175,000 time steps (140s) for full-scale water model on PIII 750 MHz PC and 28.8 CPUs per time step or 40 days for 120,000 time steps (60s) for 0.4-scale water model
- Particle motion computation takes 2.4 extra CPUs per time step for 17,500 particles or 5 days for 175,000 time steps

Flow Model Validation Study

0.4-scale water model



Simulation domain



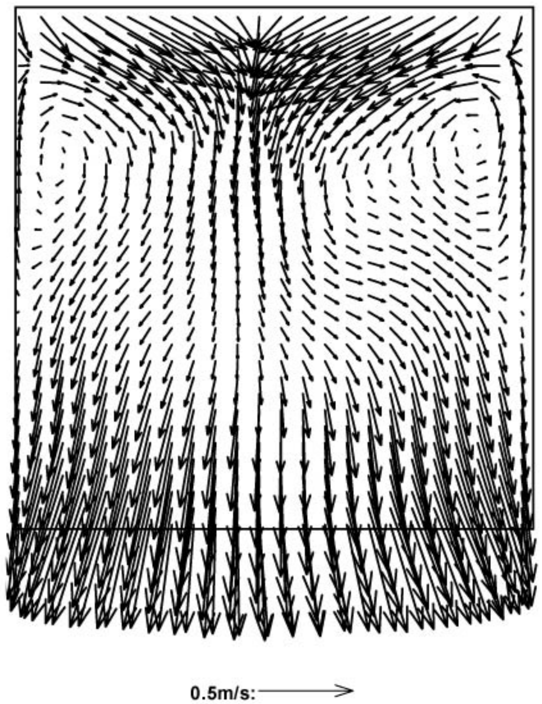
0.4-scale Water Model Experiment Conditions

Dimensions/Condition	Value
Slide-gate orientation	90^o
Slide-gate opening, linear fraction of the opening distance	52%
SEN bore diameter	32mm
SEN submergence depth	77 ± 3mm
Port Height x Width	32mm x 31mm
Port thickness	11mm
Port angle, lower edge	15^o down
Port angle, upper edge	40^o down
Bottom well recess depth	4.8mm
Water model height	950mm
Water model width	735mm
(corresponding full scale caster width)	1829mm (72 inch)
Water model thickness	95mm(top) to 65mm(bottom)
(corresponding full scale caster thickness)	229mm (9 inch)
Outlet at the bottom of the water model	3 round 35mm diameter holes
Inlet volumetric flow rate through each port	3.53×10^{-4} m^3/s
Casting speed (top thickness)	10.2mm/s (0.611m/min)
Average inlet velocity at port	0.411 m/s
Averaged inlet jet angle at port	30^o
Liquid density	1000 kg/m^3
Liquid material viscosity	0.001 Pa-s
Gas injection	0%

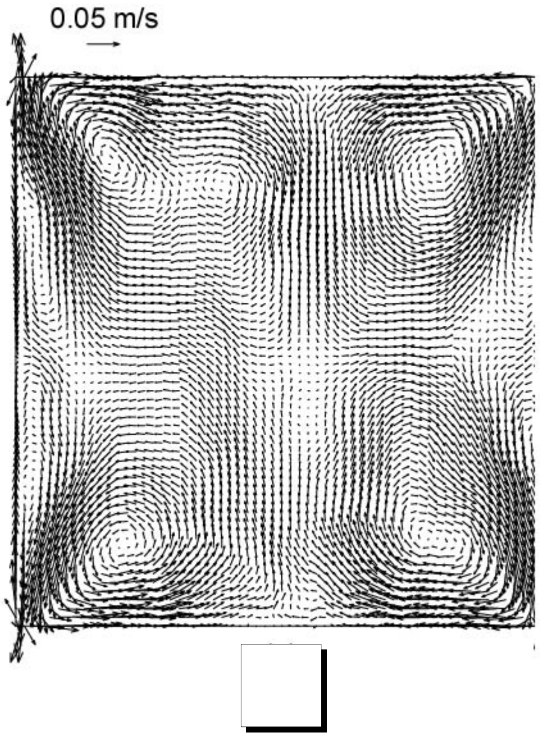
0.4-scale Water Model Computational Conditions

Dimensions/Condition	**Value**
SEN submergence depth	75mm
Port Height x Width	31mm x 31mm
Water model/Domain height	950 mm
Water model/Domain width	365 mm
Water model/Domain thickness	80 mm
Outlets at the bottom of the water model/domain	35mm x 35mm square ports
Averaged inlet velocity at port	0.424 m/s
Averaged jet angle at port	30^{o} down
Liquid flow rate through each port	3.53×10^{-4} m^3/s
Casting speed	12.1mm/s (0.725 m/min)
Liquid density	1000 kg/m^3
Liquid material viscosity	0.001 Pa-s
Gas injection	0%

Comparison of Inlet Velocity between Two LES



LES1

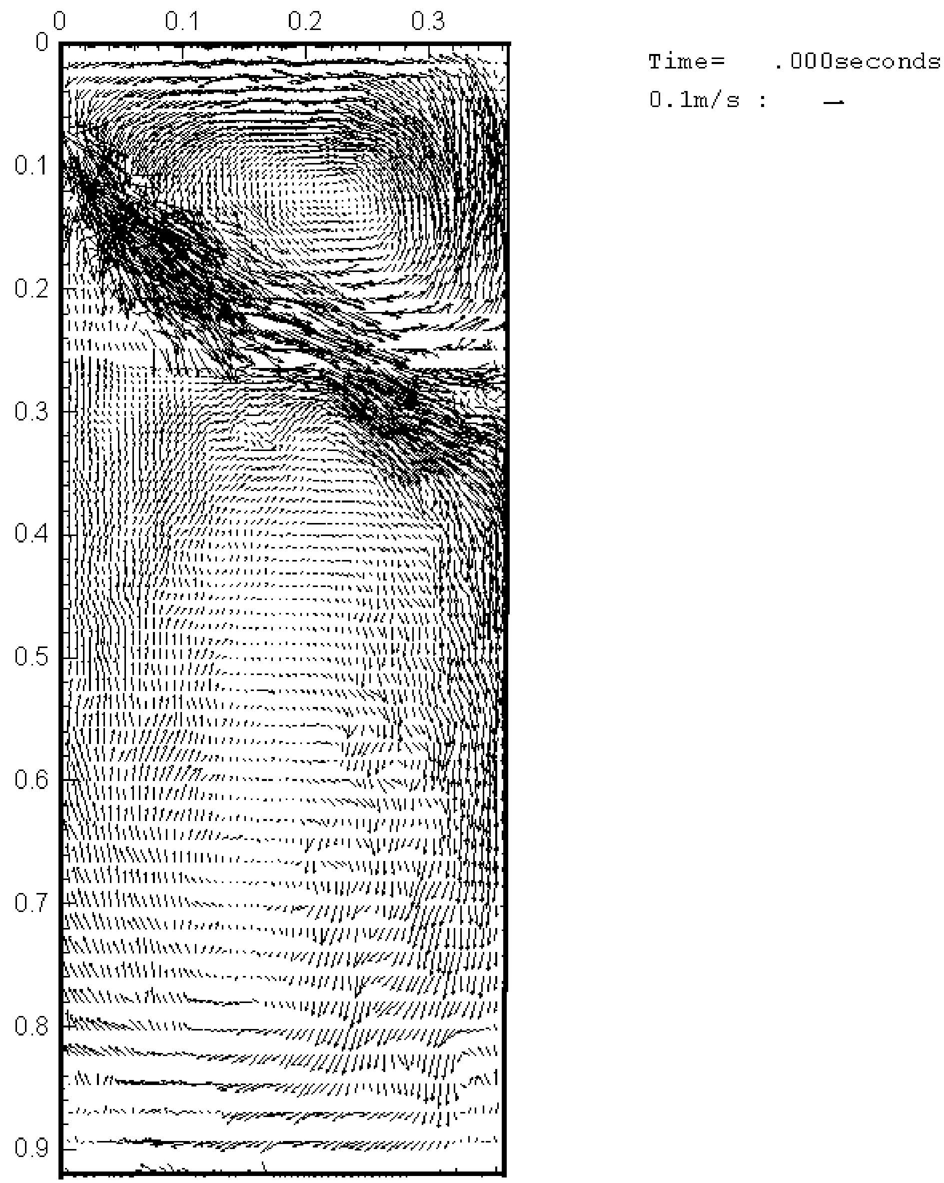


LES2

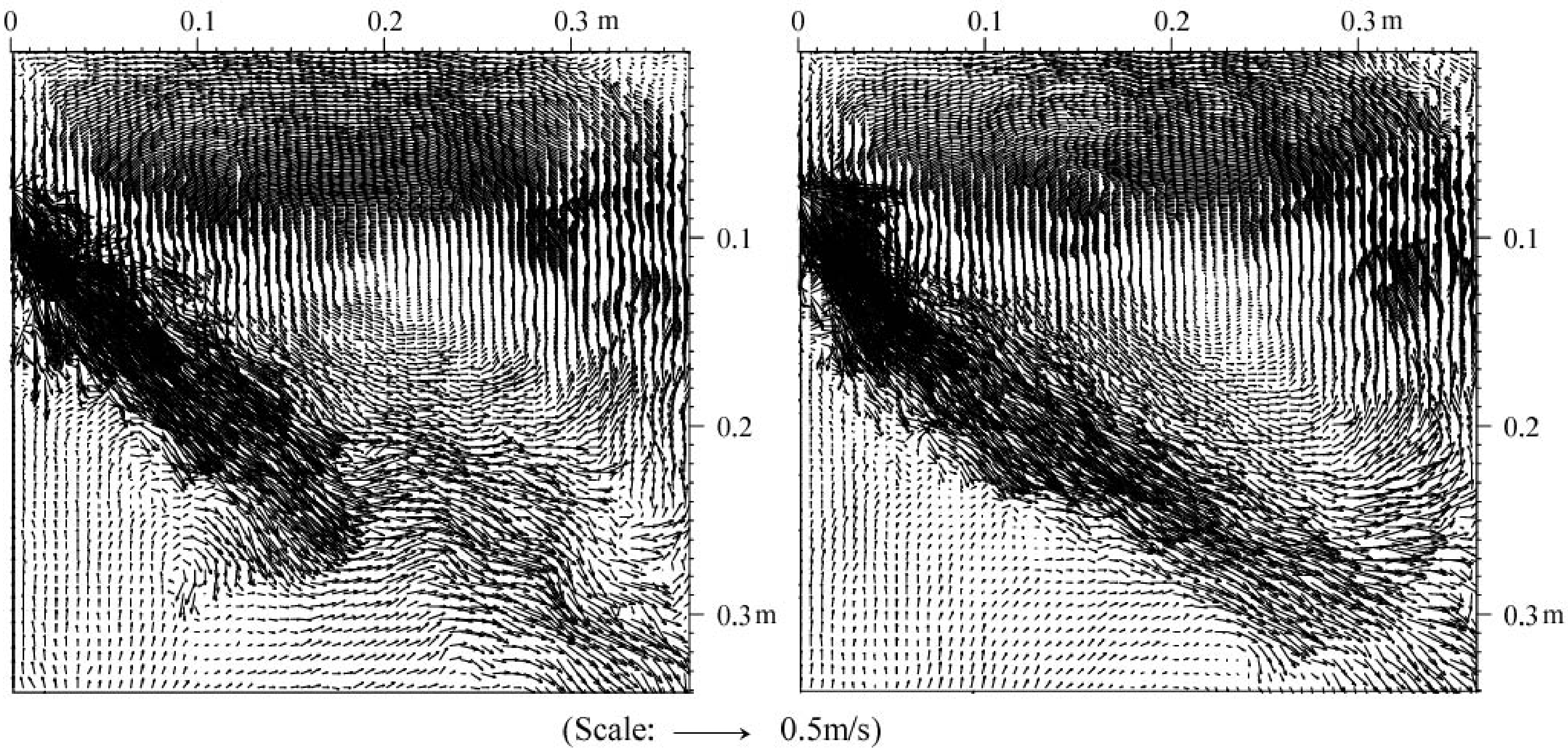
Cross-stream velocity field at the nozzle port plane, view towards nozzle port.

