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

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Acknowledgements

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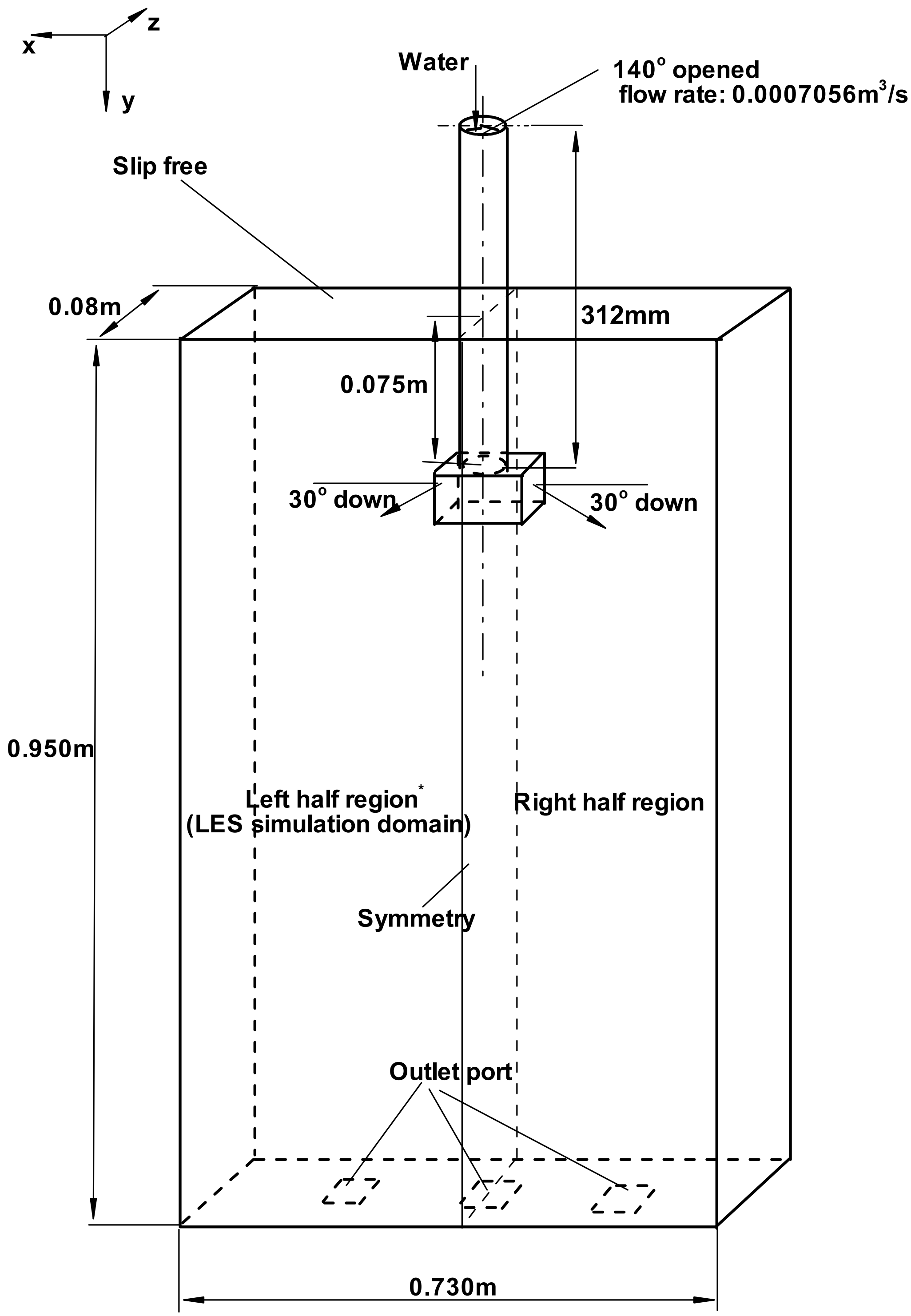
Objective

- **Investigate transient flow structure in continuous casting nozzles;**
- **Investigate the effect of inlet flow structure on**
  - **Flow pattern of the jet in the mold;**
  - **Velocity on the top surface;**
  - **Transient flow characteristics;**
  - **Validation of LES models;**
  - **Particle behavior.**

Previous Work

- **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)**
- **Investigation of transient flow in 0.4 scale water model with inlet generated from a fully developed duct using LES (Sivaraj Sivaramakrishman).**

Investigation of 0.4 Scale Water Model



Sketch of 0.4 scale water model and simulation domain

LTV 0.4 scale water model and nozzle

Dimension/Condition*	**Value**
SEN length	344
SEN bore diameter	32mm
SEN submerged depth	71-80mm
Port width x height	31mm x 32mm
Port angle	40^o upper edge 15^o upper edge
Recessed bottom well depth	4.8mm
Water model height	950mm
Water model width	735mm
Water model thickness	95mm (top) to 65mm (bottom)
Liquid flow rate	3.53×10^{-4} m^3/s
Gas injection	0%

*From:

(1) Hua Bai, "Argon Bubble Behavior in Slide-gate Tundish Nozzle during Continuous Casting of Steel Slab", Ph.D thesie;

(2) Sivaraj Sivaramakrishnan et al, "Transient Flow Structures in Continuous Casting of Steel", 83th Steelmaking Conference Proceedings, Poittburgh PA, March 26-29 2000

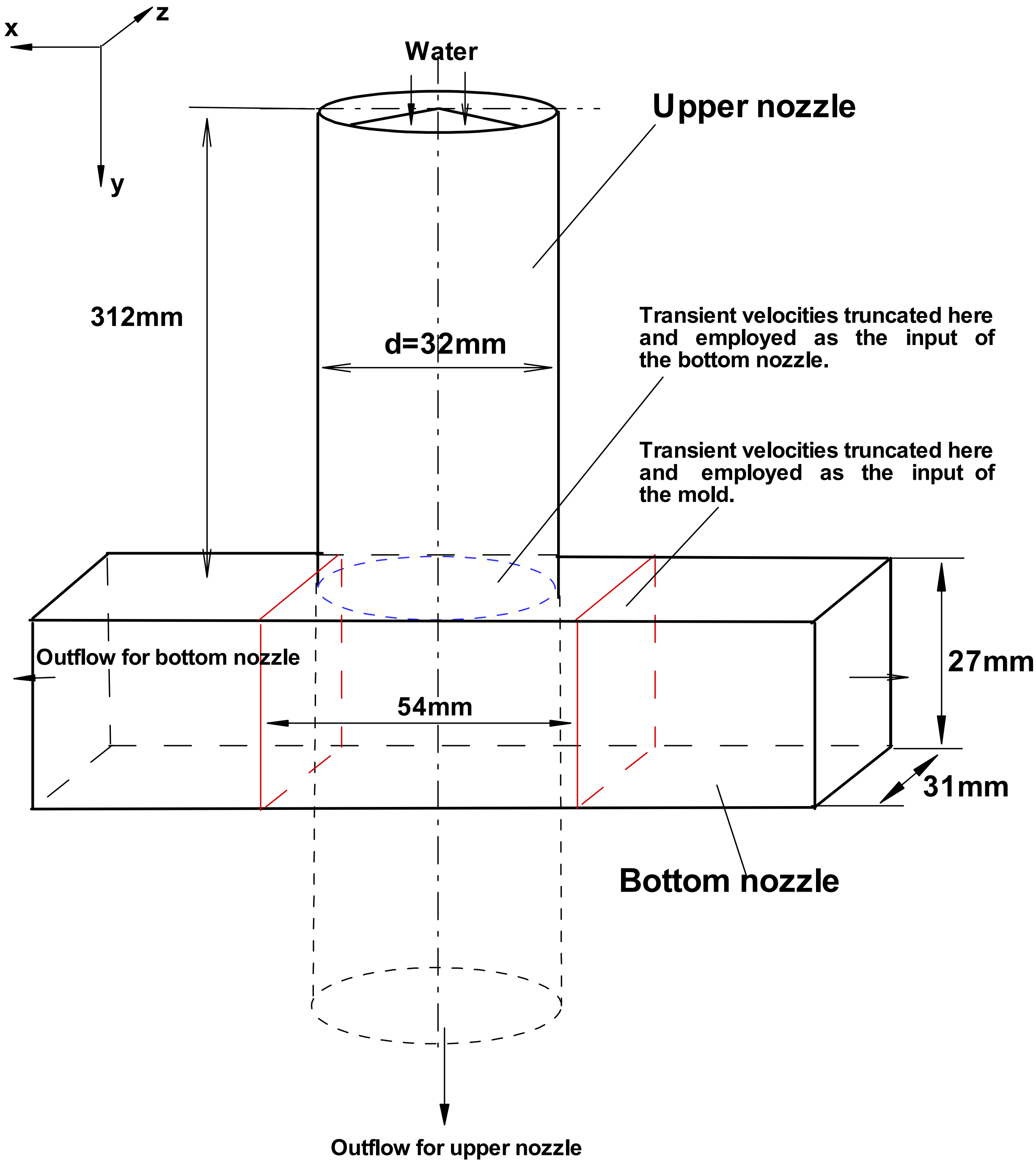
Table 1 Dimensions and conditions of the nozzle and 0.4 water model

Dimension/Condition	Value
Simulated length of upper nozzle	437 mm
Truncated length	312 mm
Diameter of upper nozzle	32 mm
Inlet velocity of upper nozzle	2.256 m/s
Height $\times$ thickness($y \times z$) of bottom nozzle	27mm x 31mm
Simulated length (x) of bottom nozzle	1266 mm
Truncated length (x) of the bottom nozzle	54 mm
Port opening of 0.4 water model	31mm x 31mm
Water model height	950 mm
Water model width	365 mm
Water model thickness	80 mm
Averaged inlet velocity at port	0.424 m/s
Averaged jet angle at port	30^o
Liquid flow rate through each port	3.5×10^{-4} m^3/s
Casting speed	0.718 m/min
Liquid density	1000 kg/m^3
Liquid material viscosity	0.001 Pa/m^2

* The dimensions of the case are to match the LTV 0.4 water model

Model assumptions

- **uniform vertical flow entering domain from slide gate bottom;**
- **pi-shaped slide gate opening**
- **one-way coupled flow between nozzle top and bottom and between nozzle bottom and mold;**
- **no gas injection or mod air pockets (fully primed) flow;**
- **flow angled exiting ports simulated by coordinates transformation of horizontal port results;**
- **Smagorinsky subgrid scale model employed in transient LES solution of N-S equations;**
- **steel shell neglected;**
- **top surface level in mold is a horizontal plane;**
- **free slip along top surface;**
- **mold bottom holes are modeled as square ports with fixed outlet velocity.**

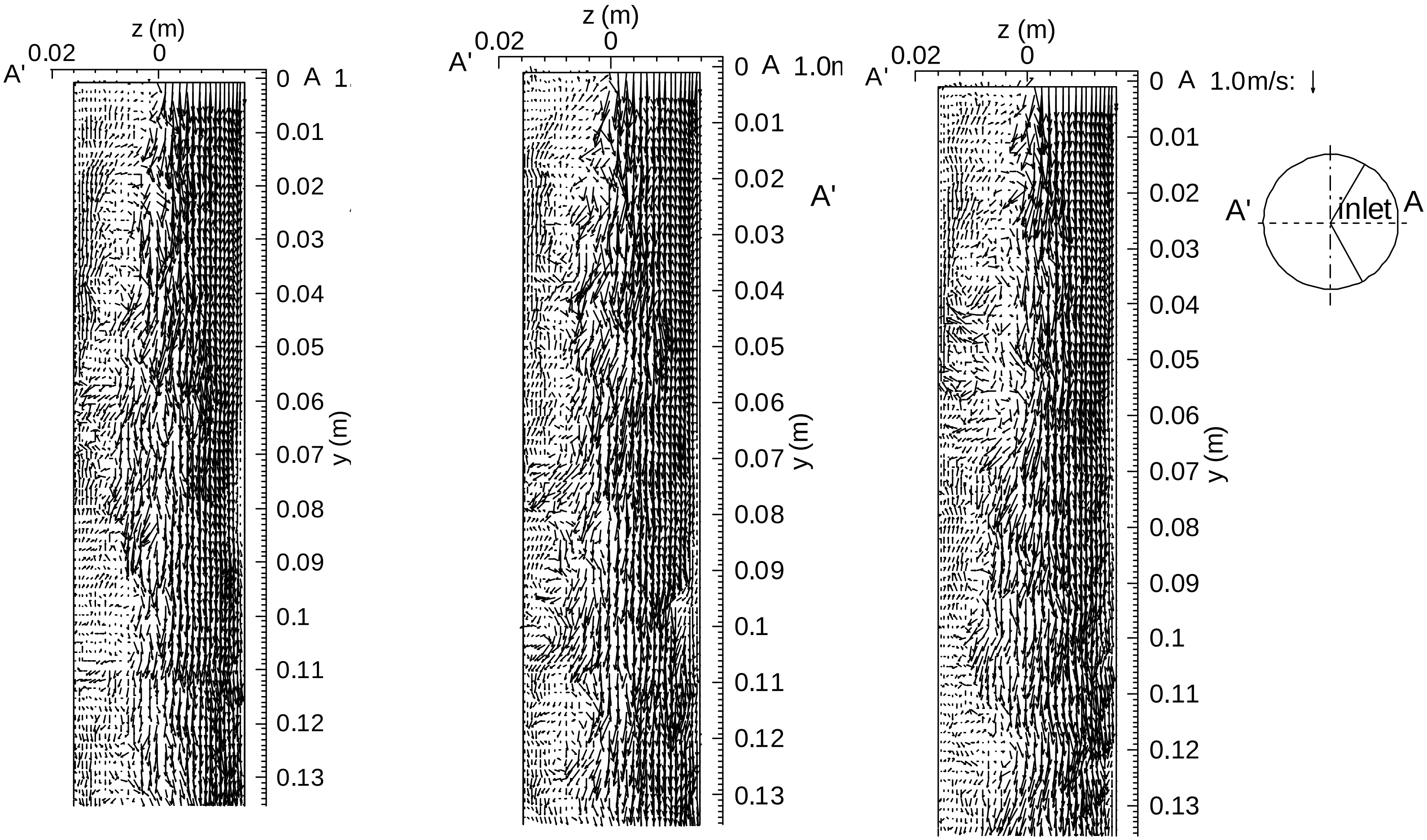


Simplified nozzle simulation

Simulation Procedure

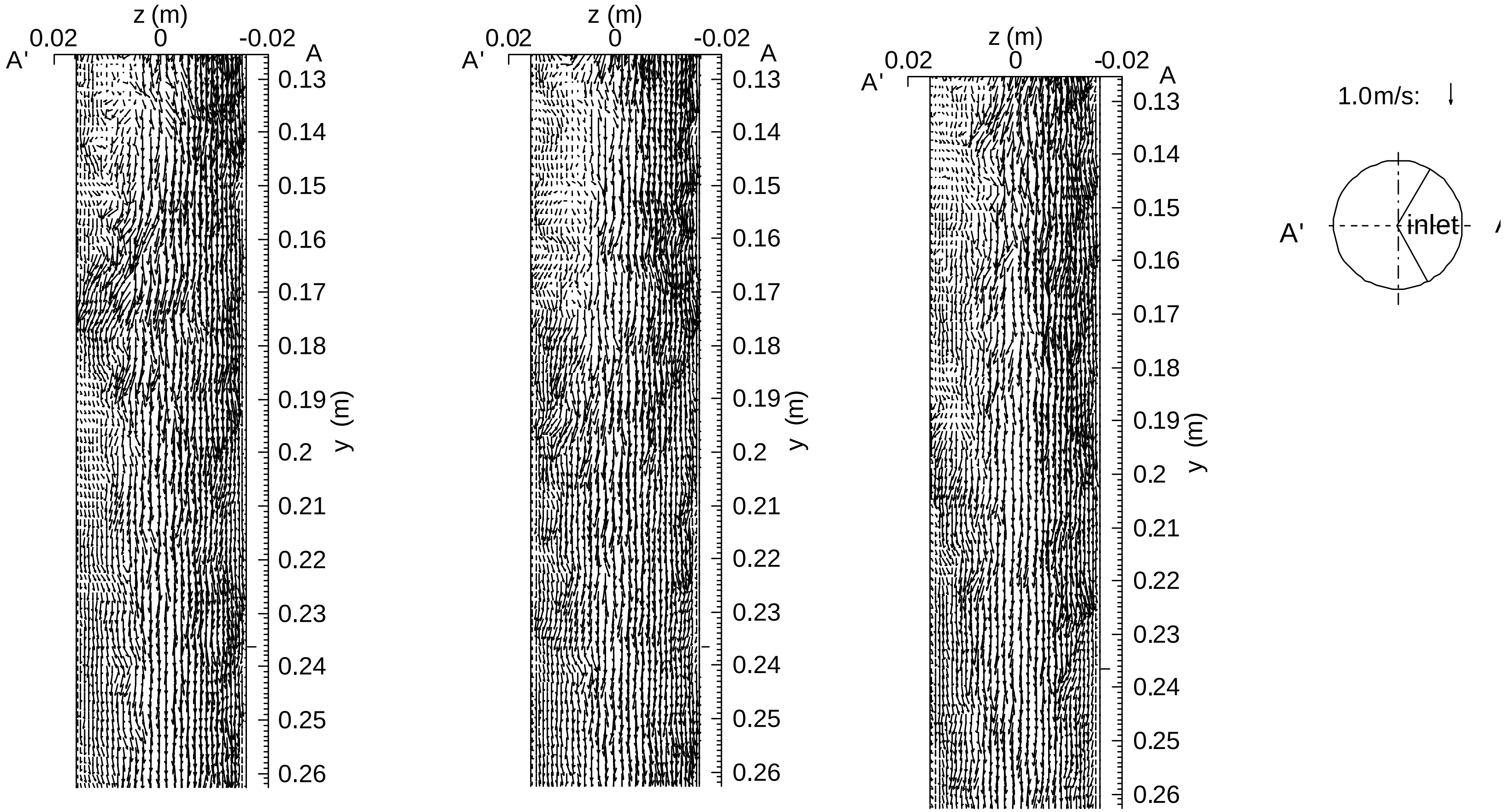
- **The nozzle was divided into 2 pieces: upper nozzle and bottom nozzle, Flow in the 2 pieces were simulated separately using LES**
- **Simulation in the upper nozzle was performed with a grid consisting of $256 \times 64 \times 32$ nodes in the direction of y, θ and r;**
- **Transient velocities in the upper nozzle were truncated 312mm below the inlet opening every 0.00175s for 0.875s after flow reached "stationary state" (0.875s prior simulation) and employed as the input of bottom nozzle, the simulation takes 12 CPU s per time step or 14 days on Pentium 450 for the total 1.750s;**
- **Simulation in the bottom nozzle was performed with a grid consisting of $32\times 256 \times 32$ nodes in the direction of x, y and z;**
- **Transient velocities in the bottom nozzle were truncated every 0.0005s for 1.750s after flow reached "stationary state " (1.750s prior simulation) ,the simulation takes 8.6 CPU s per time step or 7 days for the total 3.5s.**
- **The truncated velocities at the left port were then rotated an angle of 32.4^o to generate the 30^o down inlet jet for the model.**

Instantaneous flow in the upper nozzle (top)



