Transient Study of Turbulent Flow and Particle Transport in a Full-Scale Water Model and Continuous Steel Casting Machine Using LES

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Acknowledgements

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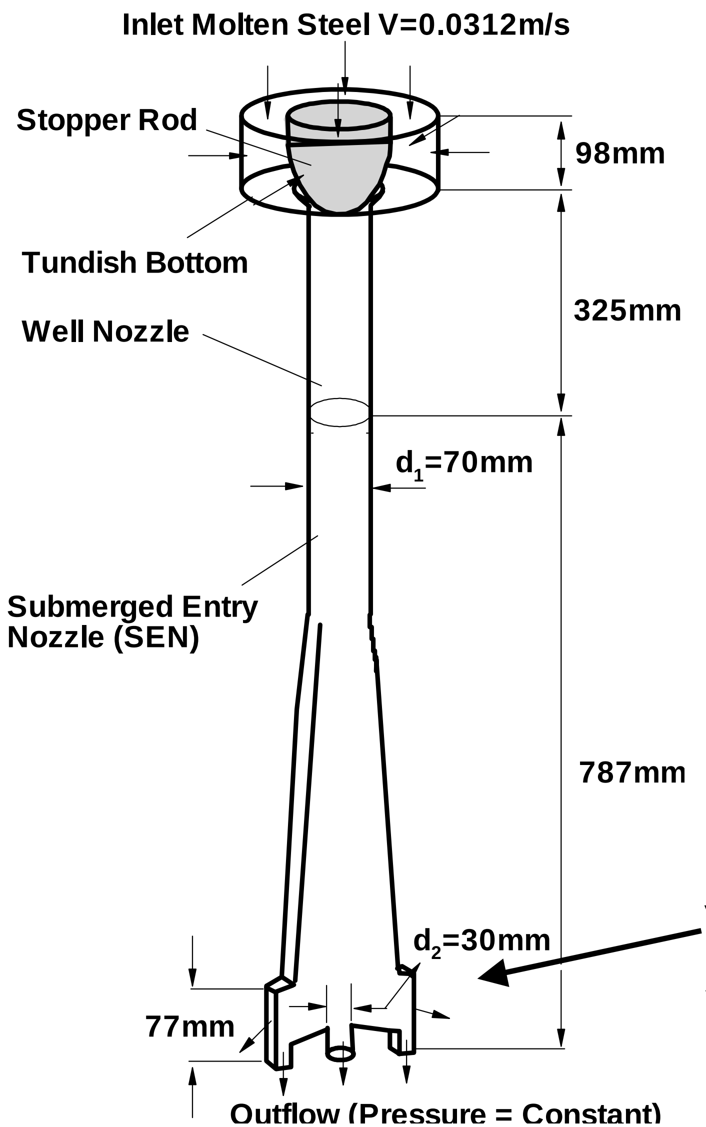
Objectives

- Transient full-mold (two sides) simulation of turbulent flow in full-scale water models and steel slab casting machines
- Investigate turbulent flow in casting machines with taking care of tapering domain, solidification and downwards withdrawing of the shell
- Compare turbulent flow in water models and steel casting machines
- Develop a mathematical model for particle entrapment
- Investigate particle transport and entrapment in steel caster

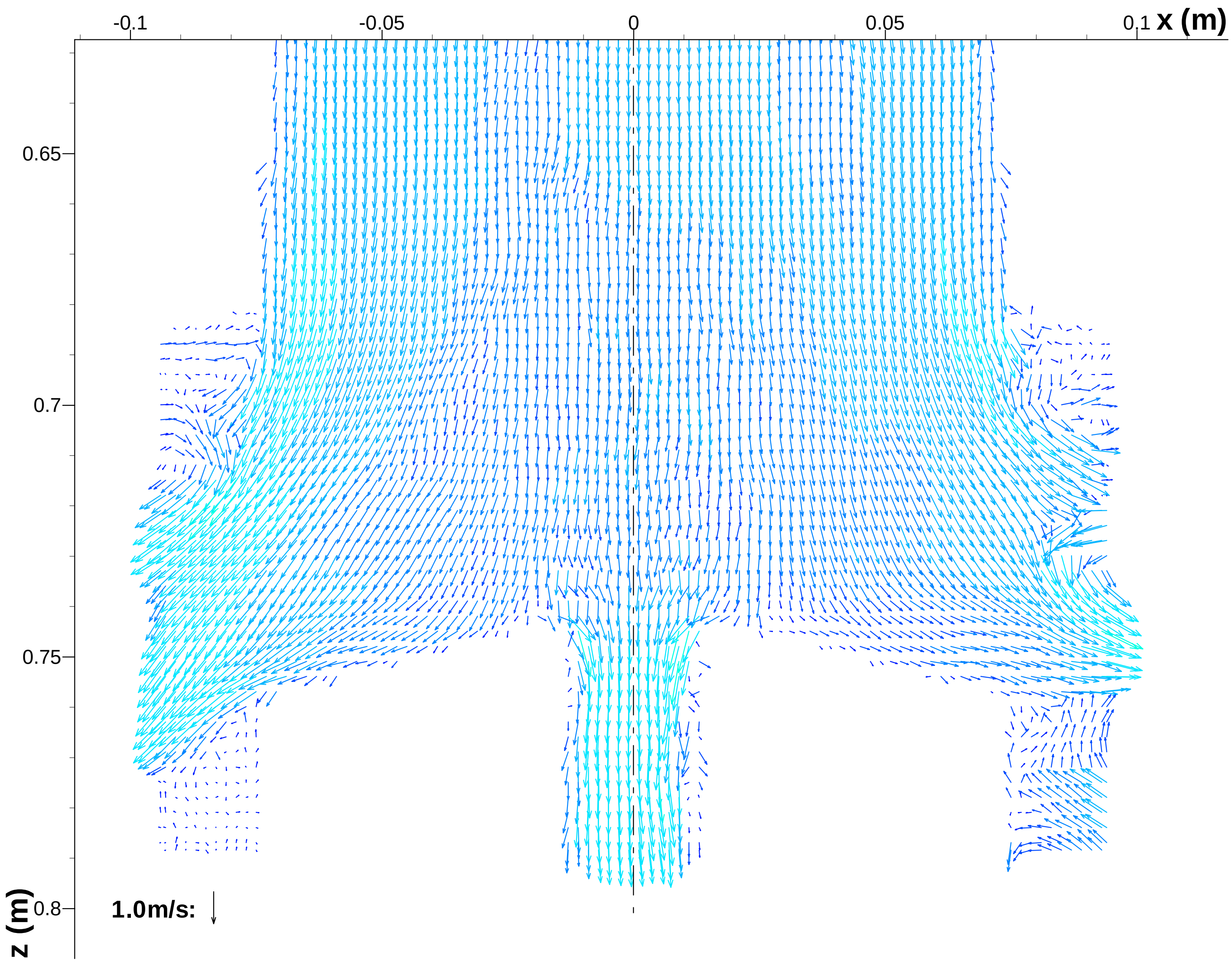
A Quick Review of Nozzle Simulation (LES)



Parameter	Value
Casting speed	25.4 mm/s (60inch/min)
SEN top diameter	70mm
SEN side port width	32mm
SEN side port height	77mm
SEN bottom port diameter	30mm
SEN length	787mm
SEN nozzle angle	15^o
Well Nozzle Length	325mm
Stopper rod opening fraction (relative to well nozzle bore area)	46.7%
Mold thickness	132mm
Mold width	984mm
Mold length	1,200 mm
Liquid steel density	7020 kg/m^3
Liquid steel molecular viscosity	0.0056 kg/ms
Port Angle – upper edge	15^o
– bottom well edge	15^o

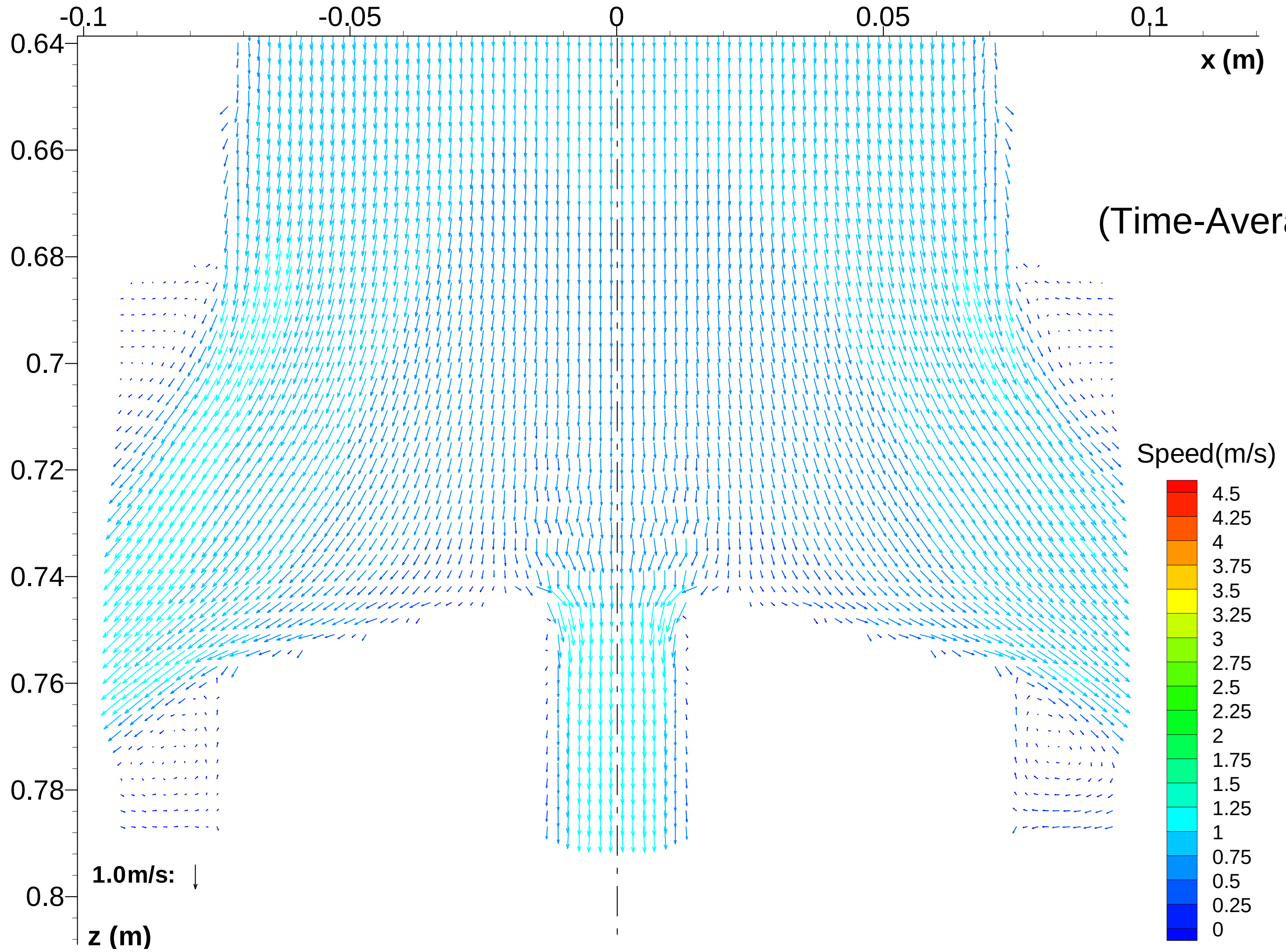
Velocities at nozzle ports are stored every 0.025 seconds for a period of 9.45 seconds; they are used as transient inlet values to mold simulations and recycled periodically.

A Quick Review of Nozzle Simulation (Instantaneous Velocities near Ports)

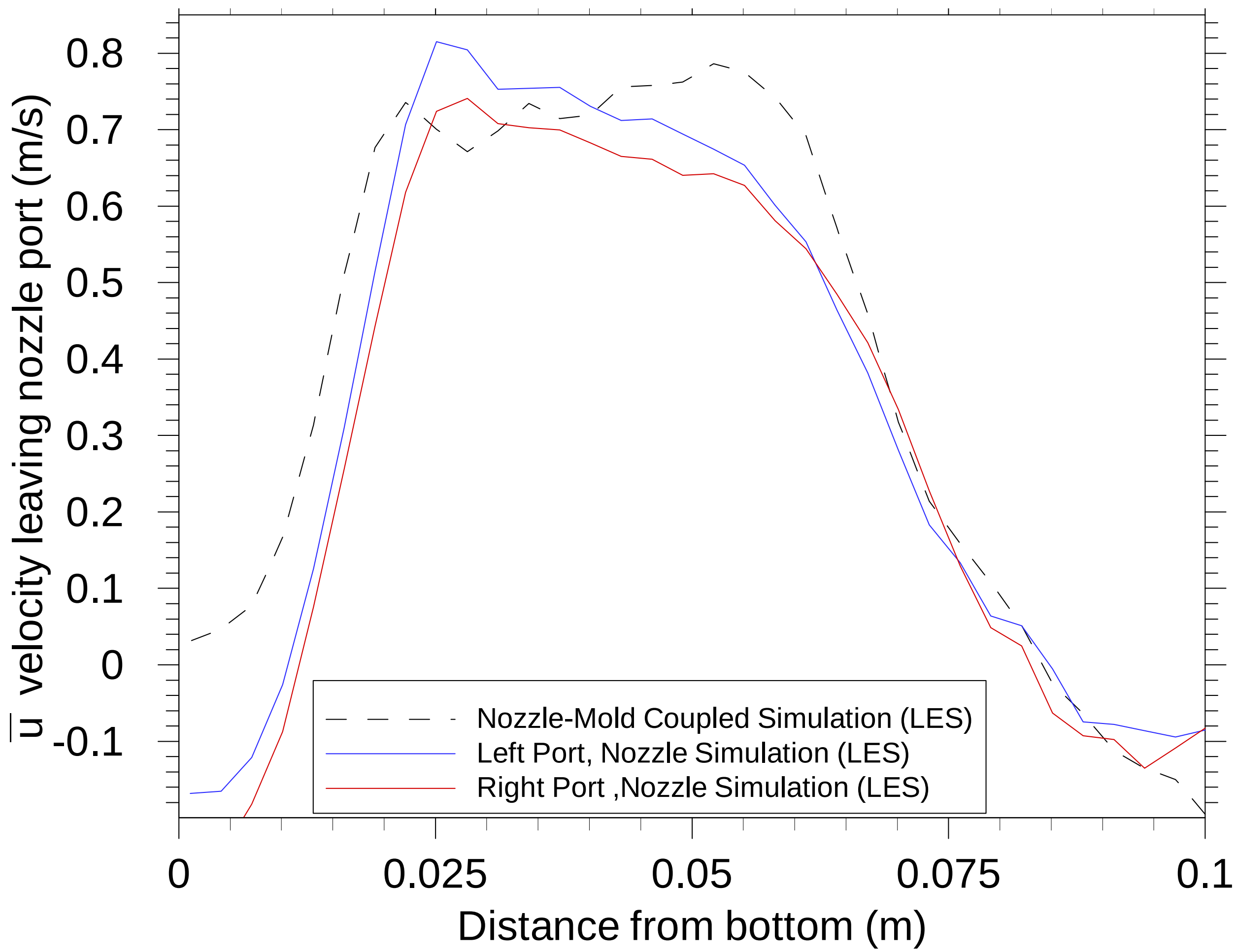


Video Clip

A Quick Review of Nozzle Simulation (Time-Average Velocities near Ports)

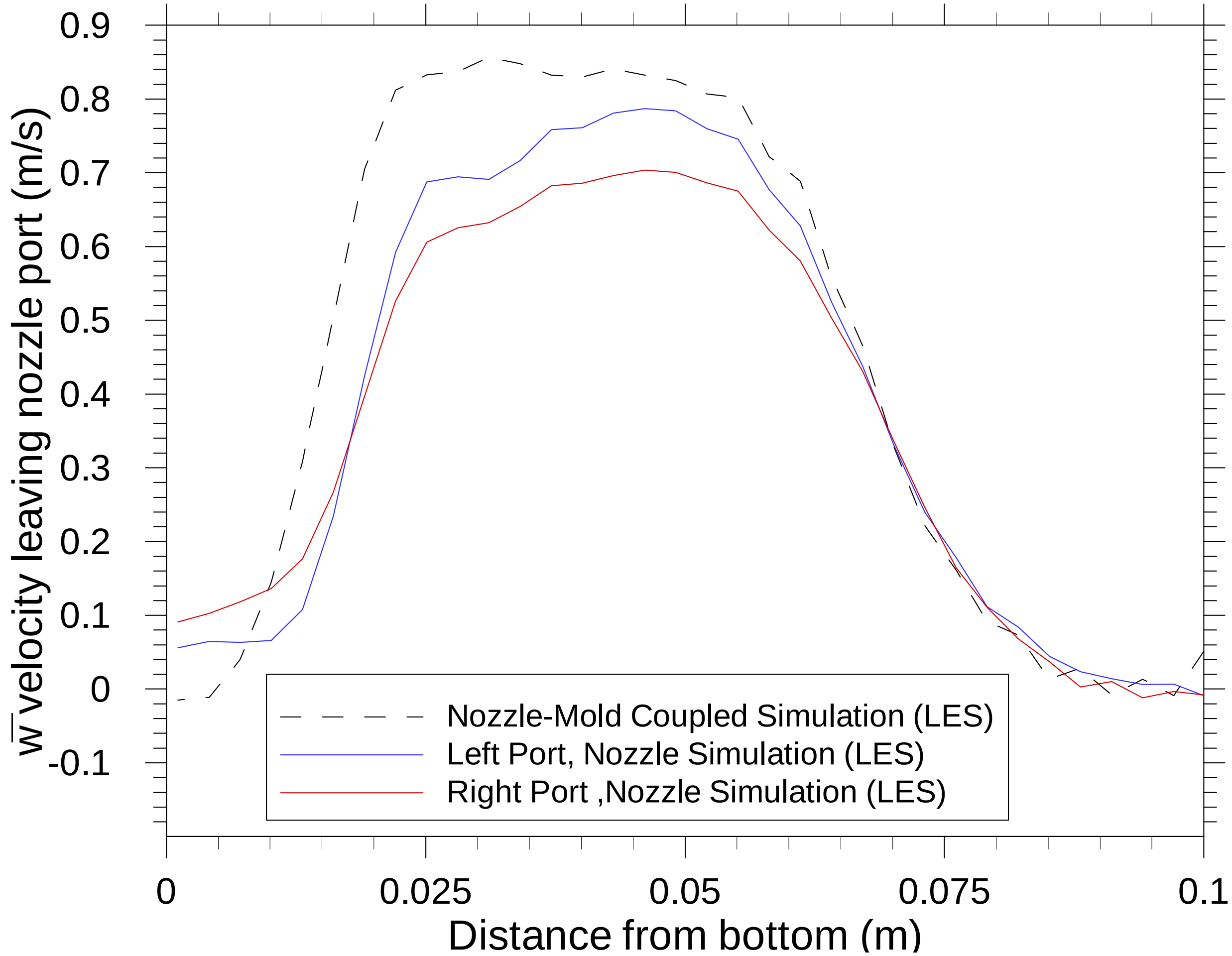


A Quick Review of Nozzle Simulation (Comparison of u Velocity along Jet)