LES2: S. Sivaramakrishnan, "Transient Fluid Flow in the Mold and Heat Transfer through the Molten Slag Layer in Continuous Casting of Steel", Master thesis, Univ. of Illinois at Urbana-Champaign, 2000.

Computed Fluid Flow at Center Plane between WF, LES1

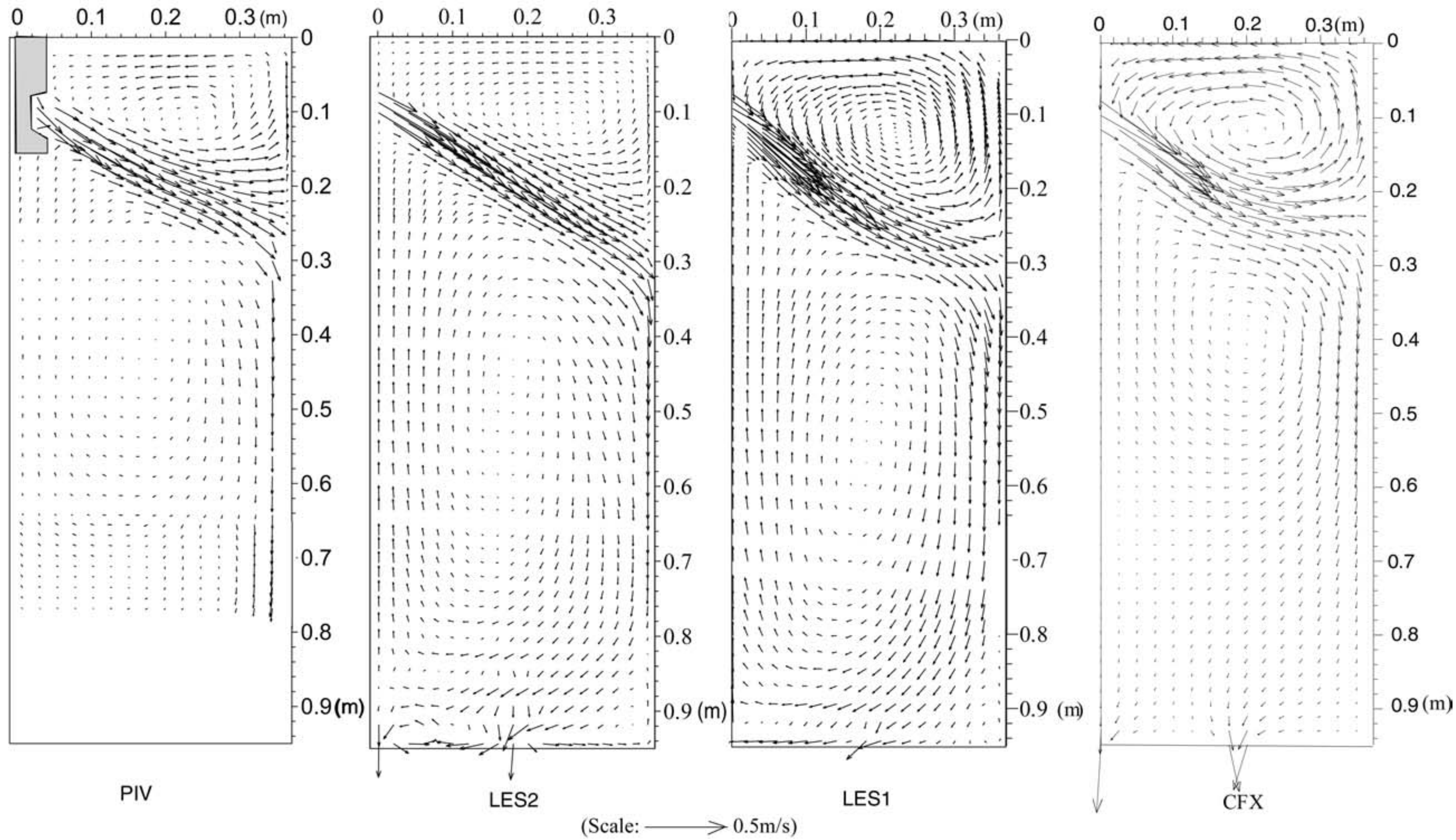


Two Typical Jet Flow Pattern in LES1



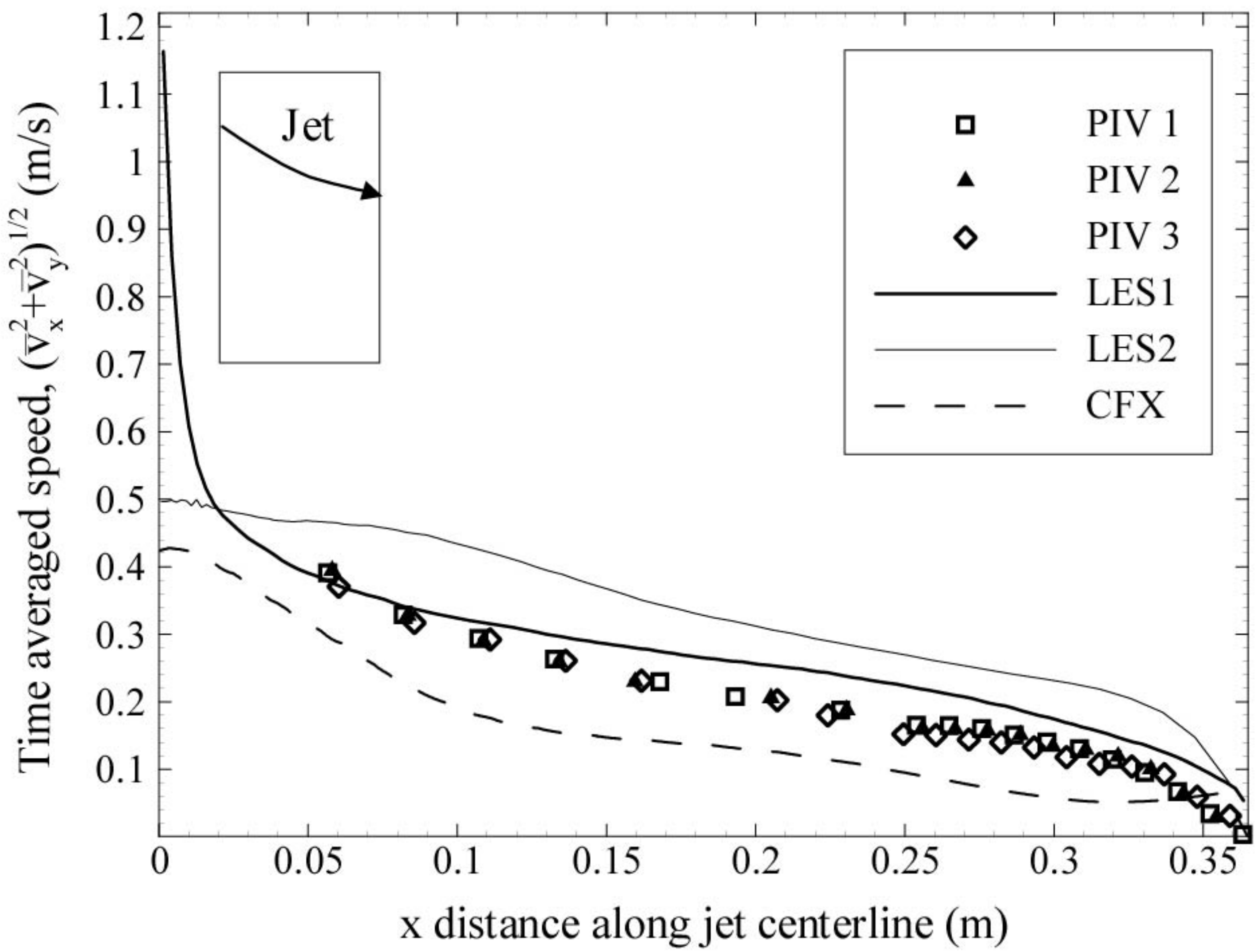
(a) “Staircase” jet flow pattern and (b) “Straight” jet flow pattern.

Comparison Time-averaged Velocity Field at Center Plane

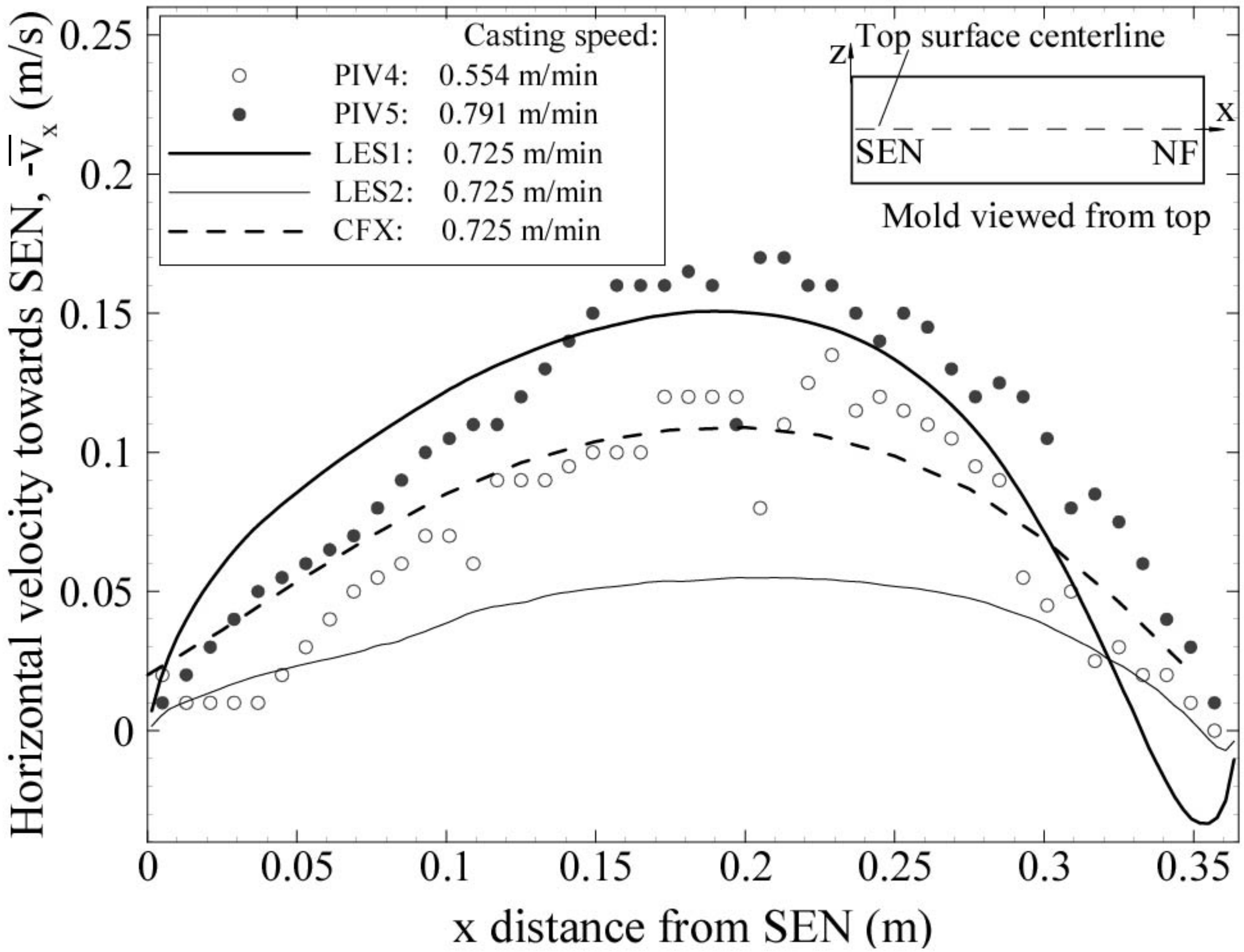


PIV, LES2: S. Sivaramakrishnan, CFX: T Shi, “CCC Report”, August 19, 1999. Same for following slides.

