Inclusion Entrapment ¾ Literature Review and Modeling

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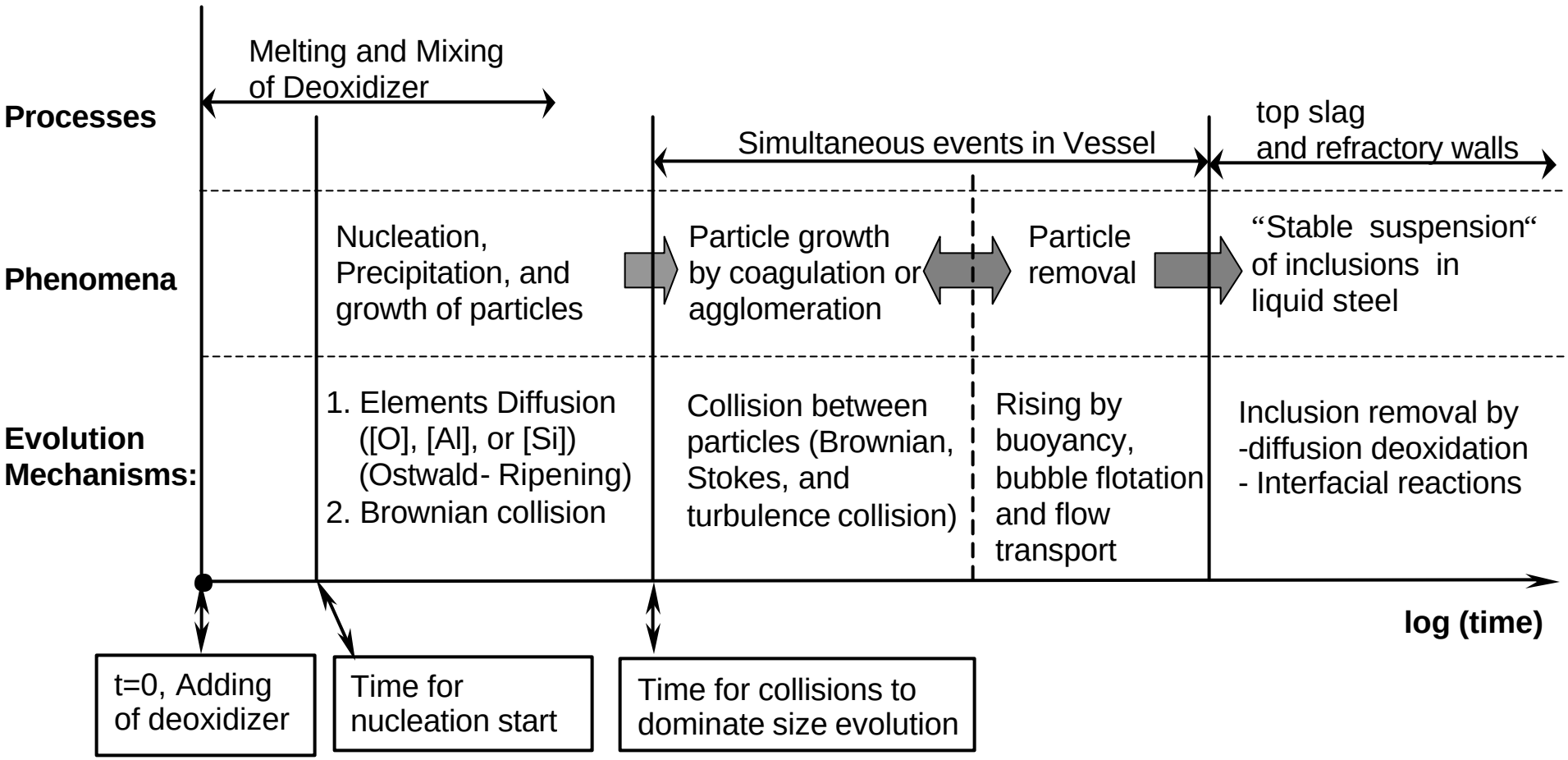
- Continuous Casting Consortium (CCC) at UIUC

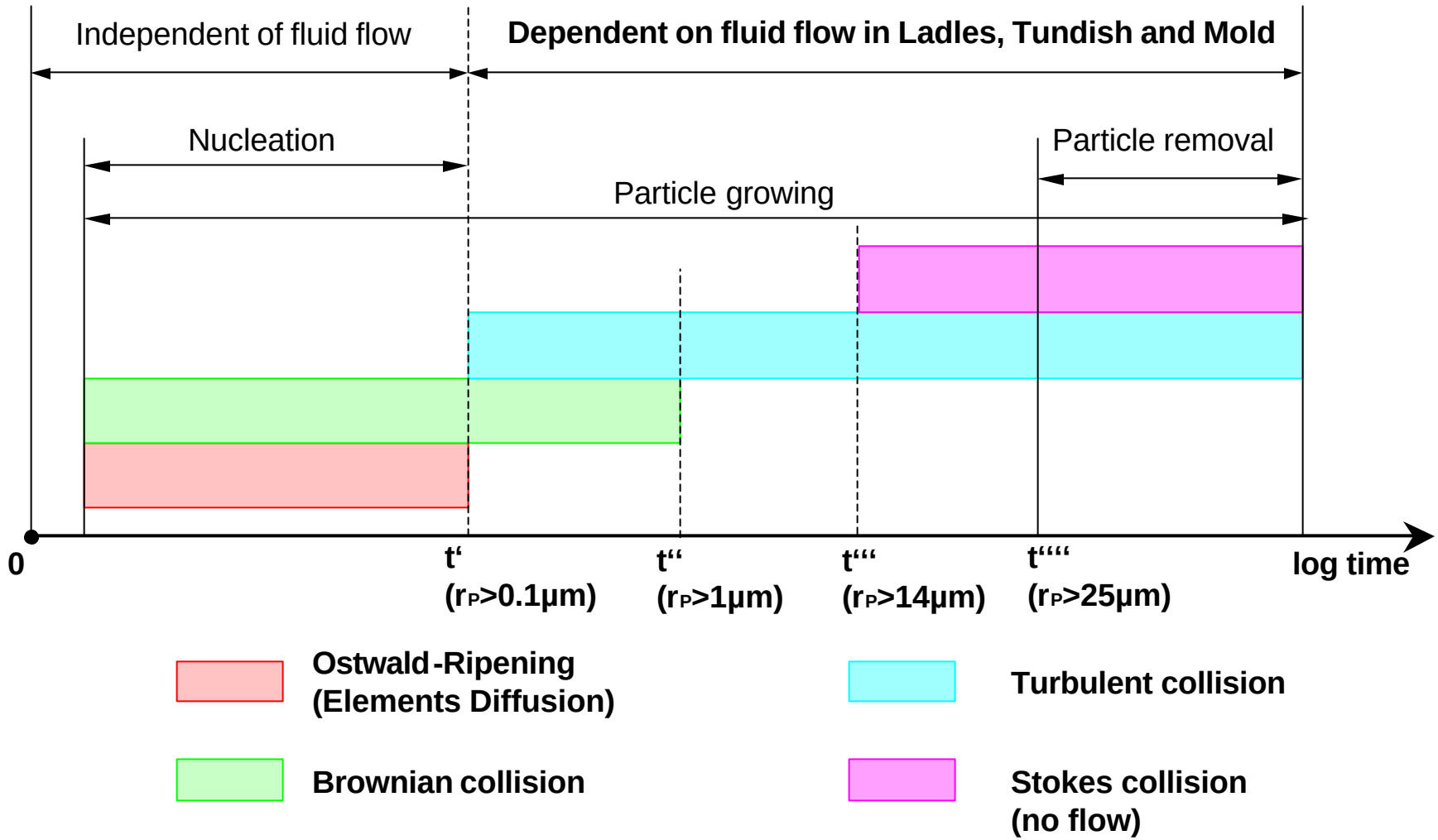
Contents

Background — Review of Inclusions in Steel

Steps of Inclusions Nucleation, Precipitation, Growth and Removal from Liquid Metals