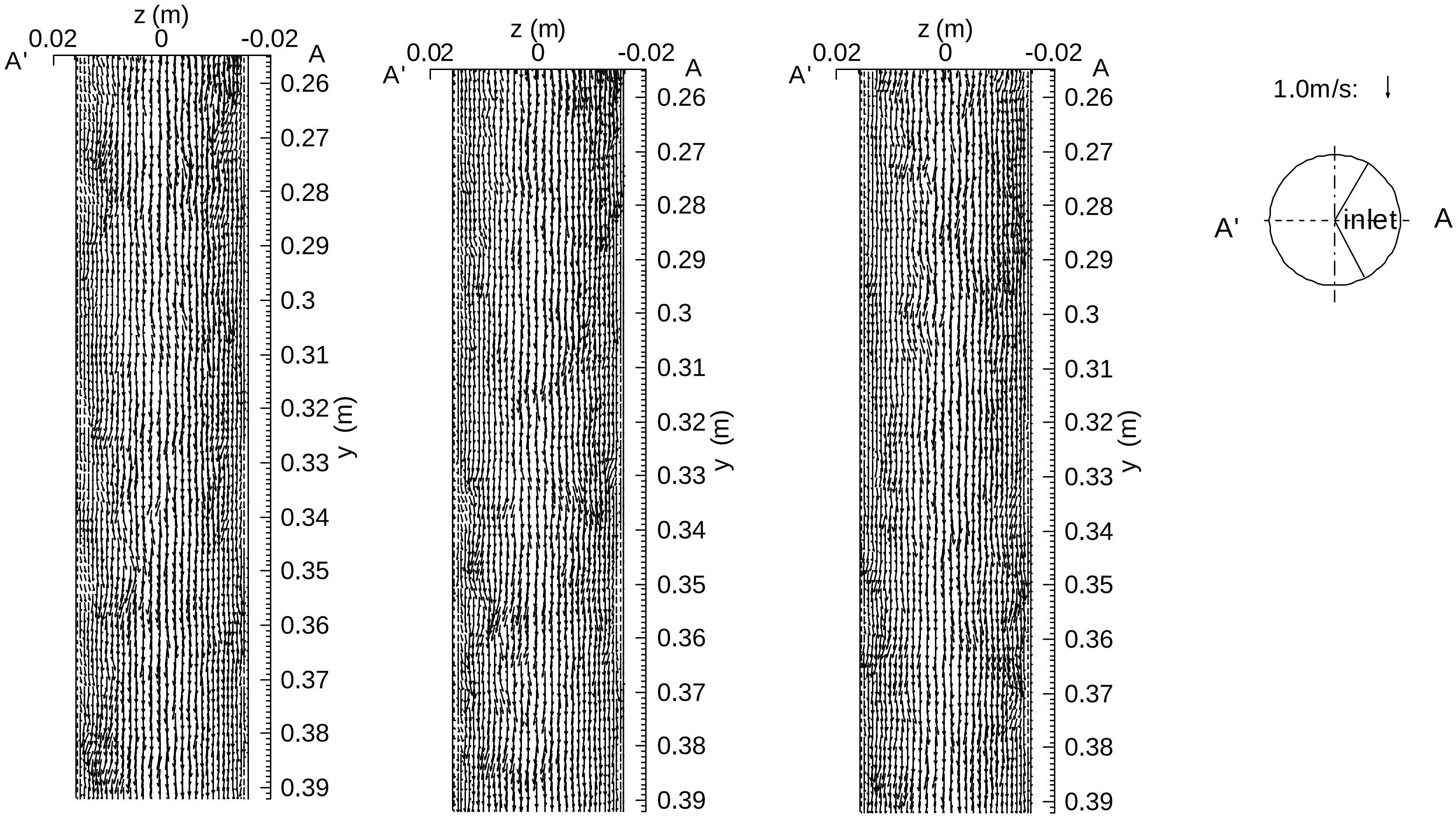
(a) $t=t_0$ **(b) $t= t_0+0.010s$** **(c) $t= t_0+0.02s.$**

Instantaneous flow in the upper nozzle (middle)



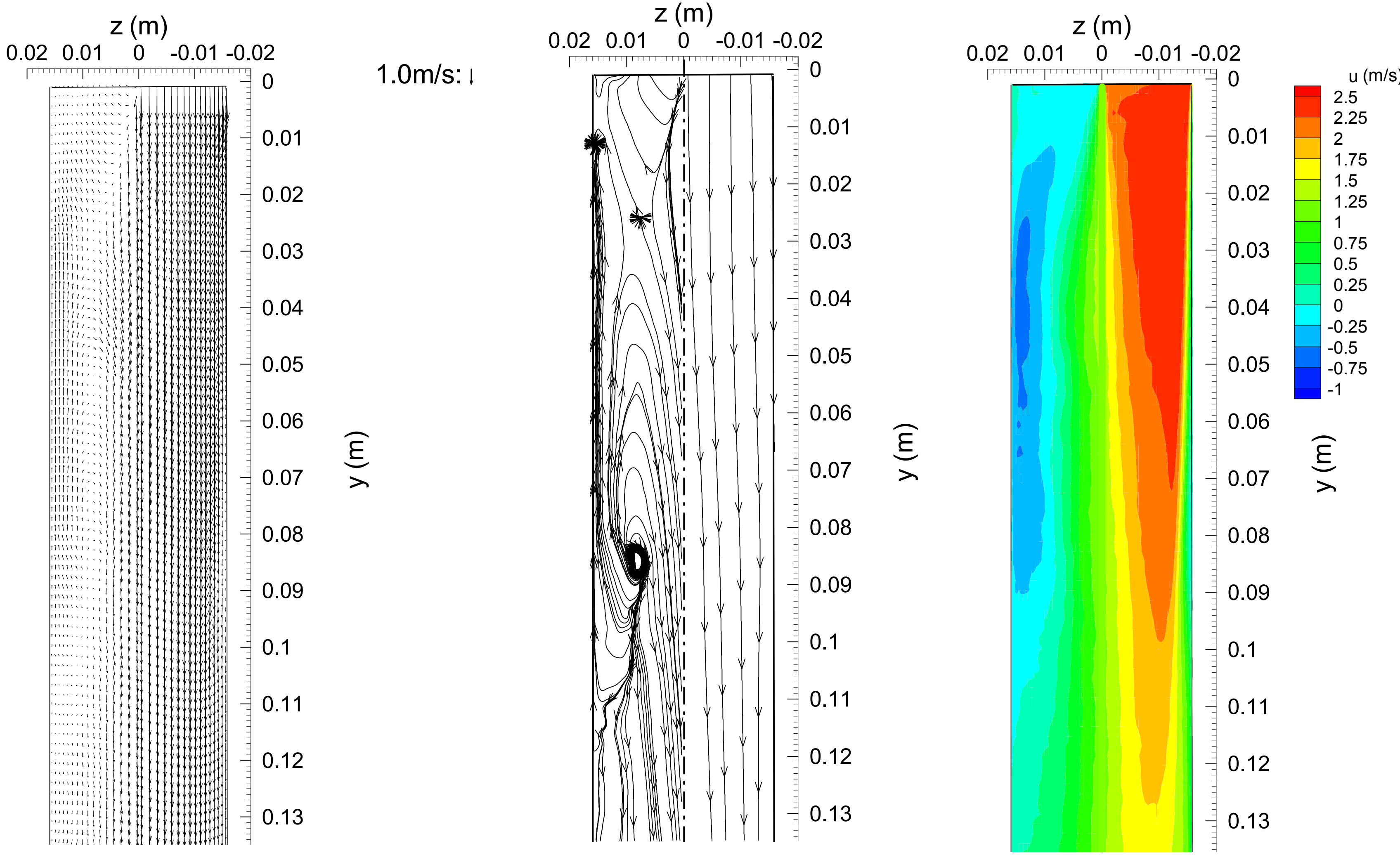
(a) $t=t_0$ **(b) $t= t_0+0.010s$** **(c) $t= t_0+0.02s.$**

Instantaneous flow in the upper nozzle (lower)



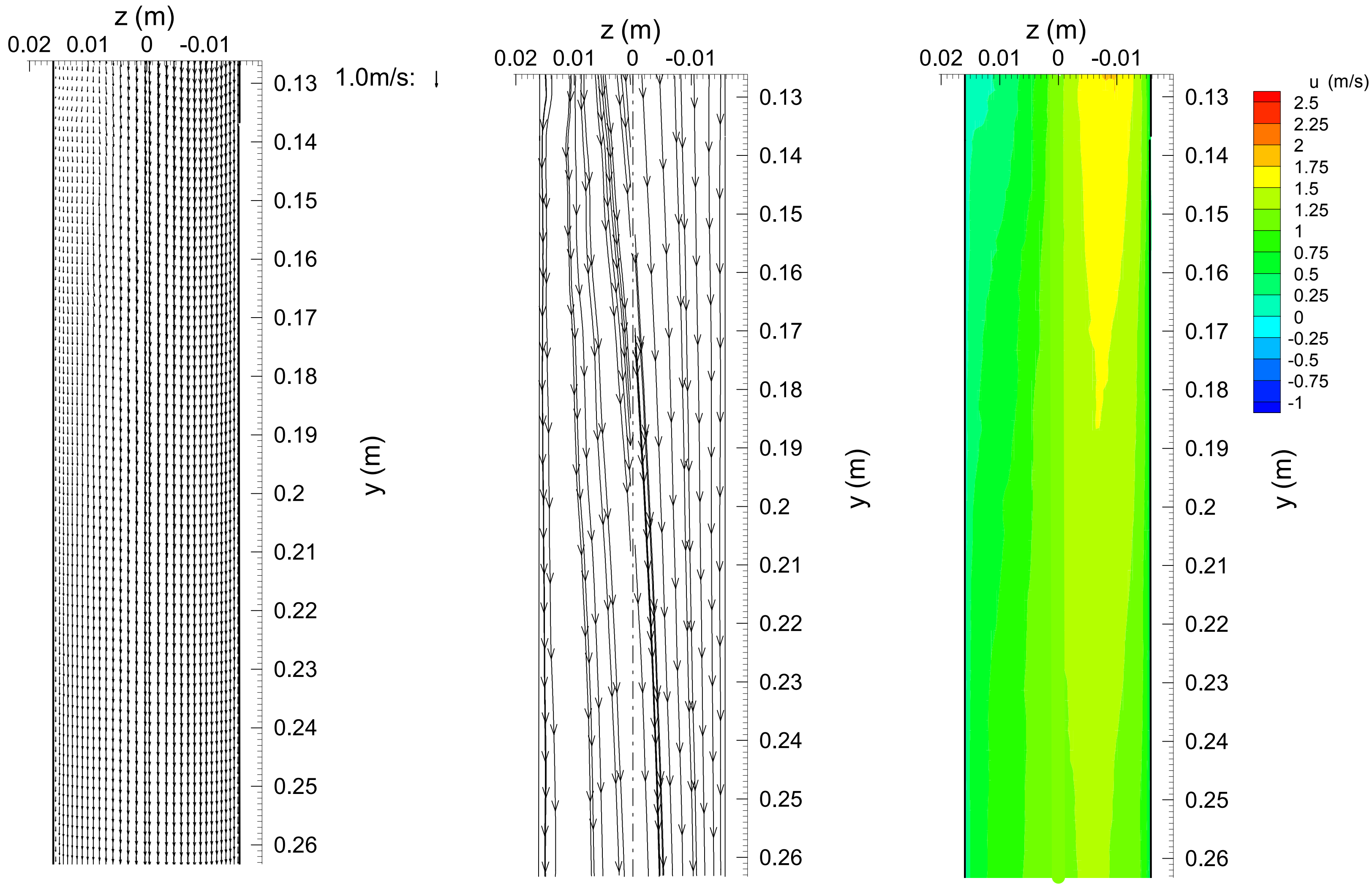
(a) t=t_0 **(b) t= t_0+0.010s** **(c) t= t_0+0.02s.**

Time averaged flow in the upper nozzle (top)



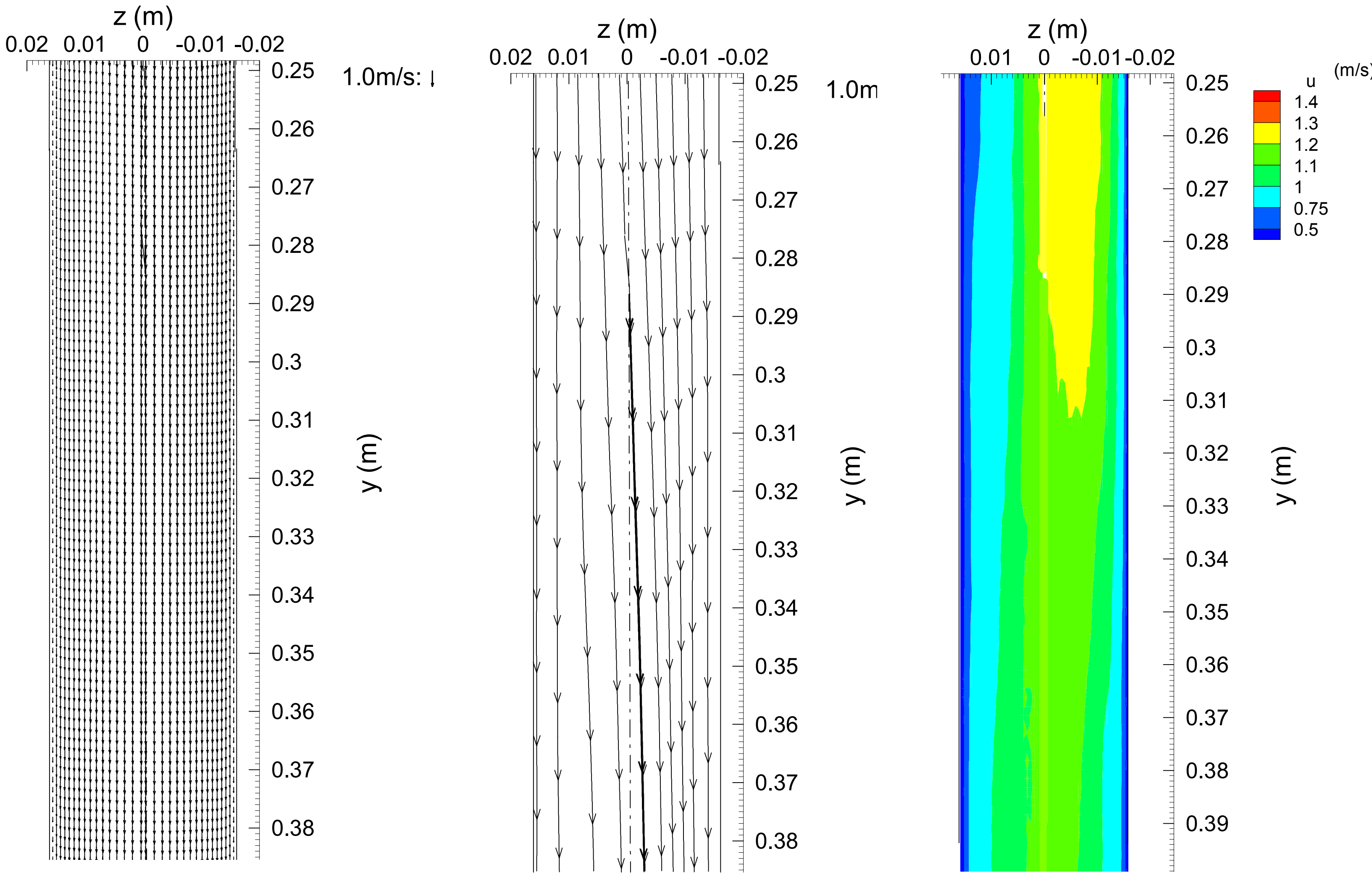
(a)velocity vector **(b) streamline and** **(c) axial velocity contour**

Time averaged flow in the upper nozzle (middle)



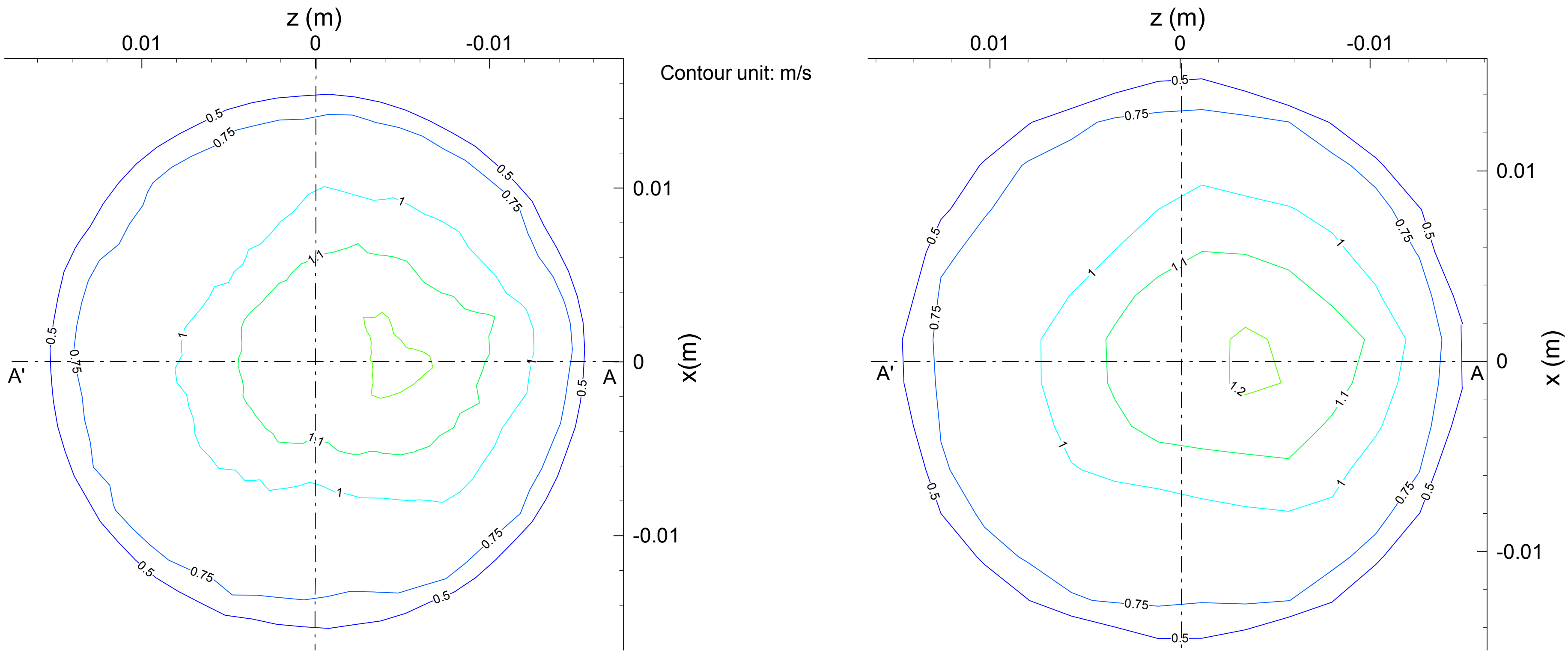
(a)velocity vector **(b) streamline and** **(c) axial velocity contour**

Time averaged flow in the upper nozzle (lower)



(a)velocity vector **(b) streamline and** **(c) axial velocity contour**

Time averaged axial velocity at the truncation plane between upper and bottom nozzle