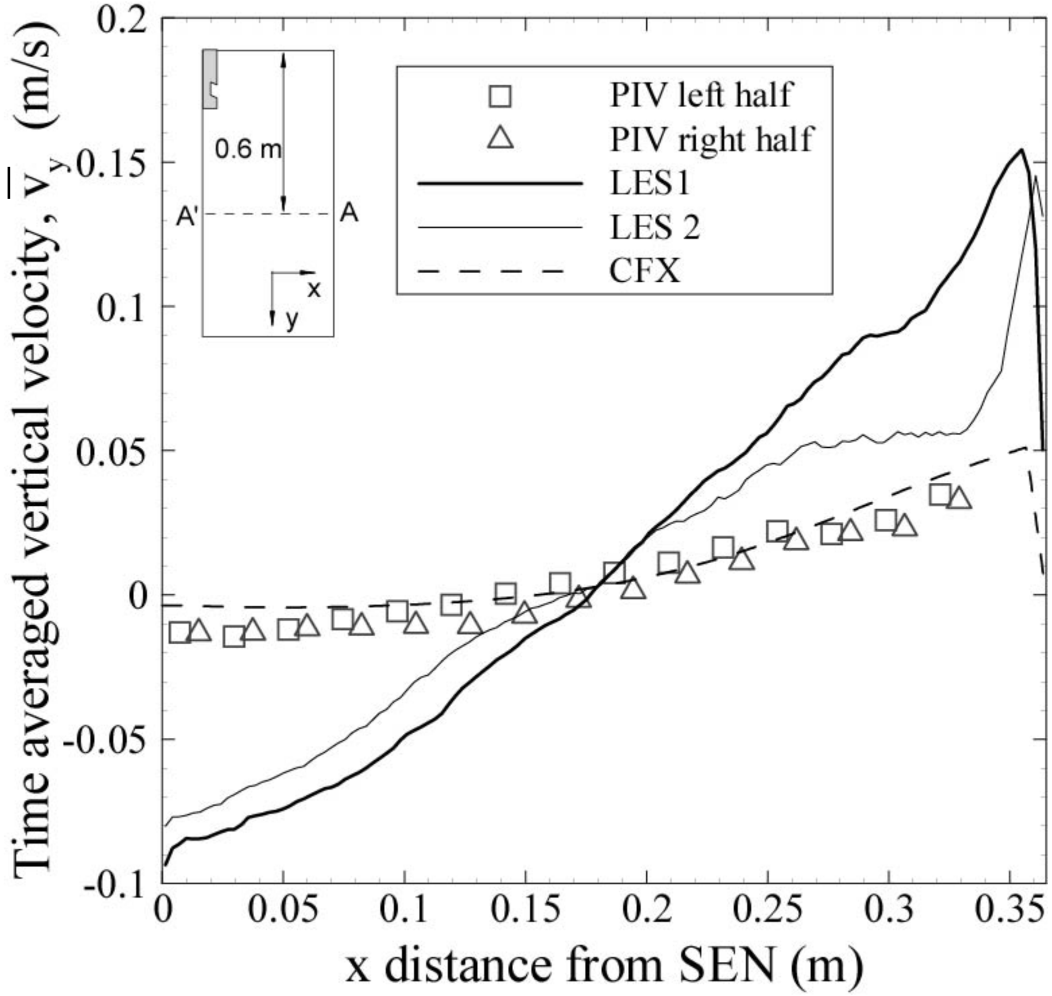
Time-averaged Speed Profile along Jet Centerline, Comparing PIV, K-ε, and LES



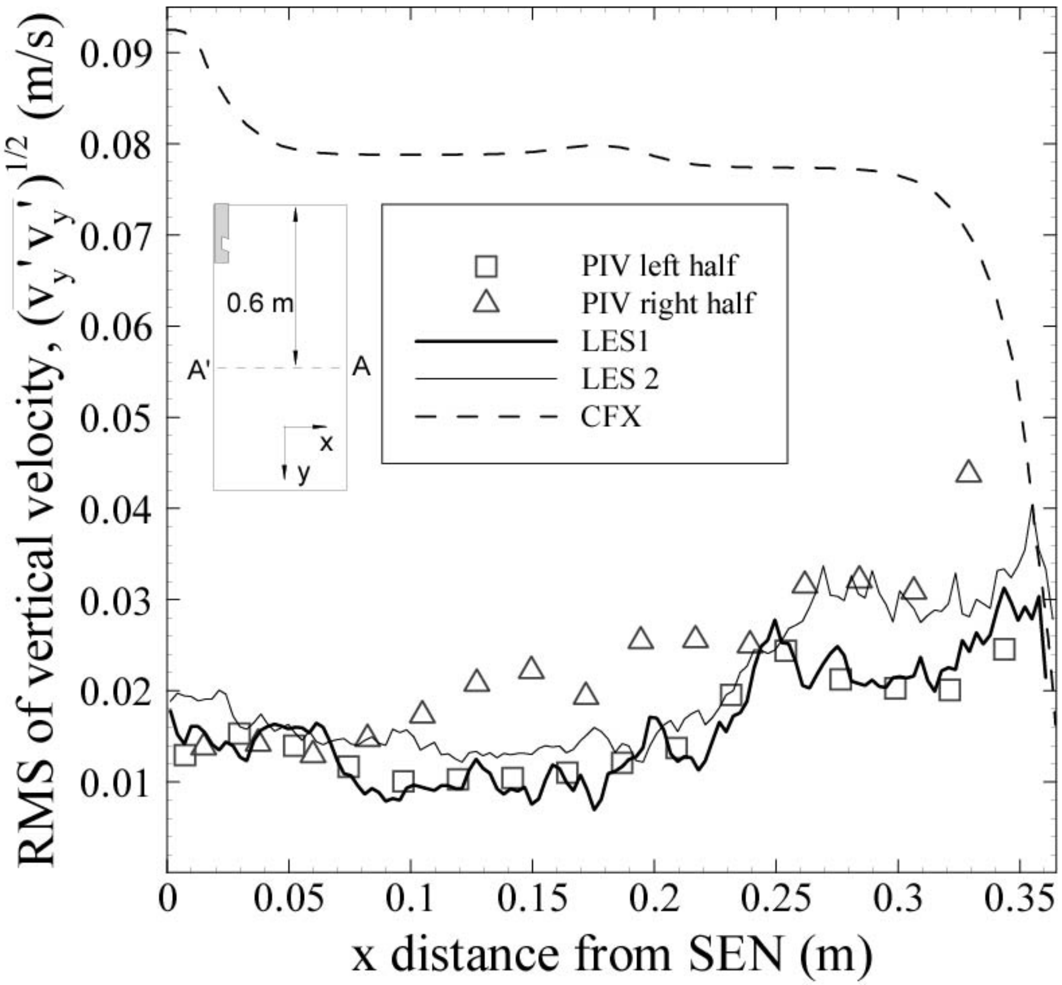
Time-average Speed Profile Along Top Surface Centerline, Comparing PIV, K- ε, and LES



Time-average Speed Profile along Horizontal Line 0.6 m below Top Surface, Comparing PIV, K- ε, and LES

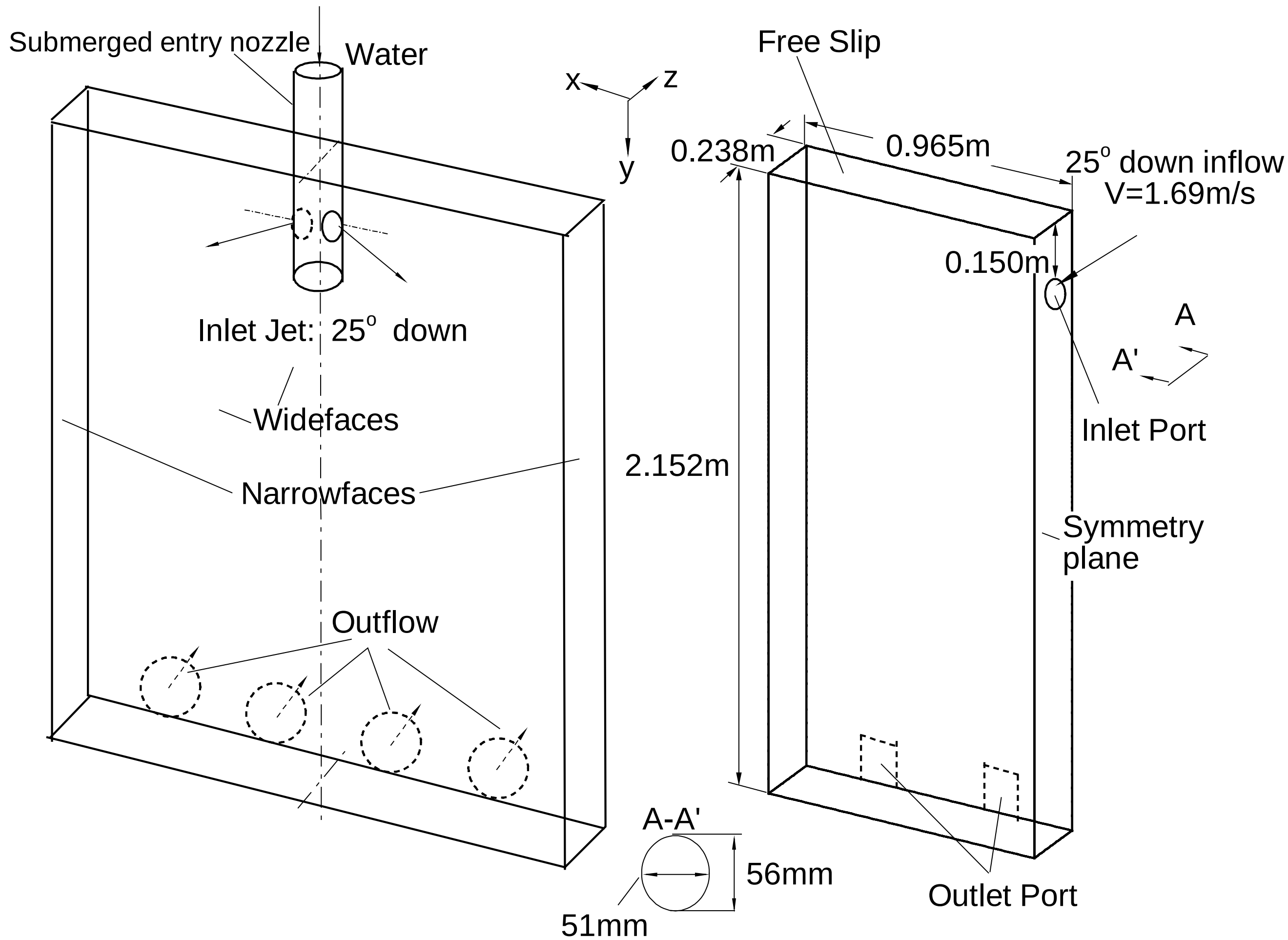


RMS of Turbulent Variation in Vertical Velocity along Horizontal Line, 0.6 m below Top Surface, Comparing PIV, K-e, and LES



Turbulent Flow and Particle Transport in a Full Scale Water Model

Full-scale Water Model (AK Steel) | Computation Domain



Water model: R. C. Sussman, M. T. Burns, X. Huang and B. G. Thomas, 1992, "Inclusion Particles Behavior in a Continuous Slab Casting Mold", *10th Process Technology Conference Proceedings*, Toronto, Ontario, pp. 291-304.