Evolution Mechnisms Related to Particle Size



Evaluation Methods of Steel Cleanliness

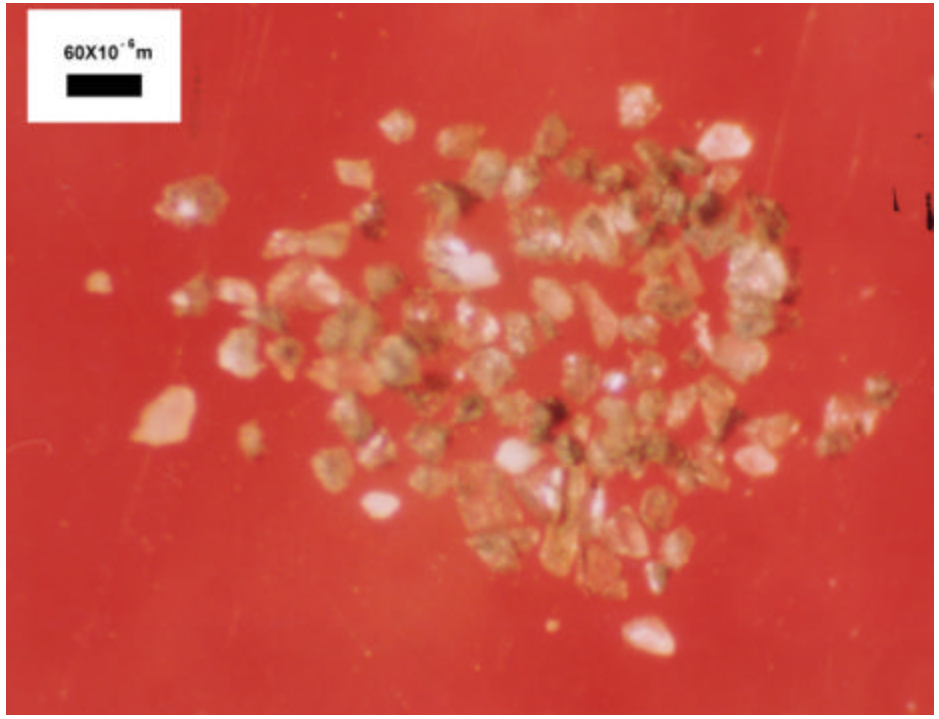
Steel Cleanliness Û Inclusions in Steel { **Size** / **Shape** }

- **Direct Measurement of Inclusions:** { ◆ Sampling difficulties / ◆ Time consuming }
  - Metallographical microscope observation (two dimensional slices)
  - Slime (time consuming)
  - Others (Cone machining, laser, electrical, ultrasonic, sulfur print)
- **Indirect Methods**
  - Total Oxygen (T.O.) measurement
  - Nitrogen Pickup
  - Dissolved Al loss for LCAK Steel
  - Analysis of slag composition evolution

Inclusions in Tunidsh Steel Samples Showing Liquid Slag

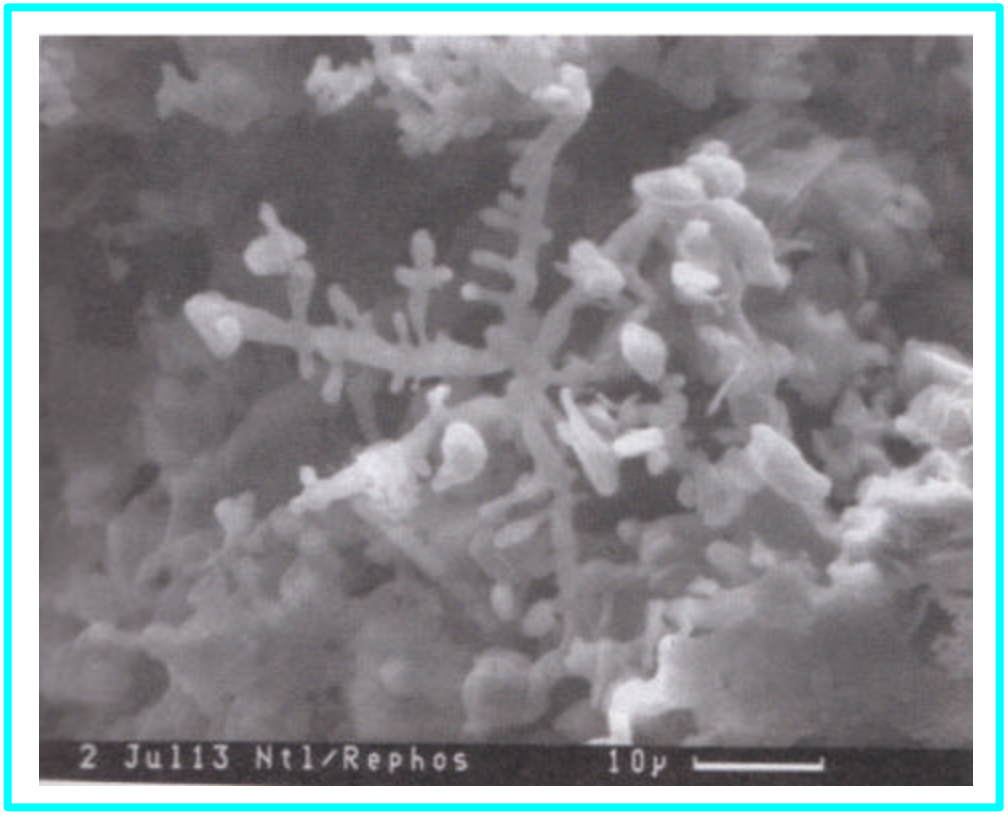
Steel grade: LCAK Steel
Source: Slime test Residual
Typical composition: Al_2O_3 24%, SiO_2 29%, MnO 20%, FeO 16%
CaO 4%, MgO 1.4%, others 4.6%

Alumina Inclusions in Continuous Casting Slab



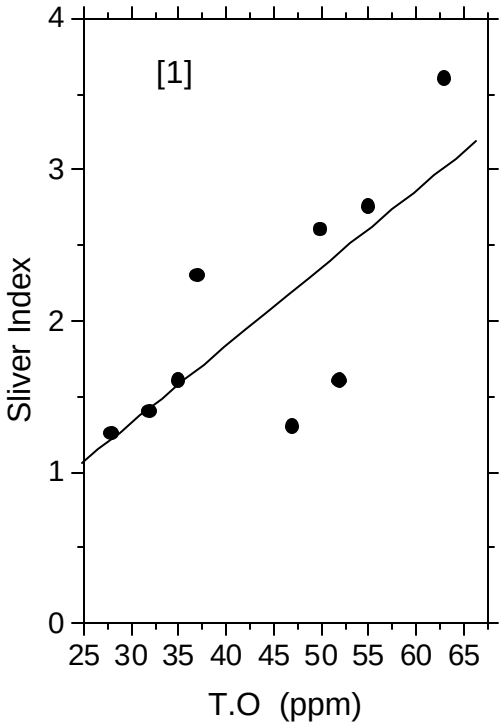
Steel grade: LCAK Steel
Source: Slime test Residual
Typical composition: Al_2O_3 96.2%, SiO_2 2.3%, MnO 1.3%, FeO 0.2%

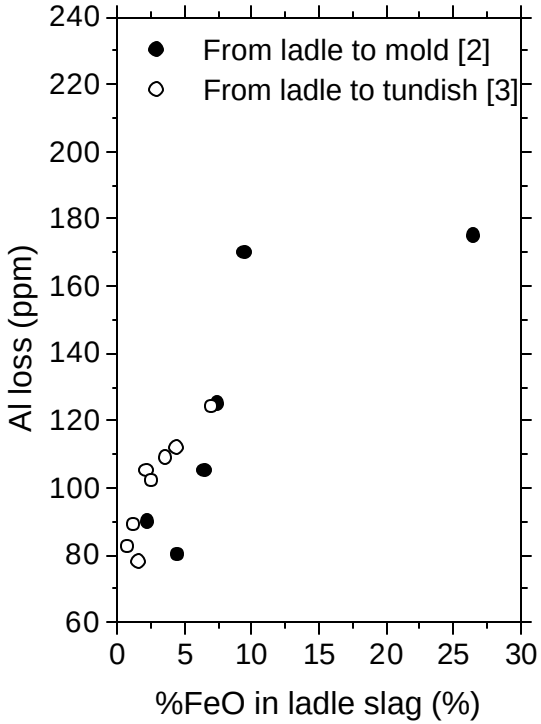
Alumina Clusters in Carbon Steel[1]