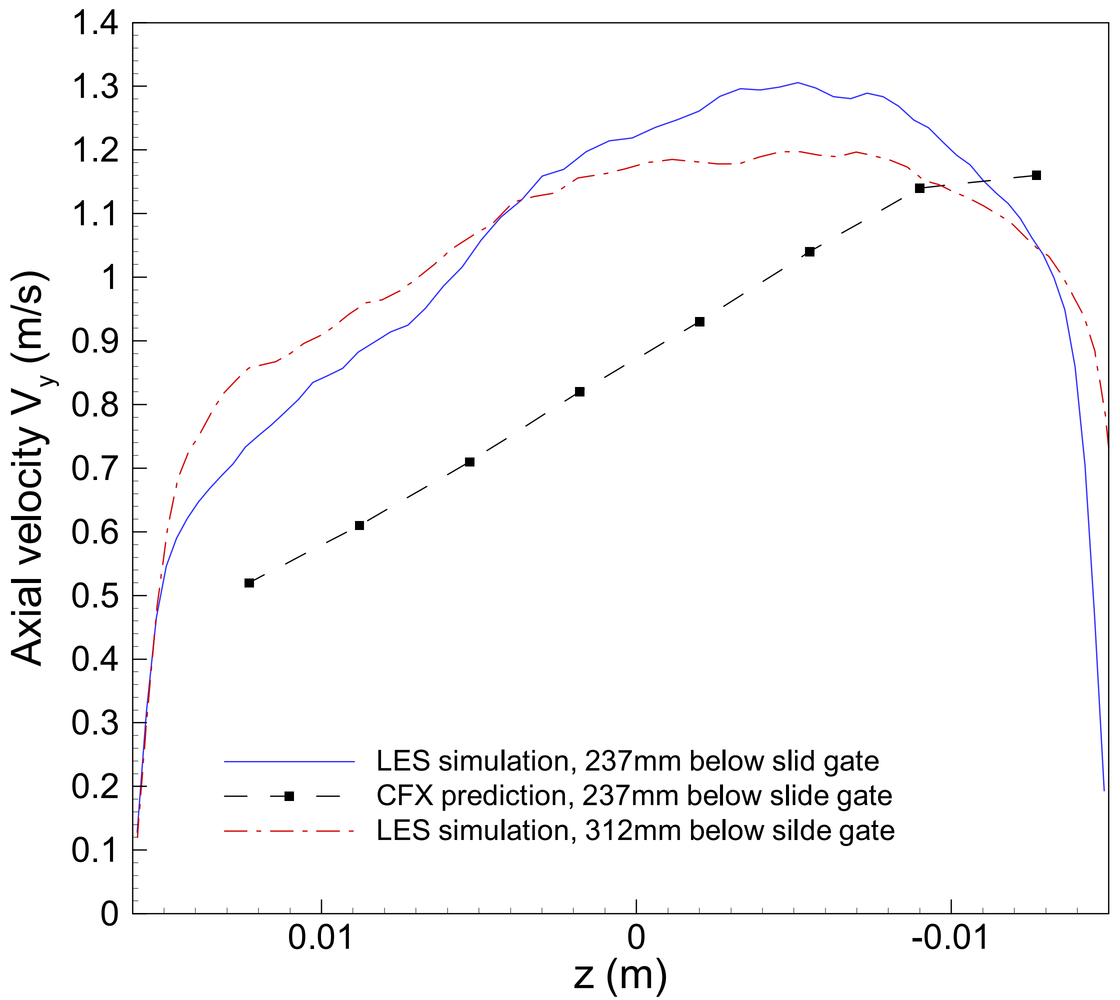
(a) Cylinder coordinates

Through interpolation

(b) Cartesian coordinates

Contour lines of axial velocity at the trunction port

Upper Nozzle Validation

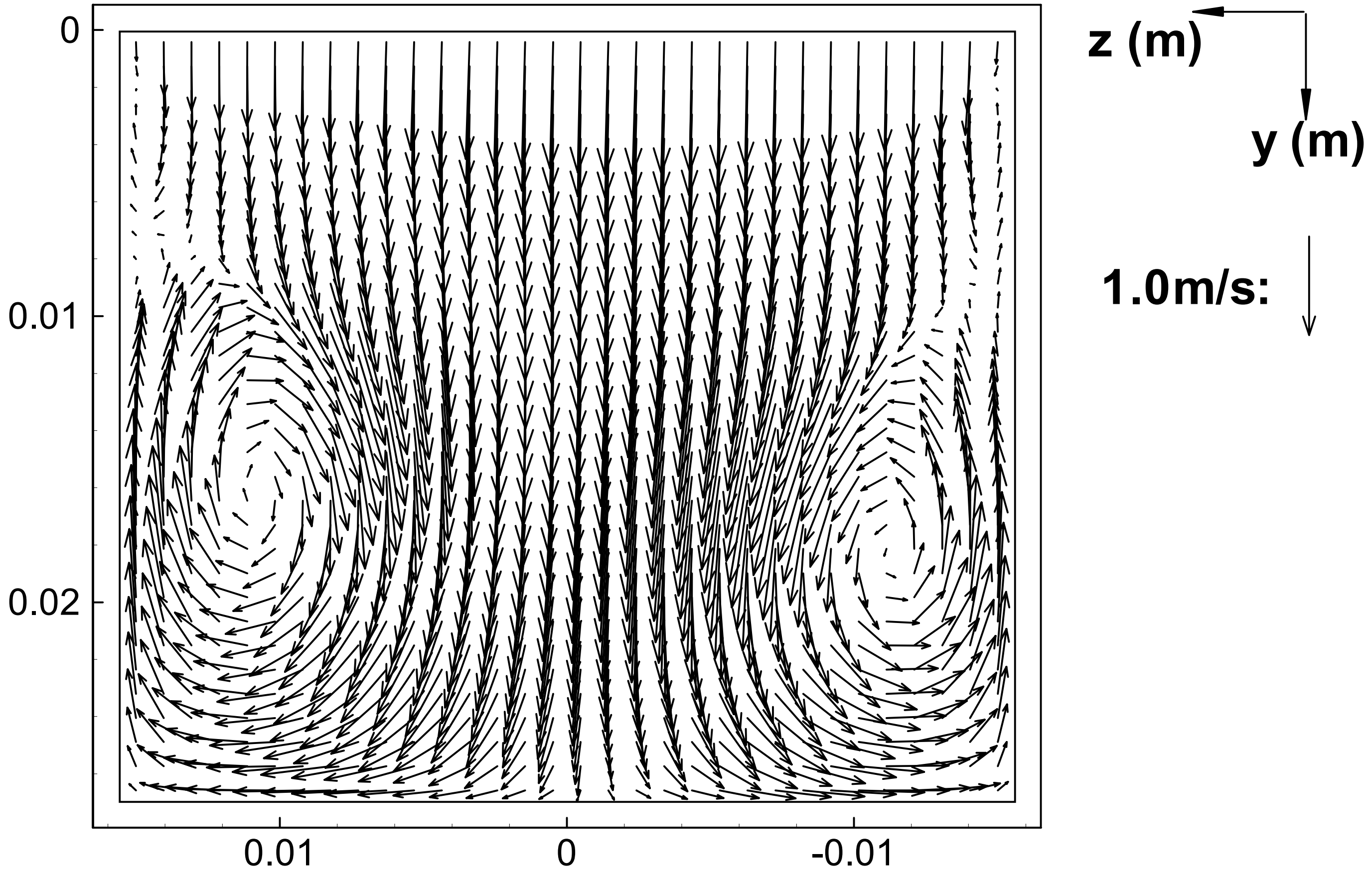


***CFX Prediction:** HuaBai, *Transient Flow Structures in Continuous Casting of Steel*, Steelmaking Conference Preceedings 2000 and unpublished results**.**

Upper Nozzle Observations

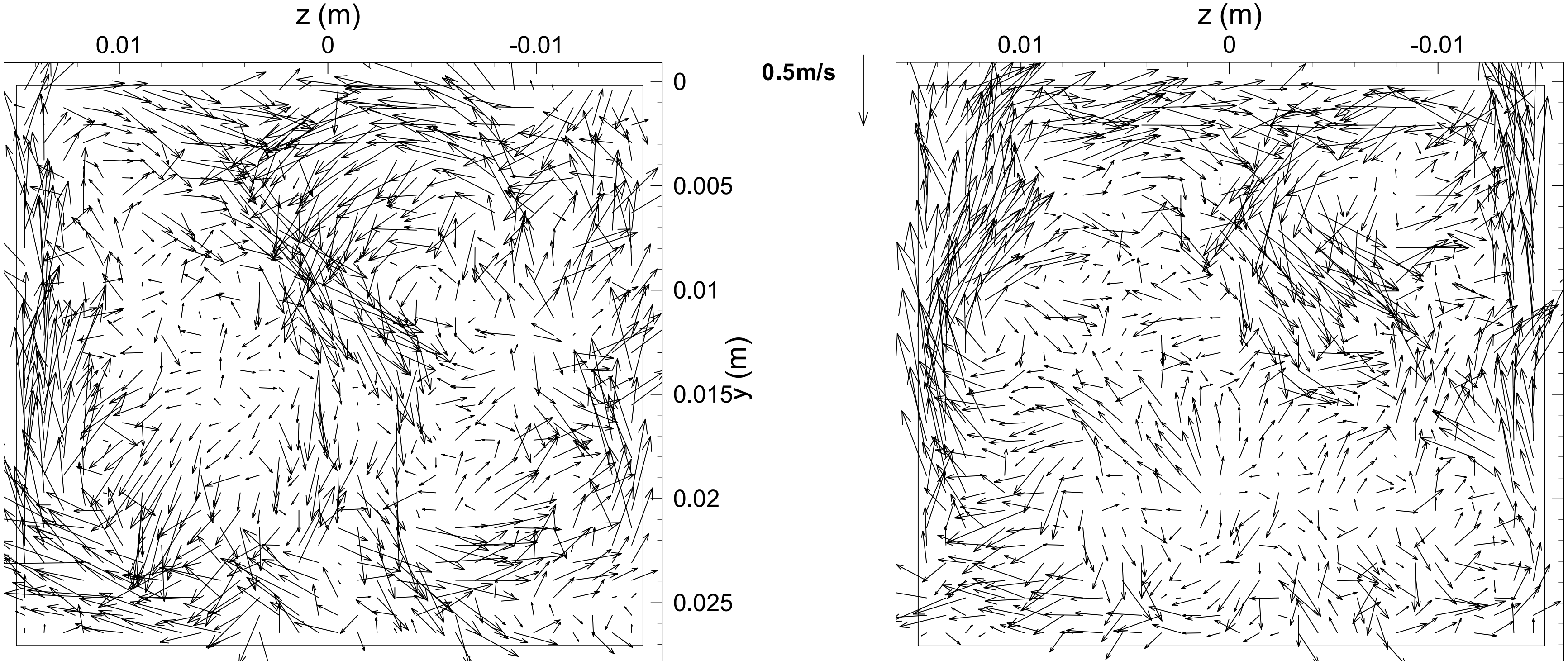
- LES simulation matches CFX prediction (validated with PIV);
- Recirculation region in the upper nozzle is located at 0-110mm below the the blocked half side of the slide gate; the transient flow structures in the recirculation region include small transient swirls which have changing location; while the time-averaged flow structure in the upper nozzle only contains 2 rolls in the region;
- No negative time averaged axial velocity was found 110mm below the slide gate;
- Axial velocity is consistently larger on the opening side than the other side; this asymmetry is still apparent at the truncation plane where the maximum of the axial velocity is displaced at 3mm from the center line of the bore;
- Turbulent flow in the nozzle is very large and significant: maximum time-averaged secondary flow speed at the truncation plane is only 0.05% of the mean axial velocity while the maximal transient secondary flow speed is 68% of the mean axial velocity.

Bottom nozzle time averaged secondary flow



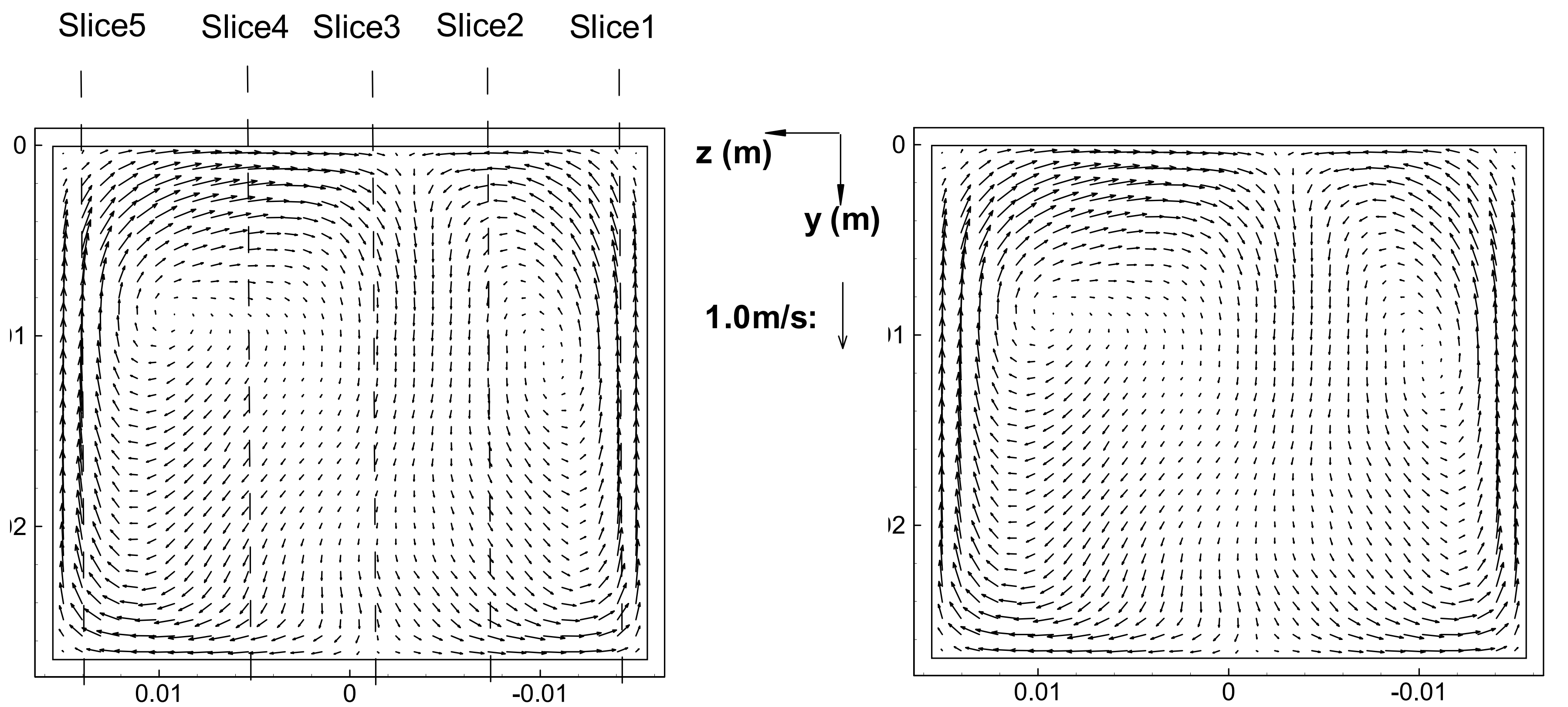
View into port: center plane between the 2 truncation planes

Bottom nozzle transient secondary flow



Secondary flow at the left truncation port at two different instant

Bottom nozzle time averaged secondary flow

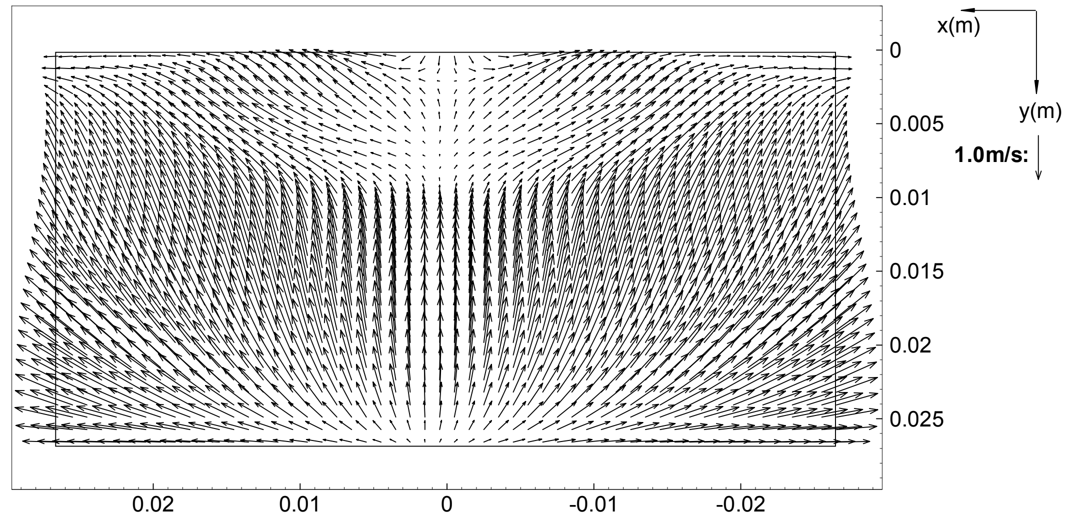


View into port: (a) left truncation plane **(b) right truncation plane***

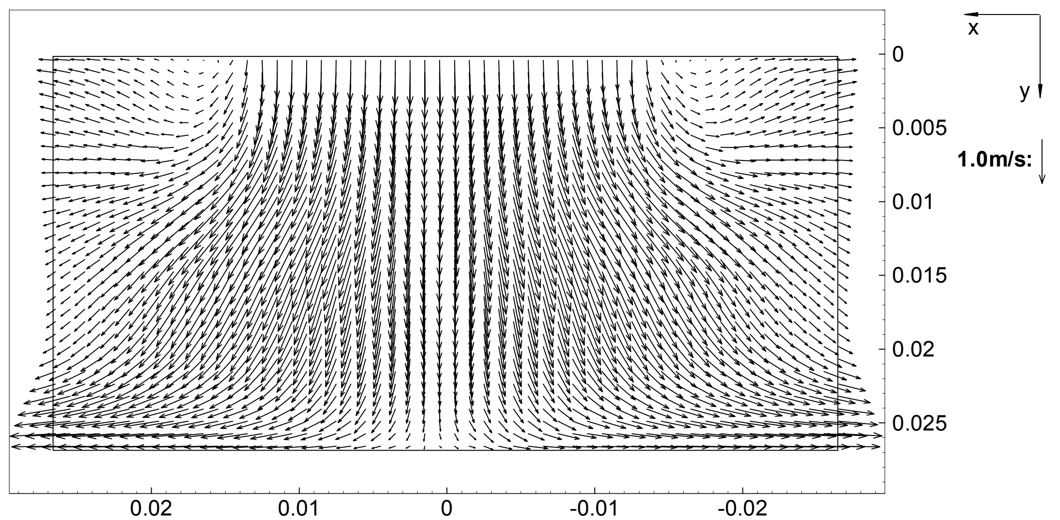
Observations:The time averaged flow contains 2 almost symmetrical rolls at both of the truncation planes corresponding to the physical outlet ports; no apparent flow pattern difference was found between the ports.

***The two planes are 26.5mm from the center line of upper nozzle.**

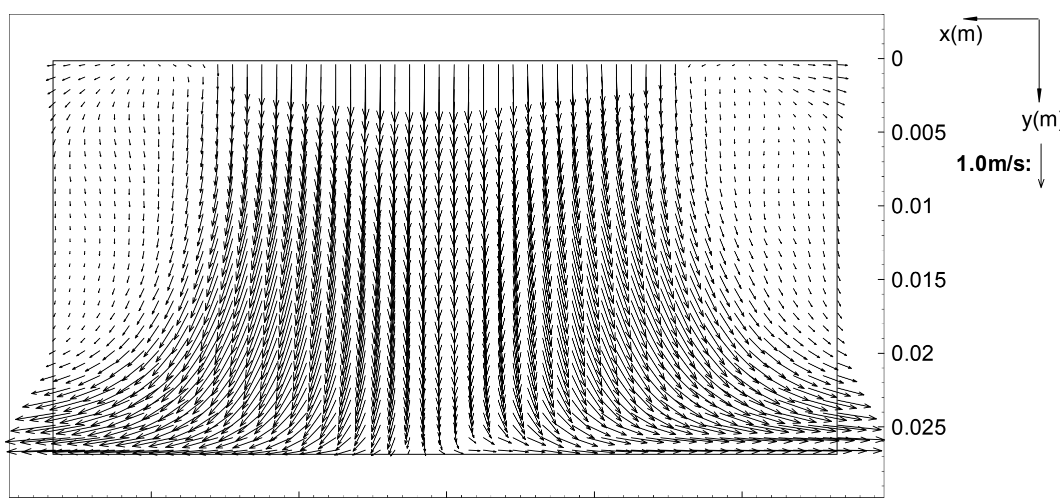
Bottom nozzle time averaged velocities (sideview)



(a) Slice 1.

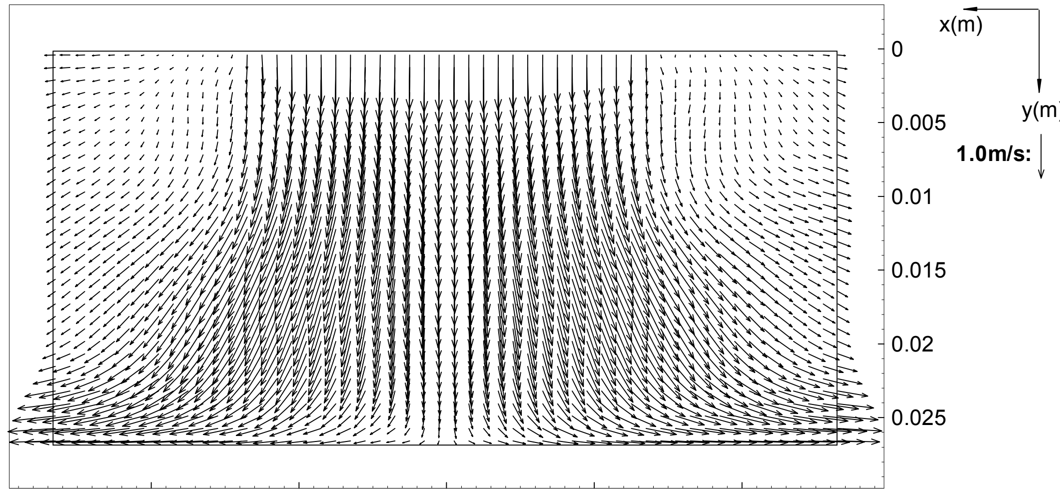


(b) Slice 2.

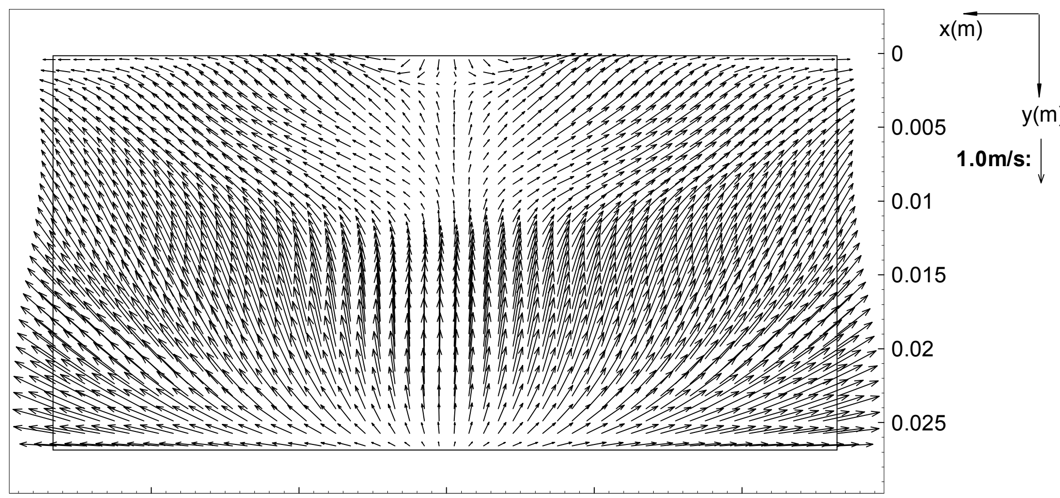


(c) Slice 3.