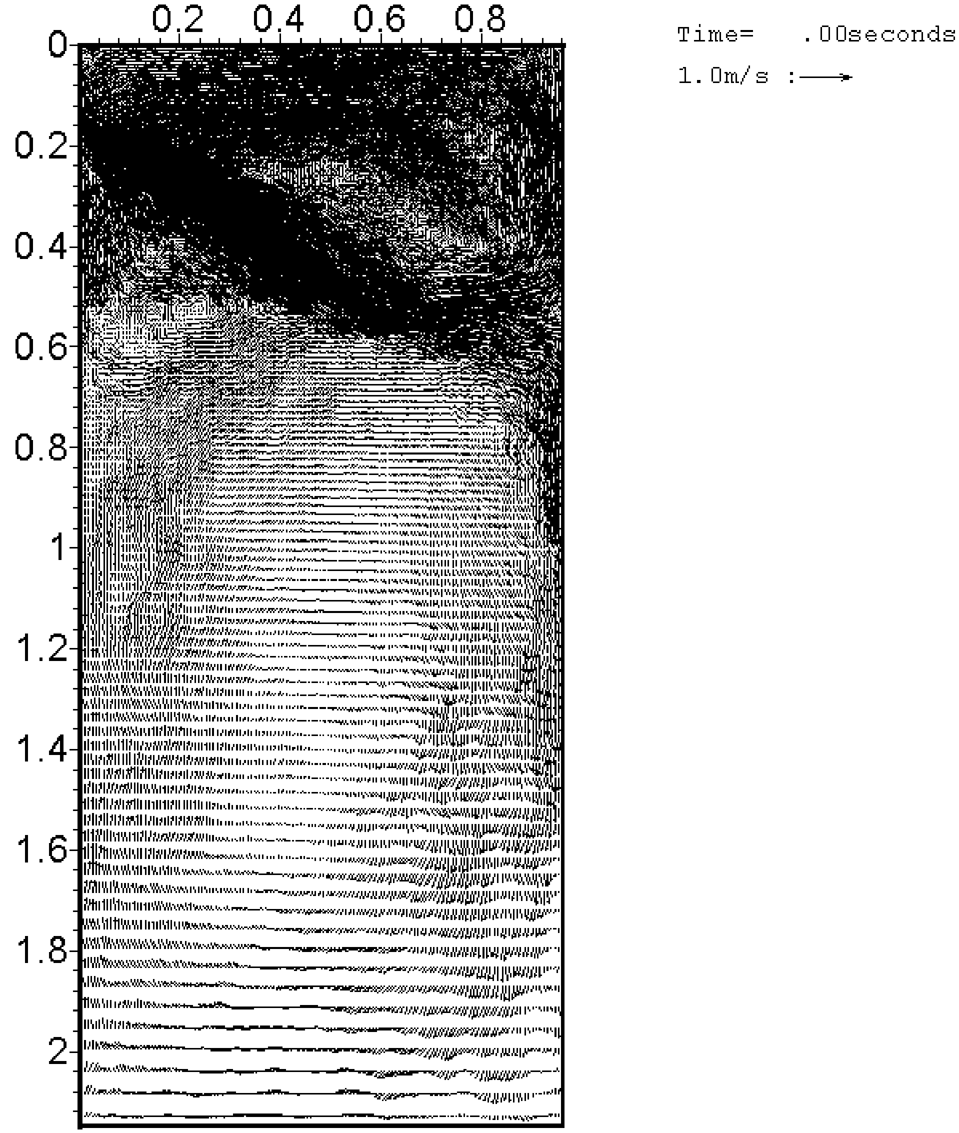
Experimental and Computational Conditions

	Experiment	LES simulation
Nozzle port size /Inlet port size (x x y)	20” x 22”	0.051m x 0.056m
Submergence depth	59.1”	0.150 m
Nozzle angle	25^o	25^o
Inlet jet angle	25^o	25^o
Mold /Domain height	847”	2.152 m
Mold /Domain width	720”	0.965 m
Mold /Domain thickness	94”	0.238 m
Average inlet flow rate	192 ton/hour for 7020 kg/m^3 steel (two nozzle ports)	0.0038 m^3/s
Average inlet speed	1.69	1.69 m/s
Fluid density	1000 kg/m^3	1000 kg/m^3
Casting speed	36’’/min	0.0152 m/s
Fluid kinematic viscosity	1.0×10^{-6} m^2/s	1.0×10^{-6} m^2/s
Particle inclusion size	2 – 3	3.8 mm (diameter)
Particle inclusion density	988 kg/m^3	988 kg/m^3
Corresponding alumina inclusion diameter in steel caster	300 μm	300 μm

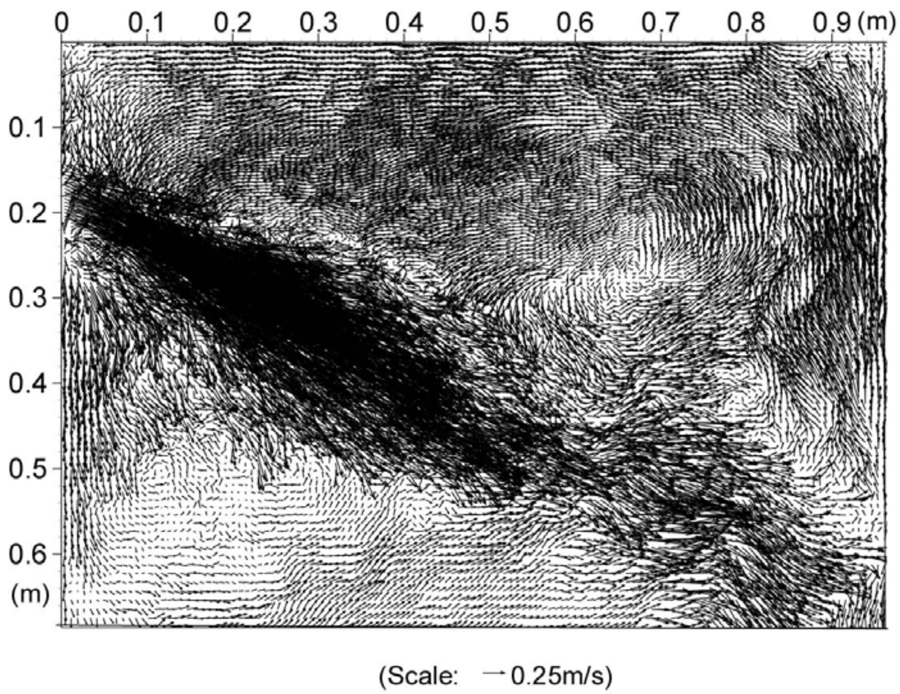
Particle Injection from Nozzle Port (LES)

Group index	Number of particles	Time of introduction
0	15000	0s – 1.6s
1	500	2s – 2.4s
2	500	4s – 4.4s
3	500	6s – 6.4s
4	500	8s – 8.4s
5	500	10s –10.4s