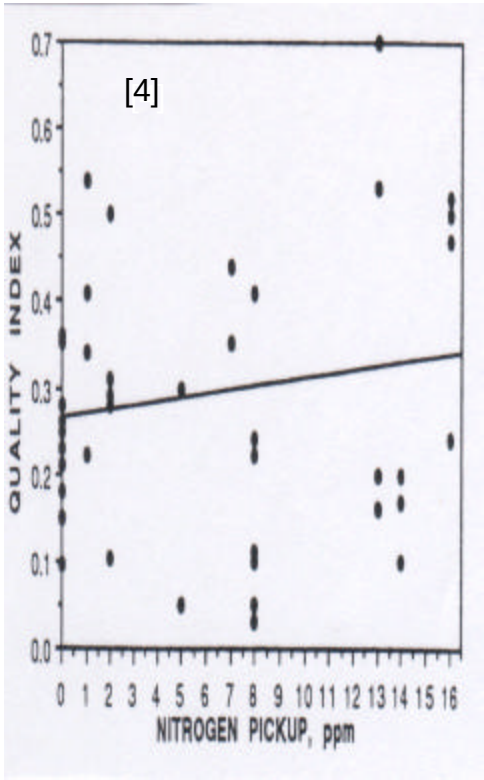


[1] R.Rastogi and A. W. Cramb. Inclusions Formation and Agglomeration in Aluminum Killed Steels. *84th Steelmaking Conference Proceedings*, ISS, Warrendale, PA, USA, P789-829

Example of Total Oxygen, Al loss, Nitrogen Pickup

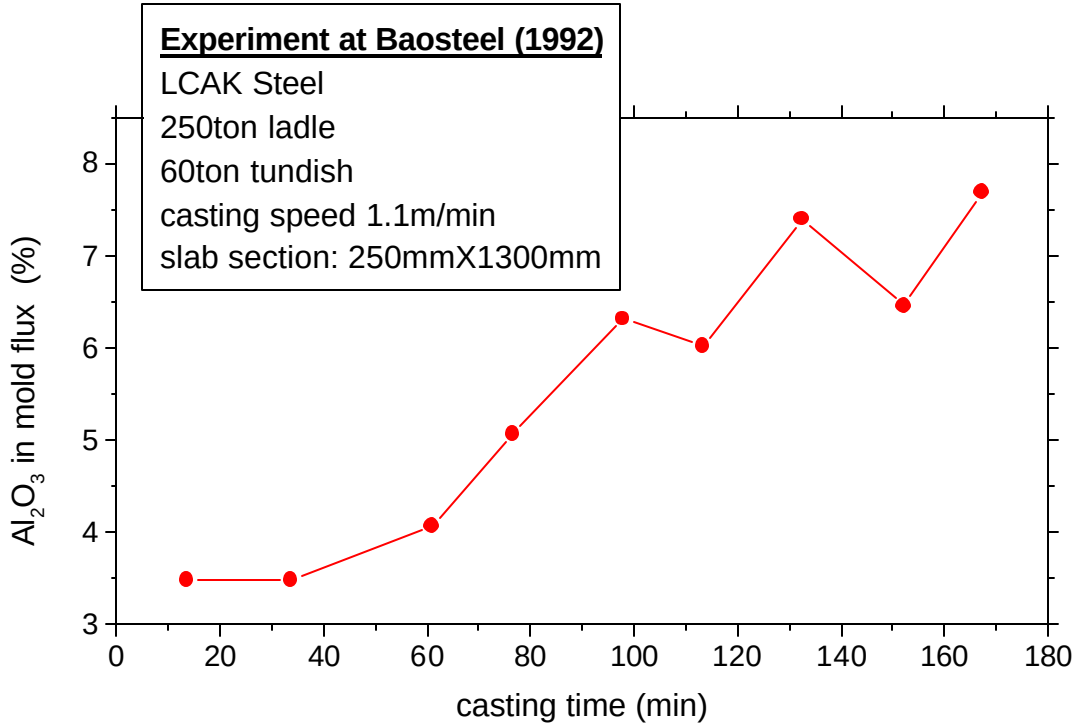






[1] Bonila C. et al. 78th Steelmaking Conference Proceedings, Vol.78, 1995, p629-635
[2] Chakraborty S. et al. 77th Steelmaking Conference Proceedings, Vol.77, 1994, p389-395
[3] Ahlborg K. V. et al. 76th Steelmaking Conference Proceedings, Vol.76, 1993, p469-473
[4] Melville S. D. et al. 78th Steelmaking Conference Proceedings, Vol.78, 1995, p563-569

Al_2O_3 Inclusion Absorption to Mold Flux



Inclusion Phenomena in Continuous Casting Mold

Inclusion Sources:

- Carrying in through nozzle
  - Deoxidation Products
  - Nozzle clog
  - Entrainment of tundish/ladle slag (reoxidation by SiO_2, FeO, MnO in slag)
- Entrainment of mold slag by excessive top surface level fluctuation
- Reoxidation by air absorption from nozzle leaks
- Argon bubbles
- Precipitation of inclusion in low superheat, such as TiO_2

Inclusion Removal:

- Buoyancy rising
- Fluid flow transport
- Attachment to bubble surface and fast rising (Bubble flotation)
- Inclusion growth by collision and Ostwald-Ripening
- Absorption from steel to slag at interface

Inclusion Destination:

- Top slag layer (safe removal)
- Trapped in solidification shell (defect)

Conclusion

All inclusions phenomena in mold are greatly affected by bulk fluid flow pattern, thus it is important to study the fluid flow in mold.

Cases of Fluid Flow and Inclusion Motion Simulation in the Current Report

Water Model:

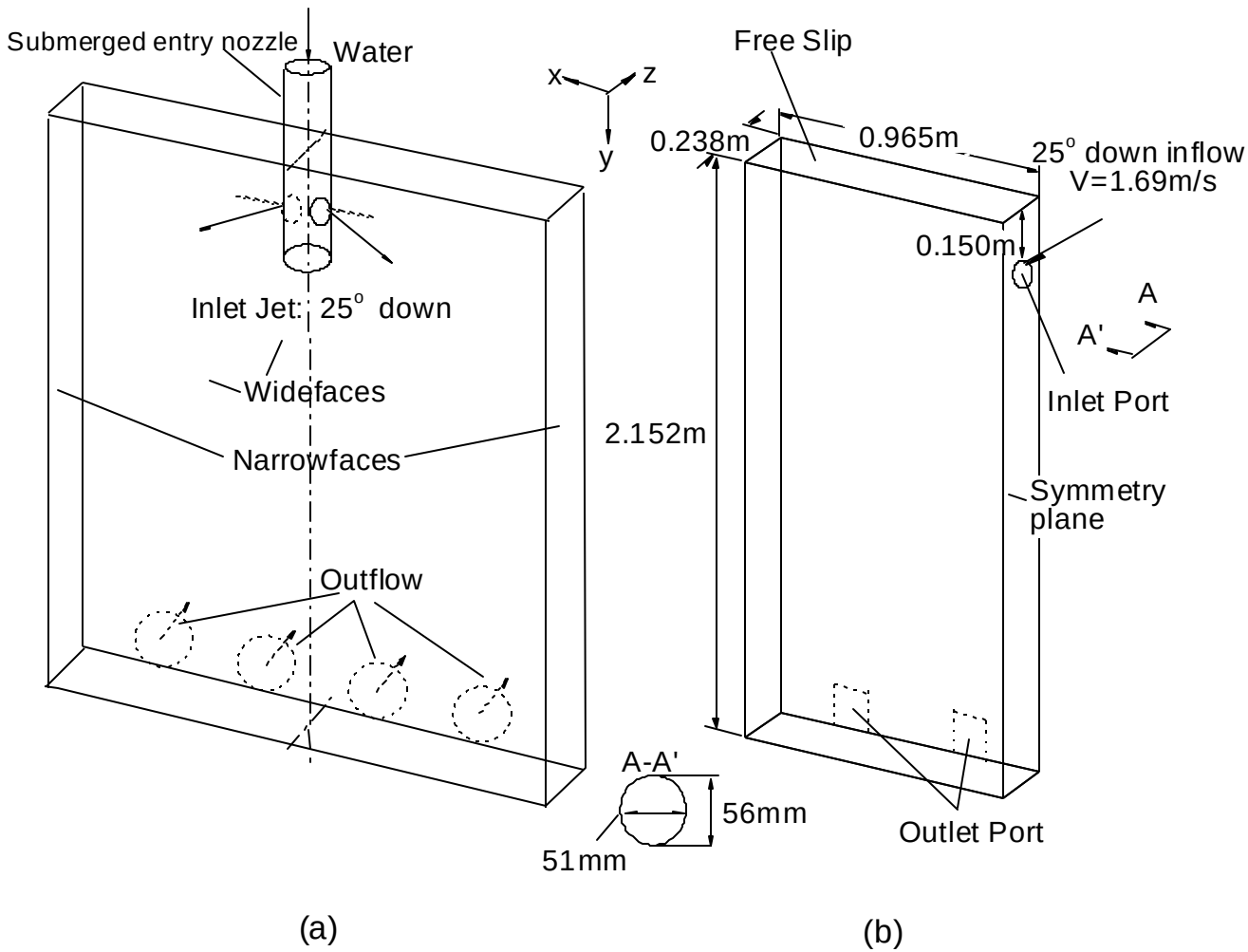
1. Large Eddy Simulation (LES)
   - Random Walk Model for Particle Motion
2. Reynolds Stress Model (RSM)
   - Random Walk Model for Particle Motion
3. *k-e* Model for Fluid Flow
   - Random Walk Model for Particle Motion
   - Streamline Model for Particle Motion
4. *k-e* Model for Top Surface Pressure and Level Fluctuation