Bottom nozzle time averaged velocities (sideview)



(d) Slice 4.



(e) Slice 5.

What is jet angles exiting the two ports:

Using Equations at the 2 truncation cross planes:

$$\bar{u} = \frac{\sum\left[\bar{u}_{i,j,k}\bar{U}_{i,j,k}\Delta y_{i,j,k}\Delta z_{i,j,k}\right]}{\sum\left[\bar{U}_{i,j,k}\Delta y_{i,j,k}\Delta z_{i,j,k}\right]};\qquad \bar{v} = \frac{\sum\left[\bar{v}_{i,j,k}\bar{U}_{i,j,k}\Delta y_{i,j,k}\Delta z_{i,j,k}\right]}{\sum\left[\bar{U}_{i,j,k}\Delta y_{i,j,k}\Delta z_{i,j,k}\right]};$$

$$\bar{\alpha} = a\tan(\bar{u}/\bar{v});\qquad \bar{U}_{i,j,k} = \sqrt{\bar{u}_{i,j,k}{}^2 + \bar{v}_{i,j,k}{}^2 + \bar{w}_{i,j,k}{}^2}.$$

$\bar{u}$ **and** $\bar{v}$ **are weighed velocity component in x and y direction respectively at the 2 planes;**

$\bar{\alpha}$ **is the weighed flow angle with horizontal plane;**

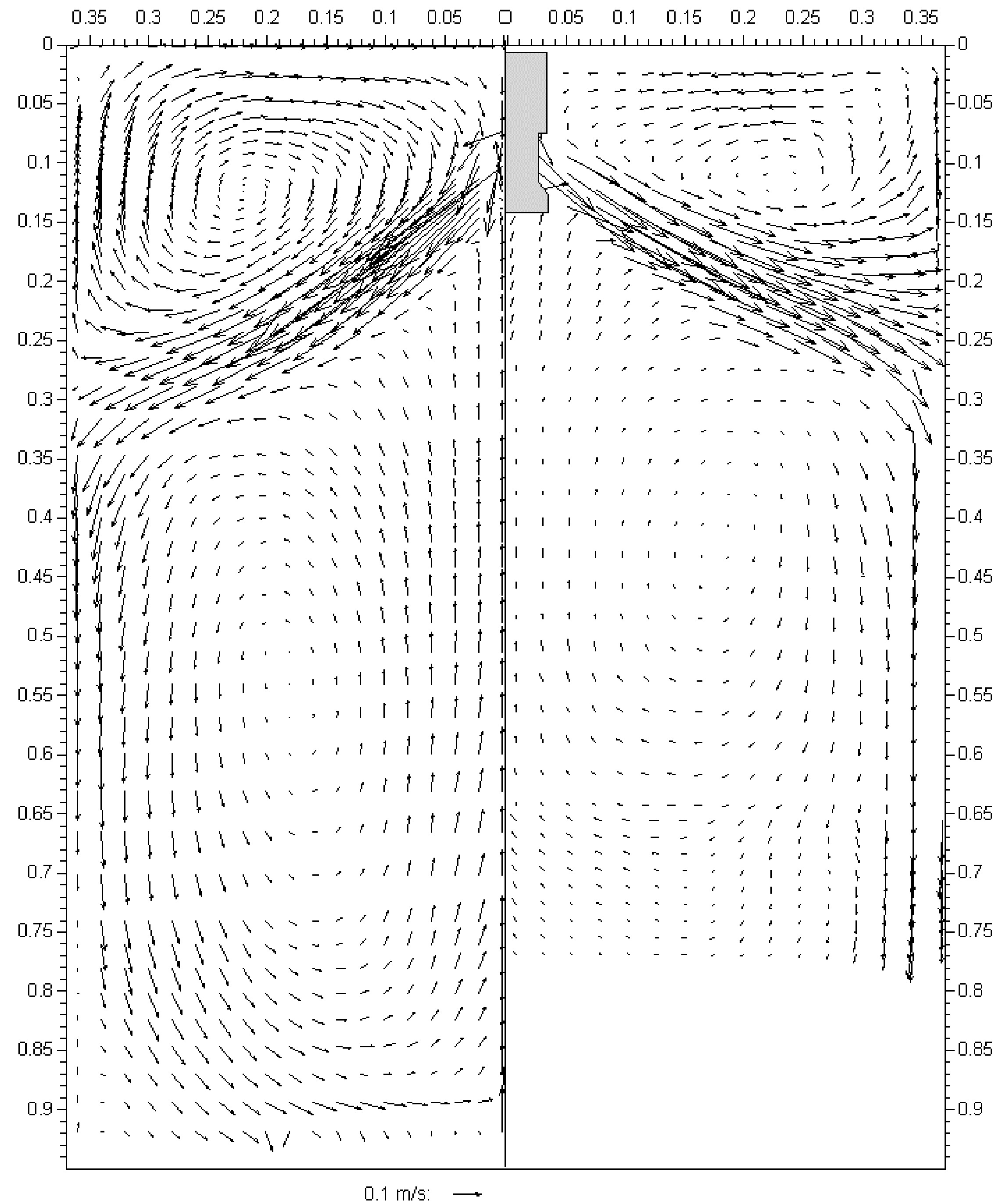
The flow is 2.37^o up at the left plane and 2.30^o up at the right plane;

Transient velocities were translate 32.4^o to generate the 30^o down angle to the mold.

Bottom nozzle observations

- The outflow of the simplified bottom nozzle contains turbulent transient swirls
- The flow at the port outlets contains important transient swirls and similar velocity variations along the vertical direction, which affects the flow pattern in the mold
- The time-averaged outflow contains 2 almost symmetrical swirls which have been observed sometimes (<2s) by Hershey; however this does not match the k-ε model's prediction for the PIV modeled nozzle (validated by experiments). The reason may be(1)the down-stream's effect on the up-stream (2) insufficient simulation time for both upper nozzle and bottom nozzle and (3) geometry simplification
- Longer simulation time needed to get the low-frequency transients
- More accurate geometry should be molded to get the full swirl observed

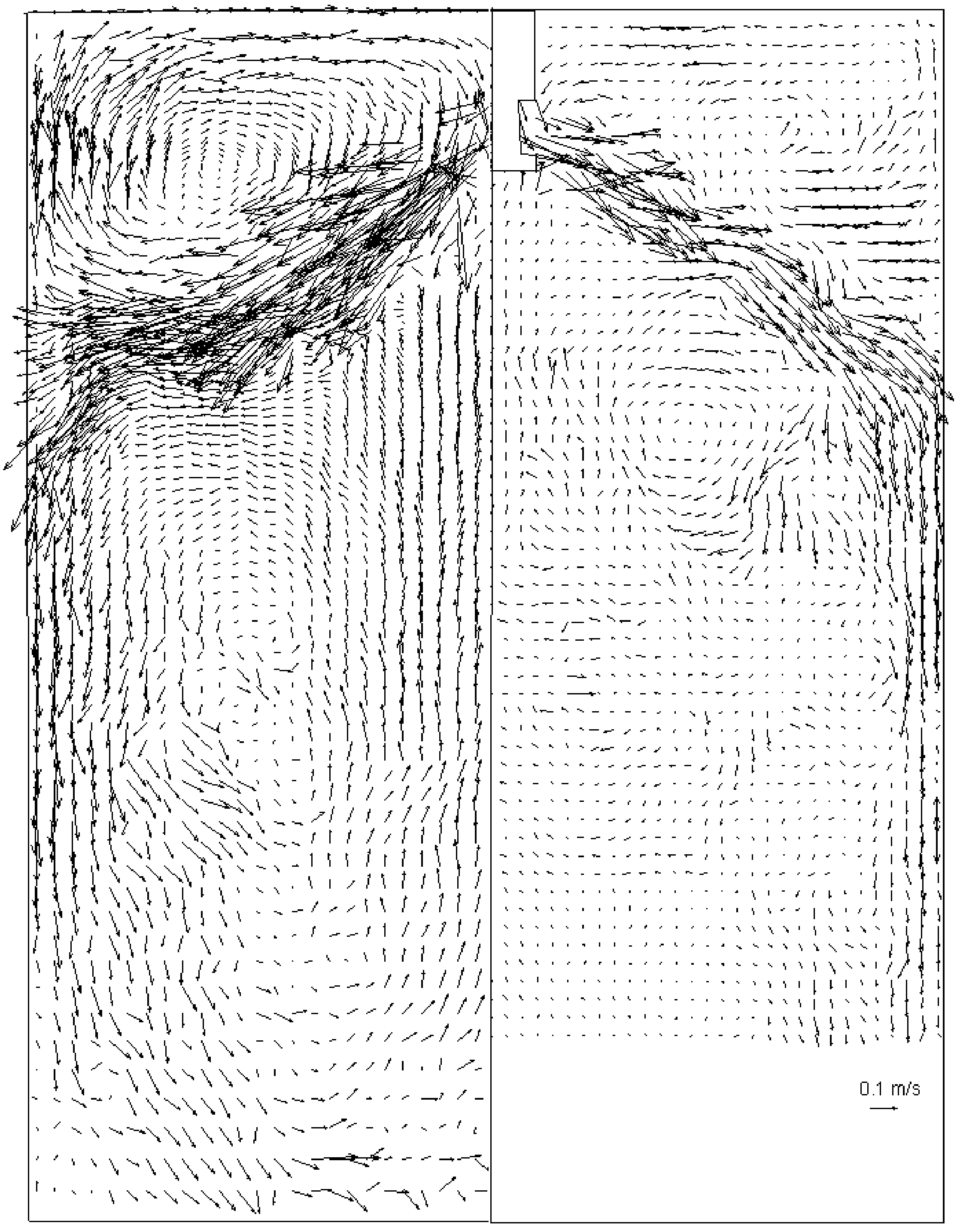
0.4 water model time averaged velocity vector



(a) LES simulation (b) PIV measurements

Center plane between wide faces

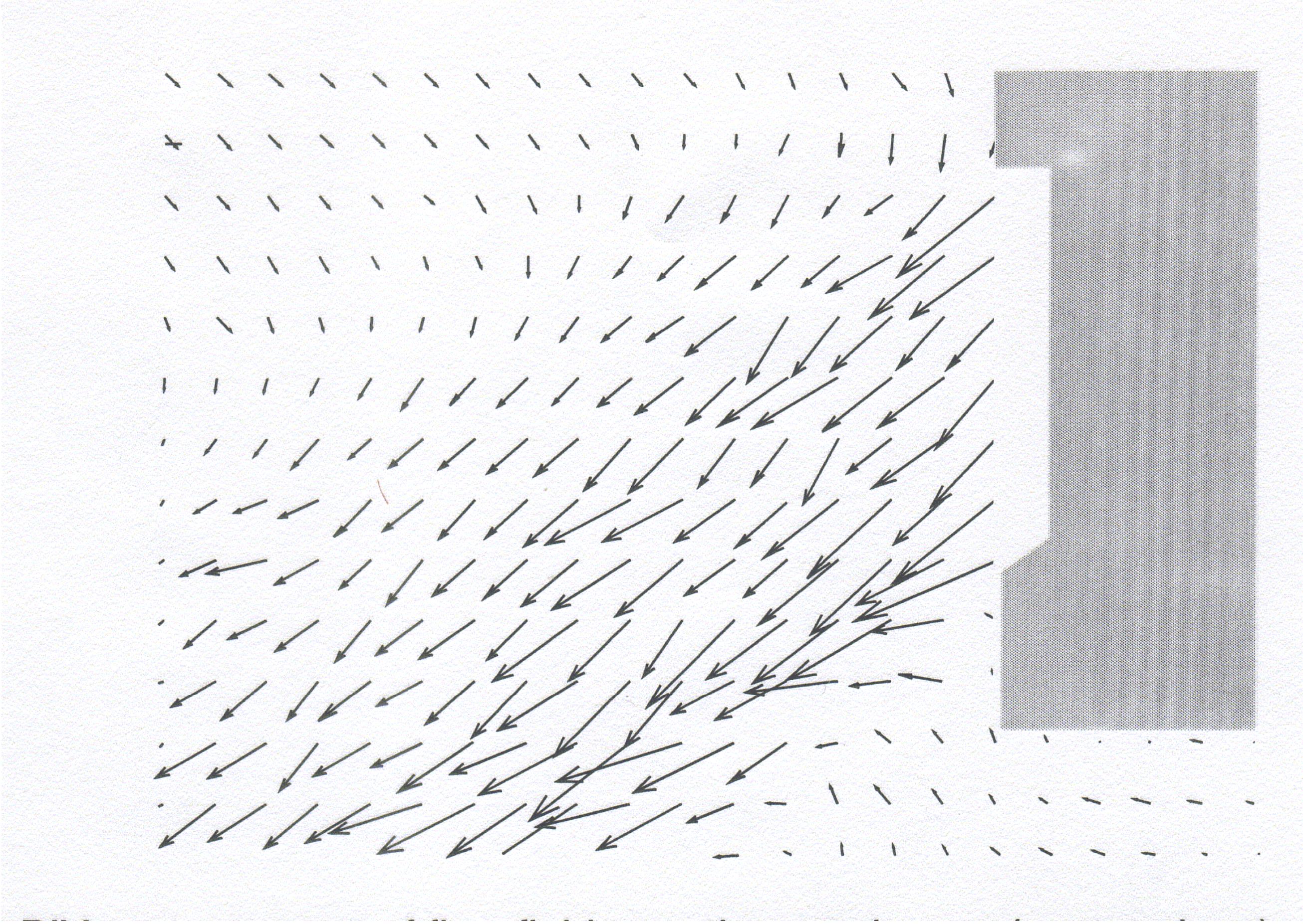
0.4 water model instantaneous velocity vector