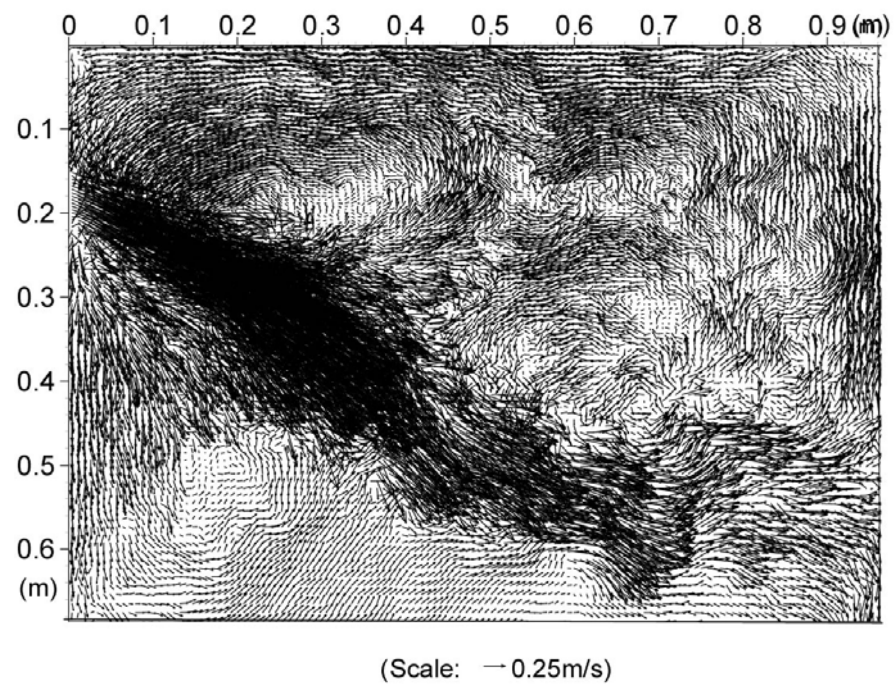
Fluid Flow Movie



Two Typical Instantaneous Flow Structures in Upper Roll

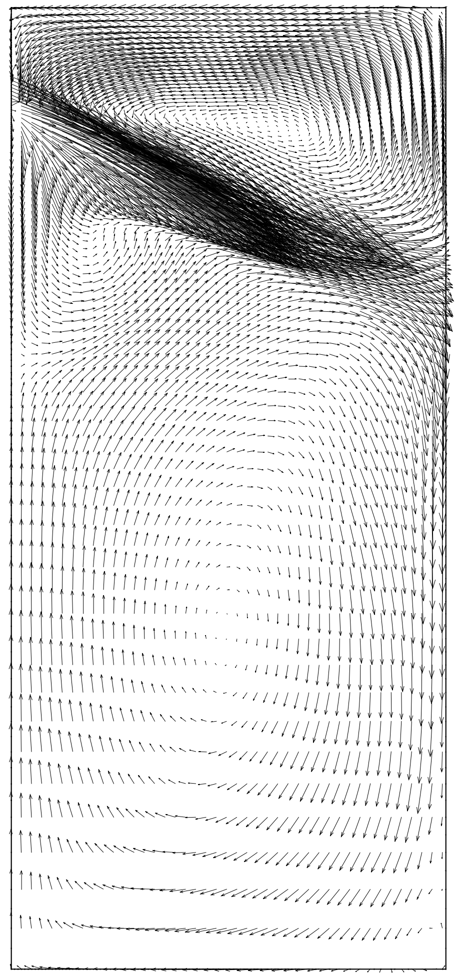


Single vortex structure



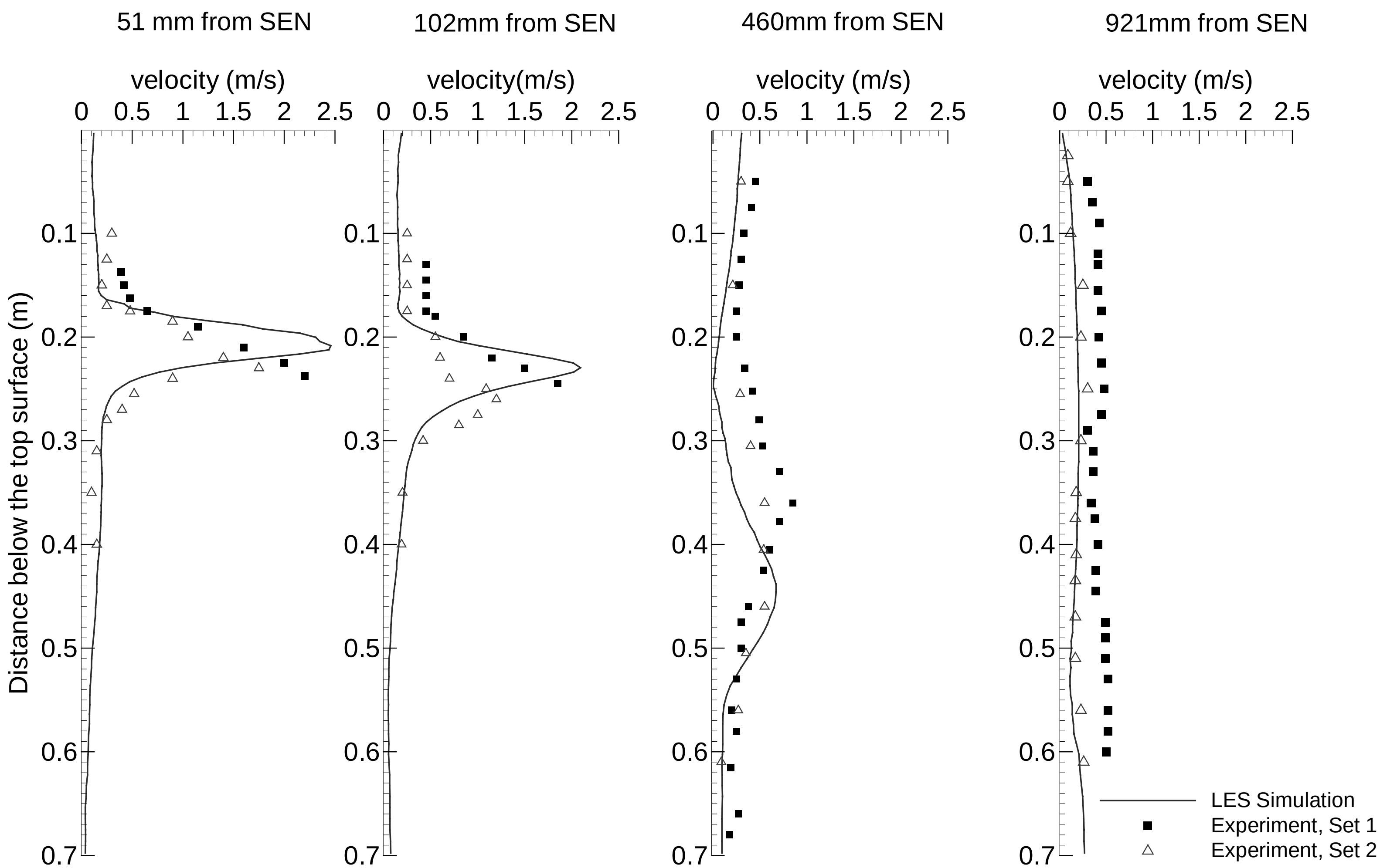
Distinct vortex structures

Time-averaged Velocity Field (Over 100s)



(scale: 0.25m/s)

Comparison With Experiments

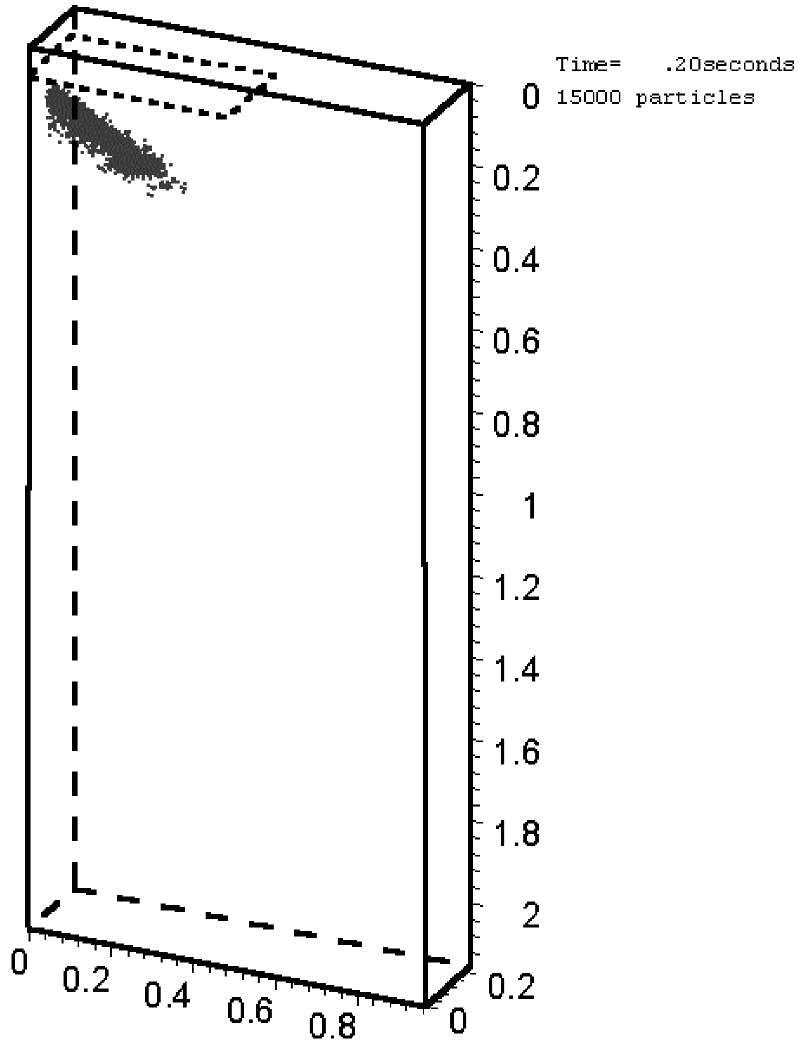


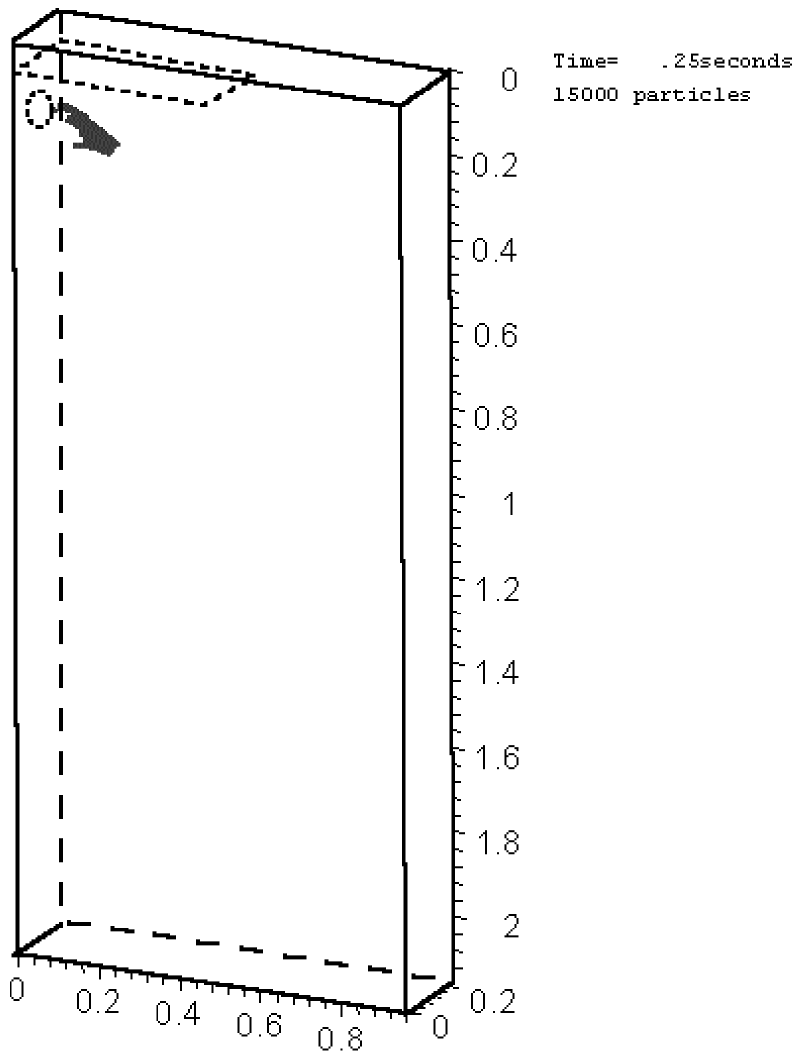
Experiments: B.G.Thomas et al, “Simulation of Argon Gas Flow Effects on a Continuous Slab Caster”, Metallurgical and Material Transaction B, Volume 25B, August 1994, pp 527-547

Motion of 15,000 Particles (0 – 100 s)

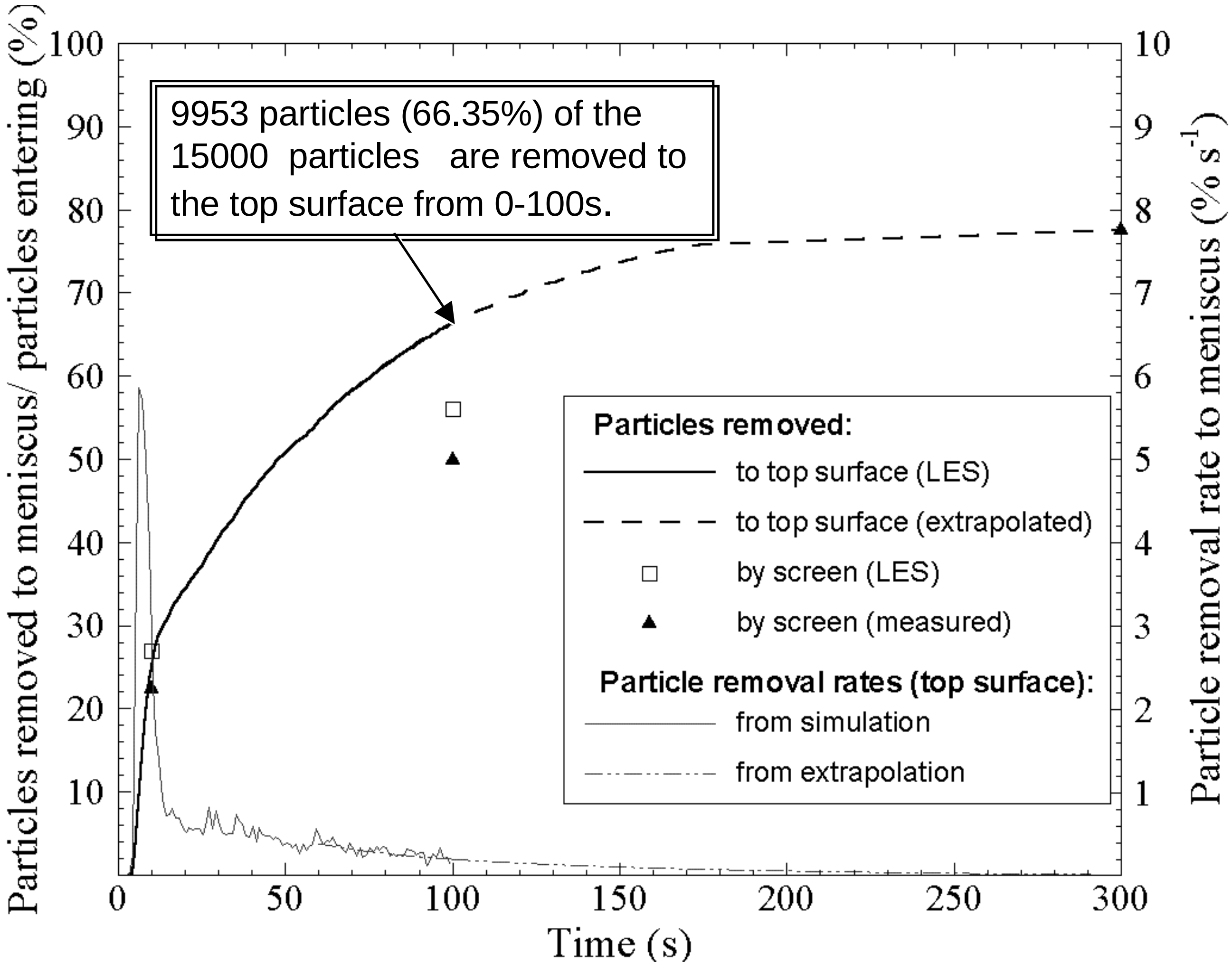
Compare to another particle computation

d_p=2.5mm; ρ_p=998kg/m³ (corresponding to 100µm alumina inclusion; 20”x20” circular nozzle ports; casting speed=22’’/min.