Steel Caster:

1. *k-e* Model for Fluid Flow
   - Four Cases for Inclusion Motion by Random Walk Model

Fluid Flow and Particle Behavior in 1:1 Water Model

Sketch of 1:1 Water Model (a) and Simulation Domain (b)[1]



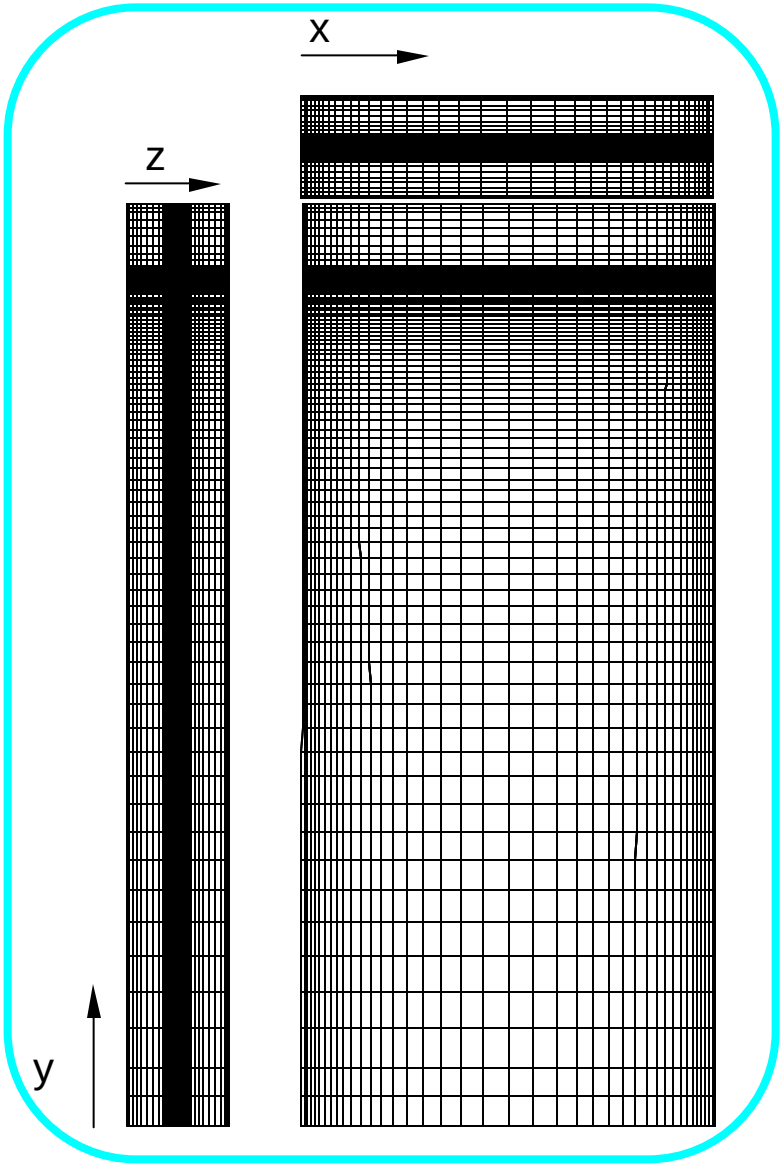
[1] Yuan, Q., S.P. Vanka, and B.G. Thomas. *Large Eddy Simulatios of Turbulence Flow and Inclusions Transport in Continuous Casting of Steel*. Turbulence and Shear Flow Phenomena Second International Symposium, June 27-29. 2001: KTH, Stockholm

Experimental and Simulation Parameters

	Experiment	Simulation
Nozzle port size/ Inlet port size (x×y) (m)	0.051×0.056	
Nozzle angle	25°	
Inlet jet angle	25°	
Submergence depth (m)	0.150	
Mold/Domain height (m)	2.152	
Mold/Domain width (m)	1.83	
Mold/Domain thickness (m)	0.238	
Average inlet flow rate (m^3/s)	0.00344	
Casting speed (m/s)	0.0152	
Fluid density (kg/m^3)	1000	
Fluid kinetic viscosity (m^2/s)	1.0×10^{-6}	
Particle size (diameter) (mm)	2-3	3.8
Particle density (kg/m^3)	988	
Corresponding alumina inclusion diameter in steel caster (μm)	300	
Inlet condition	LES pipe simulation results[1]	

[1] Yuan, Q., S.P. Vanka, and B.G. Thomas. *Large Eddy Simulatios of Turbulence Flow and Inclusions Transport in Continuous Casting of Steel*. Turbulence and Shear Flow Phenomena Second International Symposium, June 27-29. 2001: KTH, Stockholm

Mesh for *k-e* and RSM Water Model Simulations



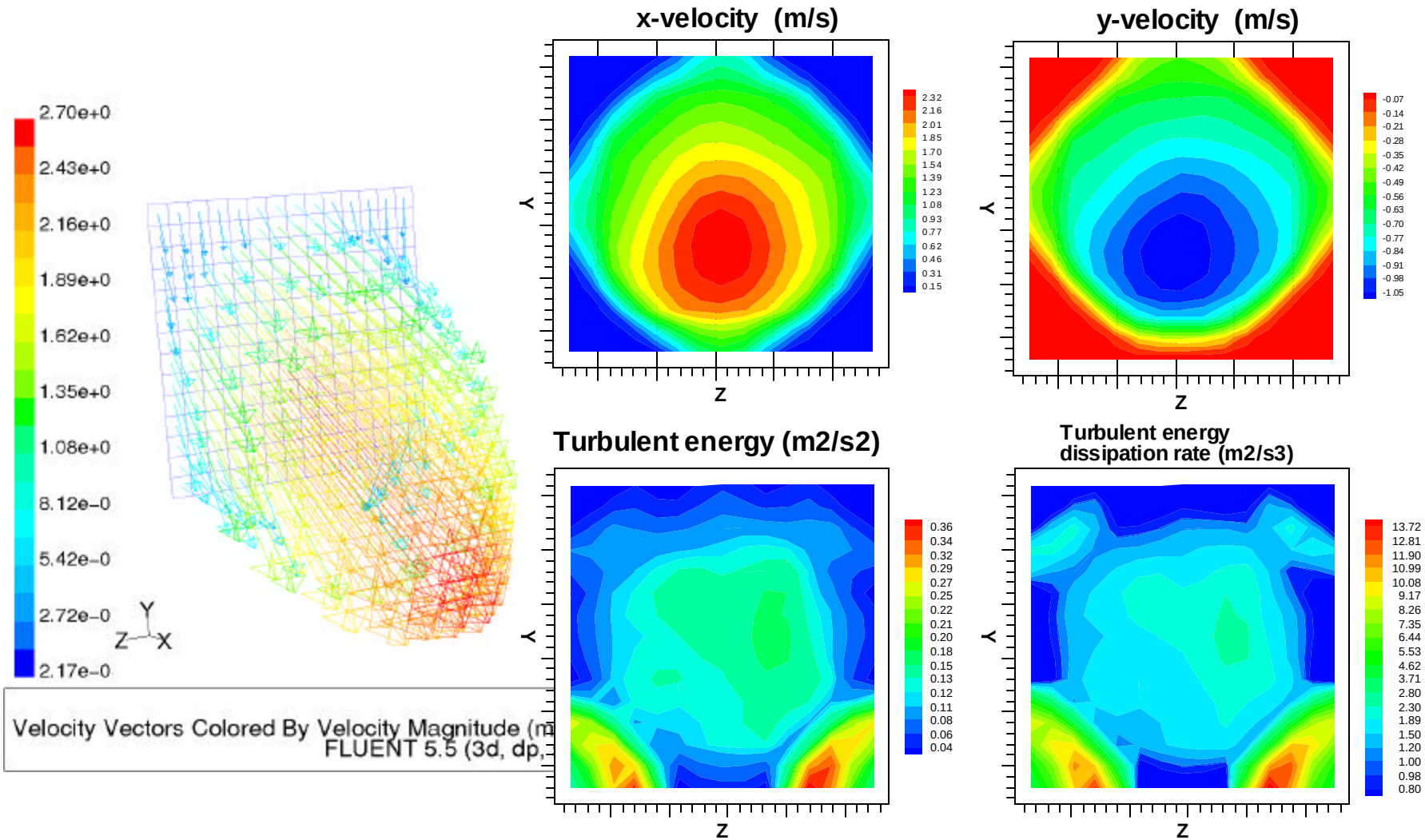
NX=40

NY=86

NZ=34

Total Nodes: 116,960

Non-Uniform Inlet Condition (LES Skewed Pipe Flow Simulation)[1]