Comparison of u velocity (normal to port) along vertical centerline
(Nozzle-Mold simulation results: B. Zhao, personal communication, 03/02)

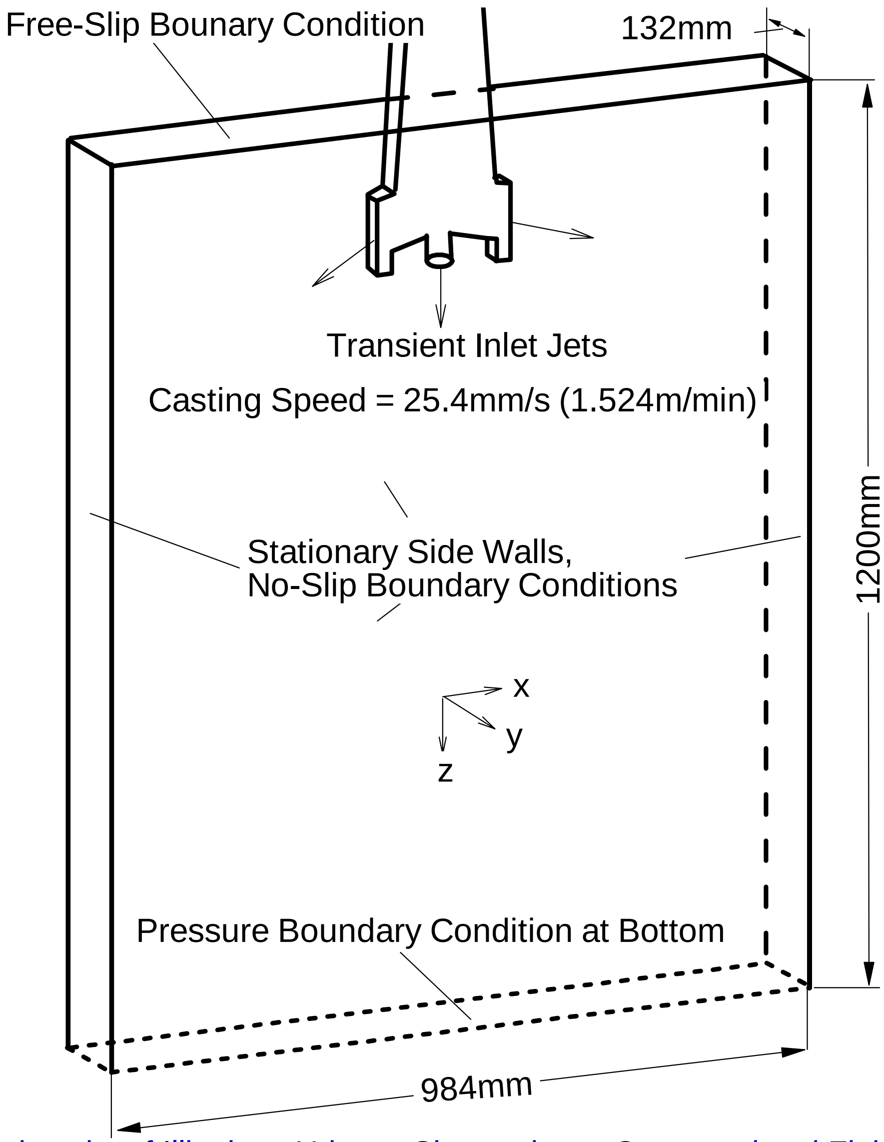
A Quick Review of Nozzle Simulation (Comparison of v Velocity along Jet)



Comparison of w velocity (downwards velocity) along vertical centerline (Nozzle-Mold simulation results: B. Zhao, personal communication, 03/02)

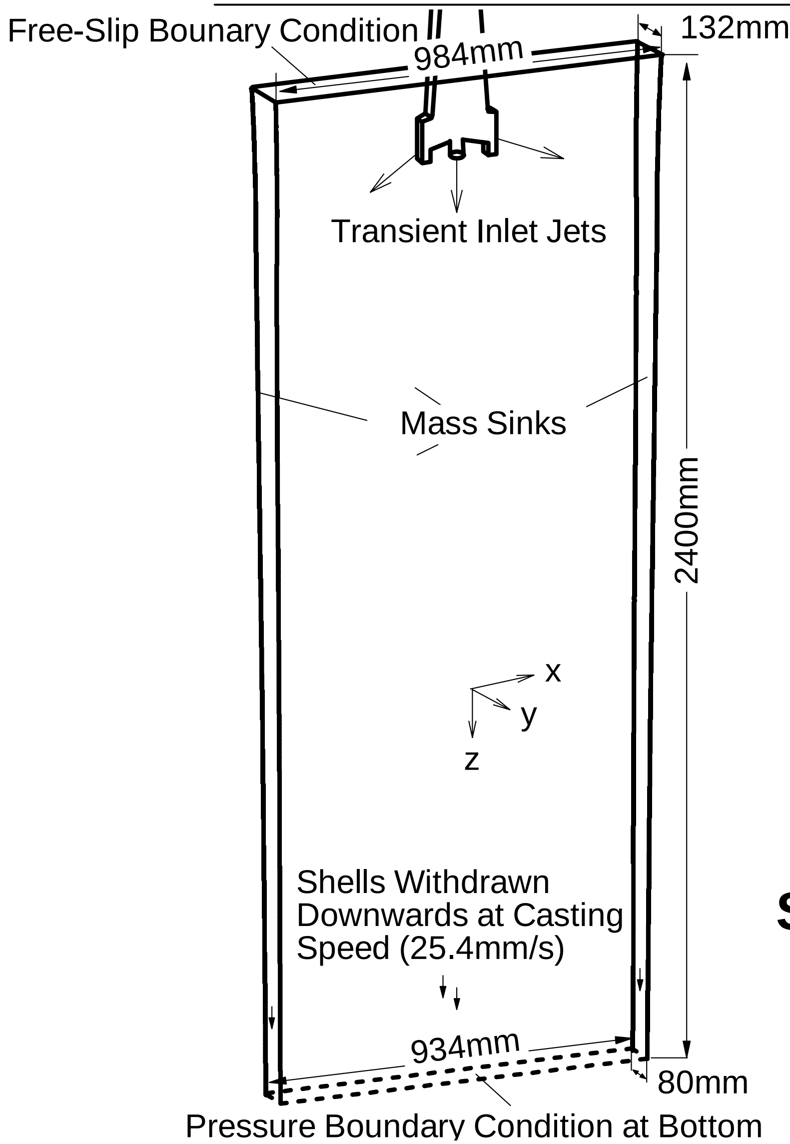
Large Eddy Simulation of Turbulent Fluid Flow in a Full-Scale Water Model and Steel Casting Machine

Schematic of Computational Domain

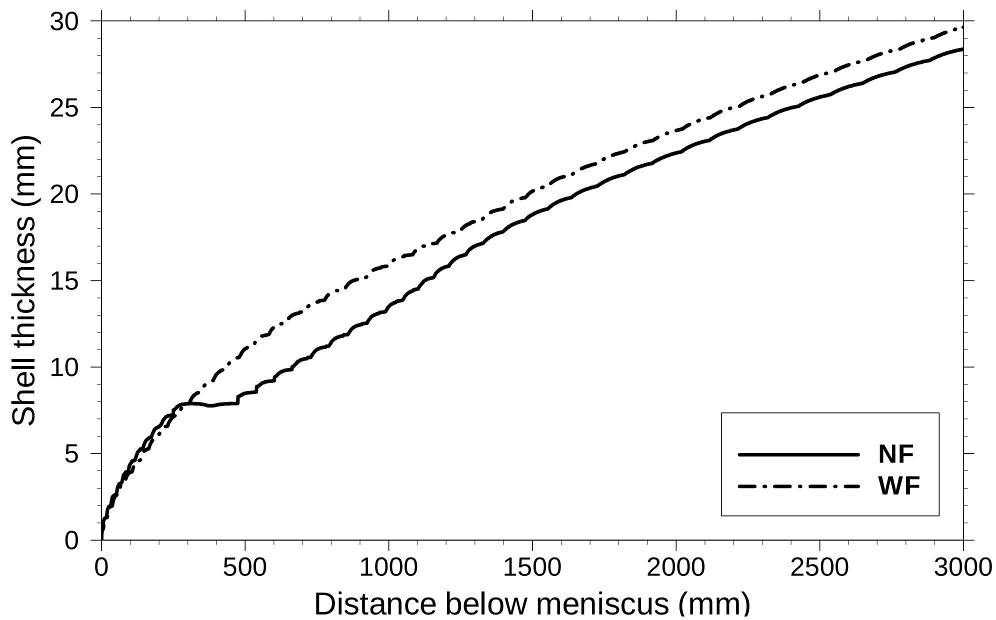


Domain for Full-Scale Water Model

Schematic of Computational Domain (ctd.)



Domain for Steel Casting Machine



Shell thickness is computed using CON1D

(by Ya Meng)

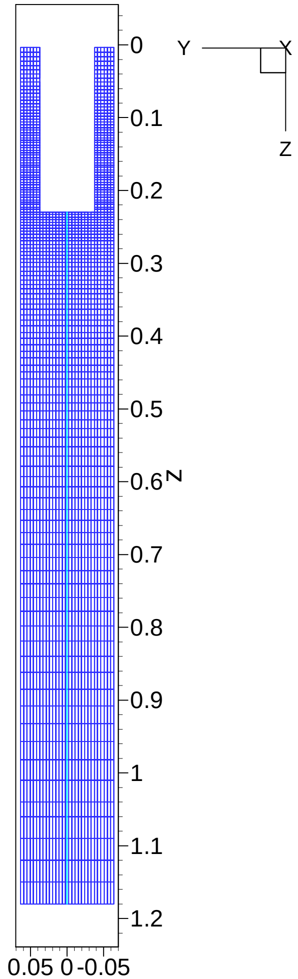
Properties and Conditions

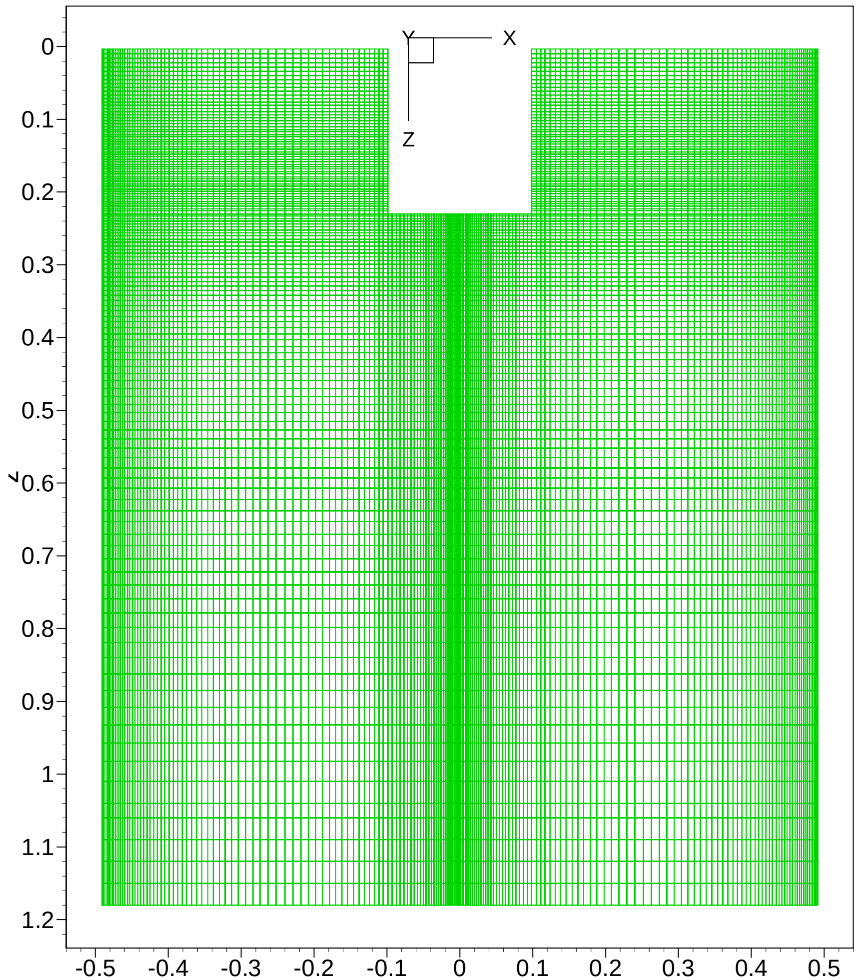
Parameter/Property	Water Model	Casting Machine
Mold Width (mm)	984	984
Mold Thickness (mm)	132	132
Water Model Length (mm)	2600	-
Mold Length (mm)	-	1200
Domain Width (mm)	984	984 (top) 934.04 (domain bottom)
Domain Thickness (mm)	132	132 (top) 79.48 (domain bottom)
Domain Length (mm)	1200	2400
Nozzle Port Height × Thickness (mm × mm)	75×32	75×32
Bottom nozzle Port Diameter (mm)	32	32
SEN Submergence Depth (mm)	127	127
Casting Speed (mm/s)	25.4	25.4
Dynamic Viscosity of Liquid Steel (m^2/s)	1.0×10^{-6}	7.98×10^{-7}

Computational Details

- 3D transient Navior-Stokes Equations
- 2nd – Order accuracy in space and time
- Non-Structured Cartesian collocation grid
- Algebraic Multi-Grid (AMG) solver is used to solve pressure Poisson Equation
- No sub-grid model (coarse grid DNS)
- 0.7 and 1.3 million computational cells for water model and casting machine simulations
- Mesh refinement is used for casting machine simulation
- 24-hour simulation on Pentium IV 1.7GHz 1GB PC generates 3s transient flow results in real(Δt=0.001s, 1.3 million cells)