(a) LES simulation (b) PIV measurements

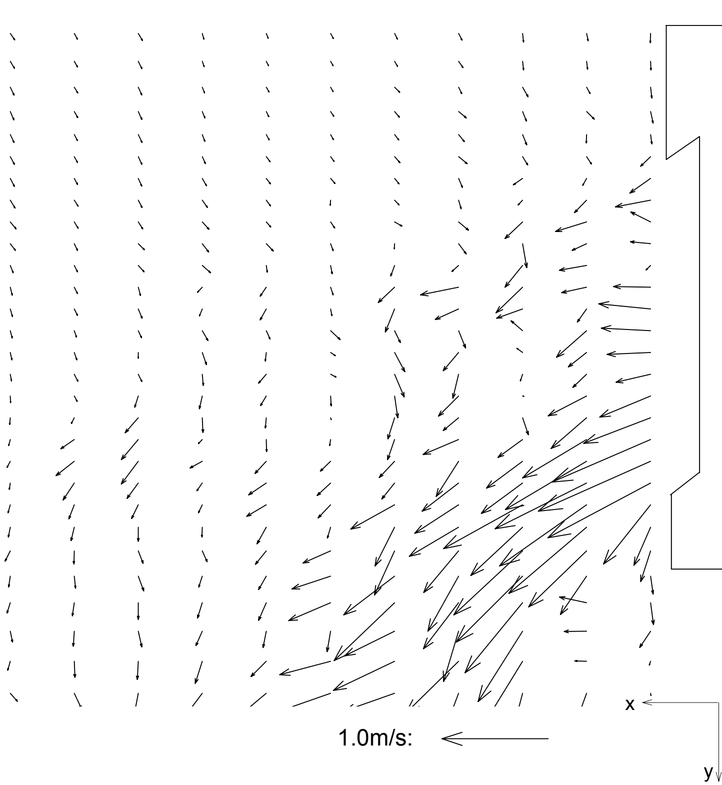
Center plane between wide faces

Flow near the nozzle port in the mold

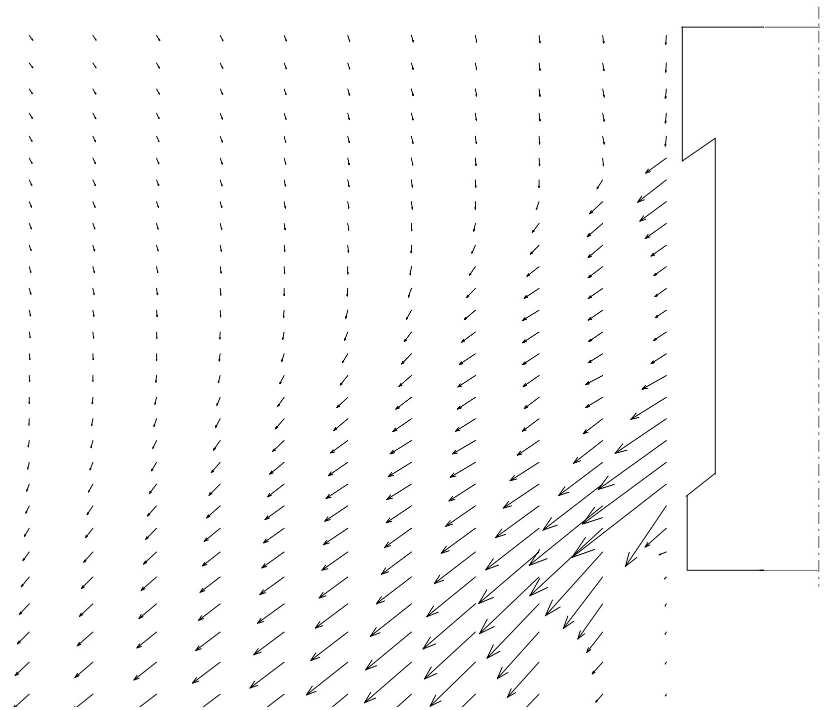


Time-averaged PIV Measurements

Flow near the nozzle port in the mold

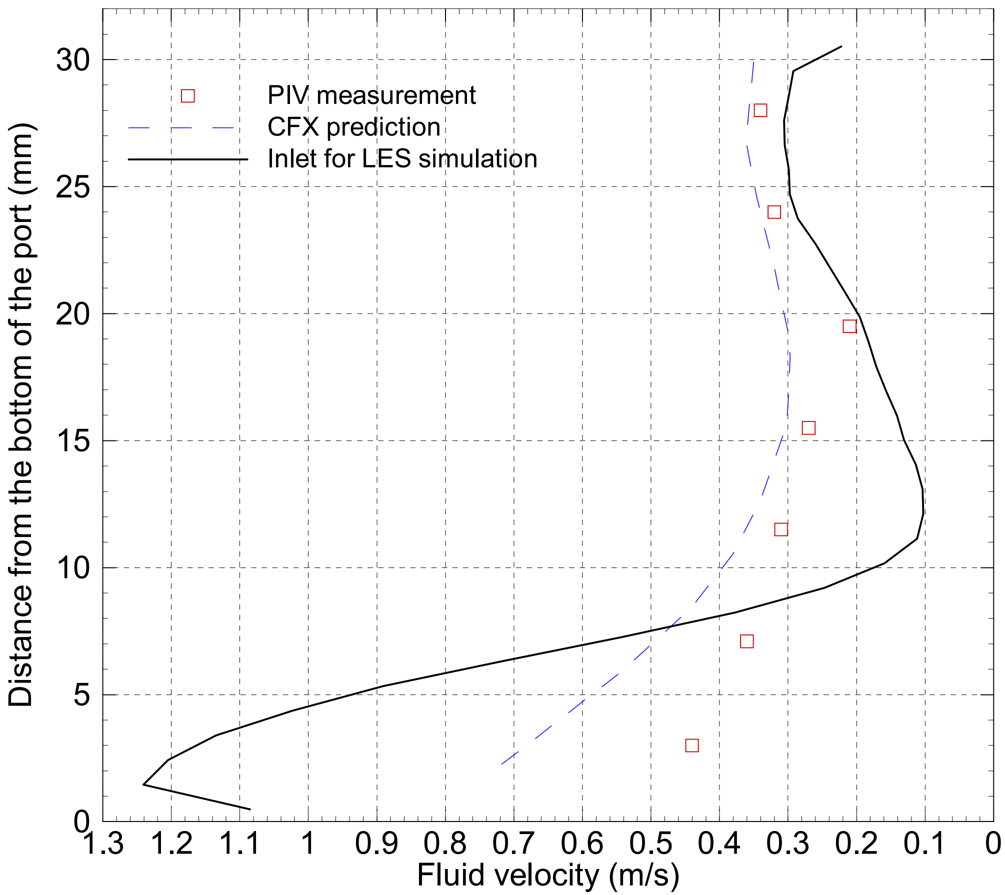


(b) transient velocity

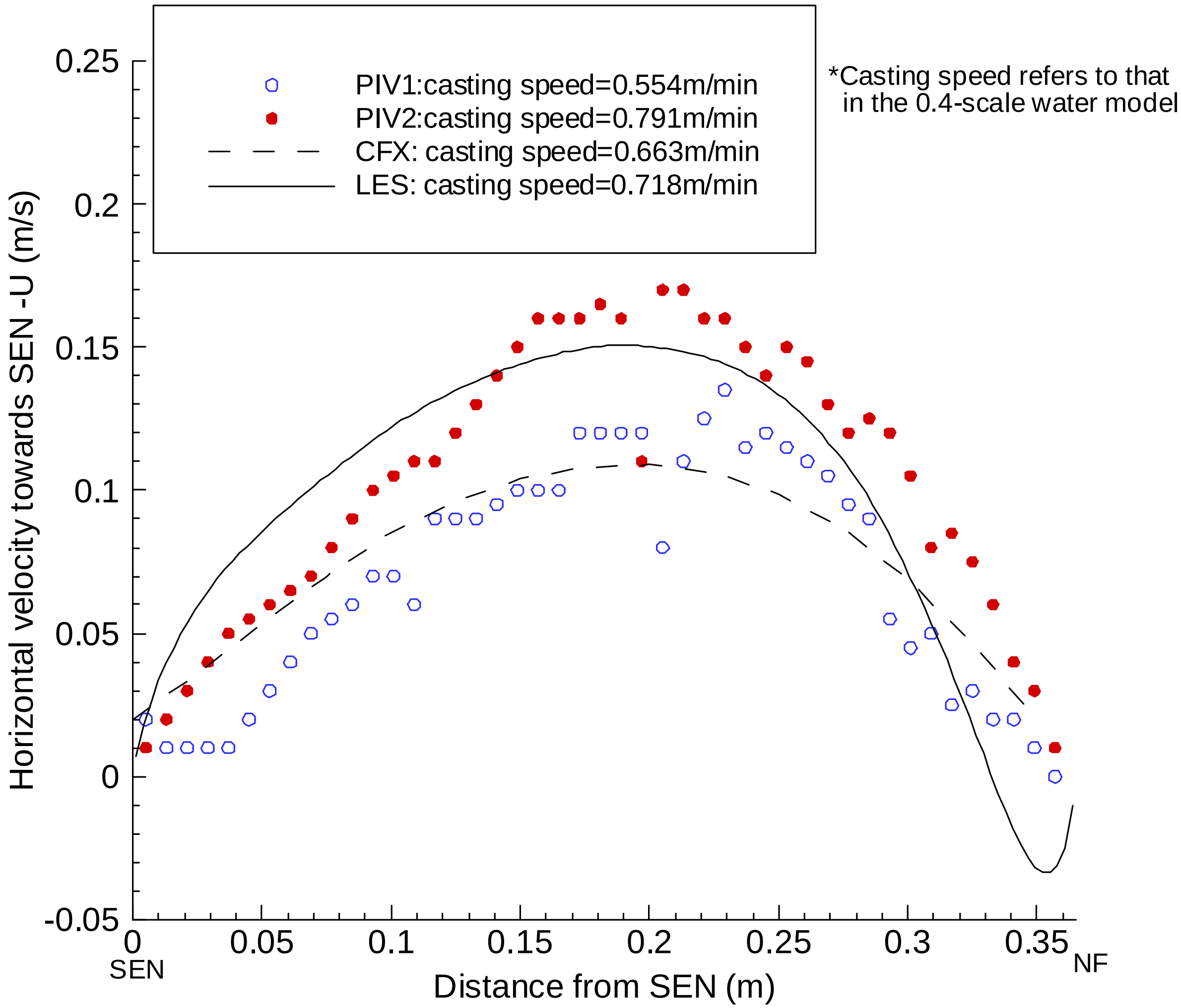


(c)time-averaged velocity

Flow near the nozzle port in the mold

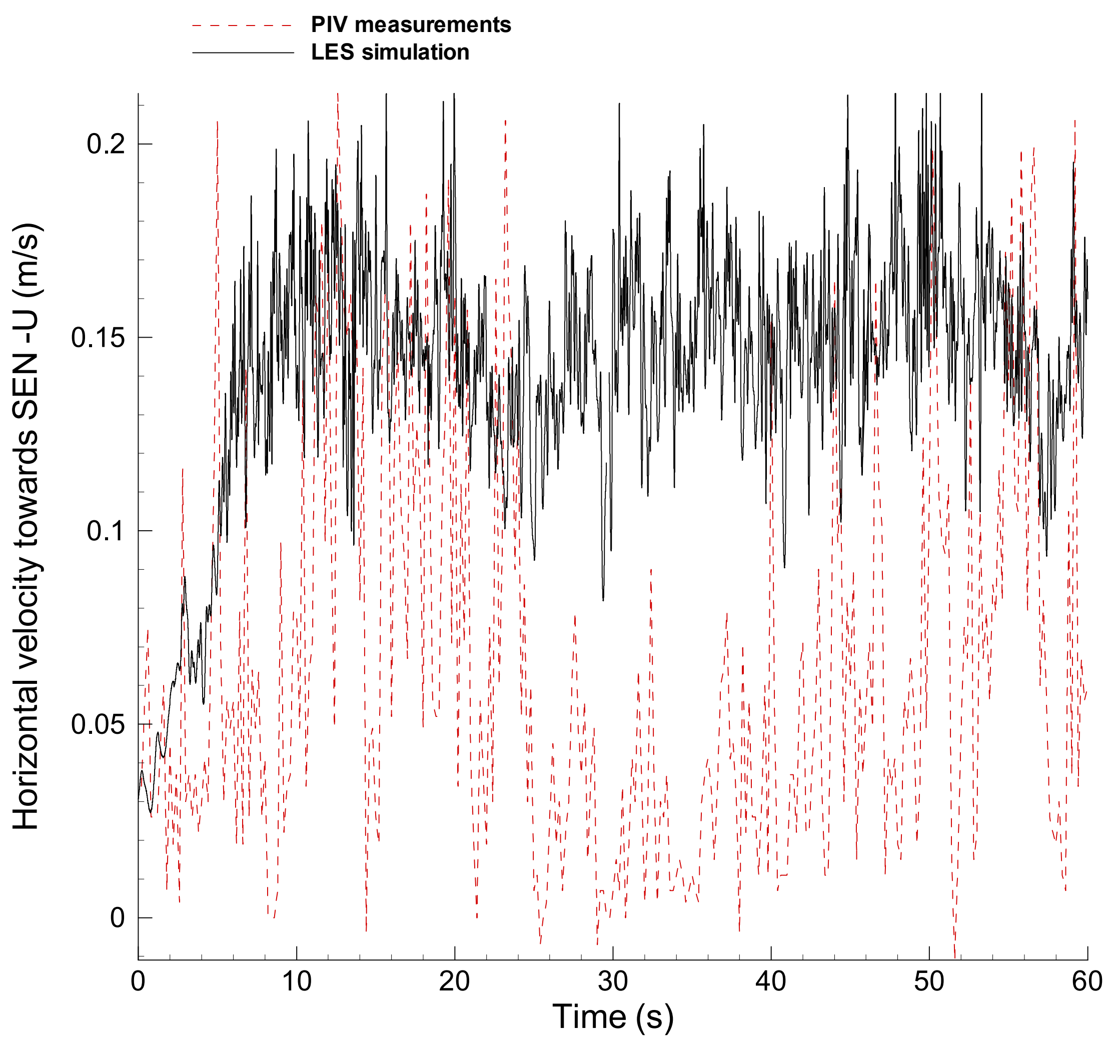


Comparison of inlet fluid velocity $(u^2+v^2)^{1/2}$ along the center line of the port



Horizontal velocity towards SEN -U along the center line on the top surface

*PIV and CFX results: Sivaraj Sivaramakrishnan et al, "Transient Flow Structures in Continuous Casting of Steel", 83th Steelmaking Conference Proceedings, Poittburgh PA, March 26-29 2000



Variation of horizontal velocity towards SEN -U at the point on the top surface half way between SEN and NF

Mold Flow Observations

- **LES simulation compares reasonably with PIV measurements and has better agreement at top surface with new inlet condition**
- **Constant symmetrical inlet swirls allow jet to bend upwards and cause higher surface velocity and generate greater velocity fluctuation on the top surface (relative to Sivaraj Sivaramakrishnan's LES simulation*, fully developed pipe inlet)**
- **The staircase flow pattern of the jet is not obvious in LES simulation, which is likely due to 2 symmetrical swirls in this inlet flow instead of a single strong swirl; further study needs to be conducted about this.**

* "Transient Flow Structures in Continuous Casting of Steel", 83th Steelmaking Conference Proceedings, Poittburgh PA, March 26-29 2000

Transient Flow and Particle Motion in a Full Scale Water Model

Sketch of the full scale water model and simulation domain

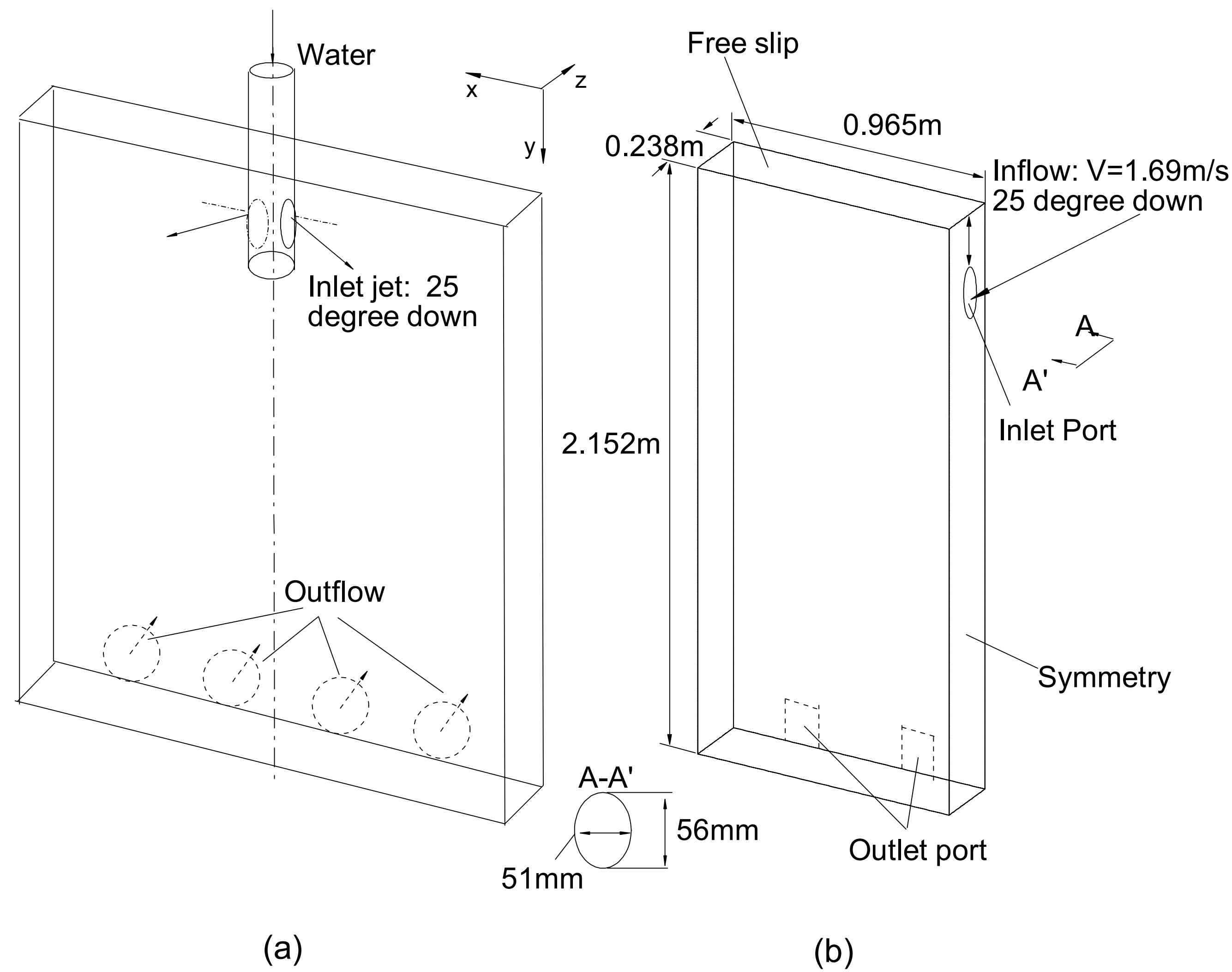


Table 2 Conditions for LES Simulation

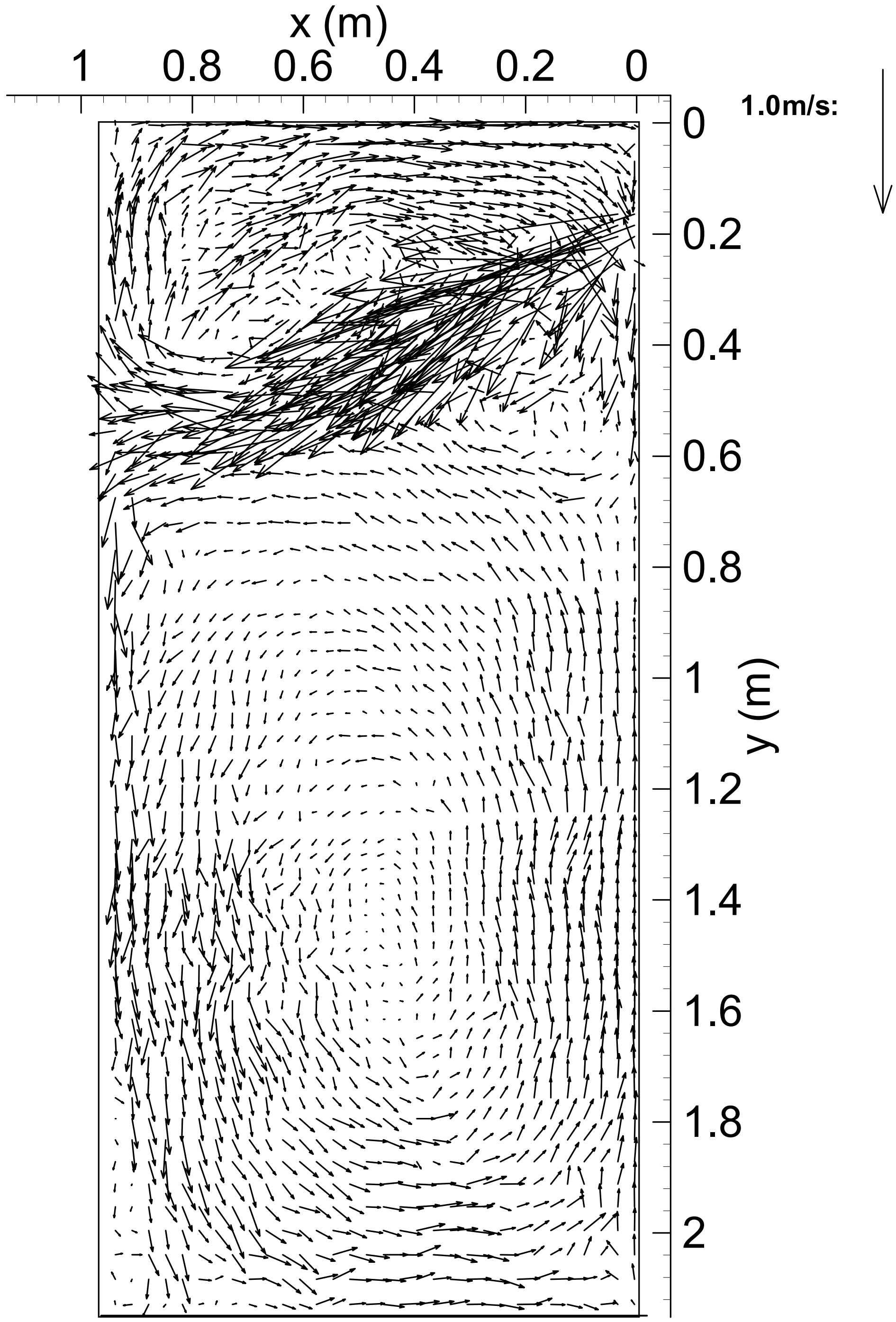
Parameter	Case 1	Case 2
Domain Length	2.152m	-
Domain Width	0.965m	-
Domain Thickness	0.238m	-
SEN Submerged Depth	0.15m	-
Averaged Jet Angle (match port angle)	25^{o} down	-
Inlet port	51mm x 56 mm oval	51mm x 51mm circular
Averaged Inlet Velocity	1.69m/s	1.156m/s
Model Inlet Velocity Profile	transient, interpolated from upper nozzle simulation	uniform
Inlet flow rate (each port)	$0.00344m^3/s$ (corresponding to 24.15kg/s of $7020kg/m^3$ density steel)	$0.00214(m^3/s)$ (corresponding to 15.02kg/s of $7020kg/m^3$ density steel)
Simulated Casting Speed	15.2mm/s (35.91inch/min or 0.912m/min)	9.3mm/s (21.97inch/min or 0.558m/min))
Laminar Kinematic Viscosity	$1.0\times10^{-6}\ m^2/s$	-
Inlet Reynolds number	86501	53499
Liquid Density	$1000kg/m^3$	-
Particle's Material Density	$988kg/m^3$	$998kg/m^3$
Particle's Material Diameter	3.8mm	2.5mm
Corresponding Inclusion Density in Steel Caster	2700 kg/m^3	2700 kg/m^3
Corresponding Spherical Inclusion Diameter in Steel Caster	300μm	100μm
Simulation Mesh ($\Delta x\times\Delta y\times\Delta z$)	128×169×64	128×236×64
Simulation Speed on Pentium 750MHz	21.6 CPU s/ time-step (3.2s /day)	25 CPU s/ time-step (3.5s /day)

- : same as Case 1

Case 1 is to match the experiment in references

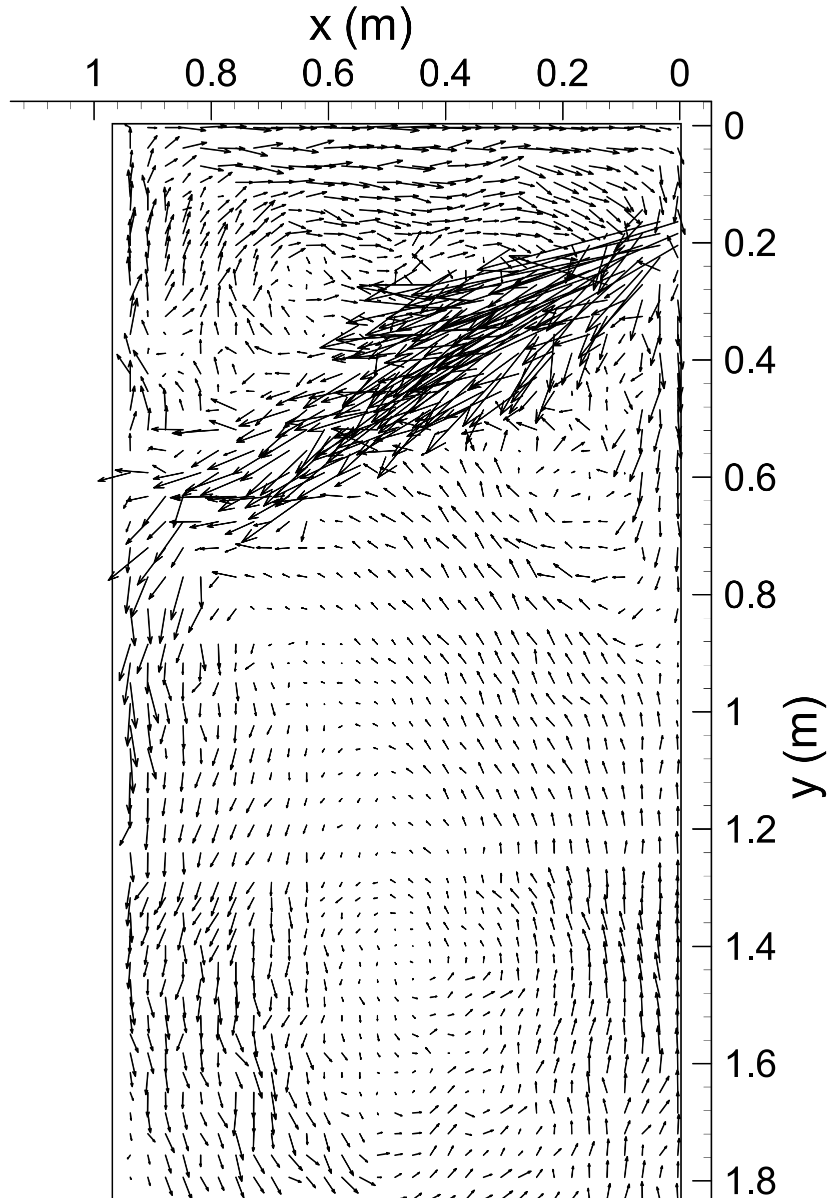
(1) R.C.Sussman et al, "Inclusion Particle Behavior in a Continuous Slab Casting Mold", Iron and Steel Society, Warrendale, PA, 1992, pp.291-304

Instantaneous velocity profile (case 1)