[1] Yuan, Q., S.P. Vanka, and B.G. Thomas. *Large Eddy Simulatios of Turbulence Flow and Inclusions Transport in Continuous Casting of Steel*. Turbulence and Shear Flow Phenomena Second International Symposium, June 27-29. 2001: KTH, Stockholm

Particle Motion Equations

$$u_{p,i} = \frac{dx_{p.i}}{dt}$$

$$\frac{du_{pi}}{dt} = \frac{3}{4}\frac{mC_D \operatorname{Re}_P}{r_P d_P^2}\left(u_{Pi} - u_i\right) + g_x \frac{\left(r_P - r\right)}{r_P} + a_{other,i}$$

$u_{p,i}$, the particle velocity at *i* direction;
$x_{p,i}$, the particle position at *i* direction;
m is the fluids viscosity;
r_p , r , the particle density and fluid density respectively;
$\mathrm{Re}_{p,}$, the particle Reynolds number;
C_D , the drag force coefficient;

$$C_D = \frac{24}{\operatorname{Re}_p}\left(1 + 0.186 \operatorname{Re}_p^{0.653}\right)$$

g, is the gravitational acceleration;
$a_{other,i}$, the other forces' acceleration, which is ignored in the present study.

Boundary condition for particles:

Escape from top surface and outlet, reflect from other faces (no entrapment to solidified shell)

Random Walk Model

Model: The particle interacts with fluid phase turbulent eddies over the eddy lifetime. When the eddy lifetime is reached, a new value of the fluids instantaneous velocity is obtained by applying a new value of random number ξ .

Each eddy is characterized by:

- a Gaussian distributed random velocity fluctuation *u'*, *v'*, *w'* , keeping constant over the characteristic lifetime of the eddies
- a lifetime scale, t_e

Instantaneous fluid velocity: $u = \bar{u} + u'$

$$u' = x\sqrt{\overline{u'^2}} \xleftrightarrow{\text{for k-}e\text{ model}} x\sqrt{2k/3}$$

$\bar{u}$: the mean fluid phase velocity

ξ : normally distributed random number.

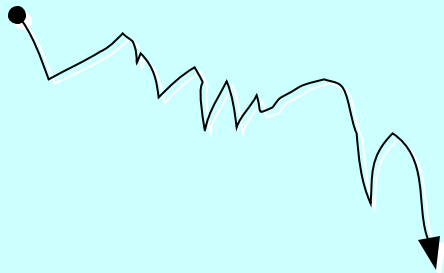
The expression of t_e:

$$t_e = 2C_L\, k/e$$

C_L =0.15.

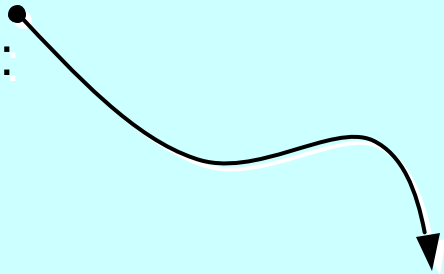
Effect of Turbulence Fluctuations on Particle Movement (Fluid Flow Simulation is by *k-e* Turbulence Model)

Random Walk Model (Stochastic Model) :



$$u = \bar{u} + u'$$

Streamline Model (Non-Stochastic Model) :

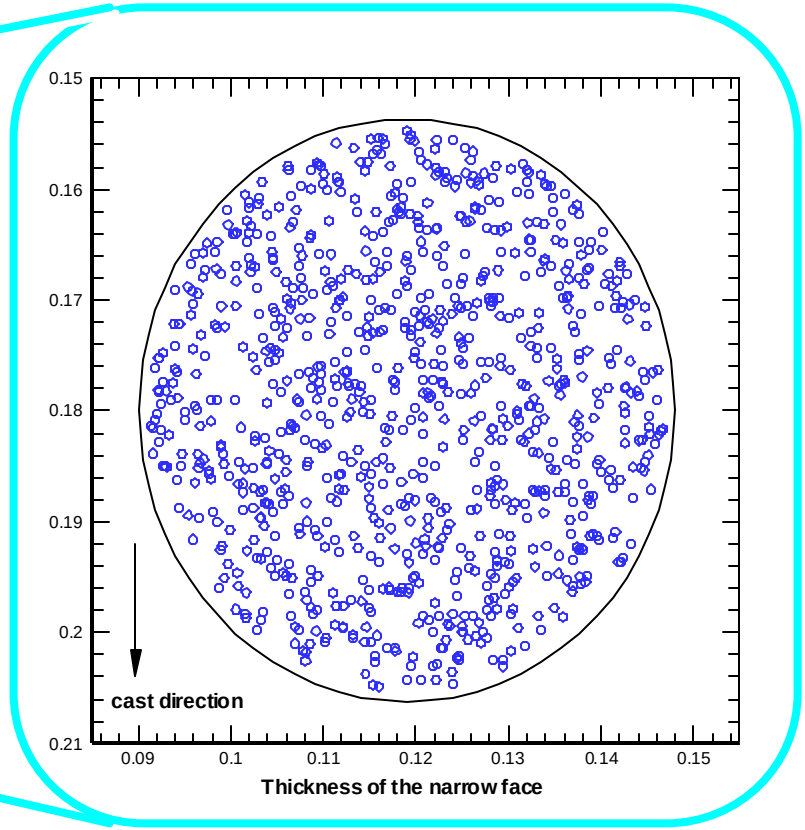


$$u = \bar{u}$$

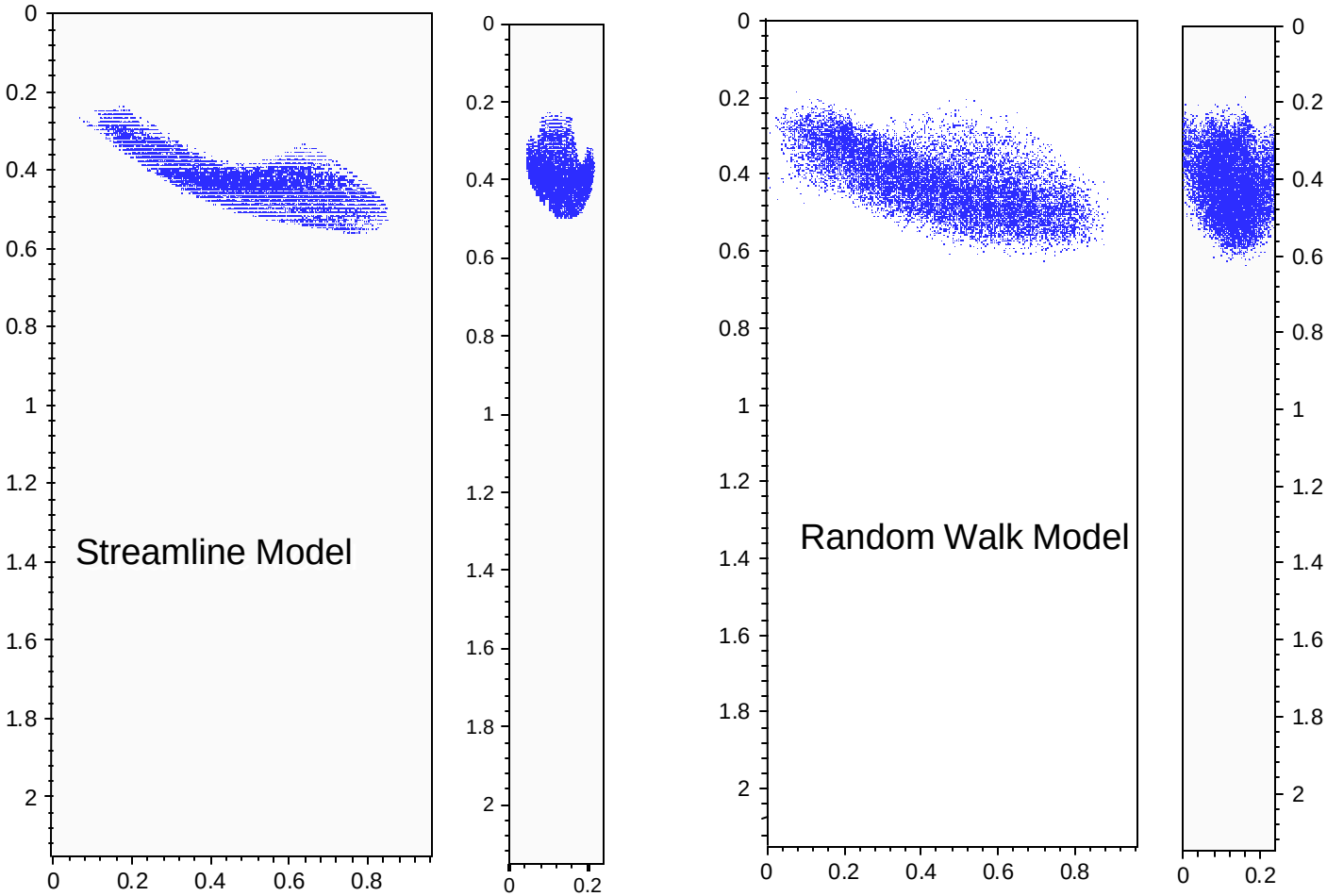
u : The instantaneous fluid velocity
$\bar{u}$: the mean fluid phase velocity
u' : random velocity fluctuation

Particle Injection Method

Time step is 0.1s, and at every time step, 938 particles are injected into mold through the 938 random positions on SEN port (as right figure). Total injection time is 1.6s, thus 15008 inclusions are injected into the domain.