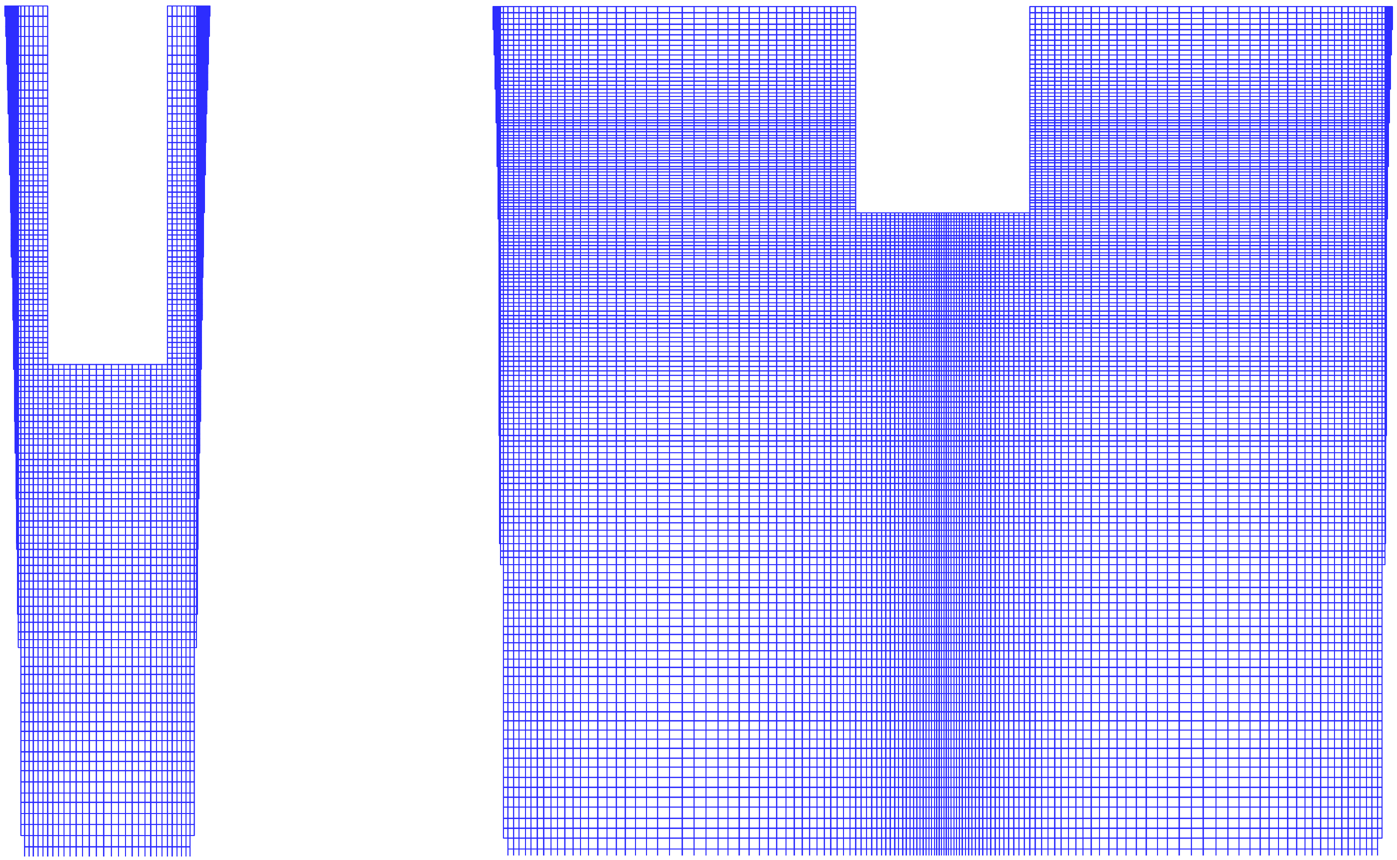
Computational Mesh





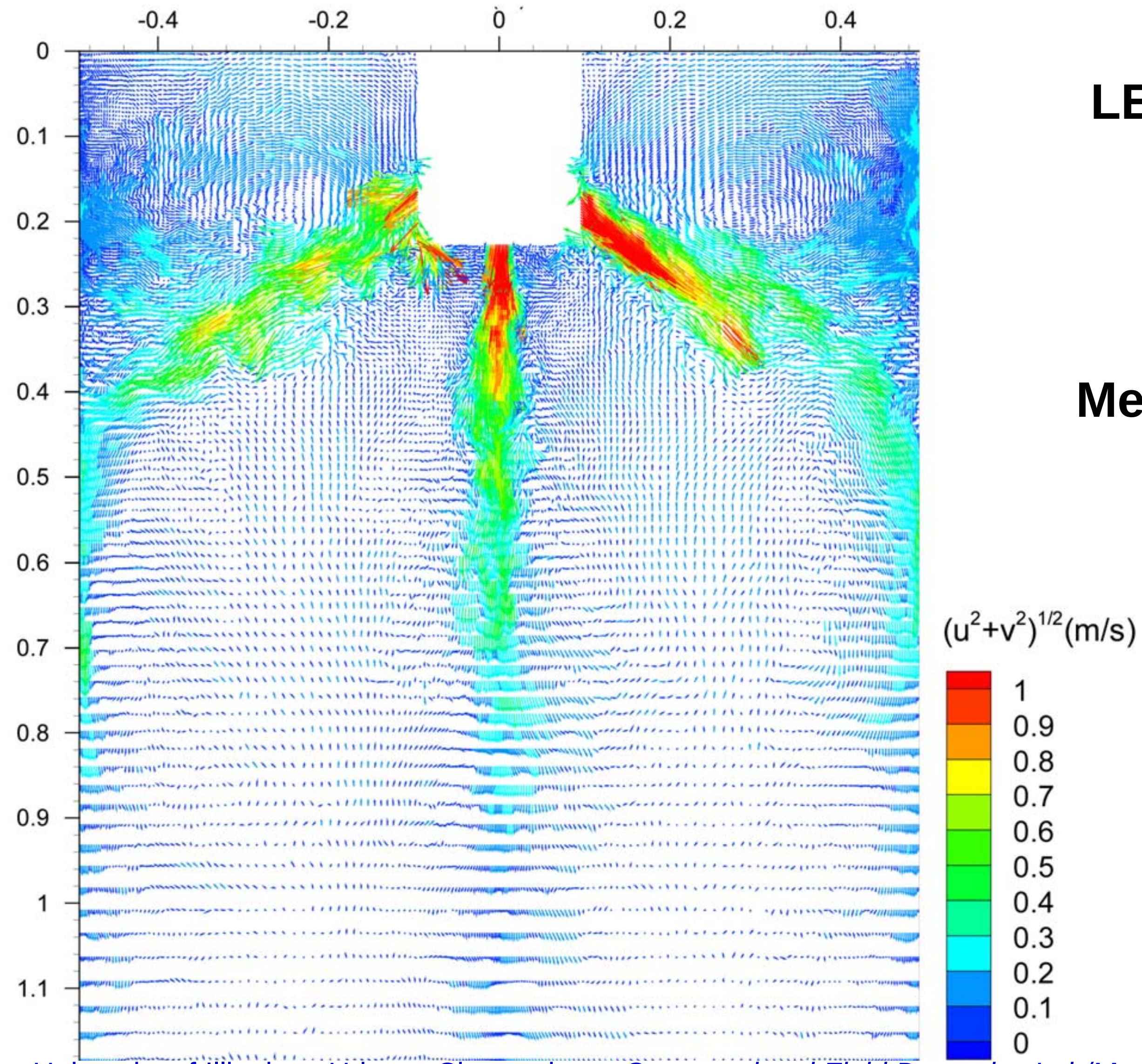
Center planes of water model between Narrowfaces and Widefaces

Computational Mesh (ctd.)



Center planes of casting machine between Narrowfaces and Widefaces (Upper region)

Transient Flow in Water Model



LES

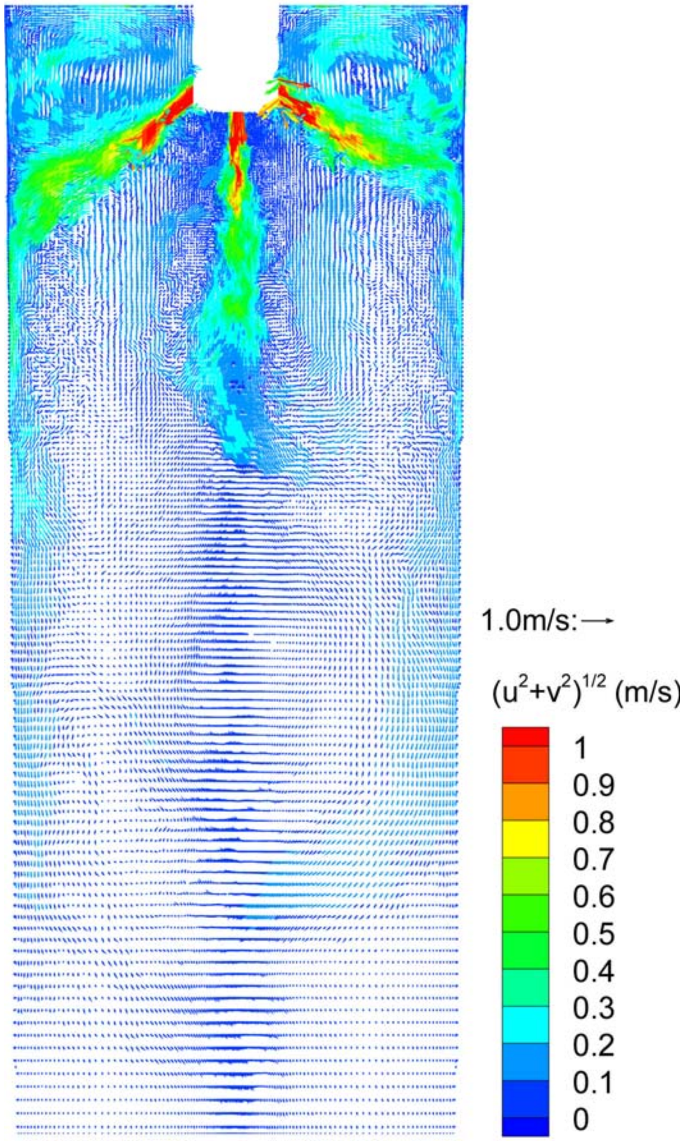
Video Clip

Measured dye injection

Video Clip

Continuous Casting Consortium

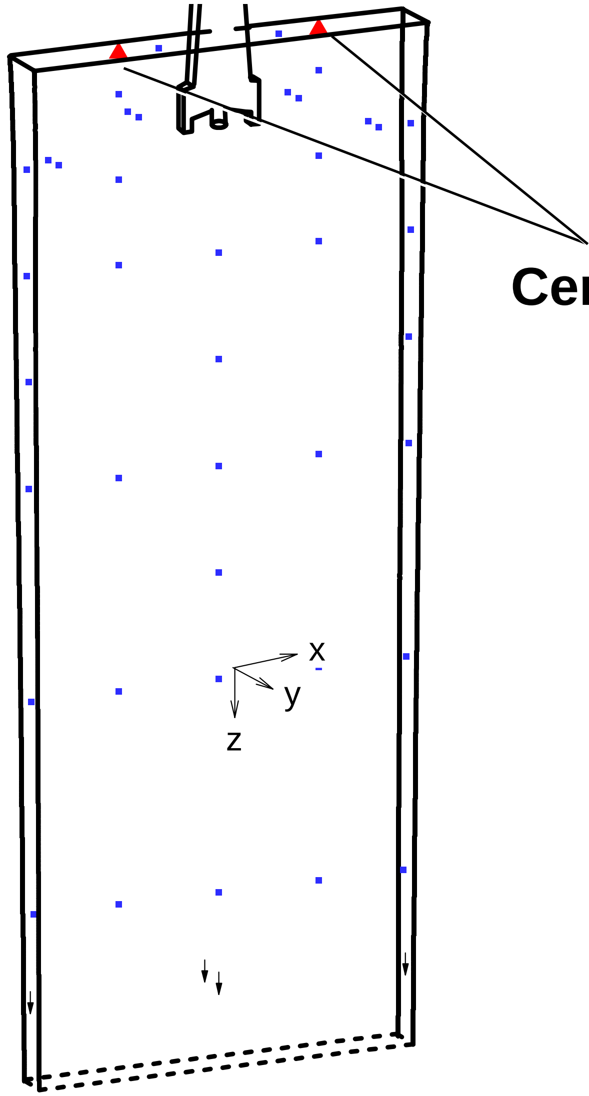
Transient Flow in Casting Machine



LES:

Video Clip

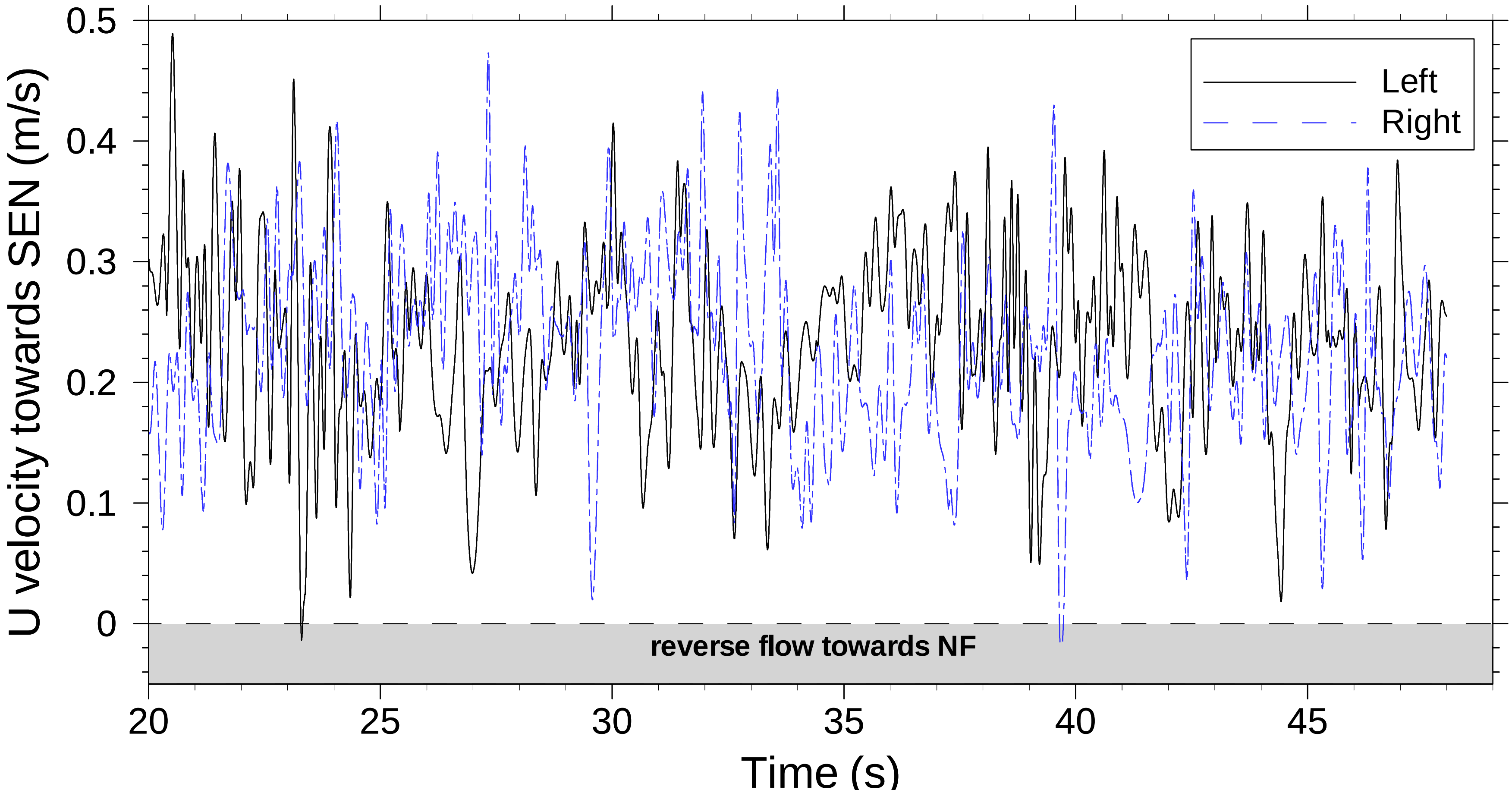
Monitoring Point Locations



Center points on top surface

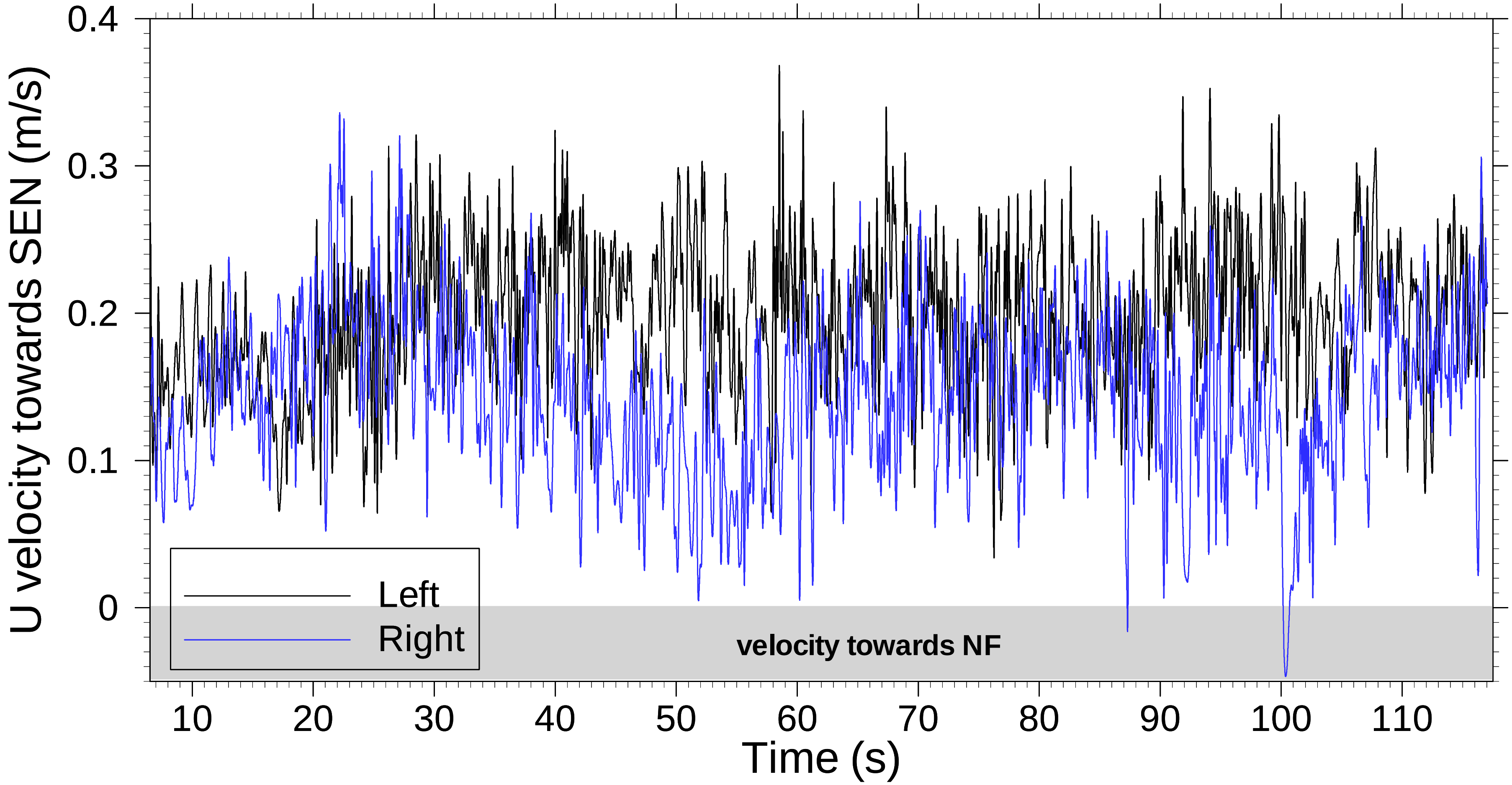
(246mm from NF)