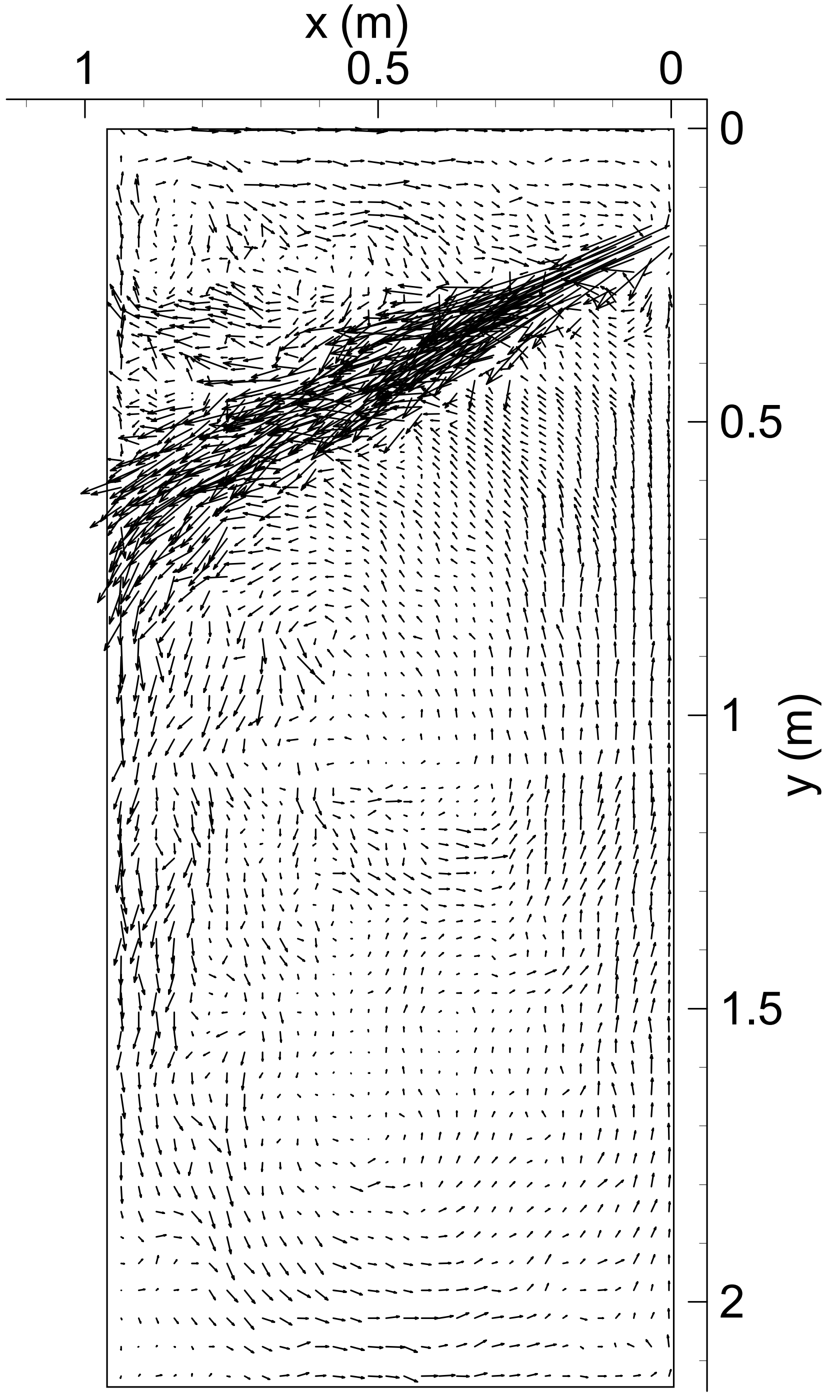
Center plane between wide faces, instant 1

Instantaneous velocity profile (case 1)



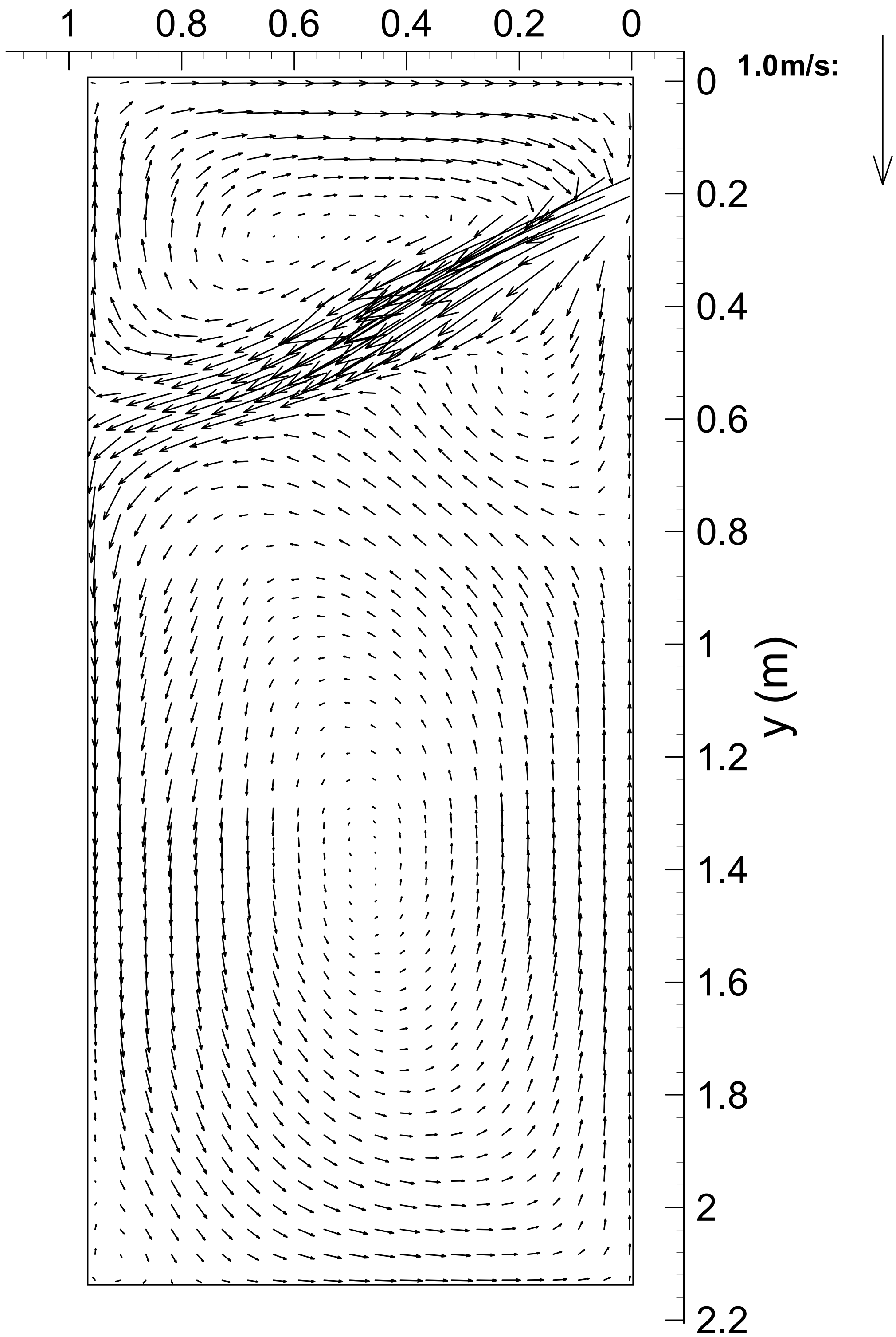
Center plane between wide faces, instant 2

Instantaneous velocity profile (case 2)



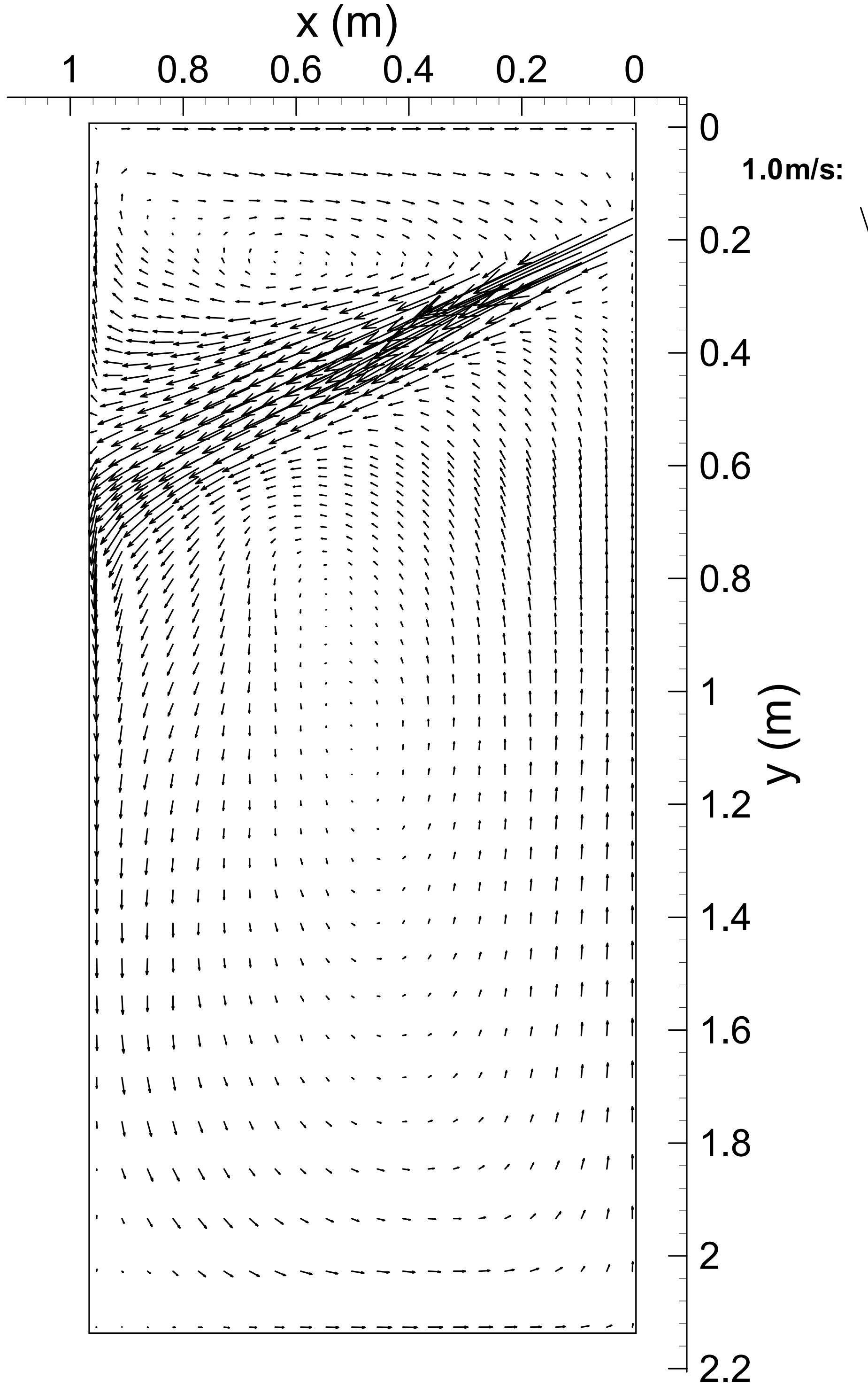
Center plane between wide faces

Time averaged velocity profile (case 1)



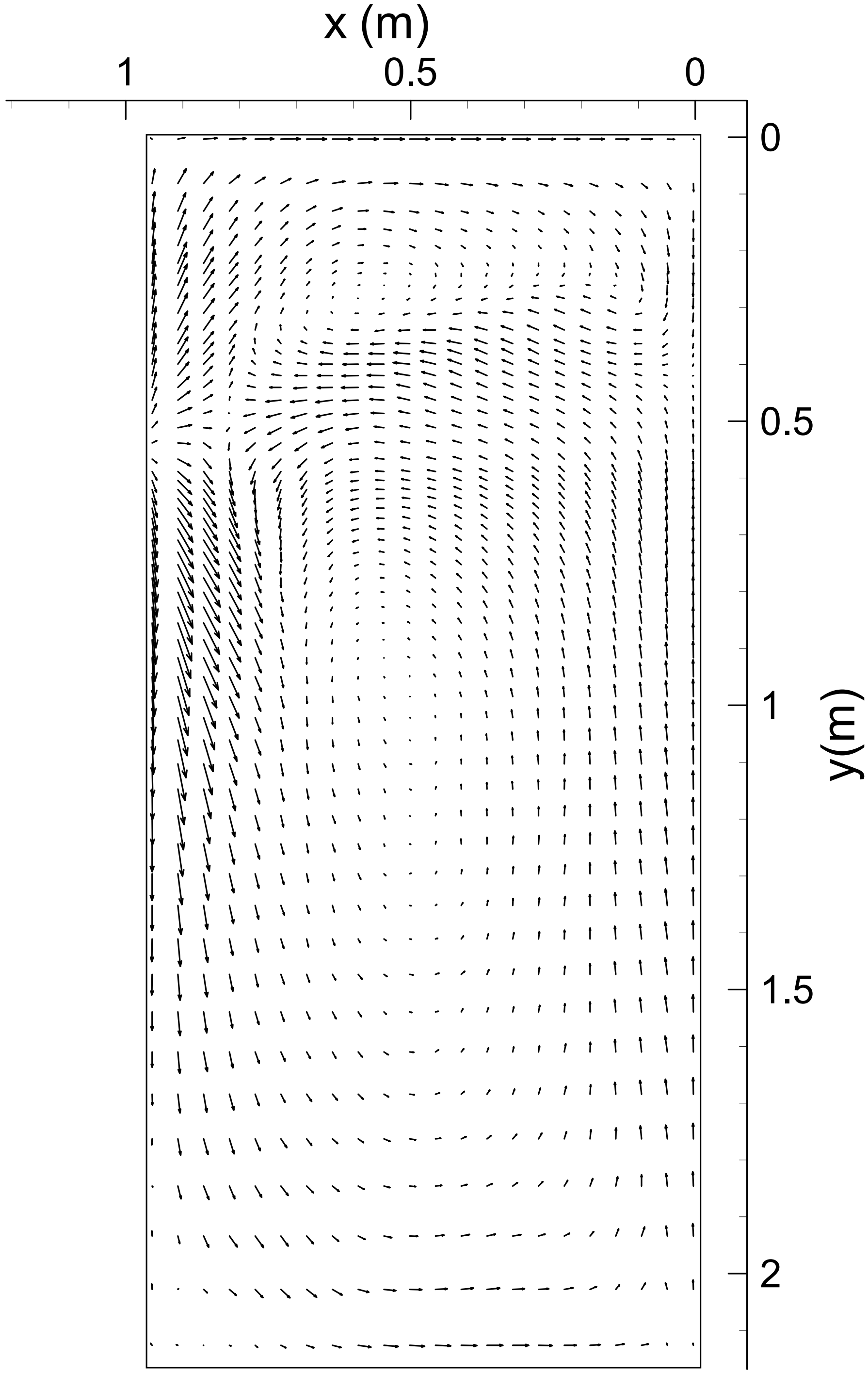
Velocity vector profile at the center plane between wide faces

Time averaged velocity profile (case 2)



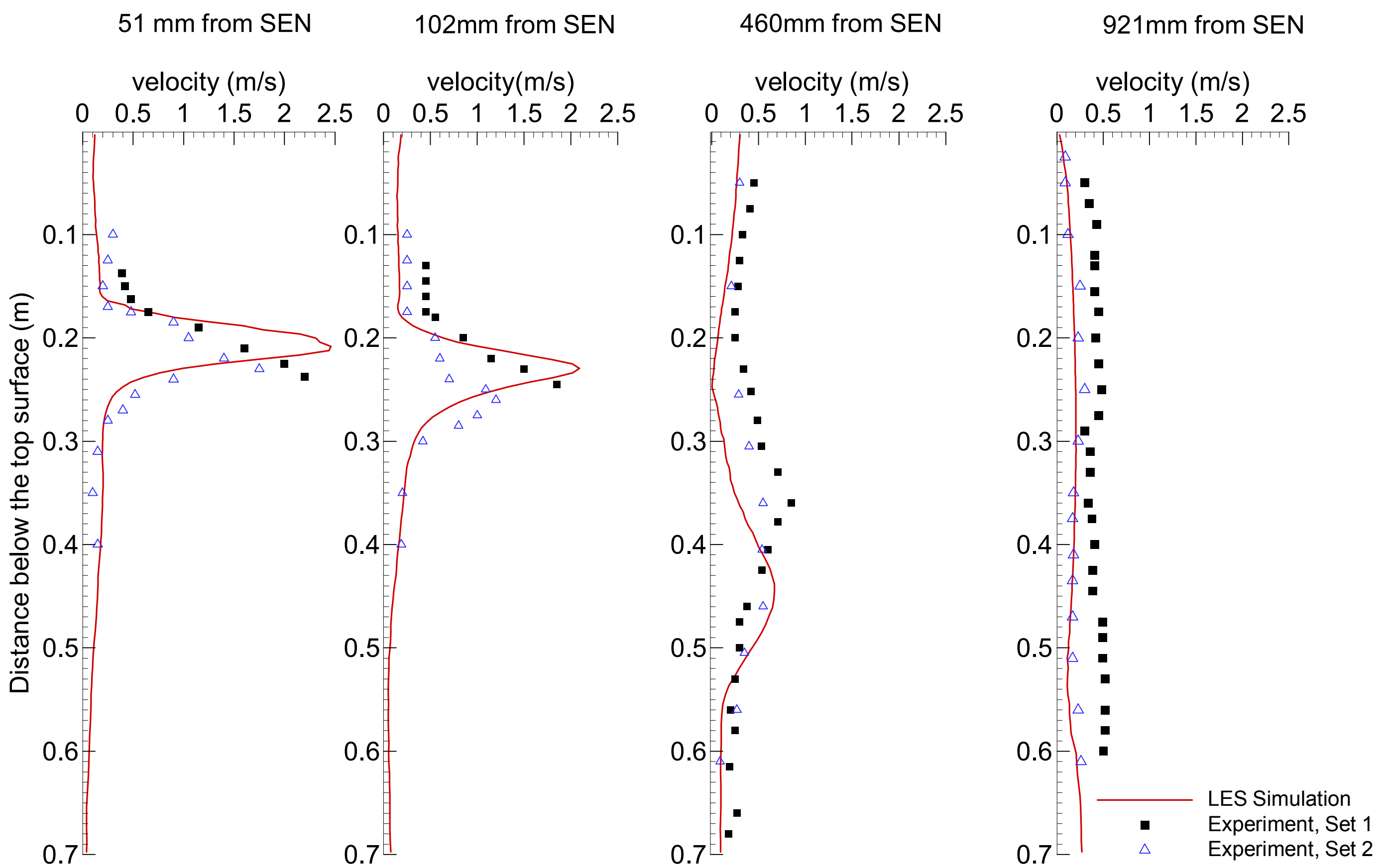
Velocity vector profile at the center plane between wide faces

Time averaged velocity profile (case 2)



Velocity vector profile at the center plane 34mm from wide face

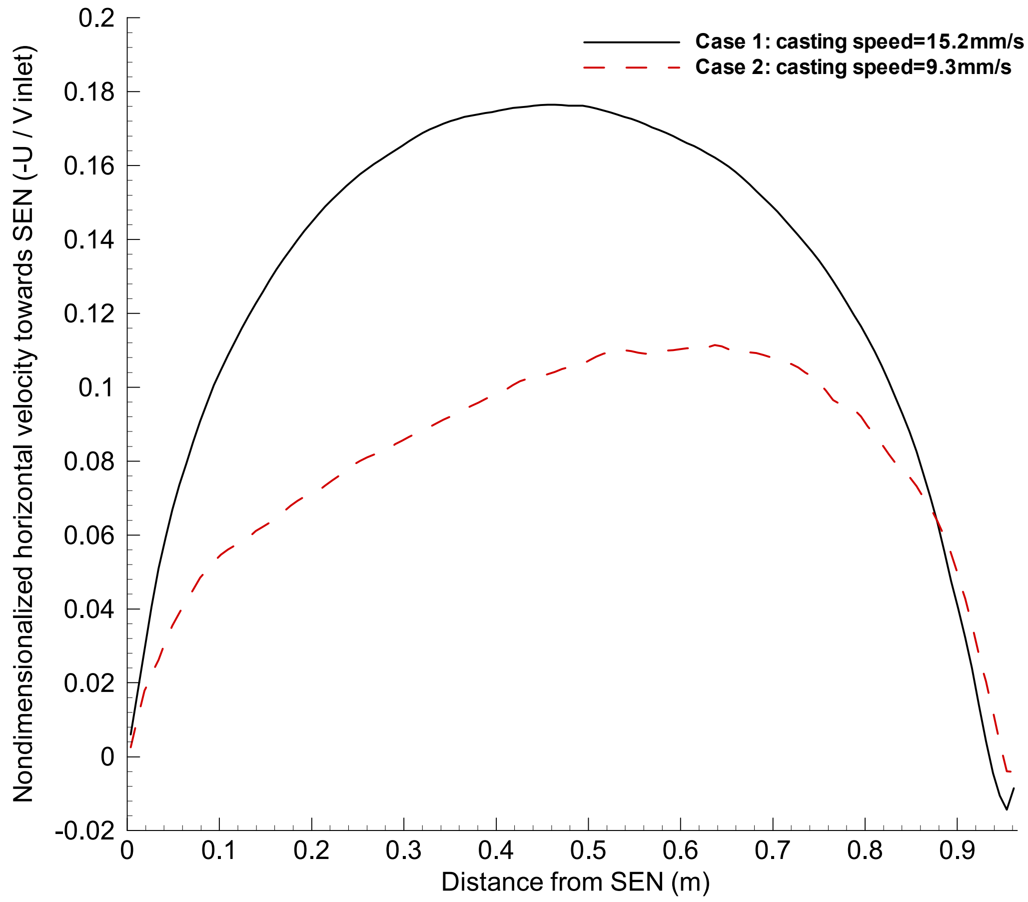
Validation of flow in the mold



Comparison of velocity $(V_x^2 + V_y^2)^{1/2}$ between LES simulation and measurements