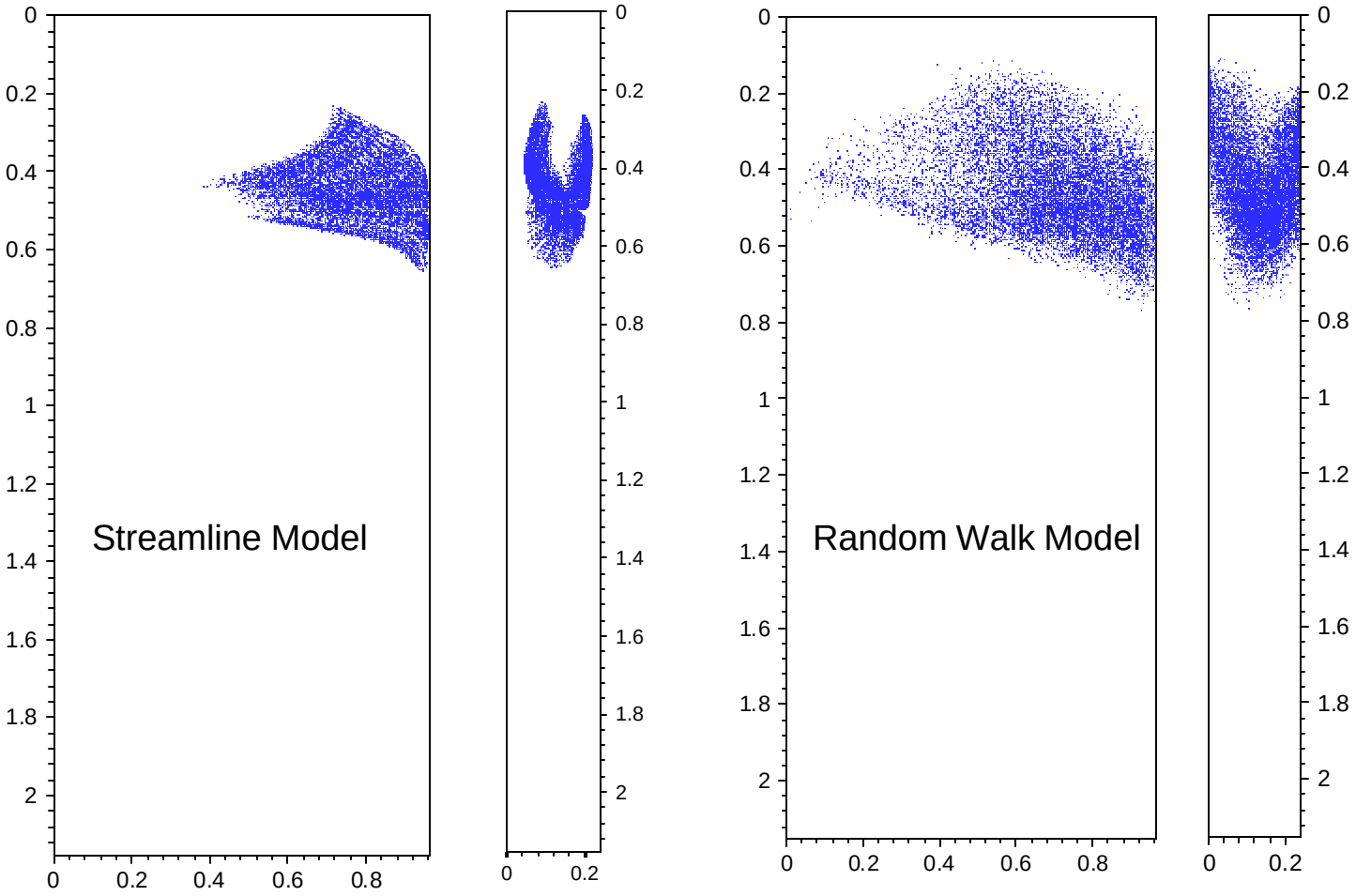


Particle Distribution (Water Model)



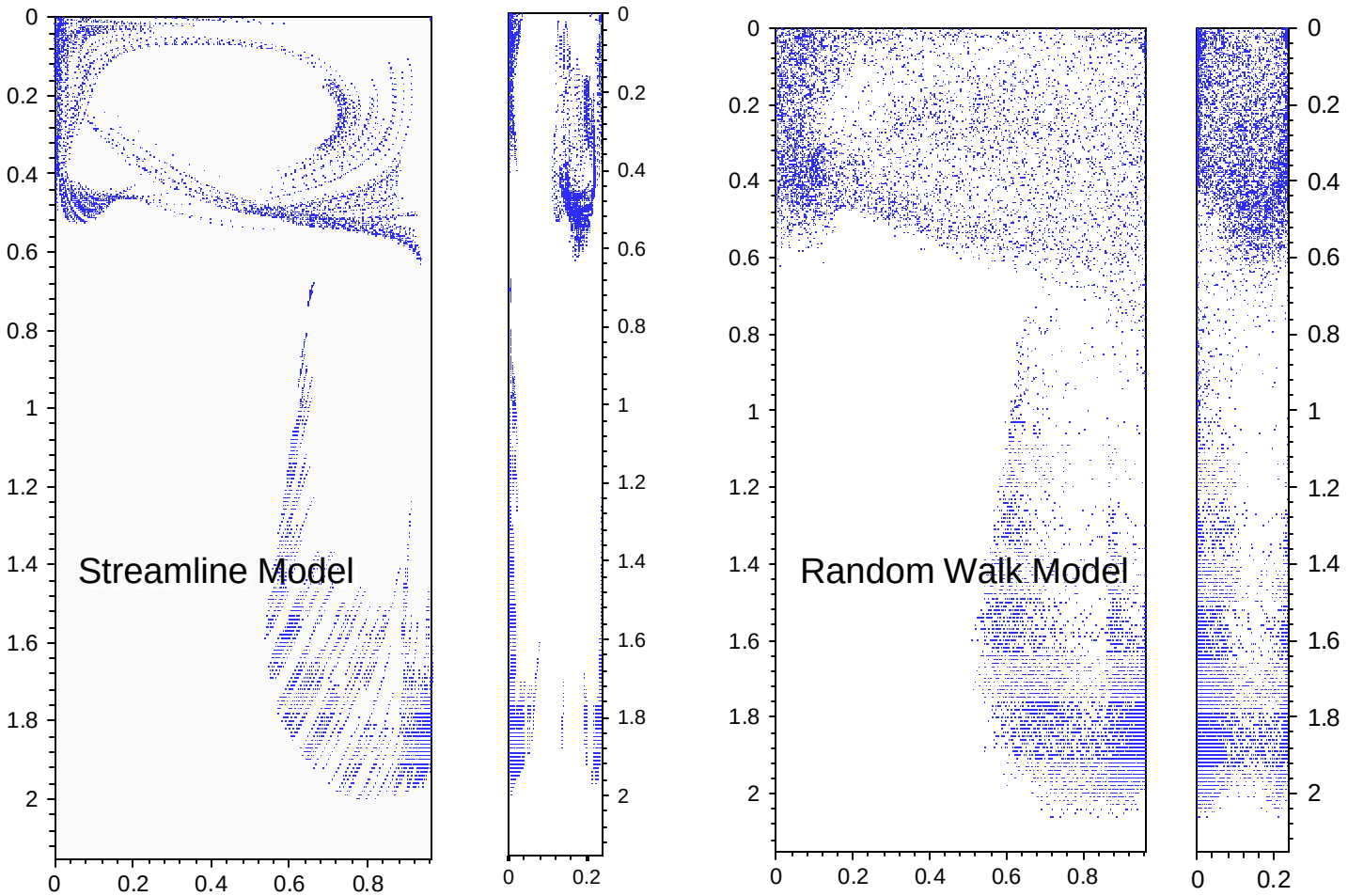
t=1.6s

Particle Distribution (Water Model)