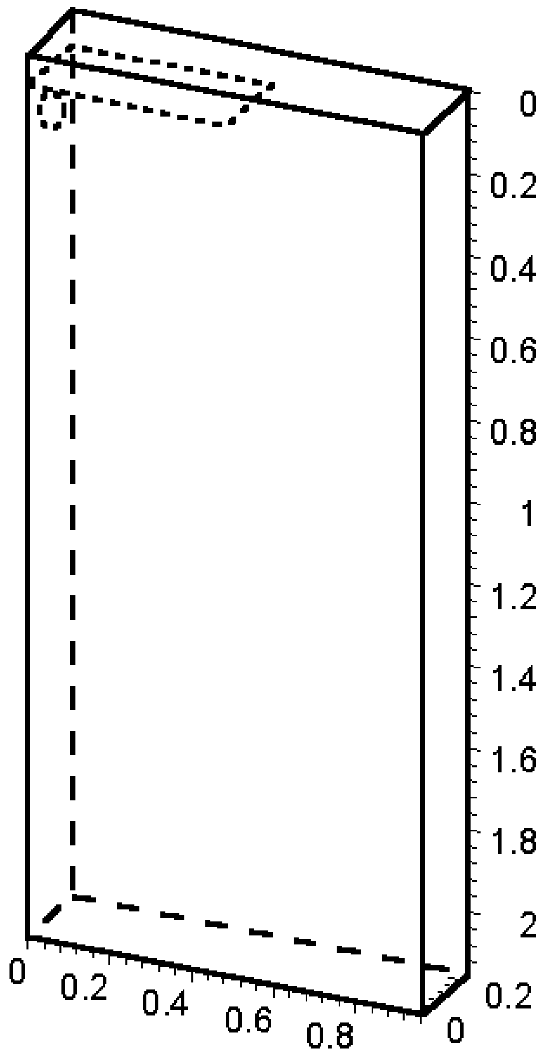


How Many Particles Are Removed to Top Surface?

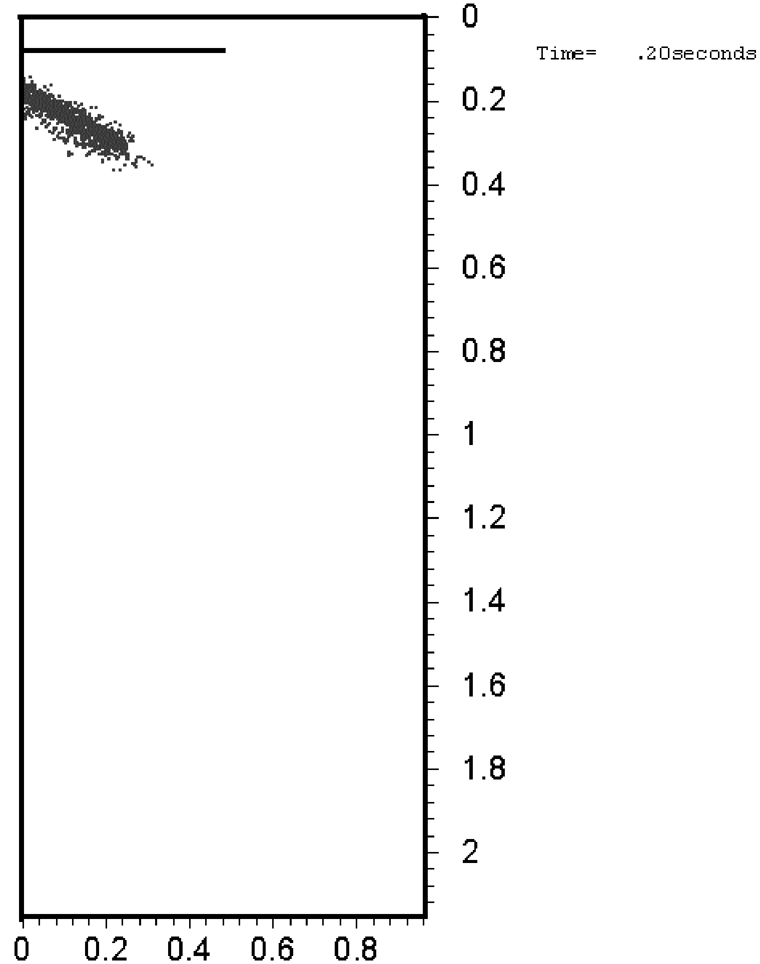


Experiment: R. C. Sussman, M. T. Burns, X. Huang and B. G. Thomas, 1992, "Inclusion Particles Behavior in a Continuous Slab Casting Mold", *10th Process Technology Conference Proceedings*, Toronto, Ontario, pp. 291-304.

How These 9953 Particles Move?



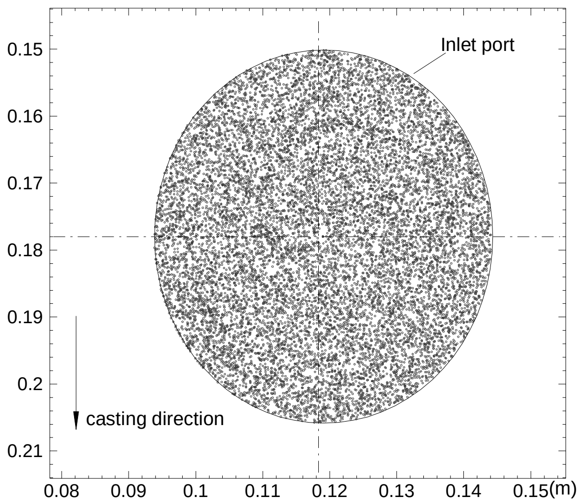
Projection
to wideface



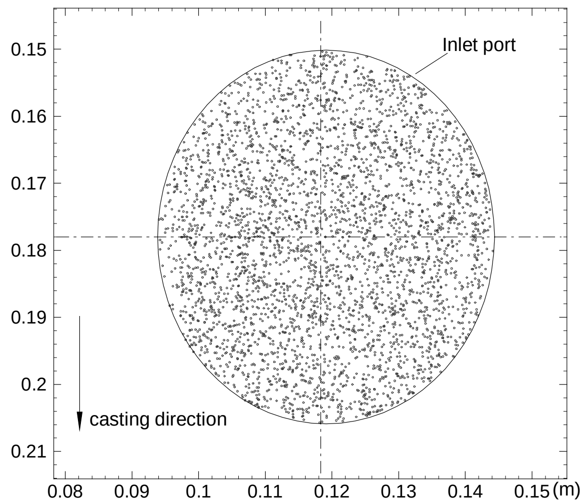
Particles Entering from Which Part of the Inlet Port Are Most Likely Removed to Top Surface?

Initial positions of each particle type

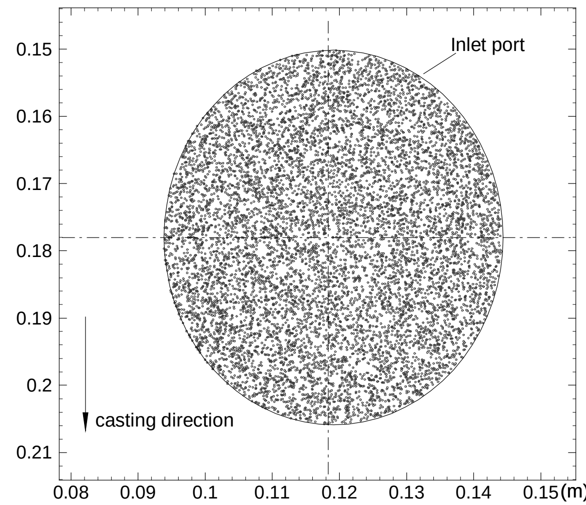
Total (15000 particles)