Time History of Top Surface Velocity



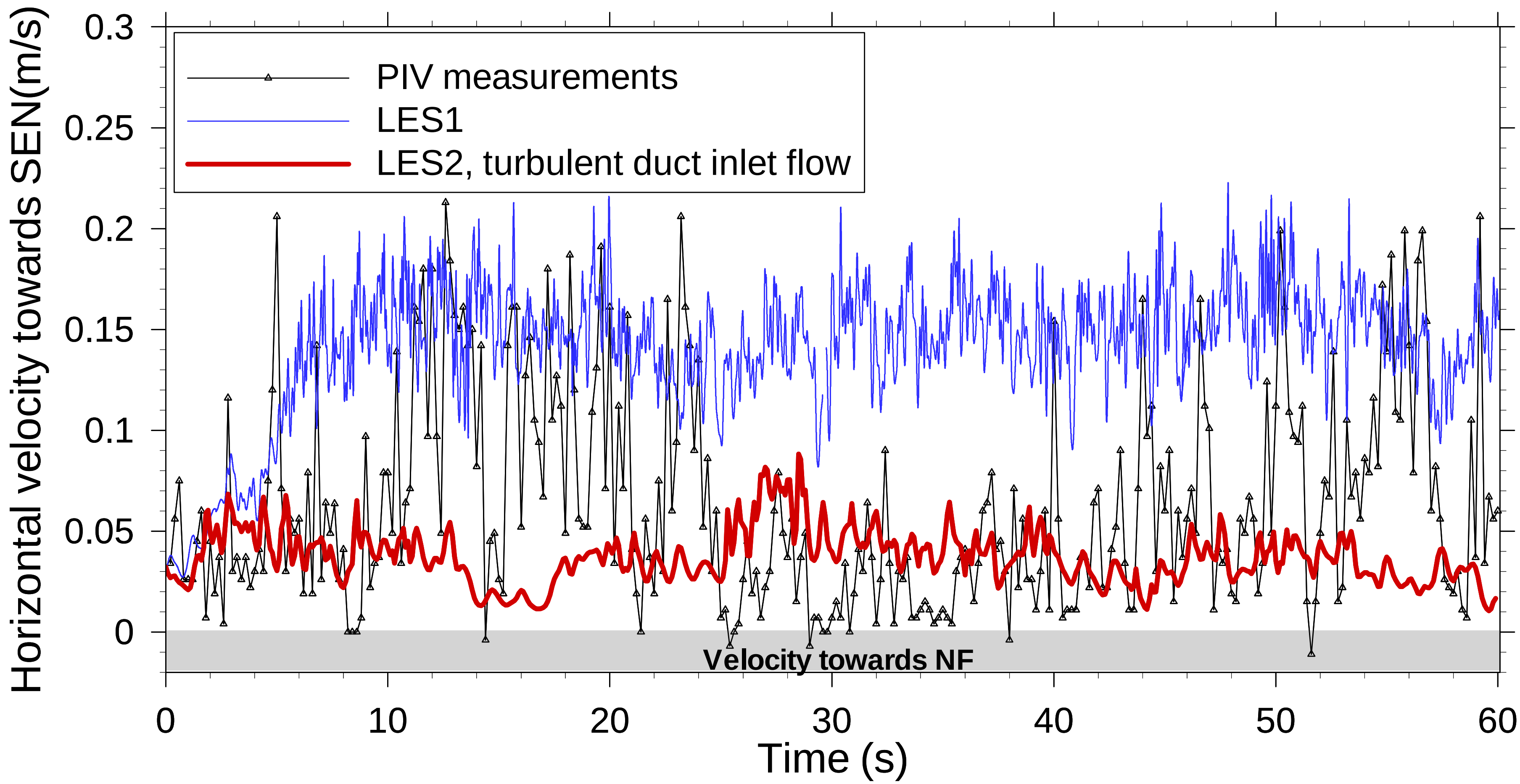
Horizontal Velocity towards SEN at top surface center points (casting machine)

Time History of Top Surface Velocity (ctd.)



Horizontal Velocity towards SEN at top surface center points (full-scale water model)

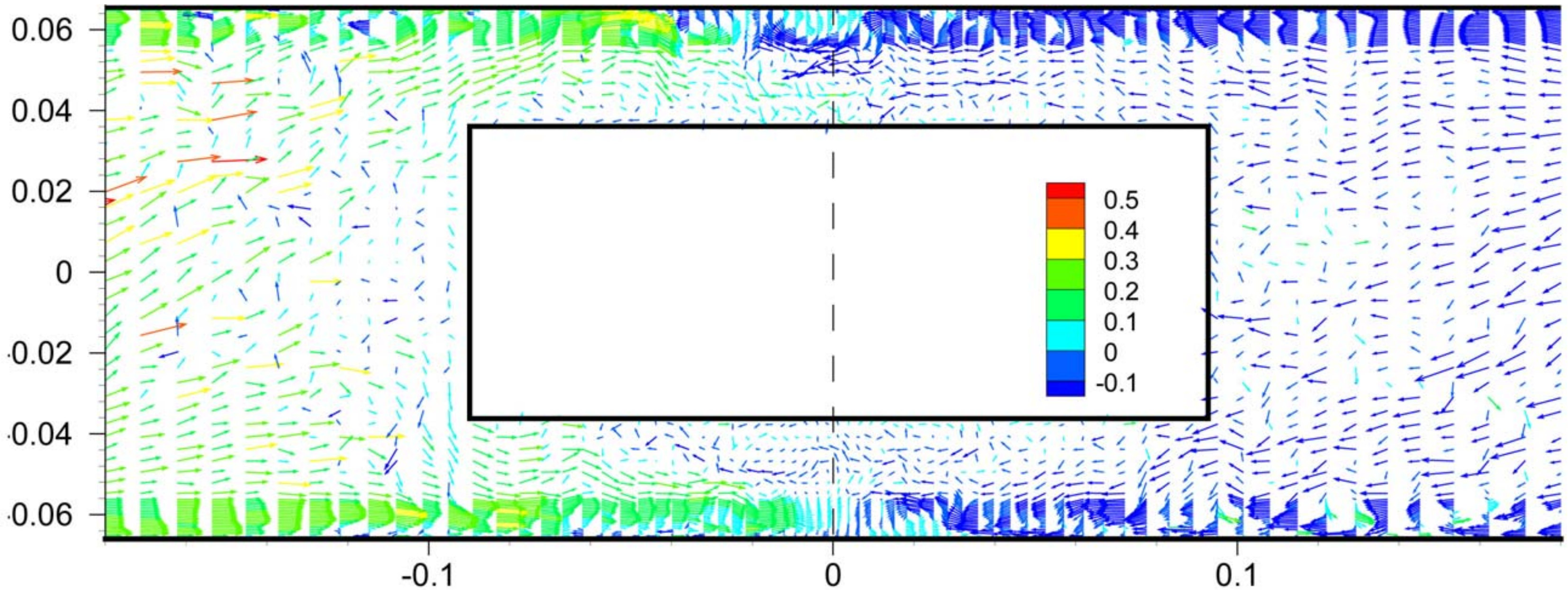
Time History of Top Surface Velocity (ctd.)



Horizontal Velocity towards SEN at top surface center points

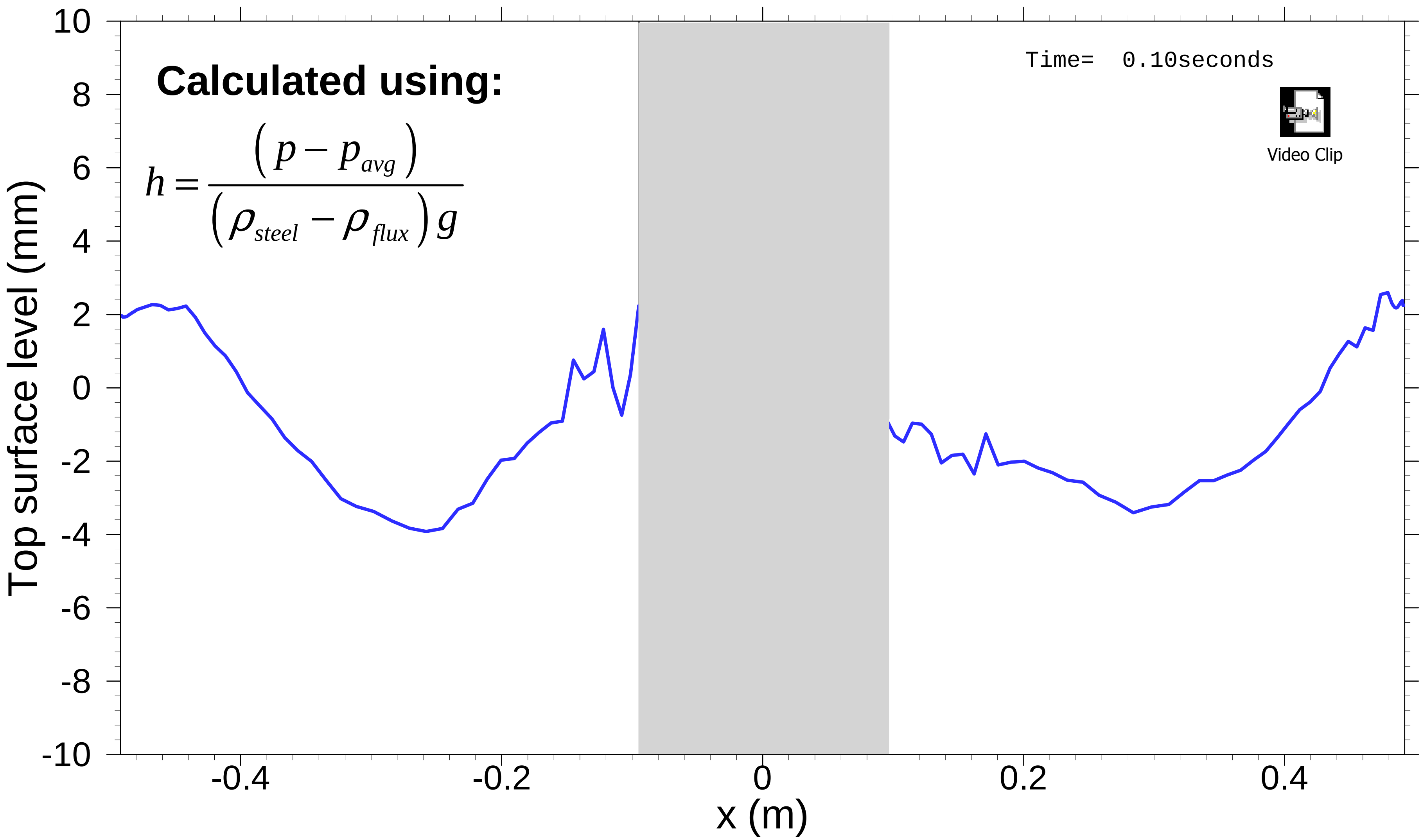
(0.4-scale water model, half mold simulation for LES)

Top Surface Velocity Fluctuations



Video Clip

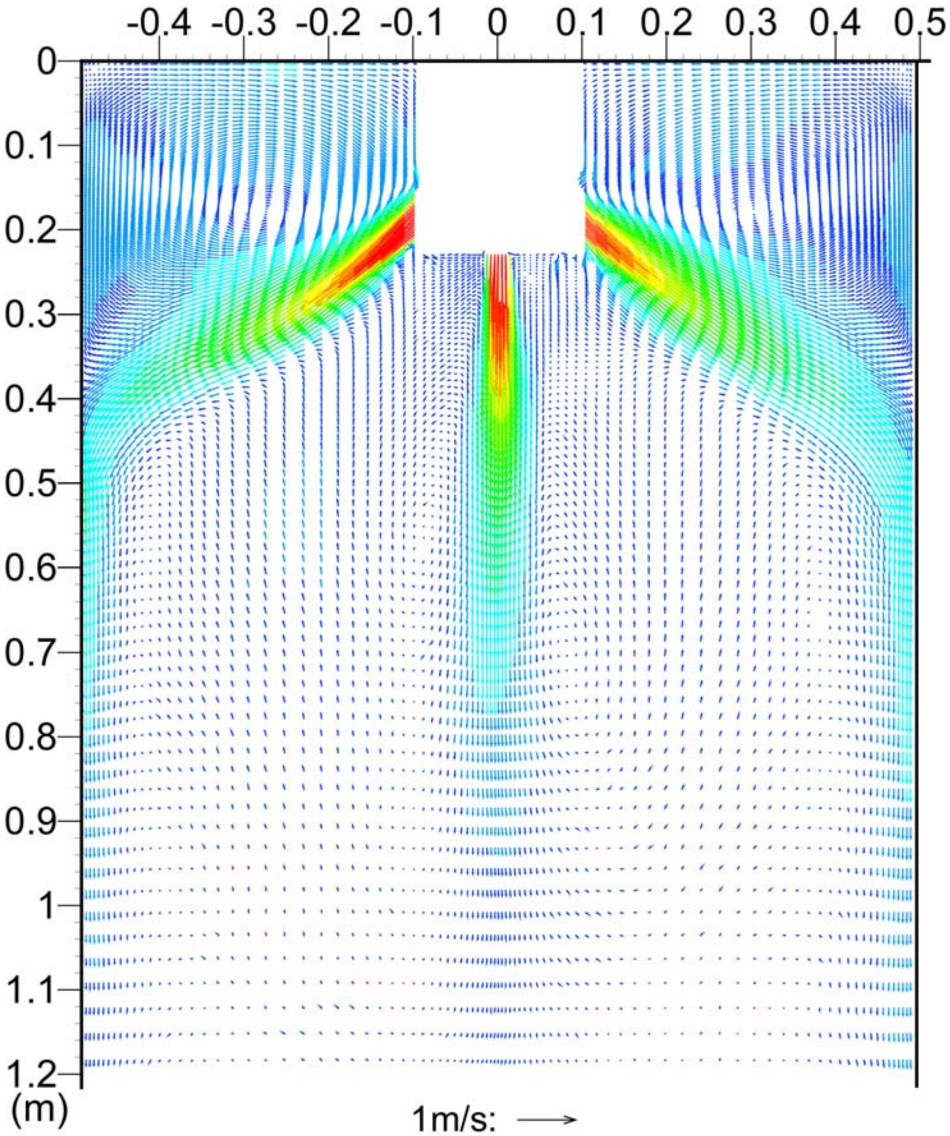
Approximated Top Level Fluctuation



Calculated using:

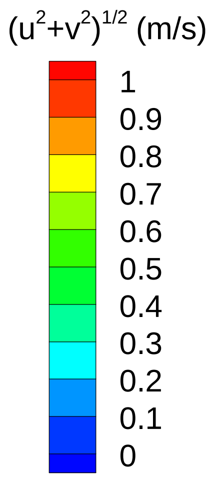
$$h = \frac{\left(p - p_{avg}\right)}{\left(\rho_{steel} - \rho_{flux}\right) g}$$

Time Averaged Flow Field - Water

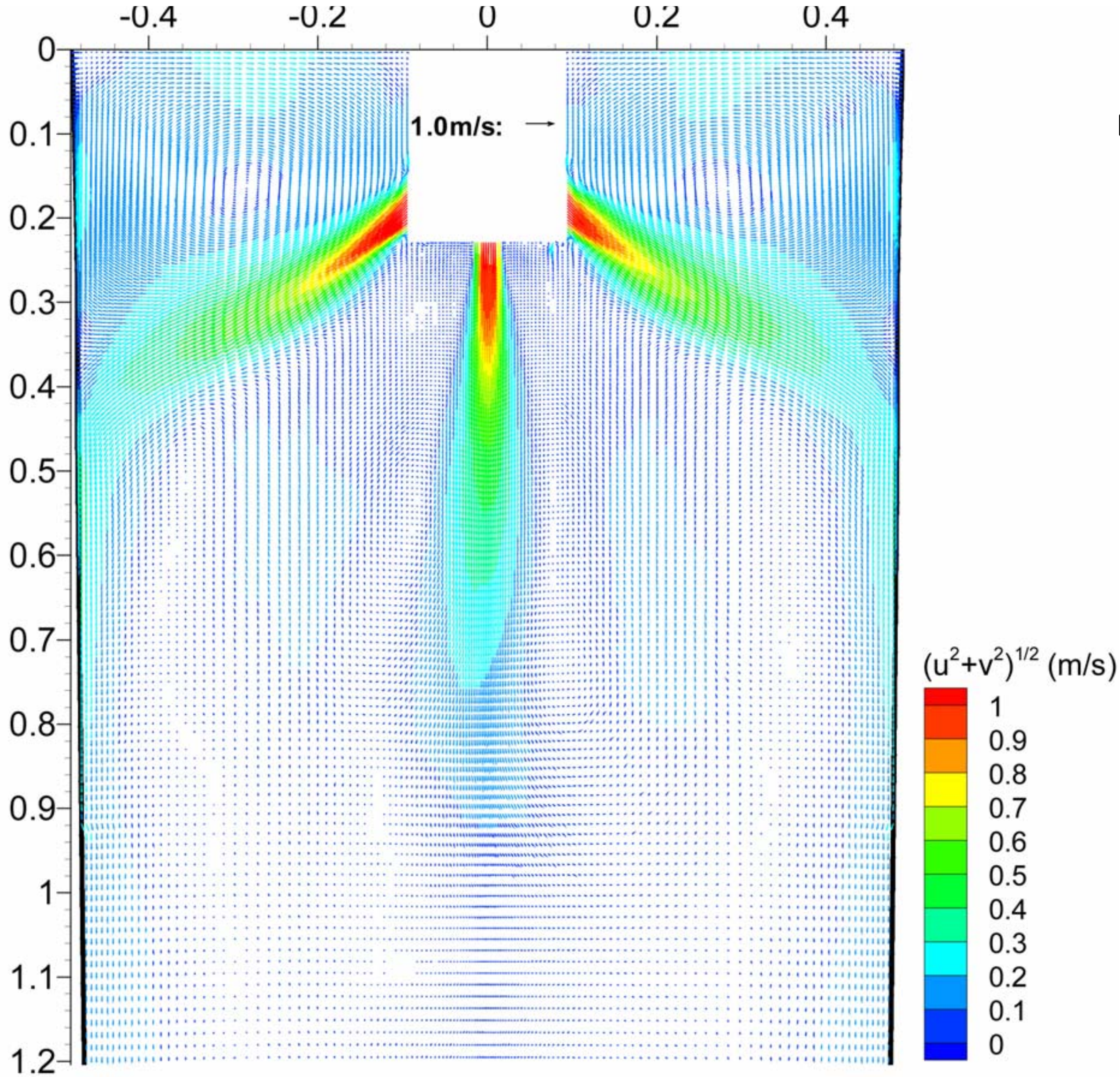


Full-scale water model, center plane

(time-averaged over 48.5s)