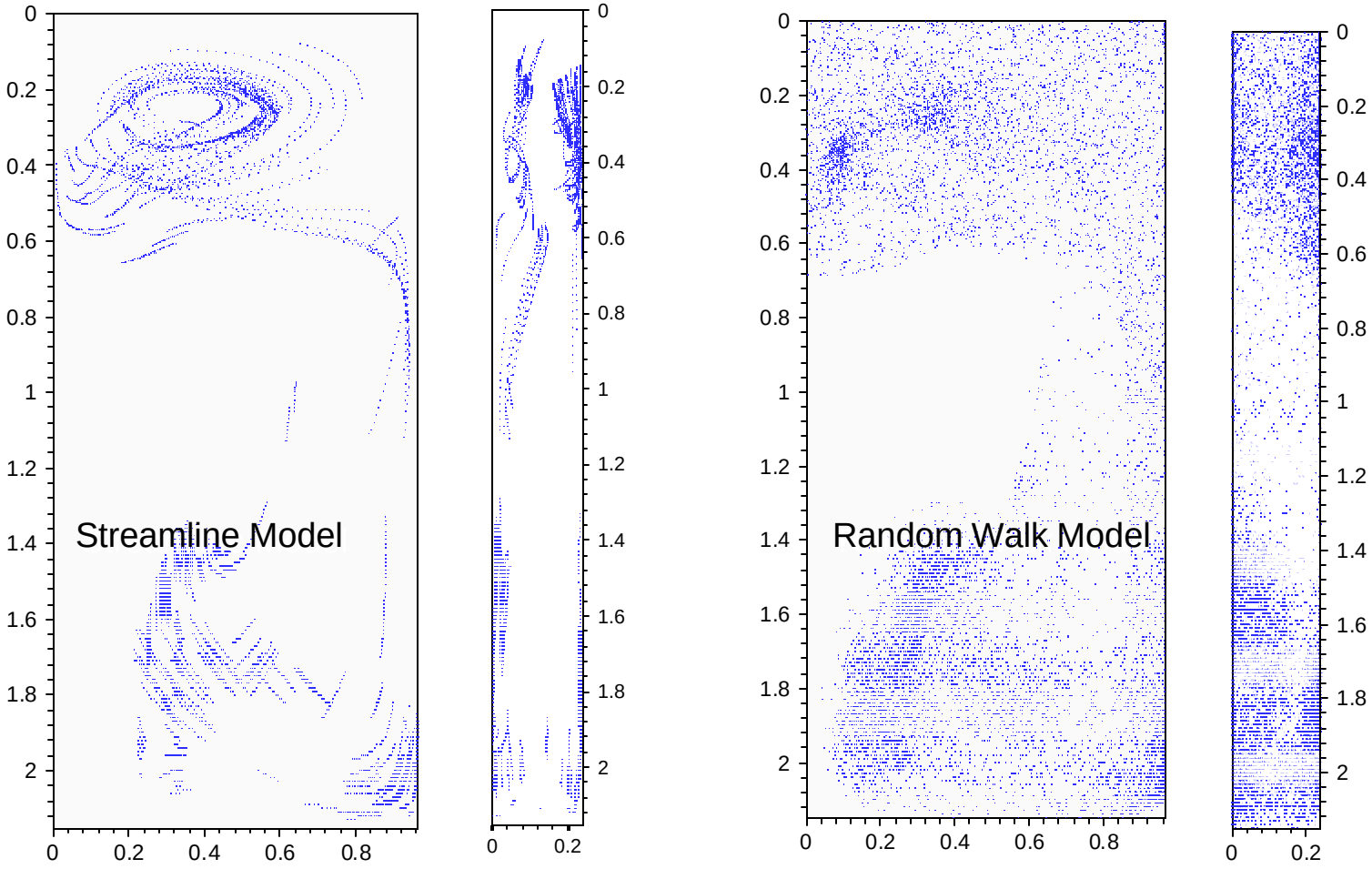
t=2.6s

Particle Distribution (Water Model)



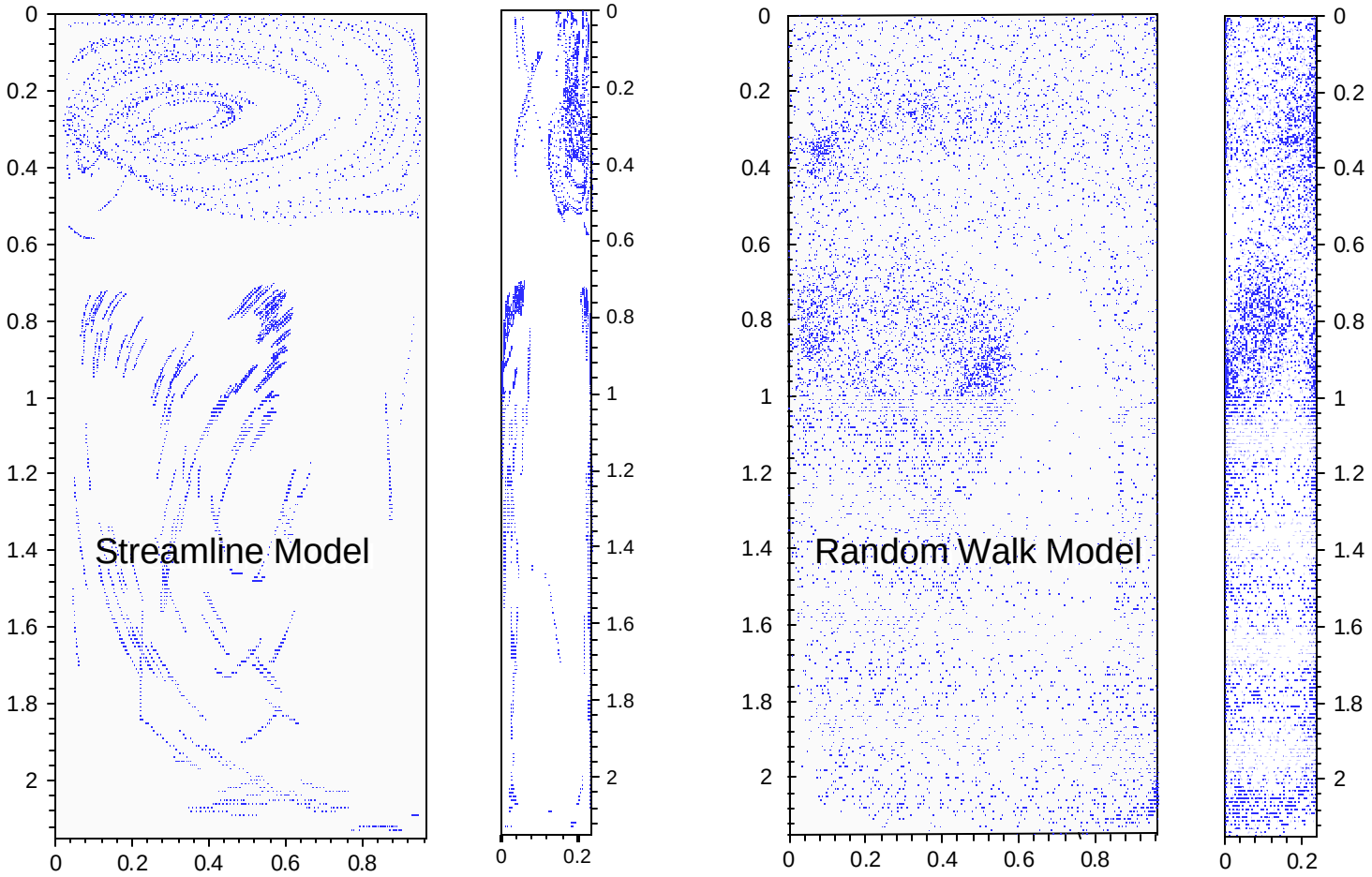
t=10s

Particle Distribution (Water Model)