Removed in first 10s

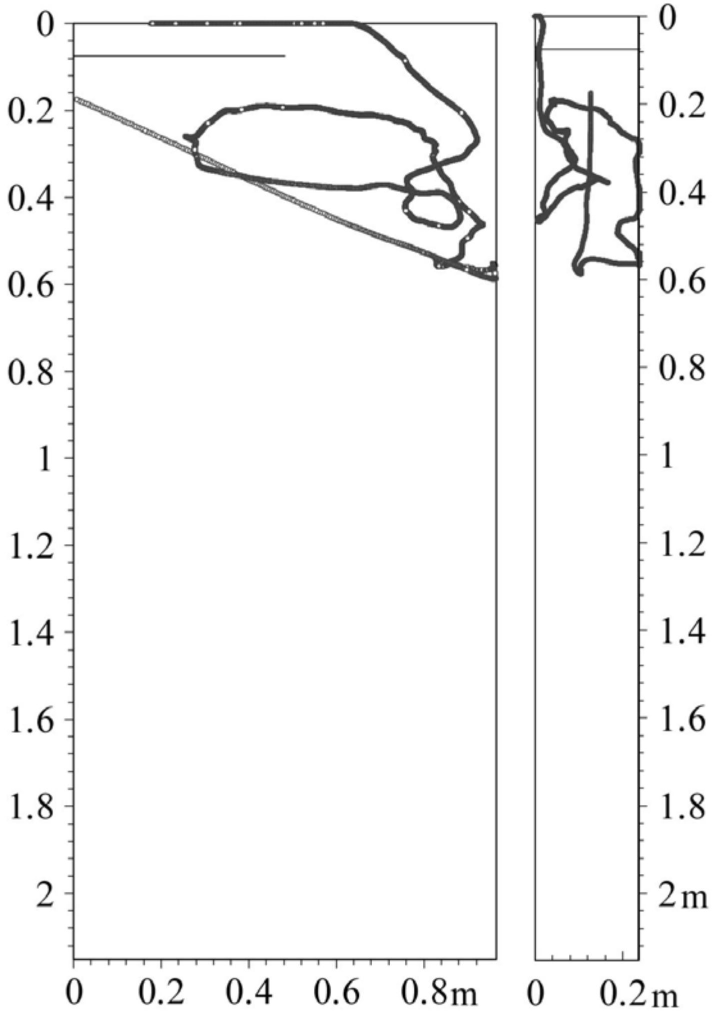


Removed in first 100s

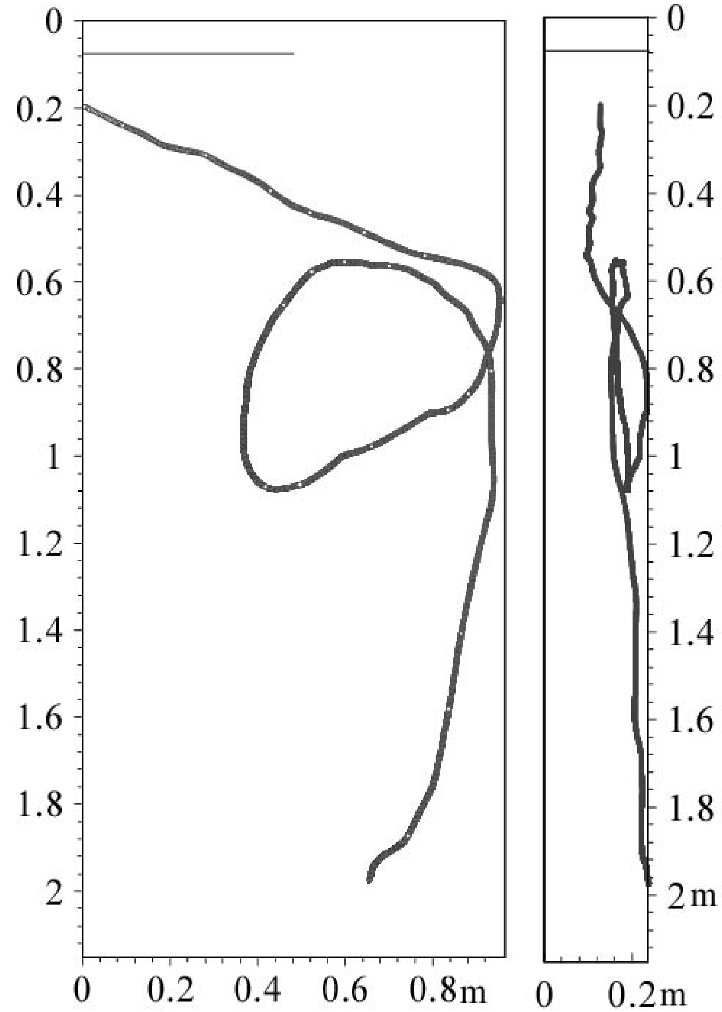


Typical Particle Trajectories

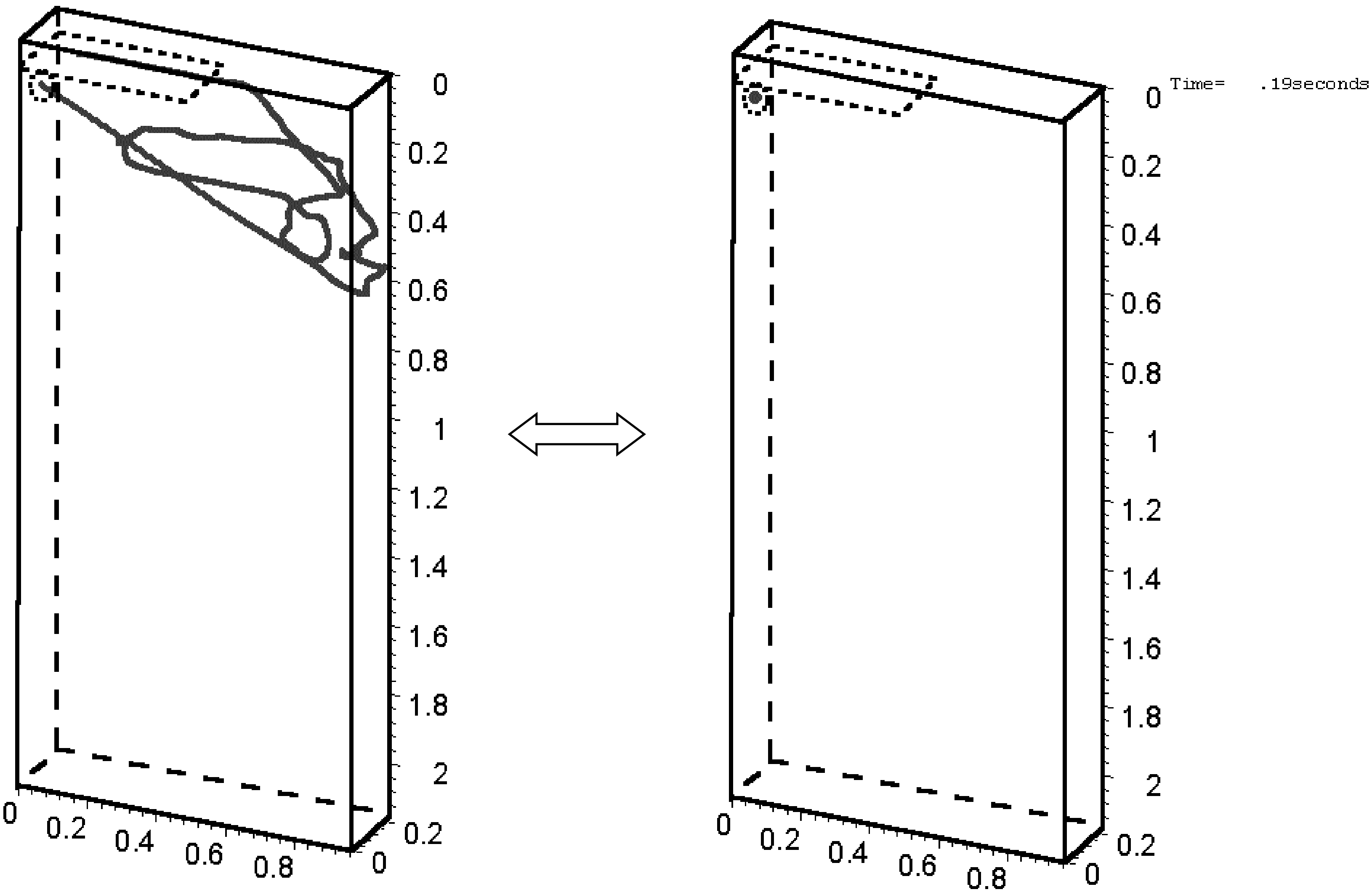
Removed to top surface



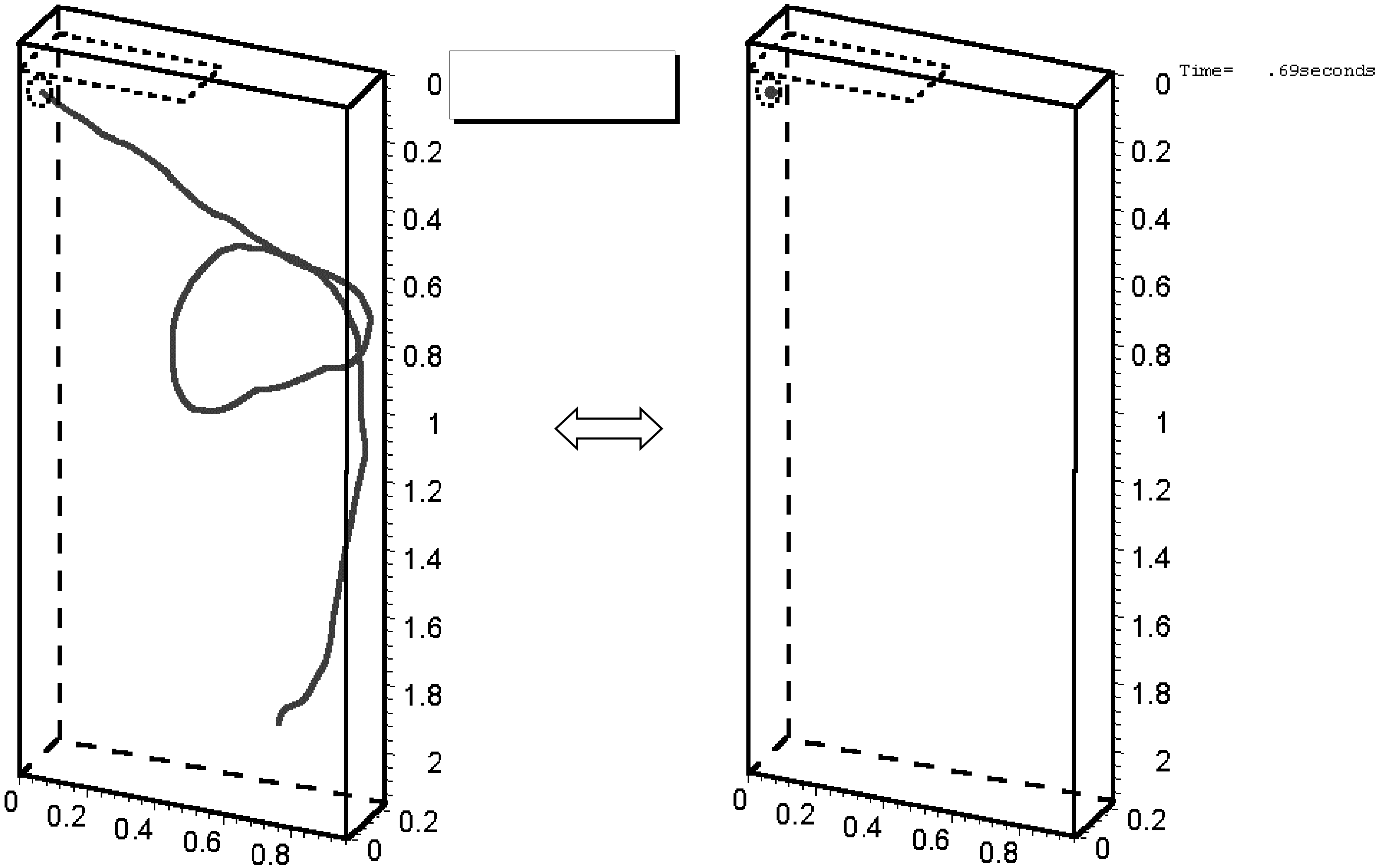
Entrapped



How Does a Typical Removed Particle Move?