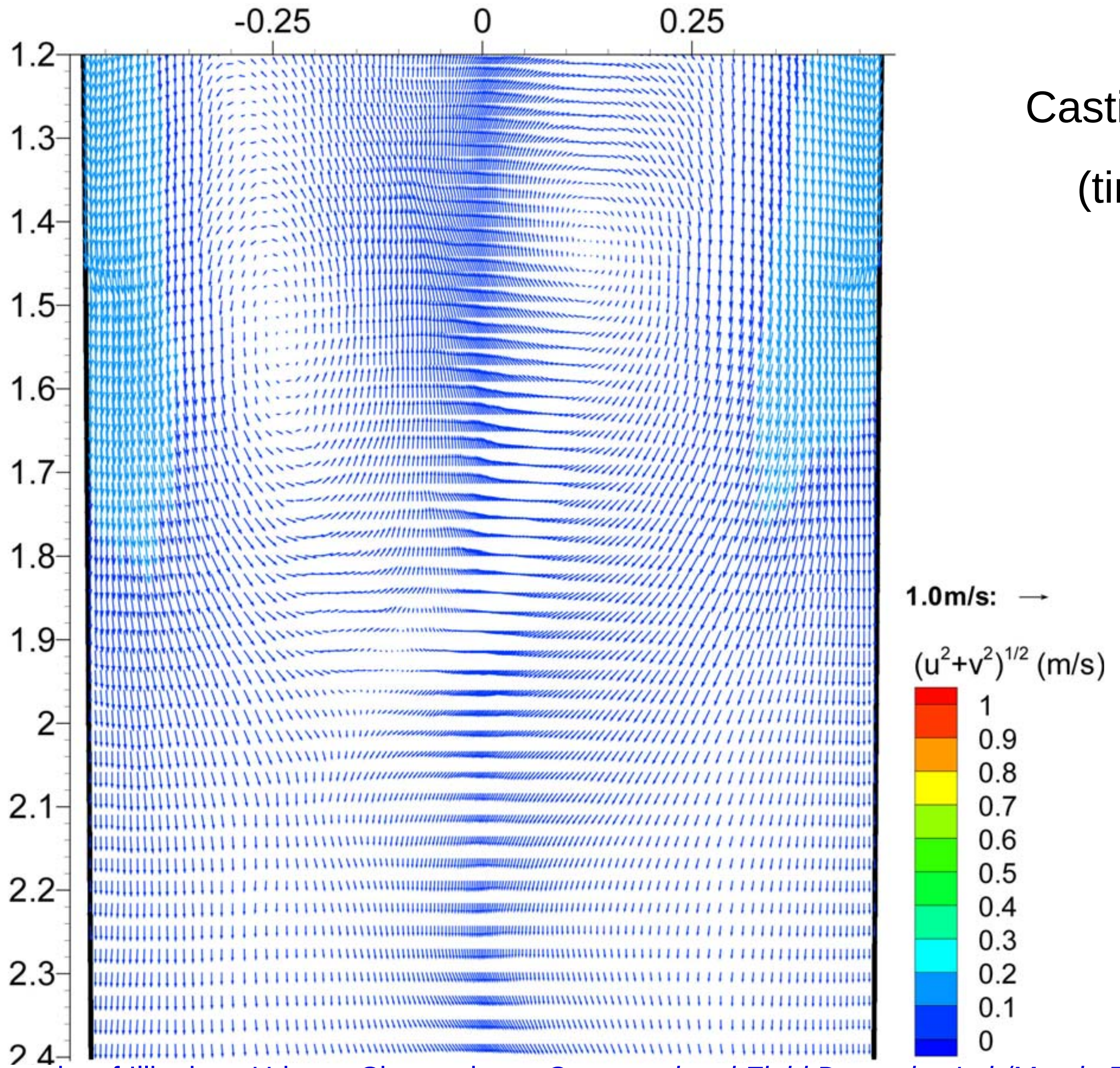
Time Averaged Flow Field - Steel



Casting machine, center plane

(time-averaged over 28s)

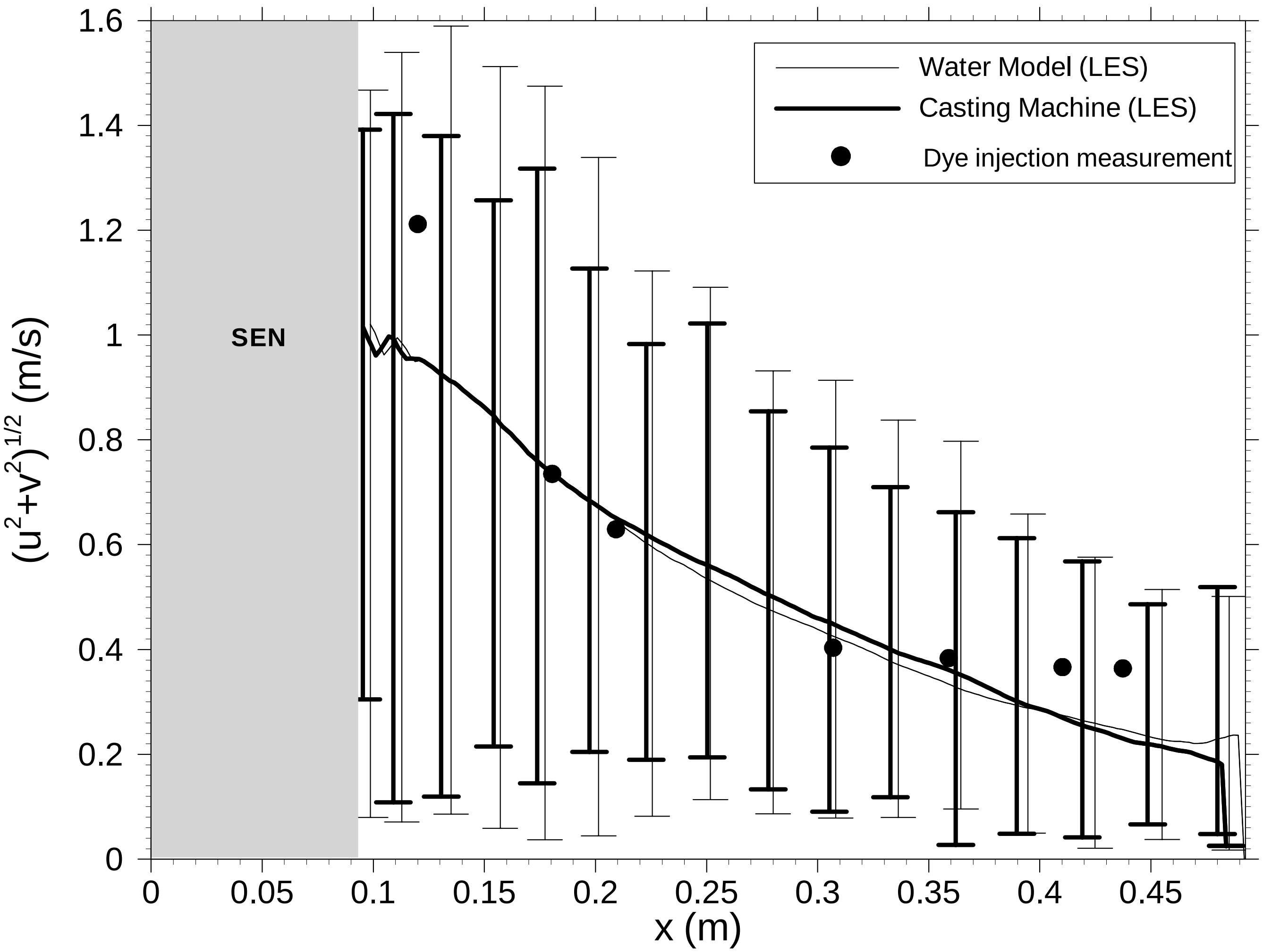
Time Averaged Flow Field - Lower



Casting machine, center plane

(time-averaged over 28s)

Comparison with Measurements



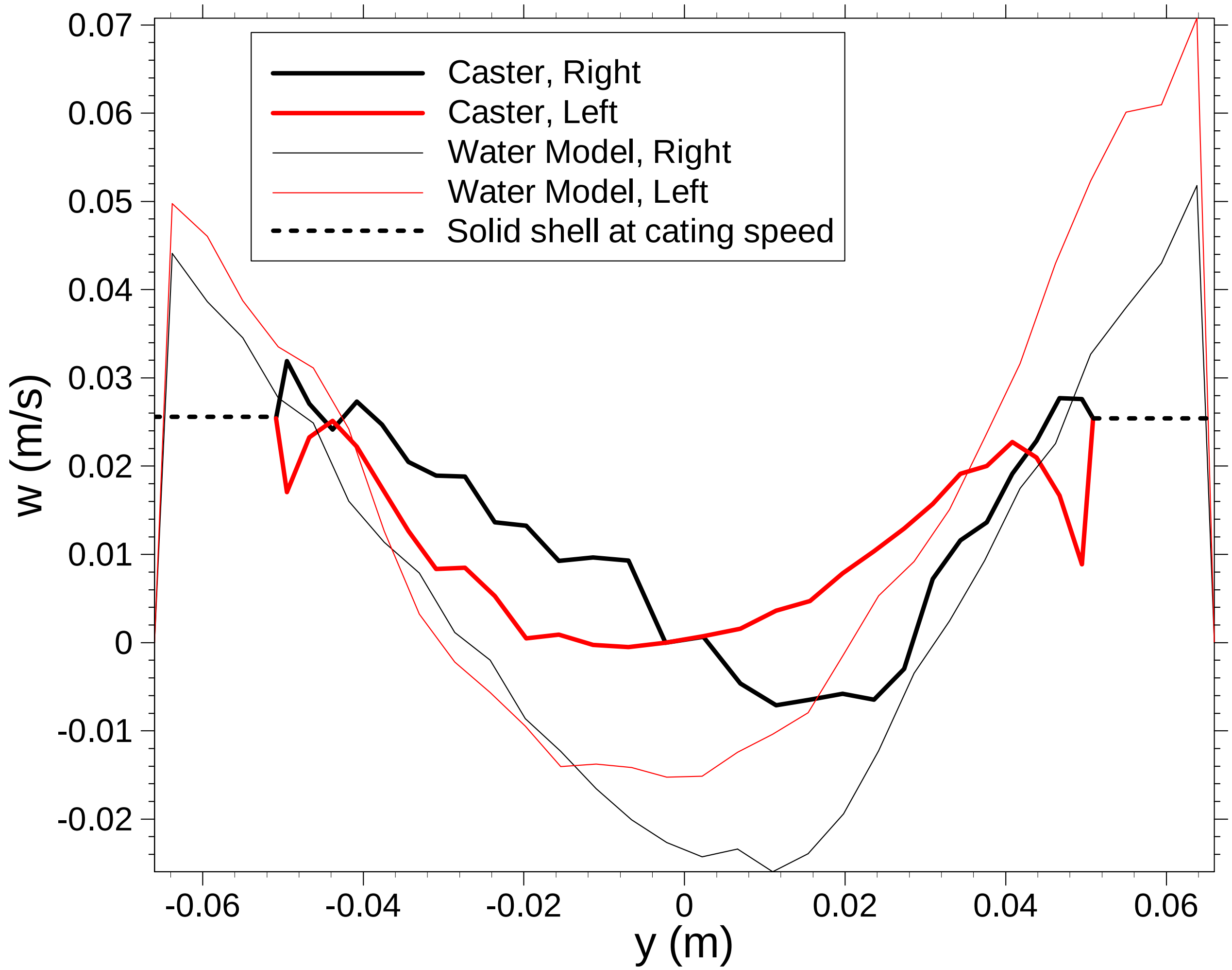
Comparison of speed $(u^2+v^2)^{1/2}$ along the jet center line

Bars mean

Min and max

computed

Downward Velocity Comparisons



Two comparisons:

Water model vs.

Steel caster

left vs. right side

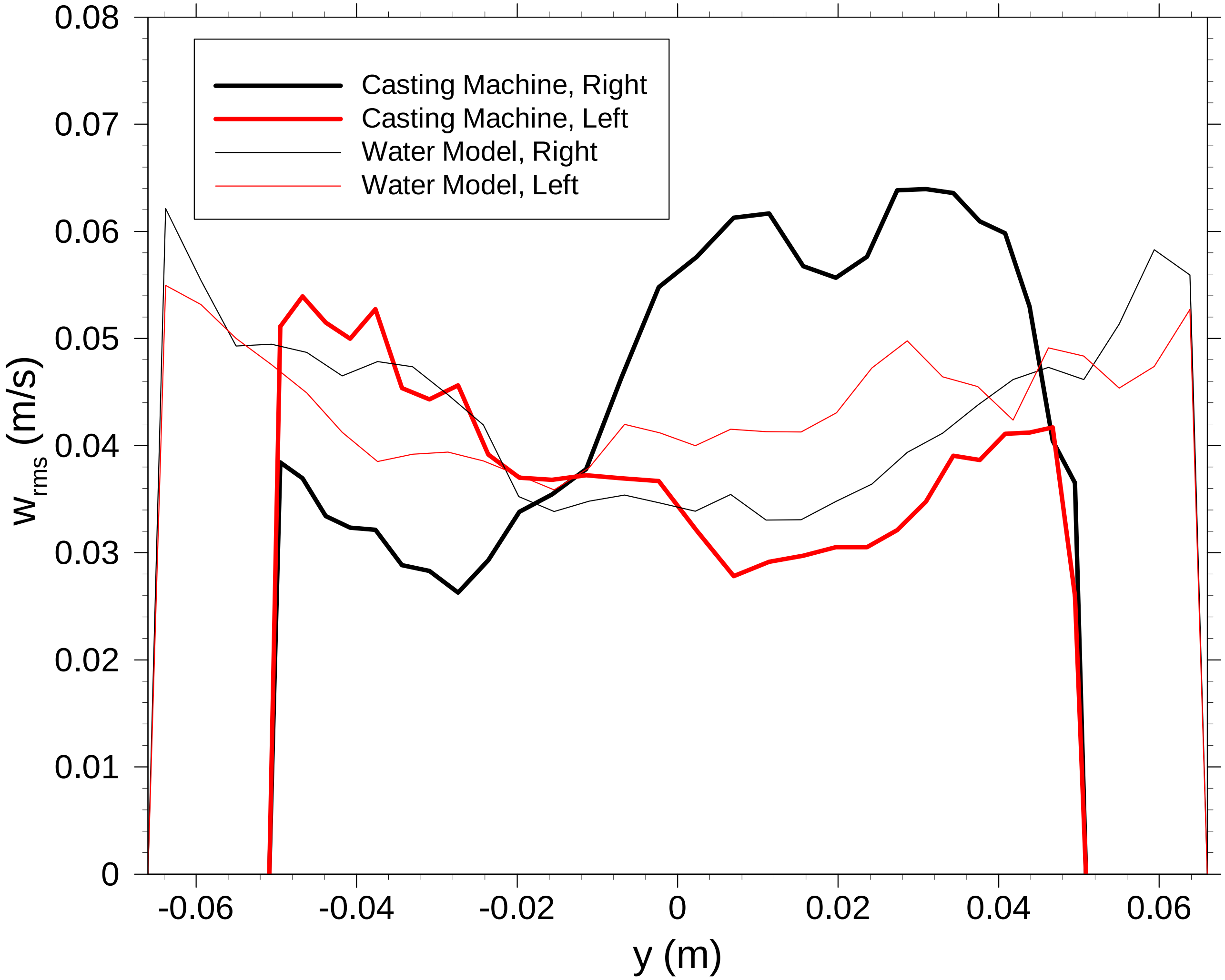
Time averaged for

48.5s (water)

28s (steel)

Comparison of the downwards velocity (w) along the horizontal line 1m below top surface, 164mm from NF

Velocity Fluctuation Comparisons



Comparison of *rms* of the downwards velocity(w) along the horizontal line 1m below top surface, 164mm from NF

Time length for *rms*:

Water model: 27 s

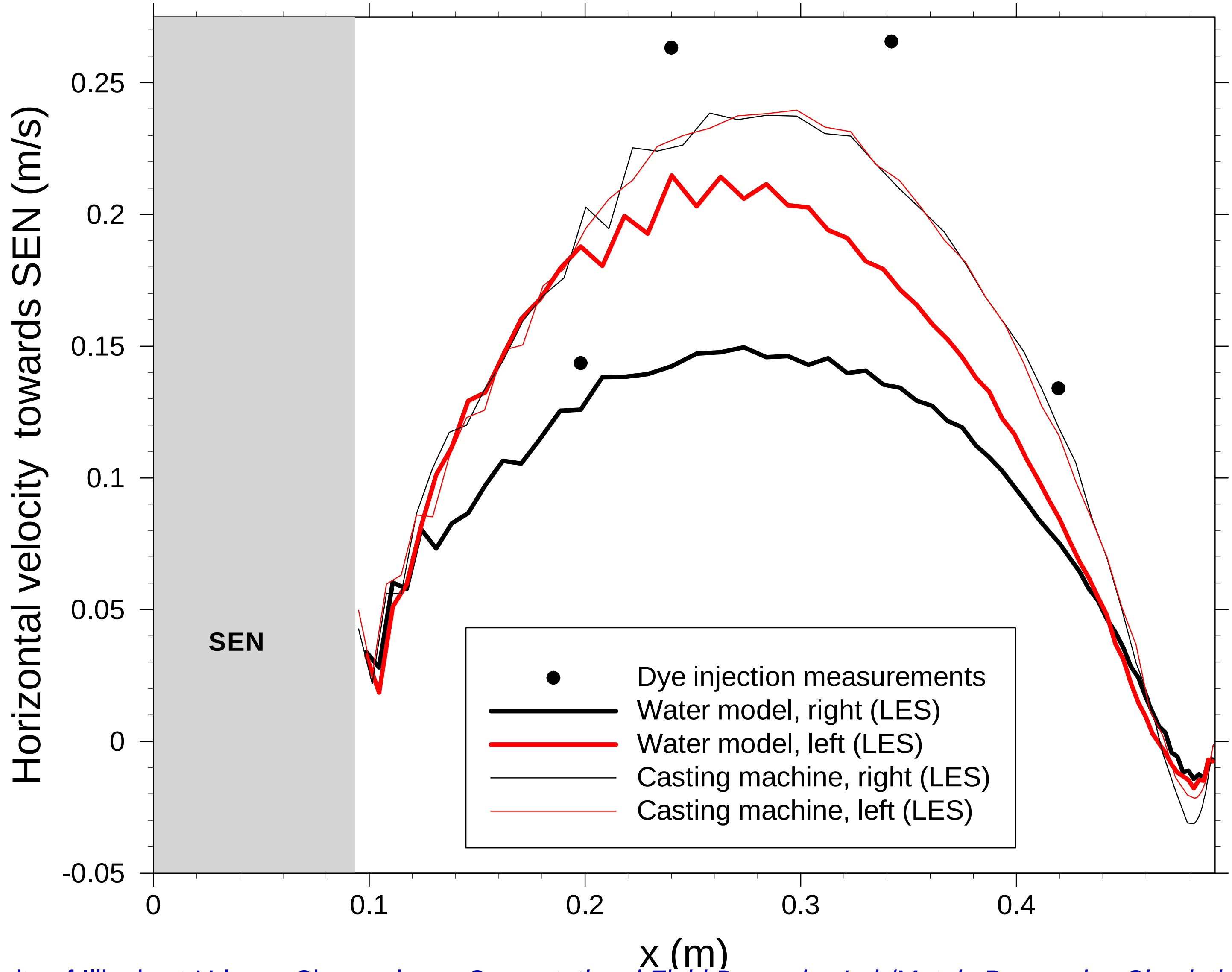
Casting machine: 6s

Reminder:

$$rms = \sqrt{\frac{\sum_{i=1}^{N}\left(u-\overline{u}\right)^2}{N}}$$

where $\overline{u}$ is the mean of *u.*

Top Surface Velocity - Time-Averaged

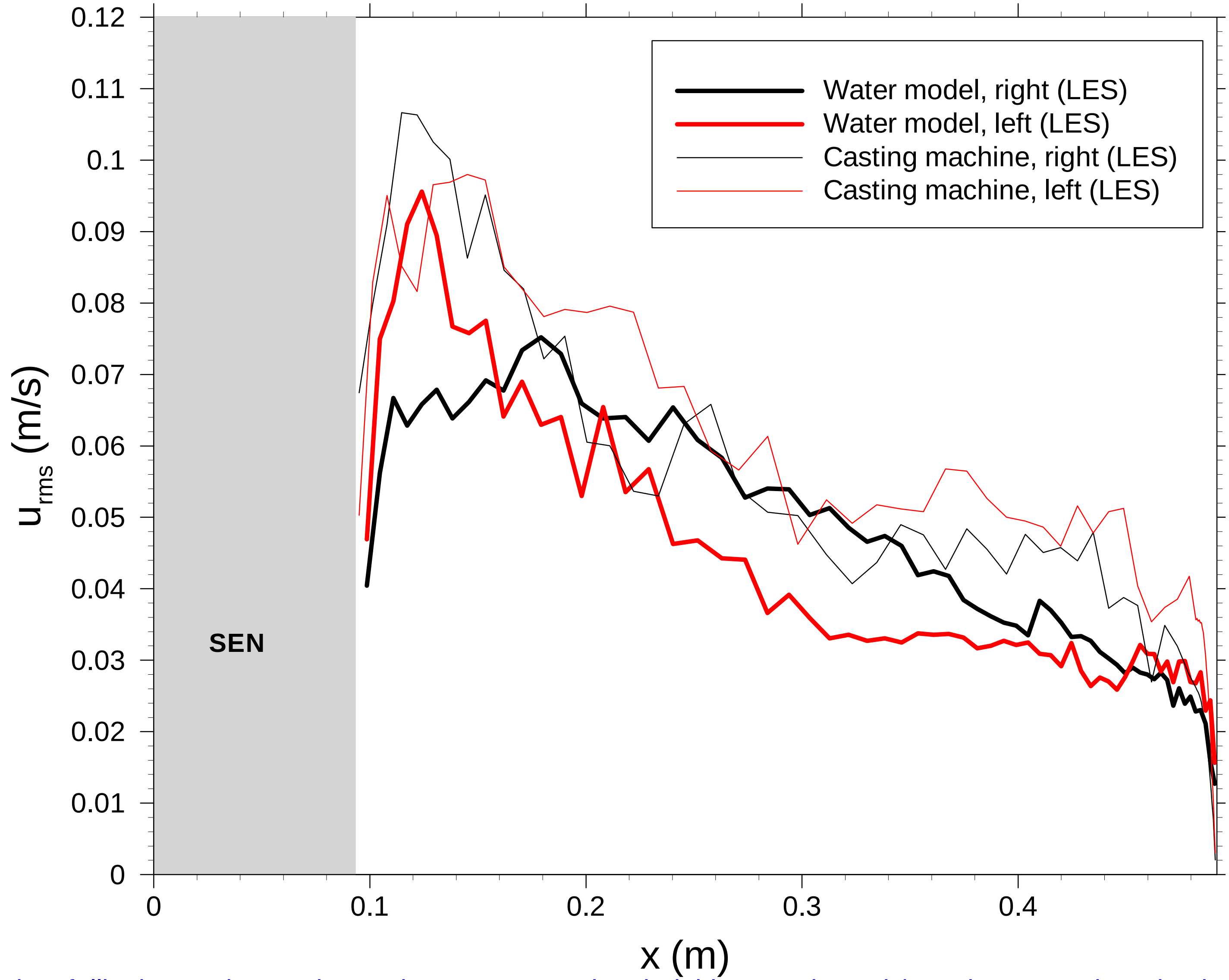


Time averaged for

48.5s (water)

28s (steel)

Top Surface Velocity - *rms*



Time averaged for

27s (water)

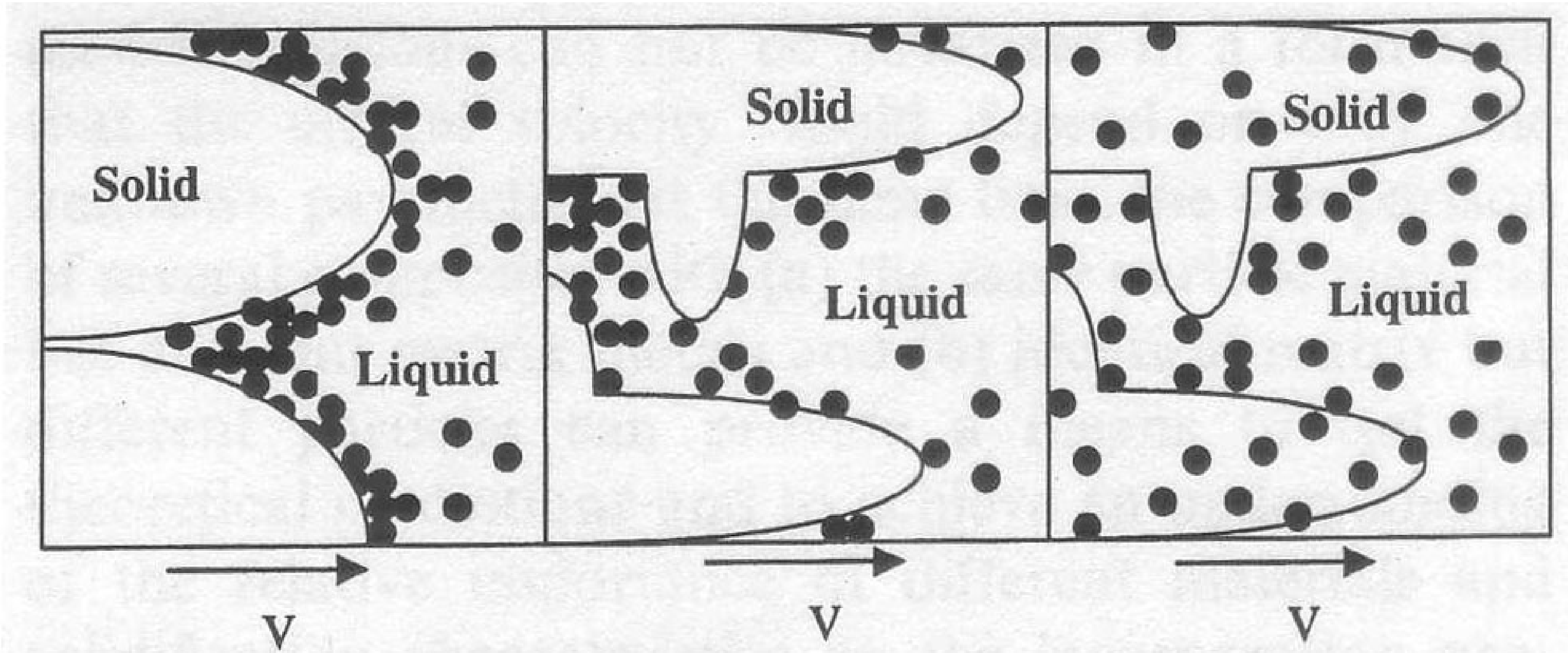
6s (steel)

Observations

- CART3D is capable of simulating the transient flow phenomena during continuous casting
- Significant velocity fluctuations on top surface are most likely caused by the interaction of the flow in the two sides of the mold to SEN
- Downward velocity in the lower region (beneath jet impingment points) in steel casters may be more evenly distributed across the width than in water models
- Flow asymmetry is seen between two sides of the mold

Particle Transport and Entrapment in Continuous Slab Casting Machine

Inclusion Capture Mechanisms (review)

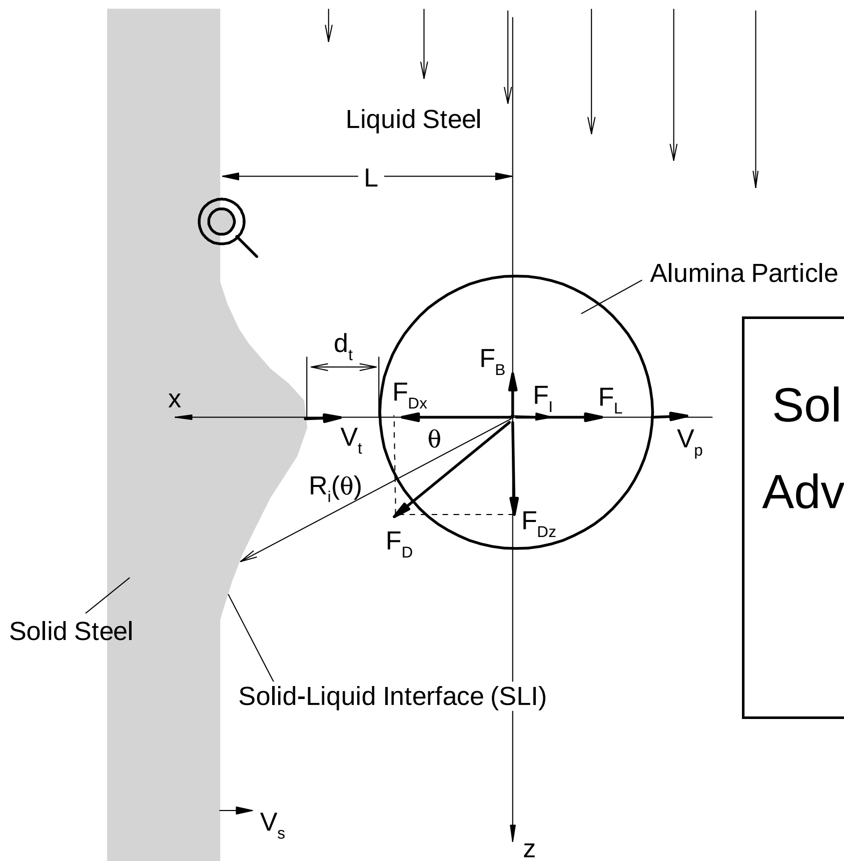


pushing **entrapment** **engulfment**

Previous studies focus on particle pushing/engulfment and sometimes entrapment for quiescent solidifying problems, in which molten matrix has no bulk velocity to wash the particles away.

From: G. Wilde, J.H. Perepezko, Experimental Study of Particle Incorporation during Dendritic Solidification, Materials Science & Engineering A283, 2000, p.25-37.

Concept of Critical Velocity (review)



Particle approaching to the solidifying front results in many forces (predominantly Van der Waals force and drag force) acting on it. The critical velocity(V_{cr}) is the velocity:

Solidifying Front Advancing Speed $\geq$ V_{cr} ⇨ Particle engulfment

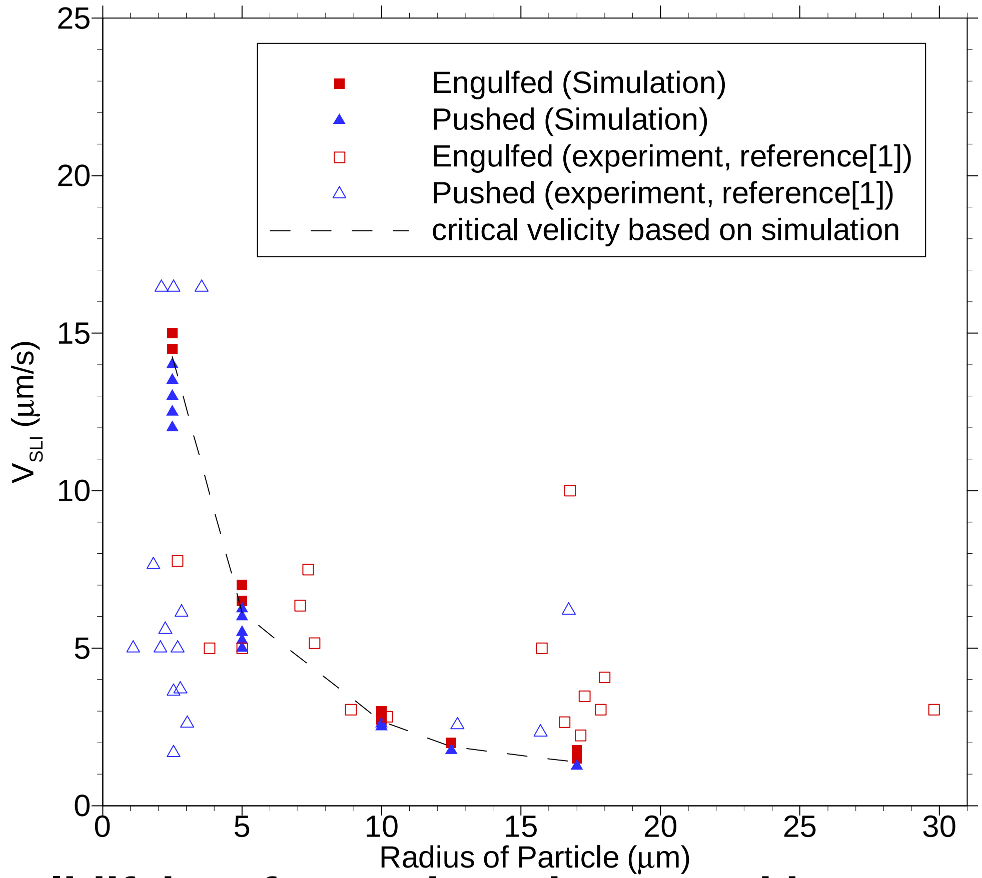
If not ⇨ Particle pushing

Particle entrapment was reported easier than engulfment*.

*From: G. Wilde, J.H. Perepezko, Experimental Study of Particle Incorporation during Dendritic Solidification, Materials Science & Engineering A283, 2000, p.25-37.

Critical Velocities of Aluminum Particles in Molten Steel

Parameter	*Value*
Density of Liquid Steel	7020 Kg/m^3
Thermal Conductivity of Liquid Steel	30 W/m-K
Density of Alumina Inclusion	2700 Kg/m^3
Thermal Conductivity of Alumina	5.5 W/m-K
$\Delta\sigma_0$	0.224 N/m
Atomic diameter of fluid	2.5×10^{-10} m

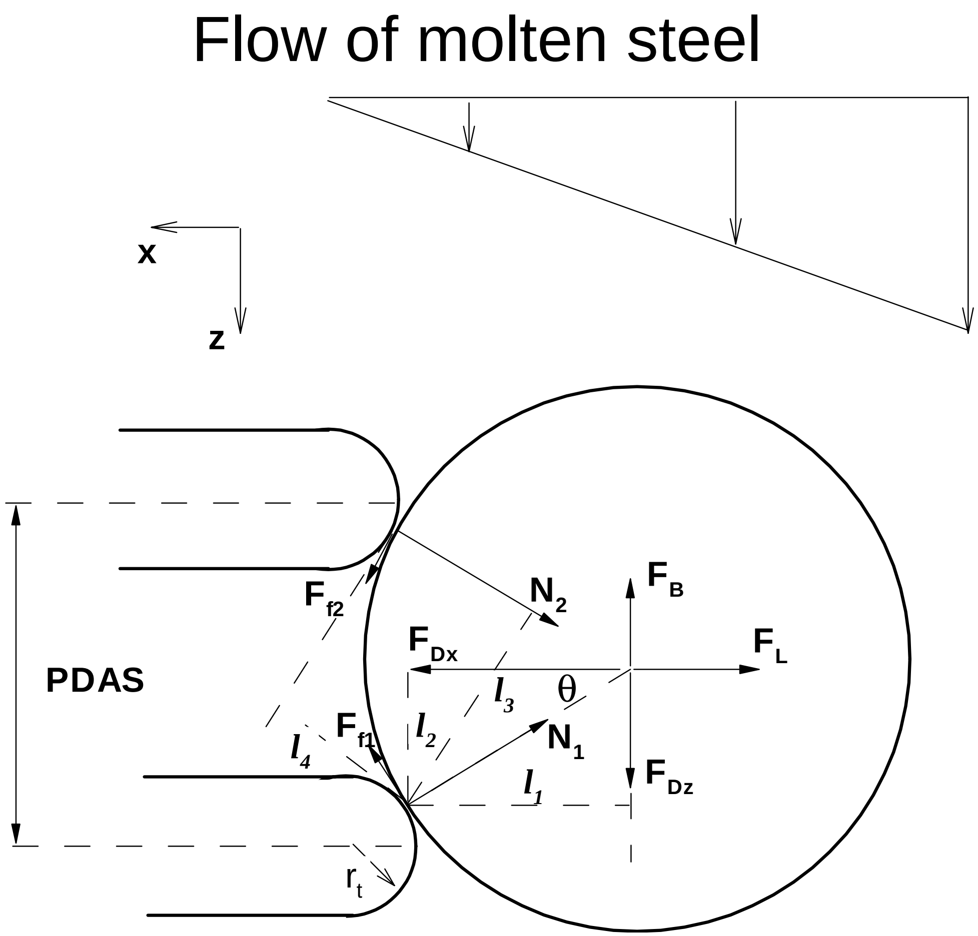


Observations:

In continuous casting process, the solidifying front advancing speed is estimated to be ≥ 200μm/s at the mold exit*, which is much bigger than the critical velocities of any nonnegligible particles.