Experiment results: B.G.Thomas, "Simulation of Argon Gas Flow Effects on a Continuous Slab Caster", Metallurgical and Material Transaction B, Volume 25B, August 1994, pp 527-547

Comparison of nondimensionalized top surface velocity



Mold Flow Observations

- **LES simulation matches the hot-wire anemometry speed measurements and was validated**
- **Time averaged jet in case 1 bends upward a little while it is straight in case 2; related to 0.4 scale water mold results, transient second flow, especially swirls, with considerable magnitude, is likely the reason to allow jet to bend upward**
- **Horizontal velocity at meniscus nondimensionalized with inlet velocity is consistently greater in case 1 than that in case 2; as found in 0.4 scale water model, the transient of inlet flow has an important influence on meniscus speed**

Particle simulation assumptions

- **Particles are sphere and have uniform size;**
- **Only drag force, buoyancy and gravity force act on each particle;**
- **Particles are small enough to achieve their local terminal velocity everywhere they move;**
- **Particle interaction neglected;**
- **Particles don’t affect flow pattern (case 1).**

Numerical settings for particle simulation

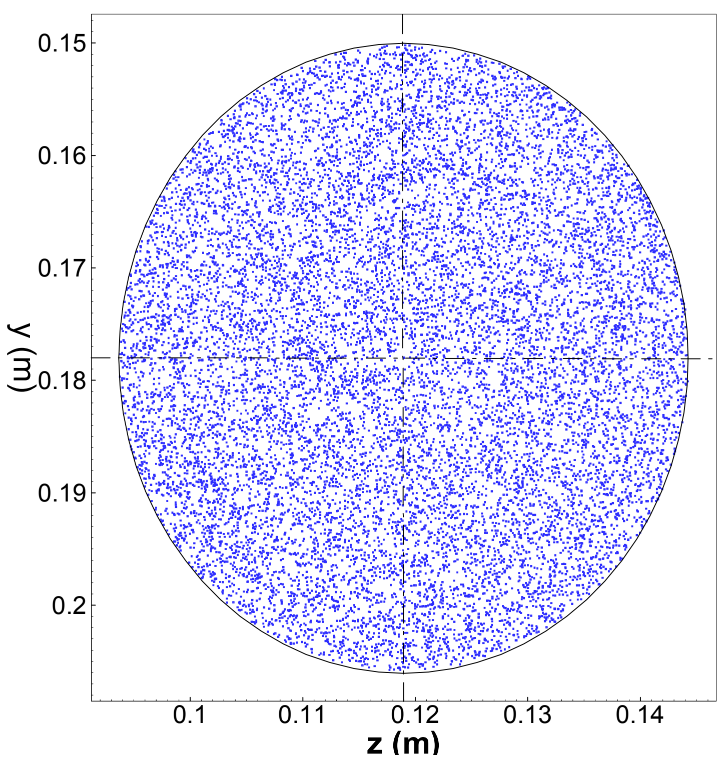
Table 4 Simulation settings for particles, case 1

Particle group index	Amount of particles	Input time
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

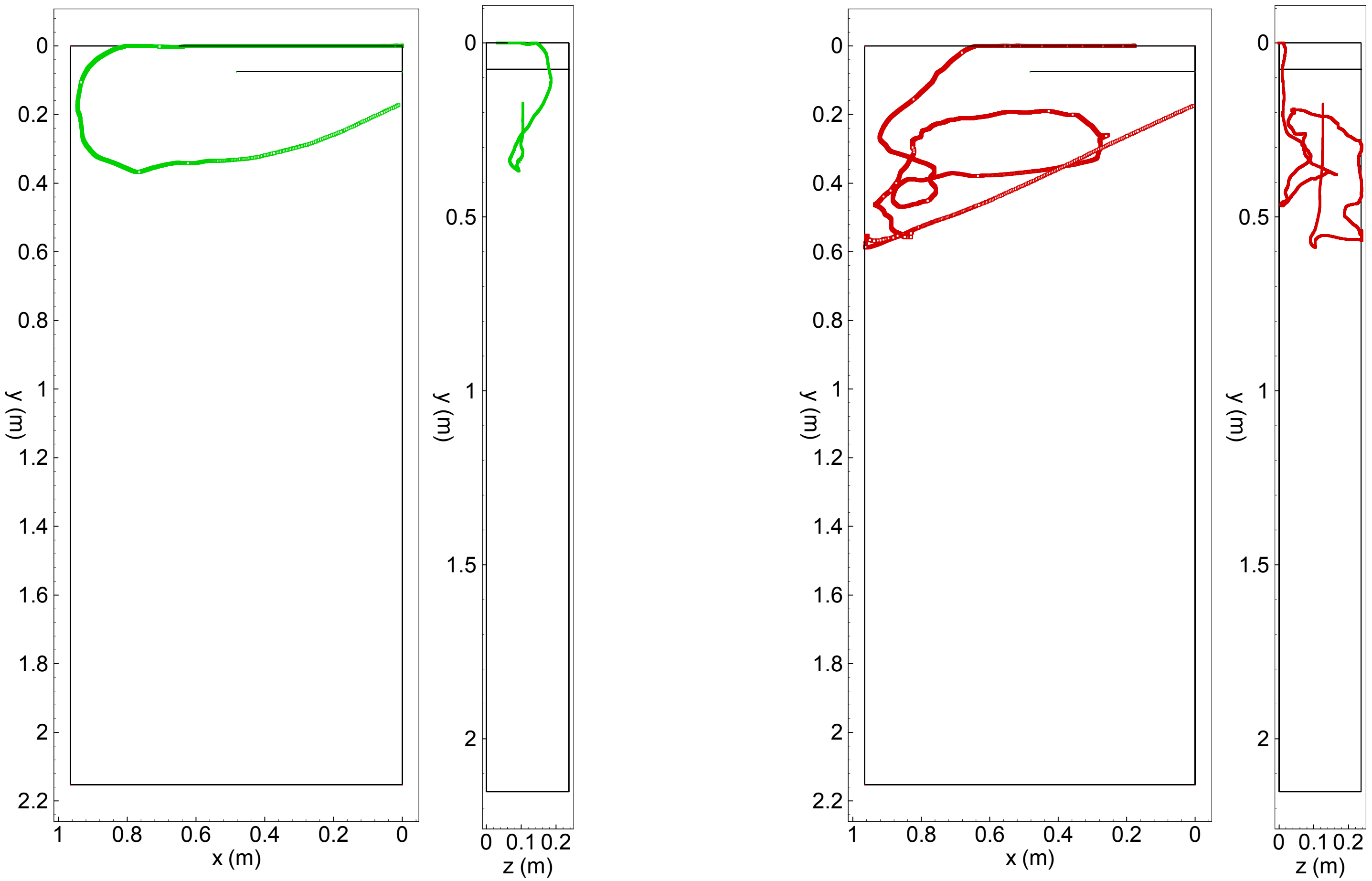
Table 5 Simulation settings for particles, case 2

Particle group index	Amount of particles	Input time
0	15000	0s
1	500	2s
2	500	4s
3	500	6s
4	500	8s
5	500	10s

Particles were input at random position at the inlet port and initialized with local transient velocity:

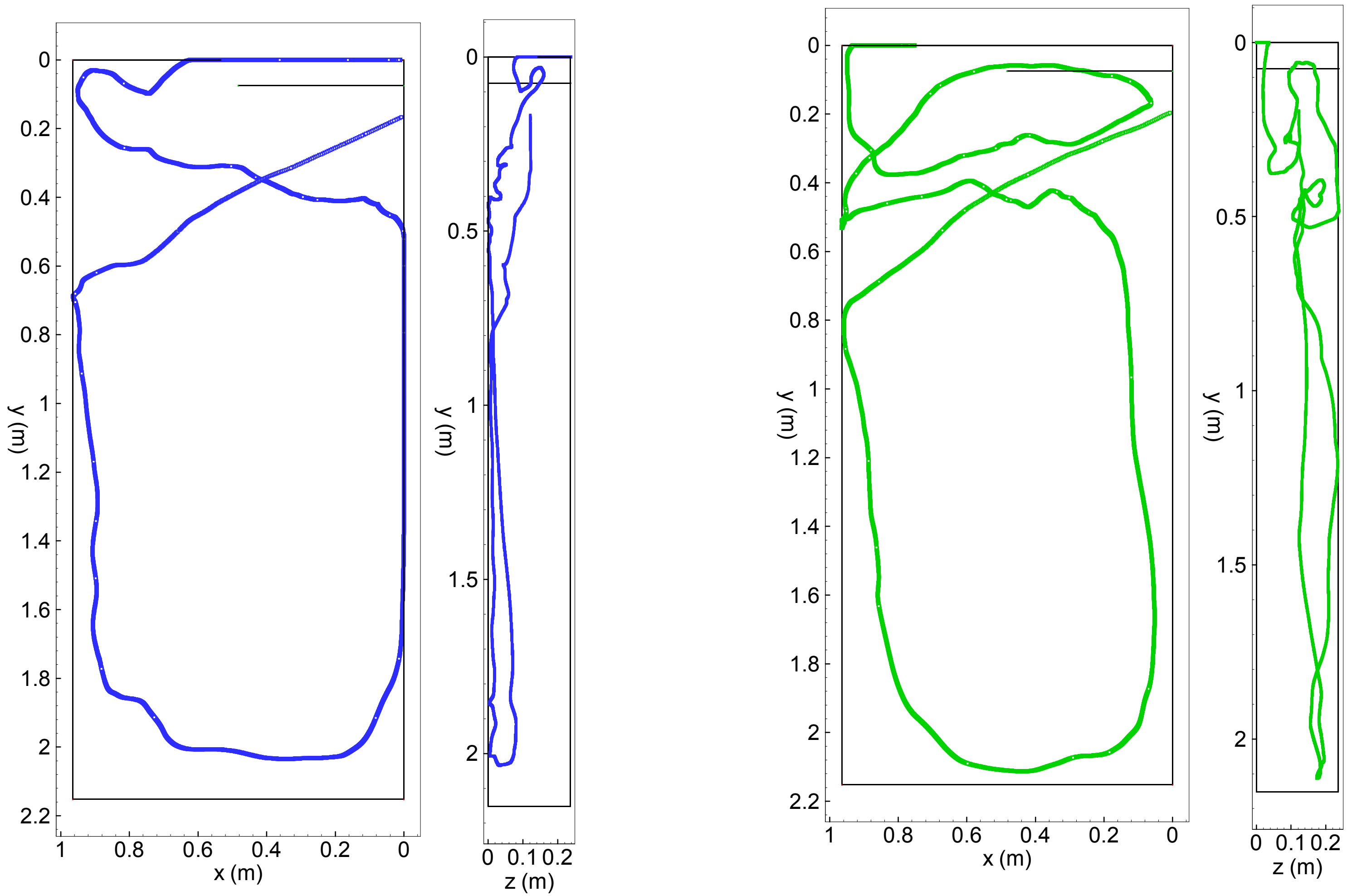


Typical particle trajectories



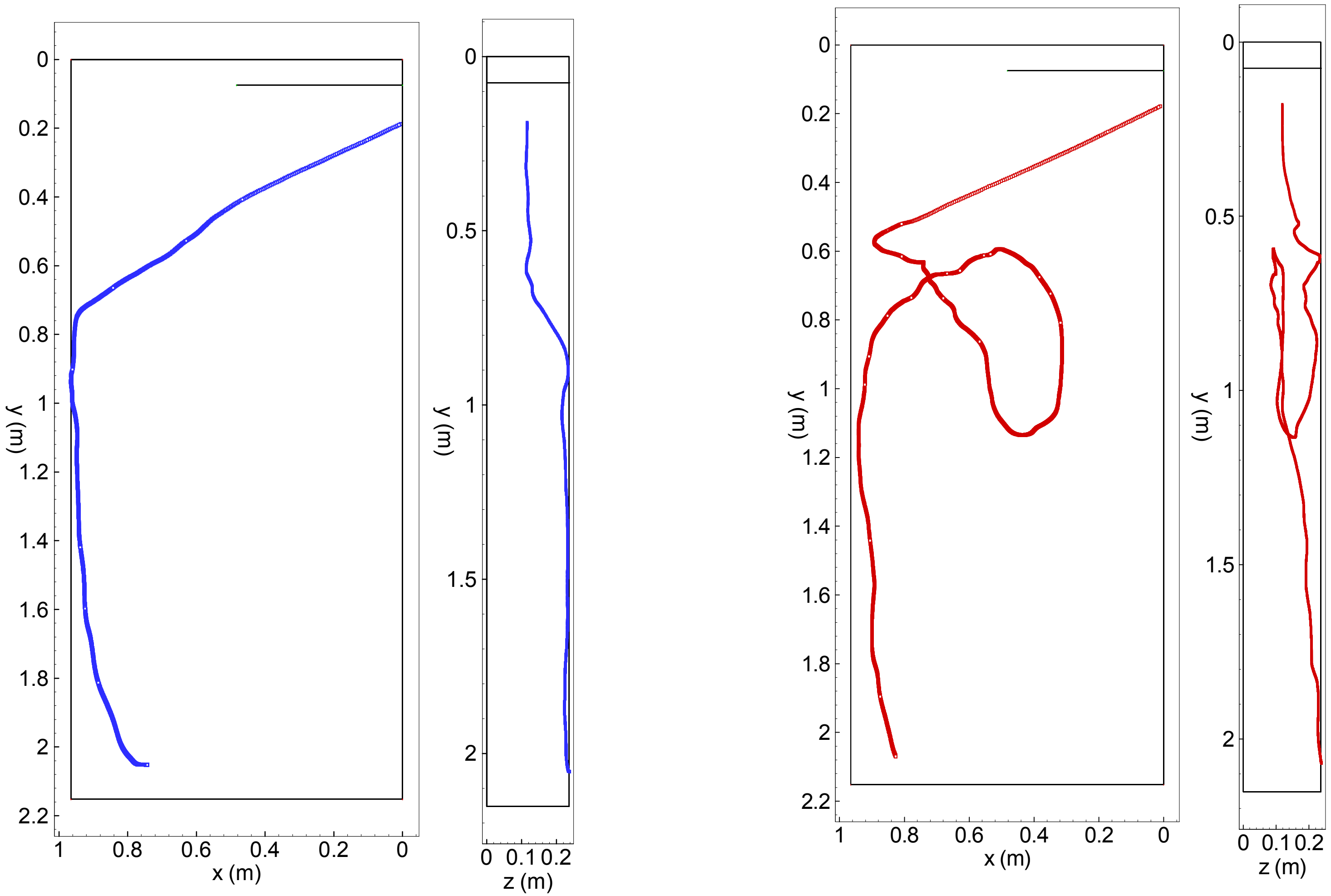
(a) Moving to the meniscus without going through lower roll

Typical particle trajectories



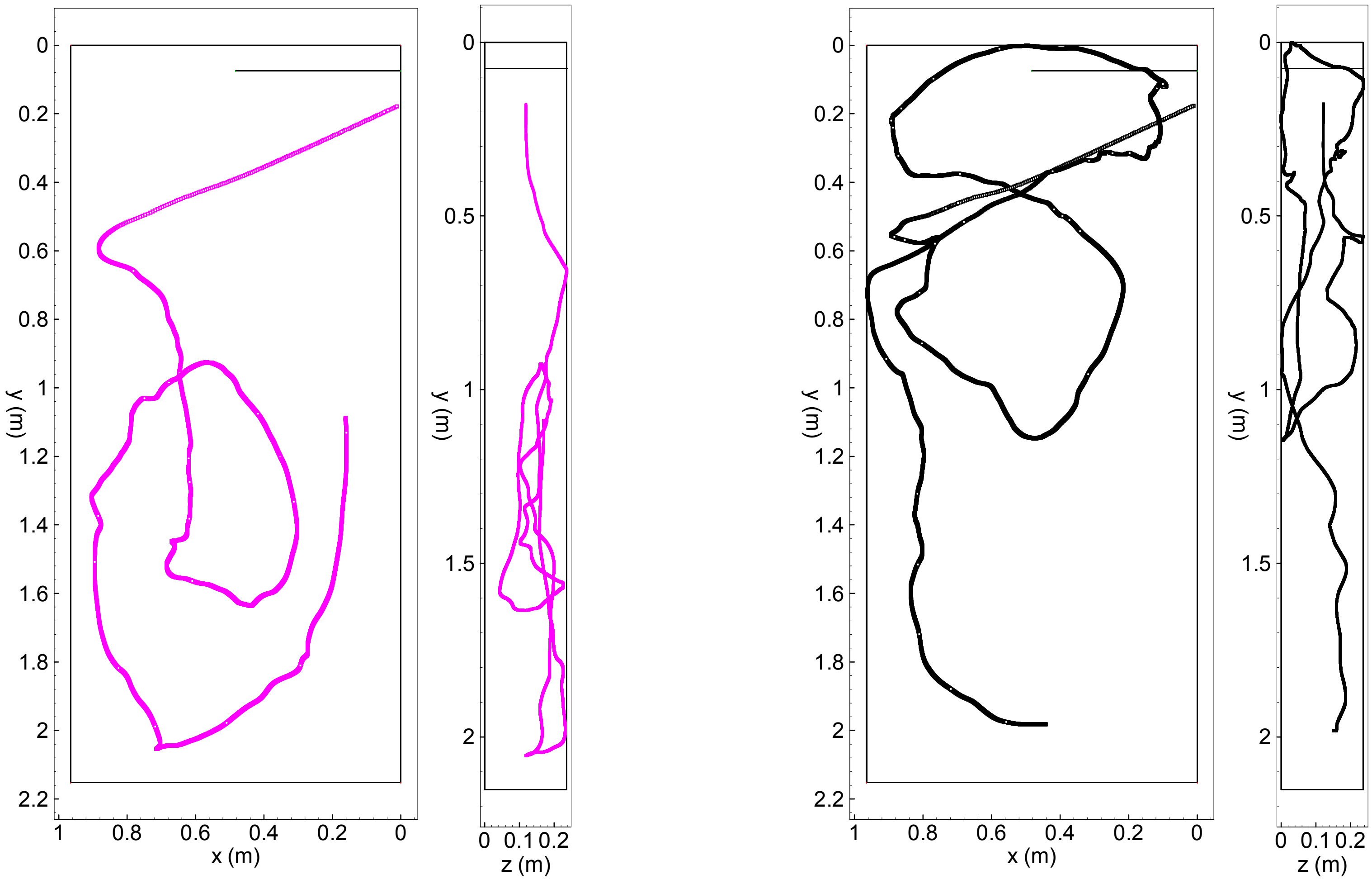
(b) Moving to the meniscus after going through lower roll

Typical particle trajectories



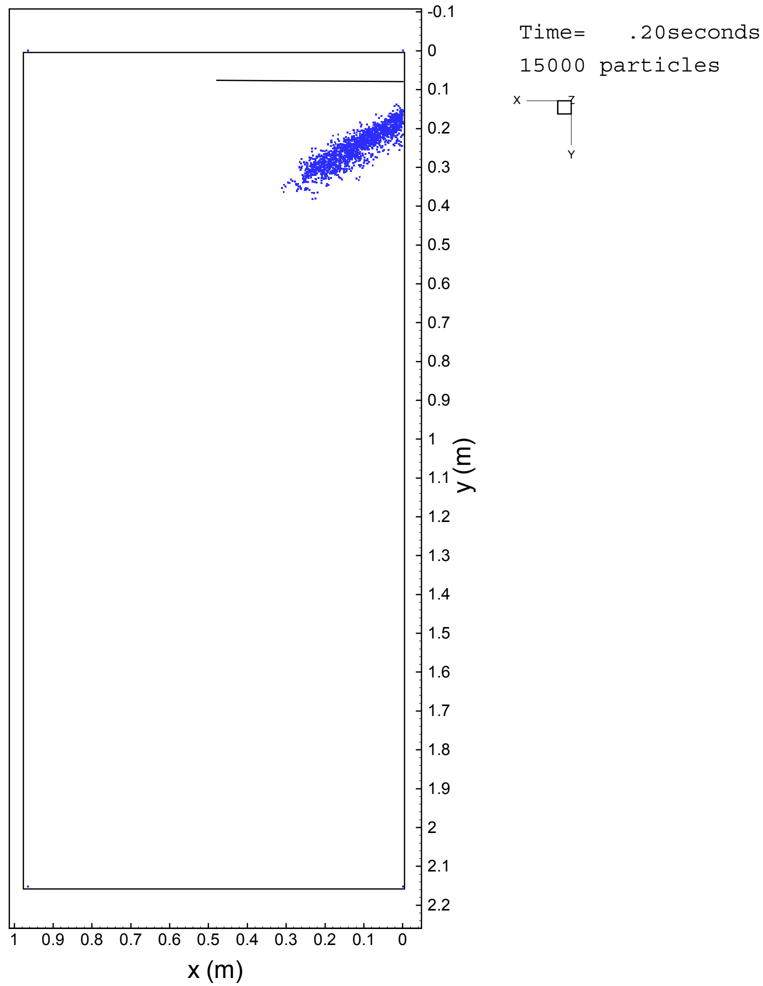
(c) Moving out of the domain through outlet port