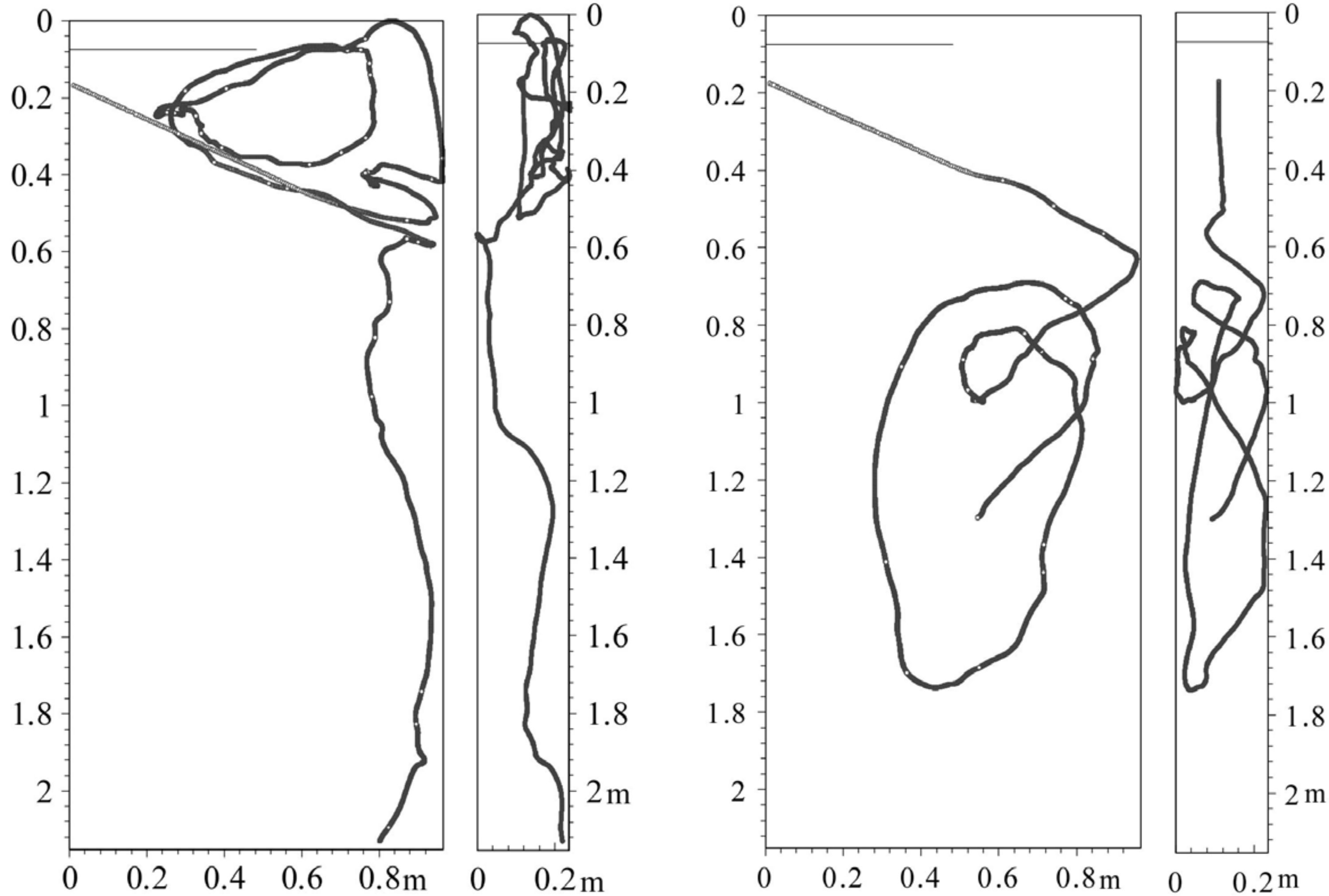


How Does a Typical Entrapped Particle Move?

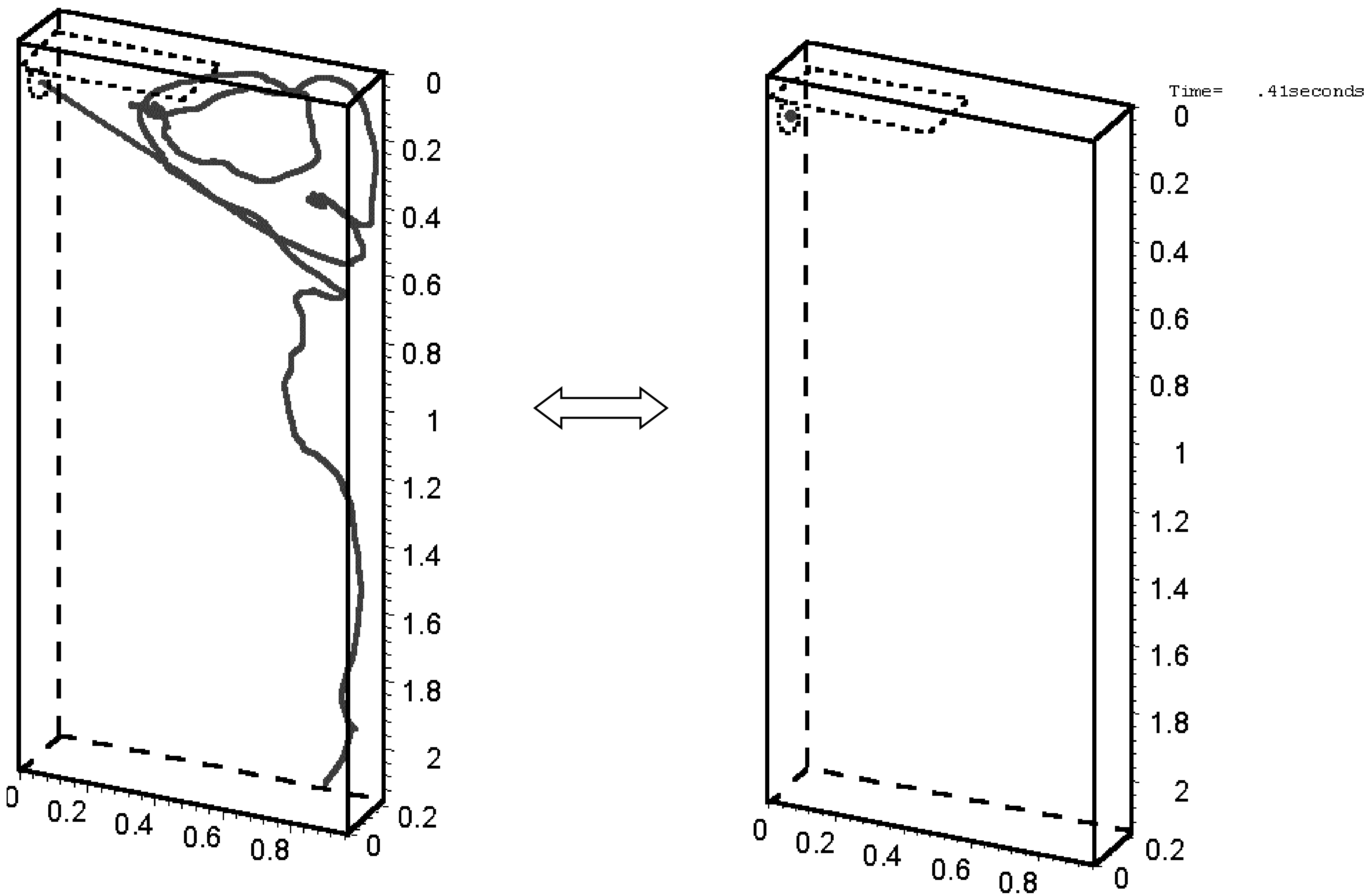


Typical Particle Trajectories

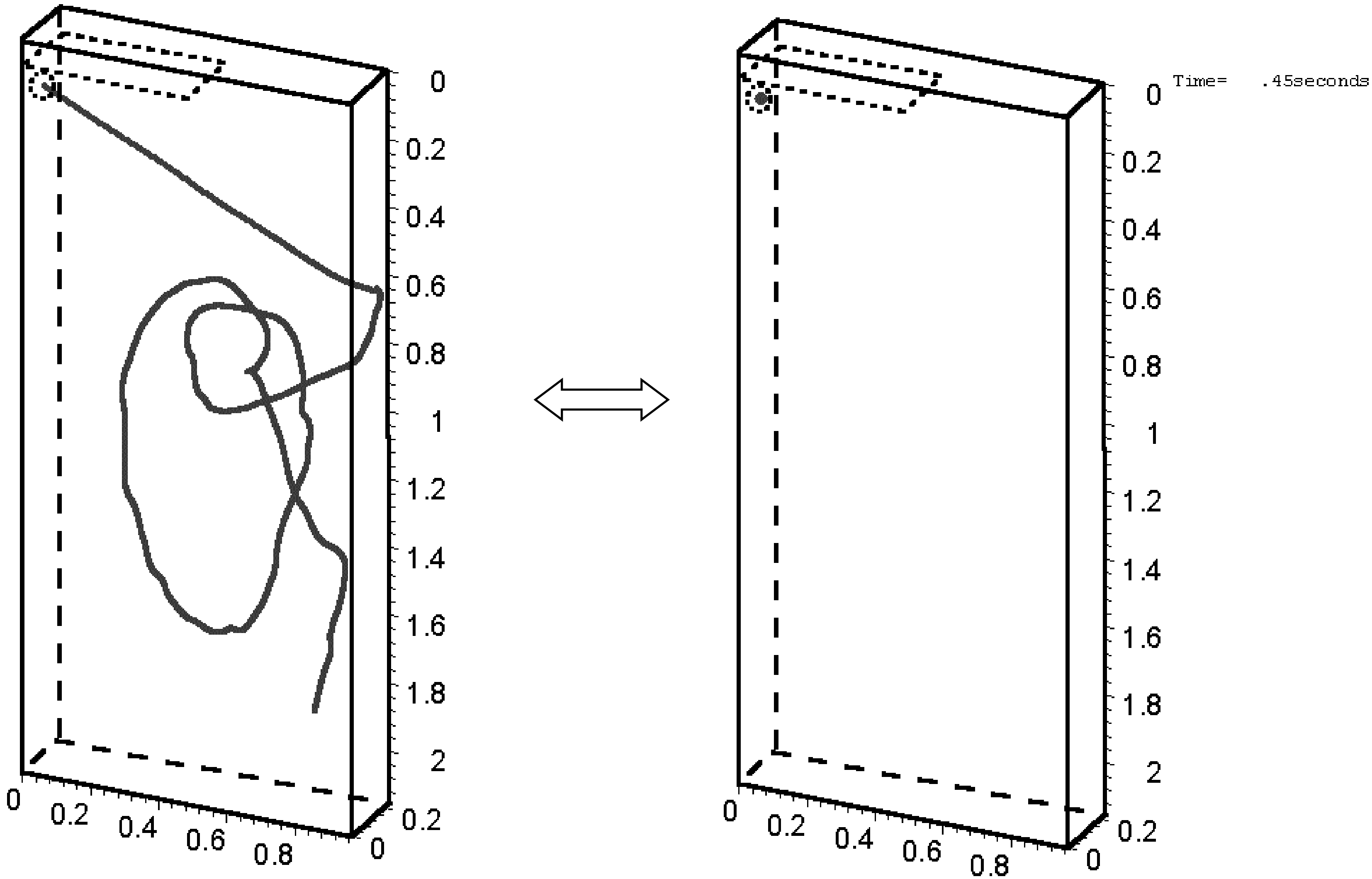
Two particles till moving after 100s



How Does the First Particle Move?



How Does the Second Particle Move?



Particle Removal Results (by Screen)

- Simulation agrees with experiment
- 50% of particles removed in 100s (no entrapment by shell)
- Particle sample size is important

		0-10 seconds	10-100 seconds
LES	500 particle groups		
	1	27.2%	23.4%
	2	17.8%	27.2%
	3	26.2%	23.0%
	4	23.8%	23.2%
	5	33.0%	18.2%
	Average	25.56%	23.0%
	15000 particles (group 0)	26.96%	26.03%
Experiment		22.3%	27.6%

Conclusions

Fluid Flow:

- **Computed velocity field in mold region using LES agrees with measurements for both full-scale and 0.4-scale water models**
- **Typical instantaneous vortex structures are found in upper roll for a full-scale water model, which is consistent with a previous 0.4-scale water model study**
- **Two jet flow patterns are seen in LES for 0.4-scale water model**
- **Inflow pattern has important influences on flow in the mold region**
- **LES is better capable of predicting turbulent variation (RMS) than RANS**

Particle Transport

- **Predicted particle removal by screen agrees well with experiment**
- **Particle removal to top surface is independent of its initial position at which particle enters the mold**
- **Large number of particles are required to study particle transport in mold region**
- **Computed typical particle trajectories agree with experimental observations**