*From: Quan Yuan, Report of Class ME497, Dept. of Mechanical Engr., Univ. of Illinois at Urbana-Champaign, 2002.

Proposed Entrapment Model



Criterion:

- **for particles smaller than PDAS, they are modeled as being entrapped by solidifying fronts whenever they touches the fronts**
- **for particles bigger than PDAS, the logic is shown in the next page**

Proposed Particle Entrapment Model (ctd.)

For particles bigger than PDAS, the entrapment logic is:

F_{Dx} F_L ?

- no → particle pushing
- yes ↓

Particle rolled forward by fluid ?
(by comparing the clockwise
and counter-clockwise torques)

- yes → entrapment doesn't occur (here)
- no ↓

Particle slided forward by fluid ?
(by comparing tangential forces)

- yes → entrapment doesn't occur (here)
- no ↓

particle entrapment

Particle Transport Computation

Particle Group Index	Particle Diameter (μm)	Particle Density (Kg/m^3)	Response Time (μs)
1	**10**	**2700**	**42.8**
2	**10**	**5000**	**79.3**
3	**40**	**2700**	**2.68**
4	**40**	**5000**	**4.96**

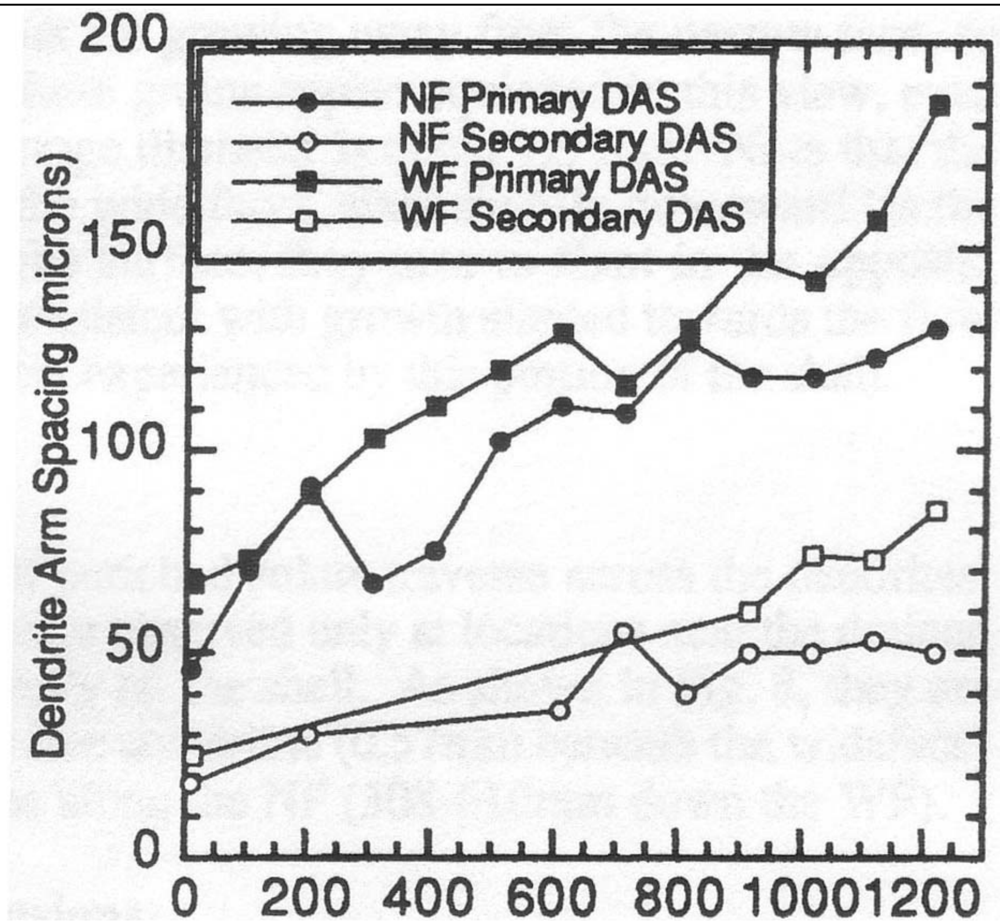
Each group consists of ~10,000 particles

Remind: response time $\tau_p = \dfrac{\rho_P d_P^2}{18\mu_f}$ **is a characteristic time after which a particle aquires 63% of flow velocity from rest.**

Particle entrapment model (for $d_p \leq 40\mu m$):

particles are modeled as entrapped by the solidifying front whenever they touch the front, for the $PDAS_{min}$ is 47μm (which is on NF close to top surface).

Variation of PDAS along Depth



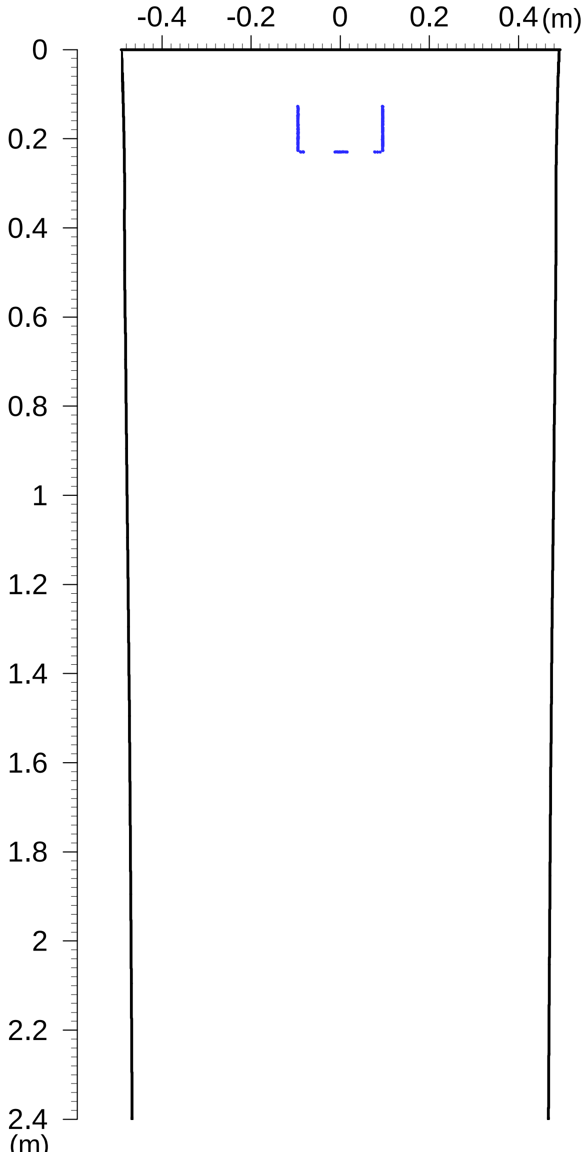
Distance below top meniscus (mm)

From: B.G. Thomas, R. O'Malley and D. Stone, *Measurement of Temperature, Solidification, and Microstructure in a Continuous Cast Thin Slab*, TMS. Warrendale, PA, 1998, pp.1185-1199.

Computational Details

- Transient Lagarangian approach of particle transport
- 4^{th} – Order Runge-Kutta method for particle transport equation
- Drag, buoyancy, gravity and lift forces are included
- Particle transport is computed every time-step after computing fluid flow field
- Motions of ~ 40,000 particles are simulated in domain
- Variable time-steps (Δt) for different diameter /density particles (Δt_{min}=2.5x10^{-6} s for the smallest and lightest particles)

Particle Transport



Projection view:

Video Clip

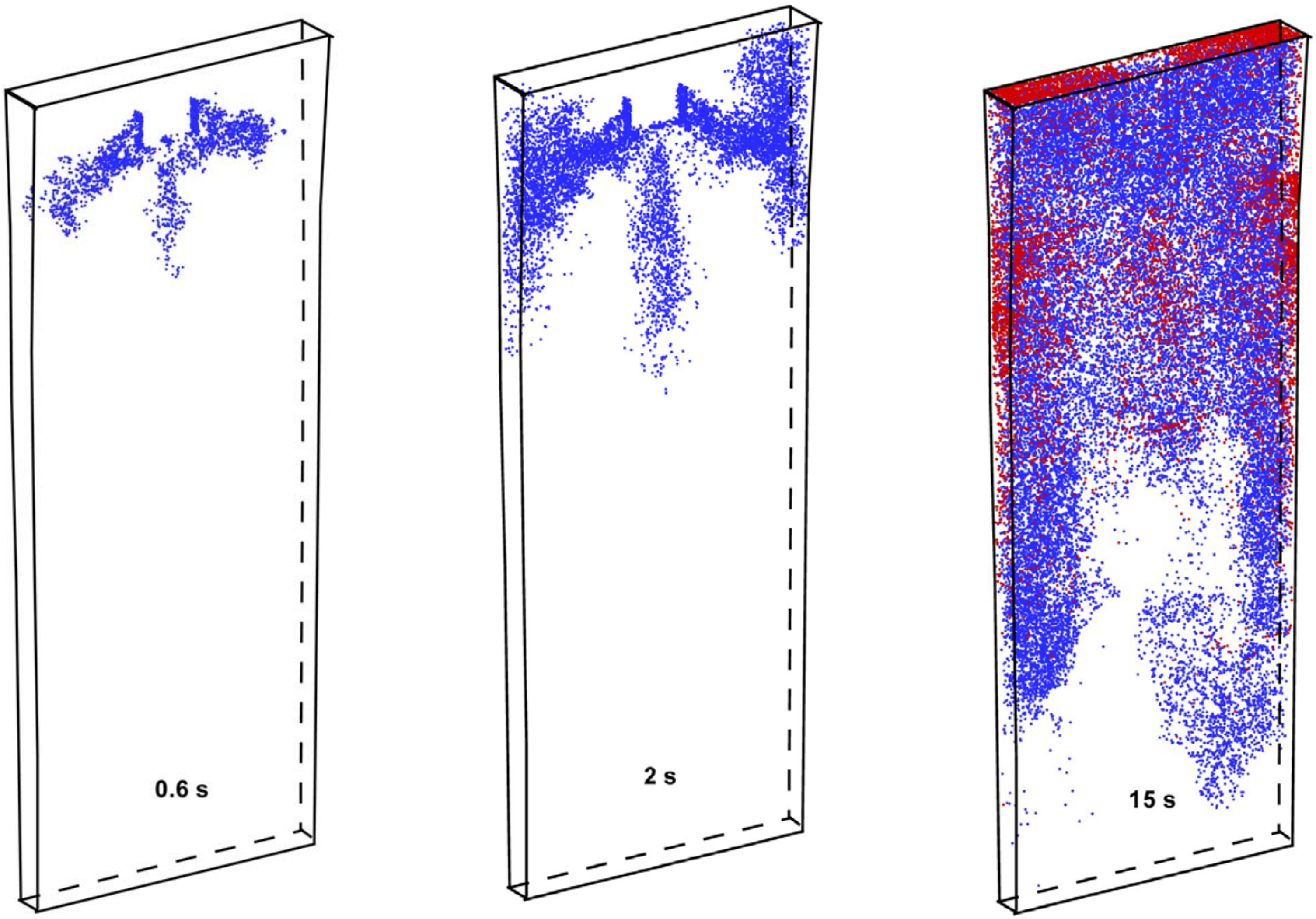
3D:

Video Clip

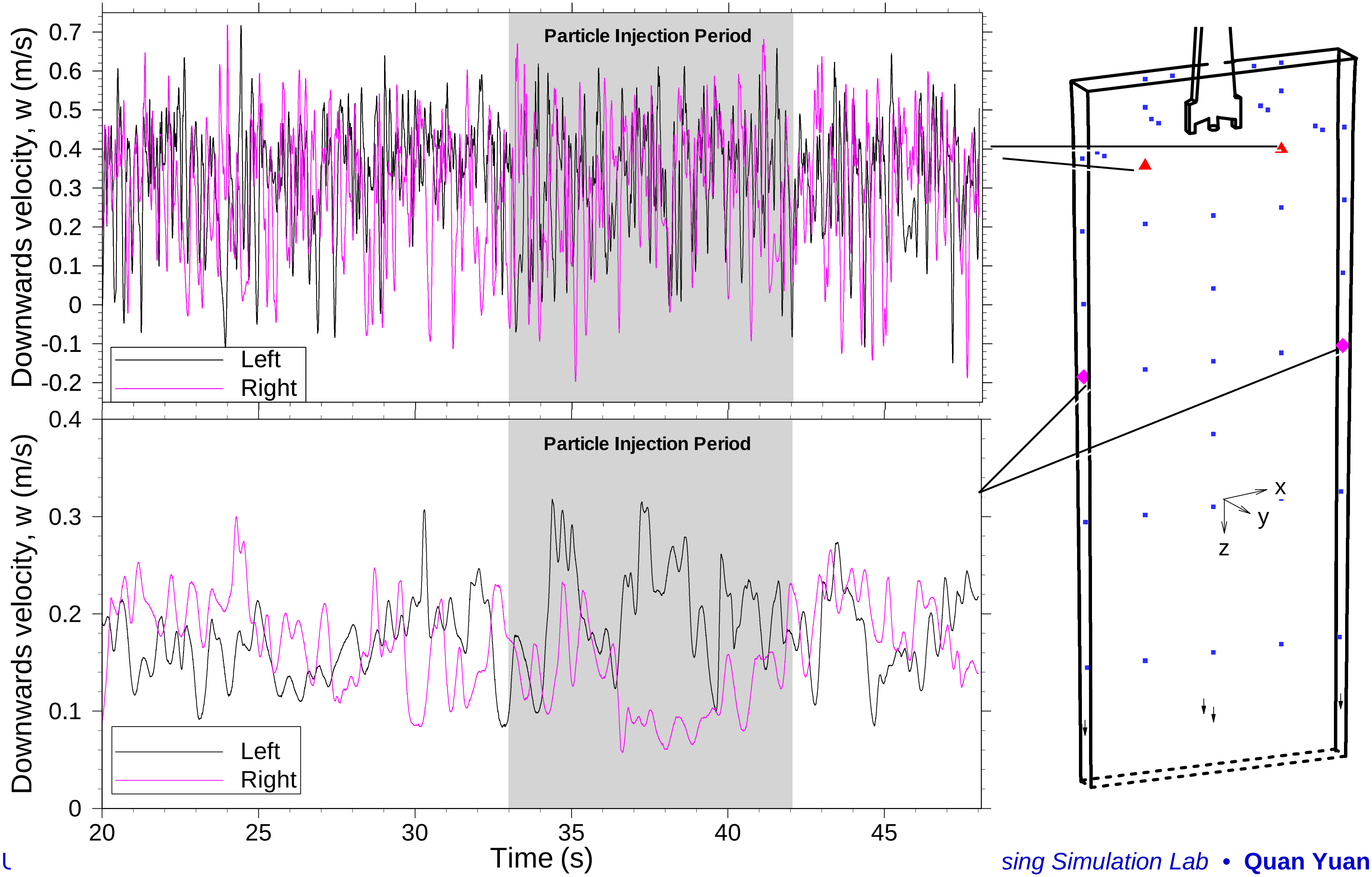
Blue: moving particles

Red: entrapped particles

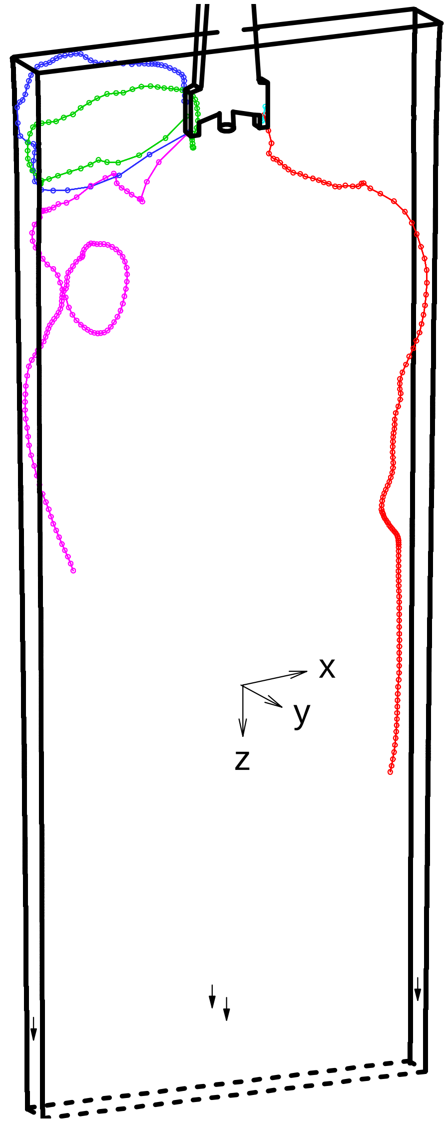
Particle Distributions at Three Instants



What Causes Asymmetry?