Typical particle trajectories

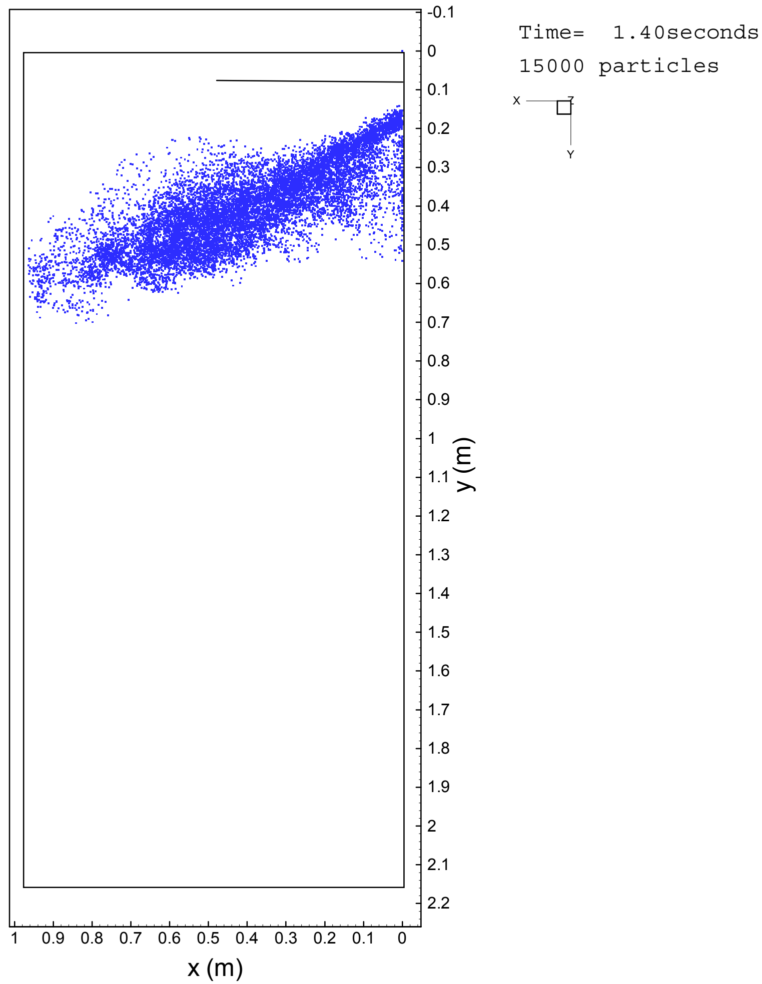


(d) Recirculation between upper and lower rolls

Particle transport in mold

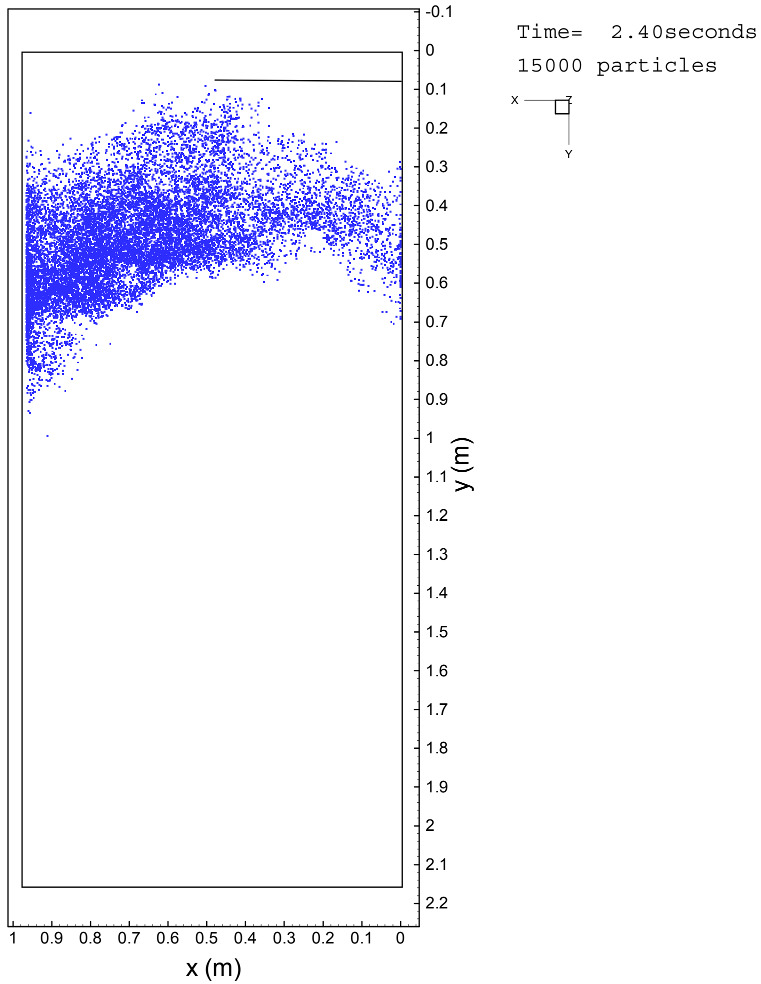


(a)

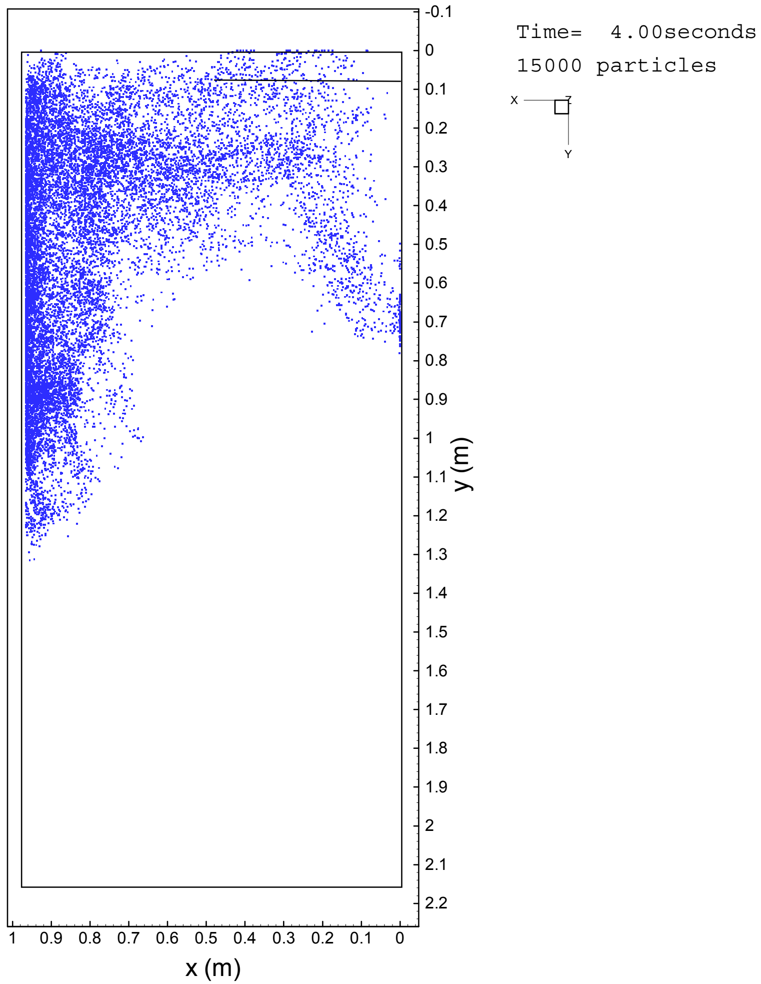


(b)

Particle transport in mold

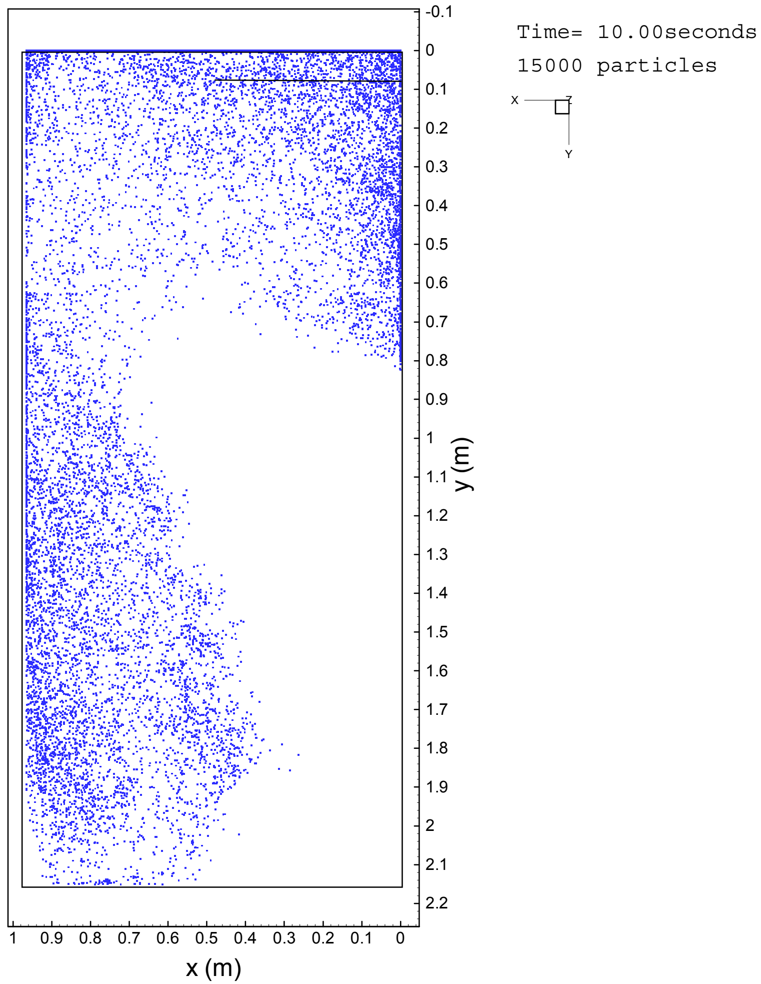


(c)

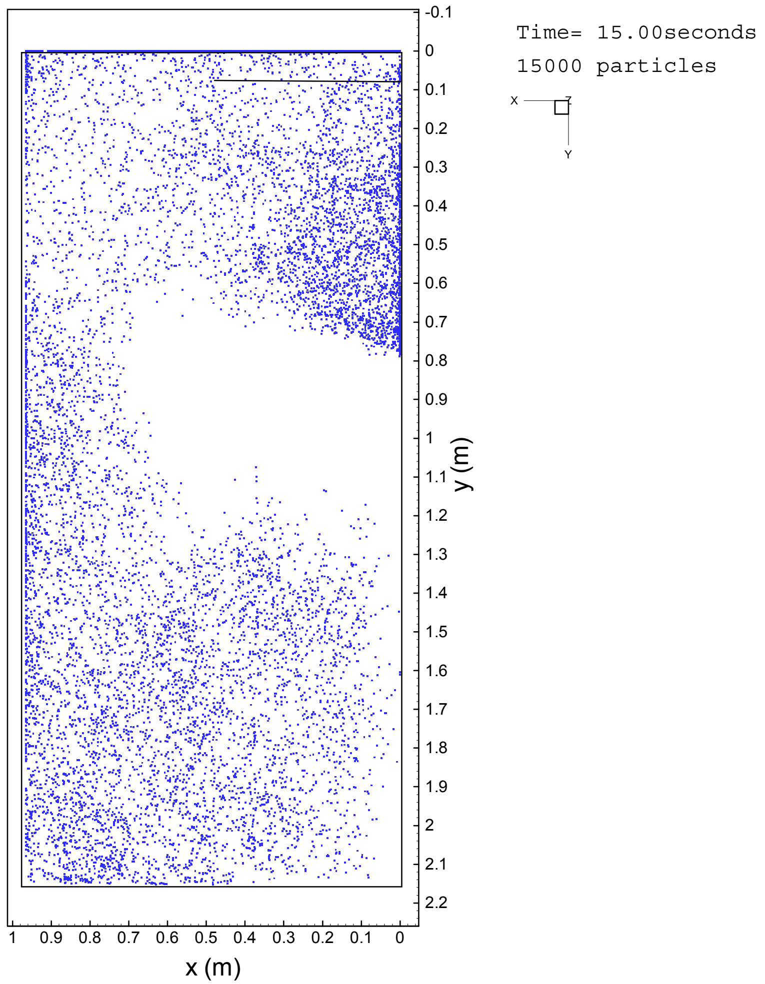


(d)

Particle transport in mold

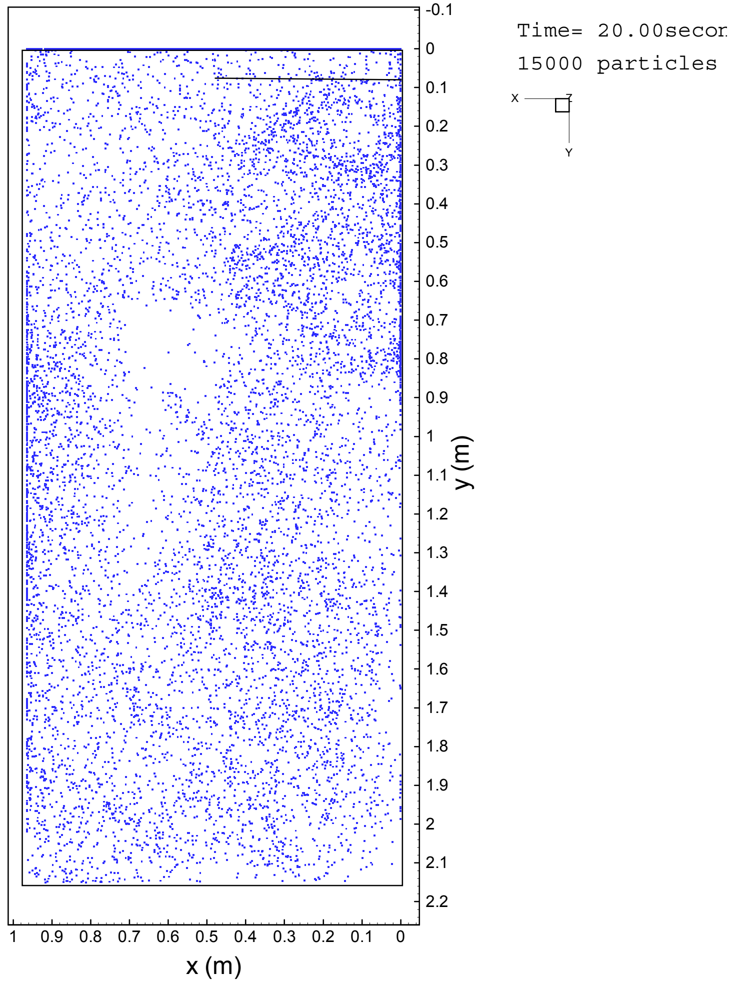


(e)

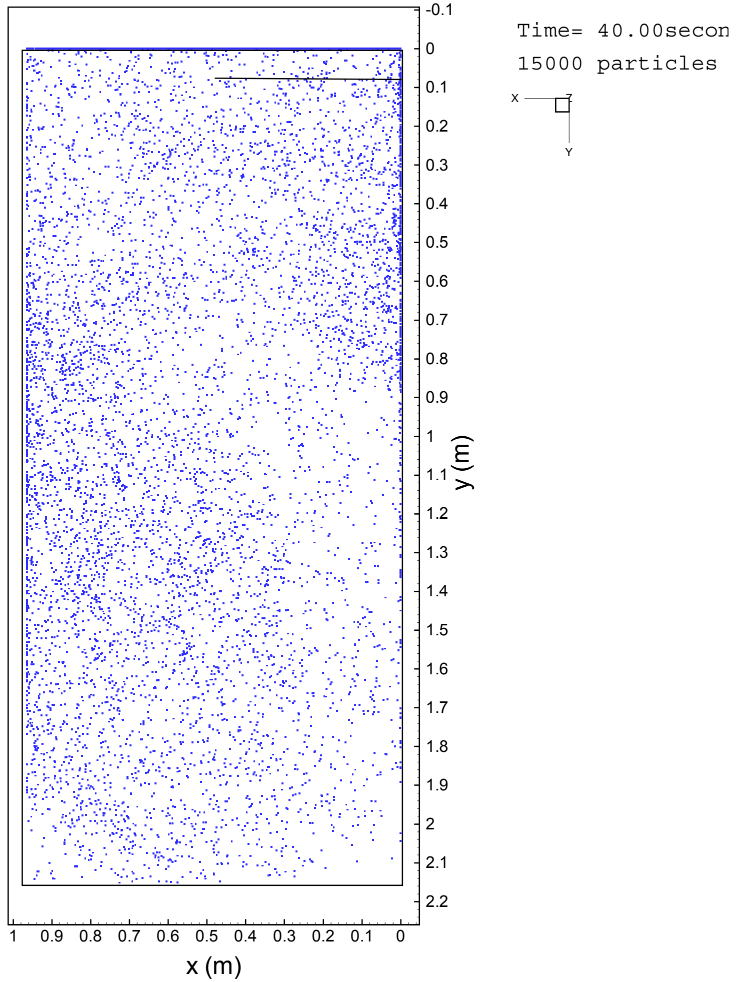


(f)

Particle transport in mold



(g)



(h)

Validation and results particle simulation:

Table 6 Statistic of particles moving to the meniscus within 10s after each group's input, case 1

Particle group index	Particles moving to the meniscus		
	Amount	Percentage	Average
0	4044	26.96%	26.96%
1	136	27.20%	25.56%
2	89	17.60%	
3	131	26.20%	
4	119	23.80%	
5	165	33.00%	

Statistic result in experiment measurements: 22.3%.

Table 7 Statistic of particles moving to the meniscus within 10s after each group's input, case 2

Particle group index	Particles moving to the meniscus		
	Amount	Percentage	Average
0	843	5.62%	5.62%
1	45	9.00%	10.28%
2	96	19.20%	
3	31	6.20%	
4	34	6.80%	
5	51	10.20%	

Particle Behavior Observations

- **Typical particle trajectories in LES simulation were similar as found in the experiment*;**
- **The percentage of particle moving to the meniscus in the simulation case1 matches the experiment measurements*, in which 23.2% particles moving into meniscus within 10 seconds after the particle injection; the mathematical model was validated;**
- **In case 1, different particle input time can lead to statistic results with considerable differences, while the averaged results converges to a constant number; this may imply that transient structures near the inlet have an important influence of particle motions and thus sufficient input time is required to get accurate statistic results; the big discrepancy in case 2 may be due to the too short input time;**
- **More particles consistently move to the top surface in case 1 within 10 seconds after their input; this suggests that jet flow pattern has an important influence on particle motions in the mold; the transient "wiggling" of the jet may contribute to the particle moving to meniscus.**

*R.C.Sussman et al, "Inclusion Particle Behavior in a Continuous Slab Casting Mold", Iron and Steel Society, Warrendale, PA, 1992, pp.291-304

Conclusions

- **LES results match PIV measurements (LTV) in top surface velocity and jet bending;**
- **Transient swirls in inlet are likely an important parameter affecting both the time averaged and transient variation of the velocity on the top surface;**
- **Transient secondary flows, especially swirls, are likely the main reason allowing jet bending upwards;**
- **Particle simulation using LES matches experiment measurements (AK Steel) in the statistic of particle moving to the meniscus within the starting 10 seconds;**
- **4 typical particle trajectories were found in the water model matching observations in the experiment (AK Steel);**
- **Transient flow in the inlet and jet have an important influence on particle motions in the mold; "wiggling" of the jet likely transport more particles to the meniscus than straight jet does.**

Future Work

- Model both left and right sides of the caster
- Model the open bottom mold side face curvature
- Investigate the behavior of a range of particles
- Investigate heat transfer in the mold