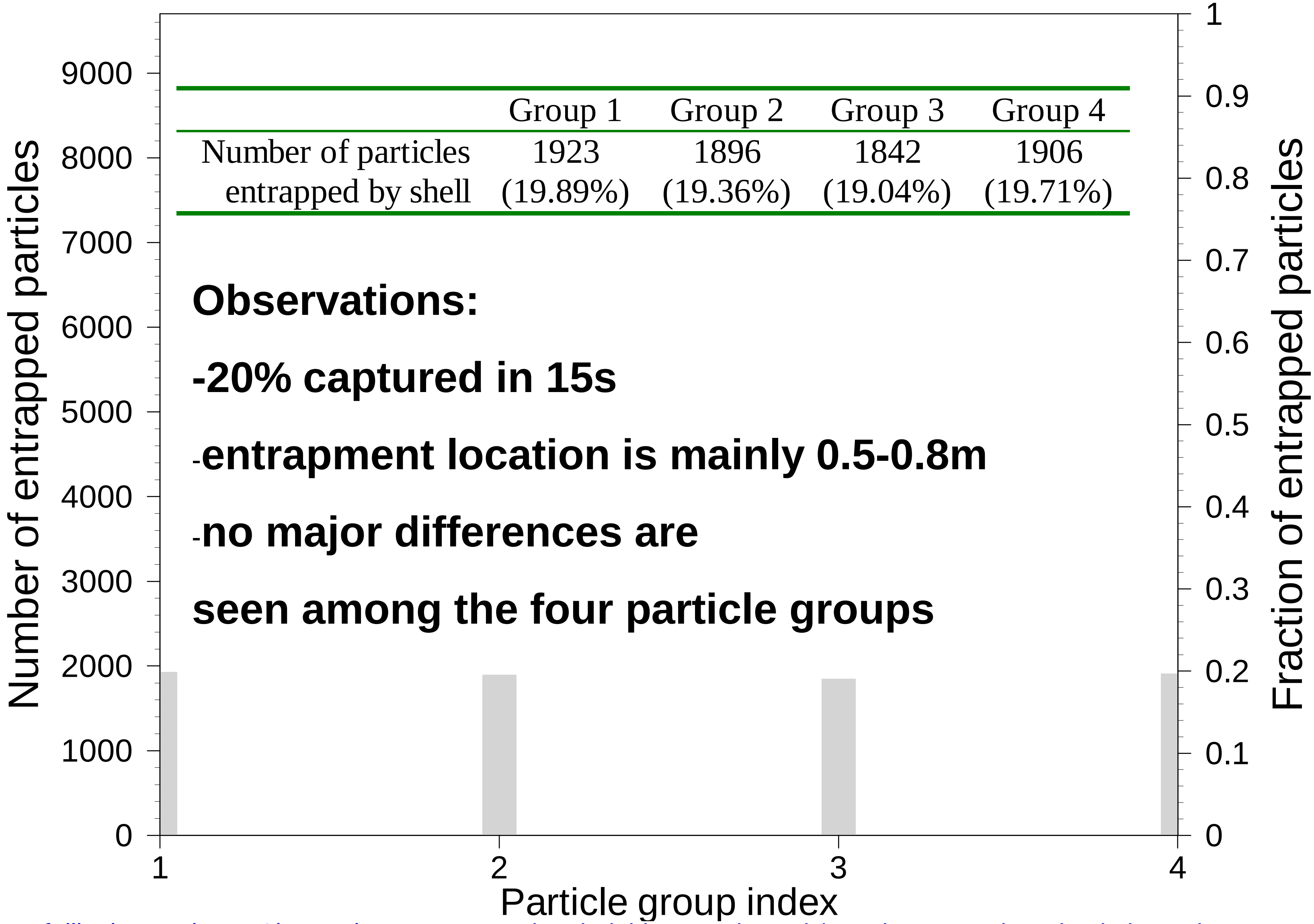


Four Typical Particle Trajectories



Trajectories up to 15s after entering mold region

Statistics of Entrapped Particles



	Group 1	Group 2	Group 3	Group 4
Number of particles entrapped by shell	1923 (19.89%)	1896 (19.36%)	1842 (19.04%)	1906 (19.71%)

Observations:

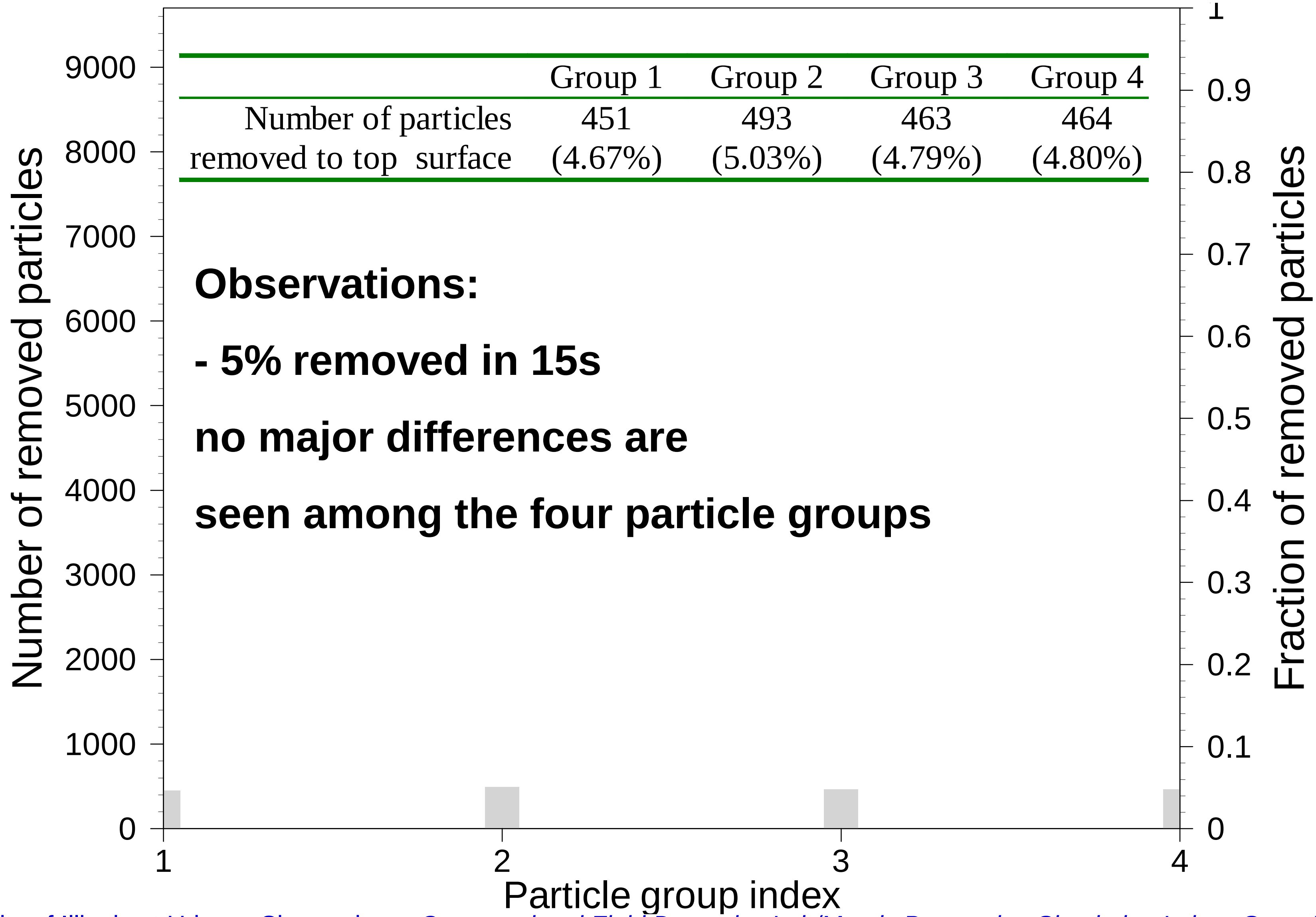
-20% captured in 15s

-**entrapment location is mainly 0.5-0.8m**

-**no major differences are**

seen among the four particle groups

Statistics of Removed Particles



	Group 1	Group 2	Group 3	Group 4
Number of particles removed to top surface	451 (4.67%)	493 (5.03%)	463 (4.79%)	464 (4.80%)

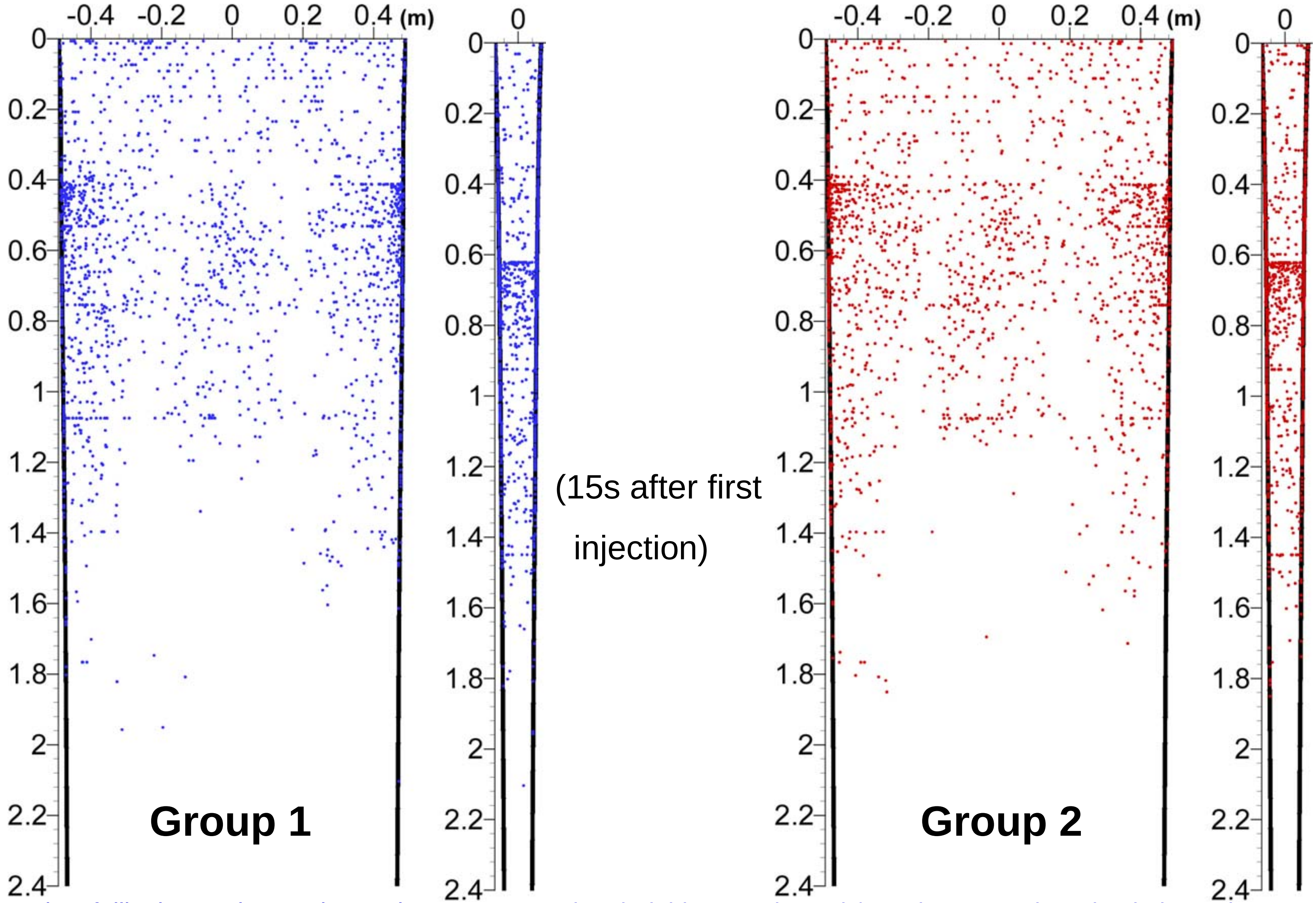
Observations:

- 5% removed in 15s

no major differences are

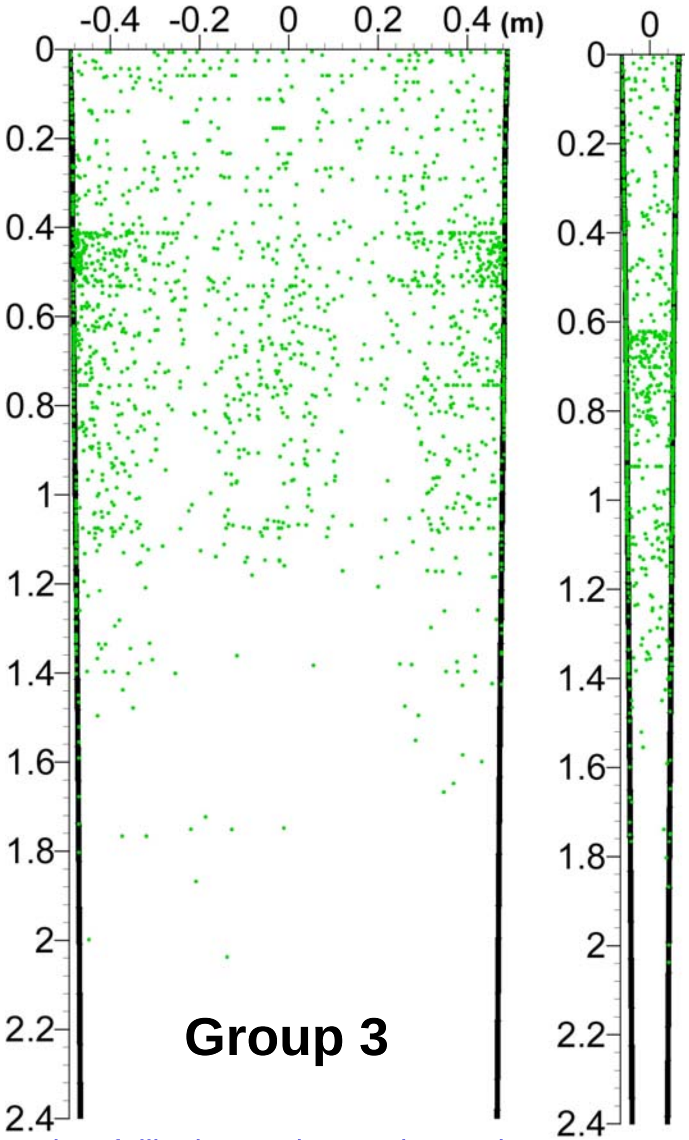
seen among the four particle groups

Particle Entrapment Locations

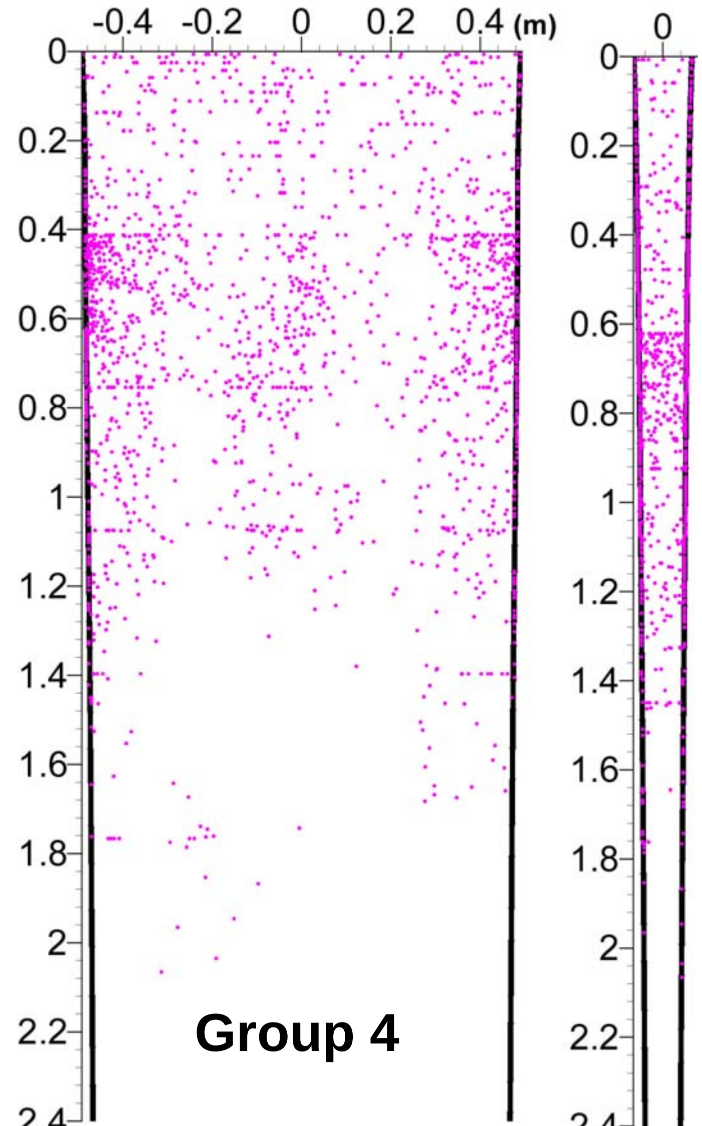


(15s after first injection)

Particle Entrapment Locations (ctd.)



(15s after first injection)



Conclusions

- CART3D is capable of predicting transient evolution of turbulent flow in continuous casting
- Two side interactions are an important cause of large top surface fluctuations, which affect entrainment of liquid flux
- Downward velocity in the lower region (beneath jet impingment points) in steel casters may be more evenly distributed across the width than in water models
- A particle entrapment model based on PDAS is proposed
- Asymmetry of particle transport and entrapment, being consistent with plant observations, is seen in LES simulations, which is found to be caused by inherent transient flow asymmetry in lower roll region
- No significant effect on transport/entrapment locations of particle size (10 & 40 micron) and density (2.7 & 5.0 s.g.)

Future Work

- Finish the proposed particle entrapment model
- Compare model prediction with measurements
- Investigate transport and entrapment of large particles (inclusions, bubbles and liquid flux)
- Investigate the effect of the center nozzle port to stabilize flow in mold region