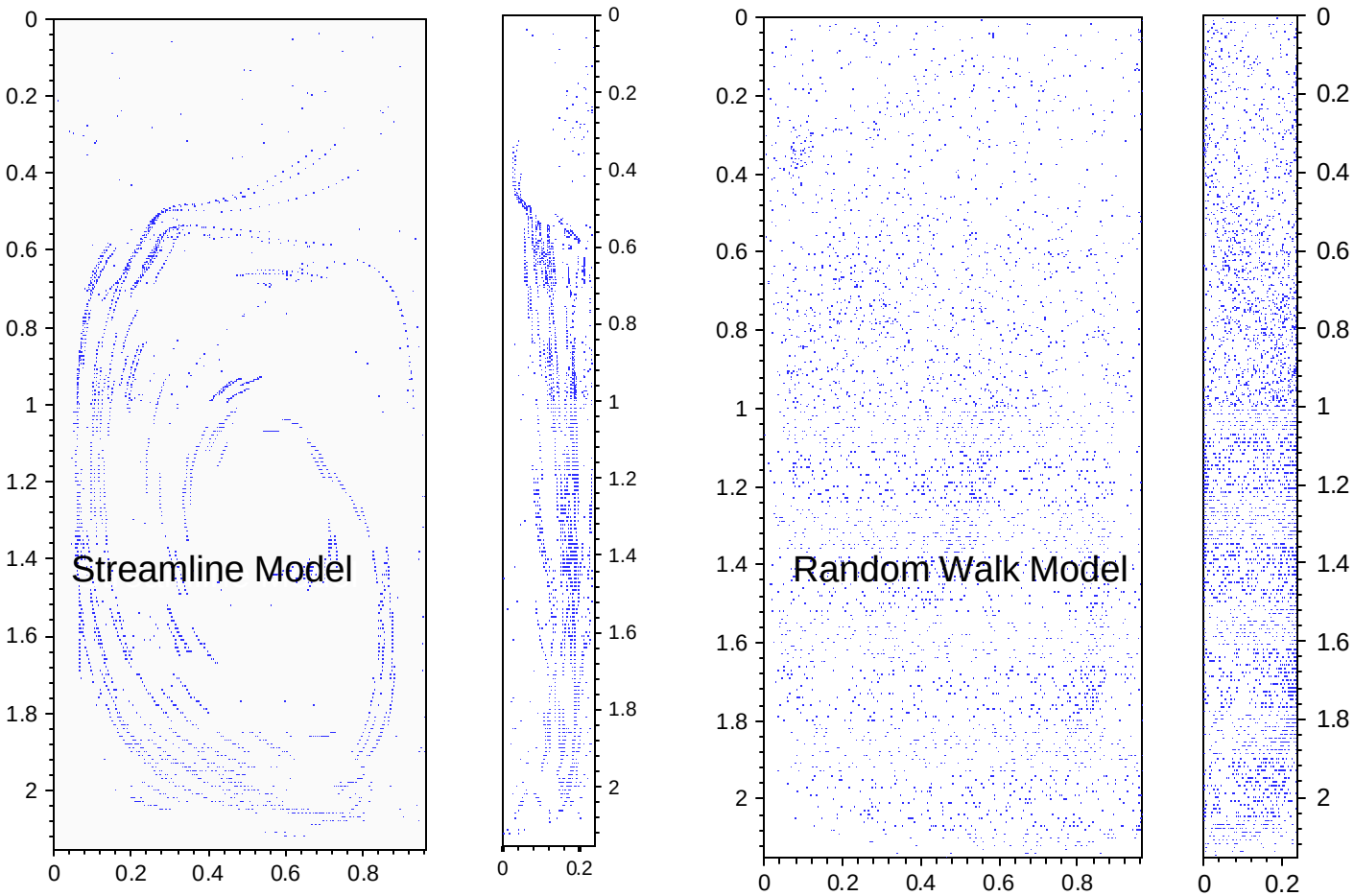
t=20s

Particle Distribution (Water Model)



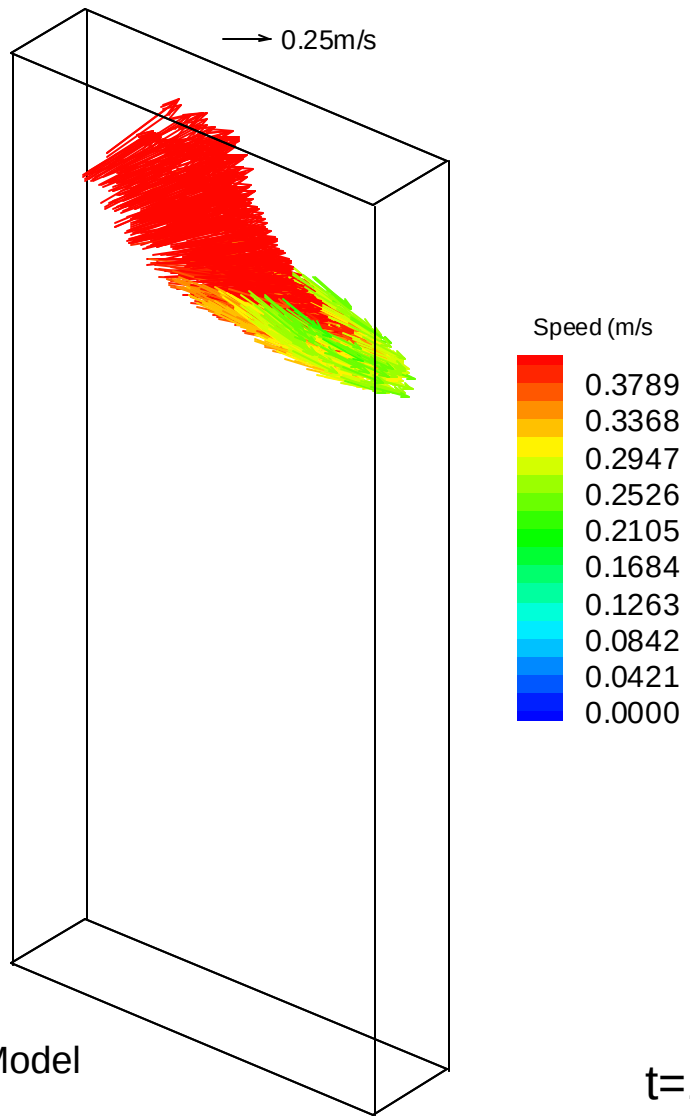
t=30s

Particle Distribution (Water Model)



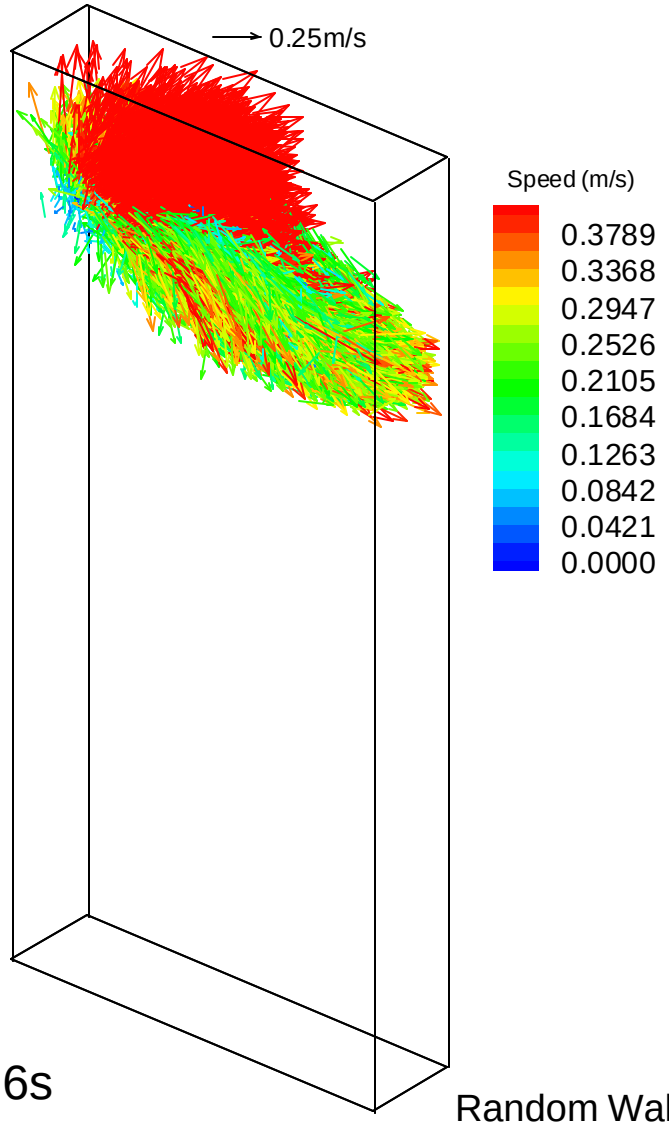
t=100s

Particle Velocities Distribution



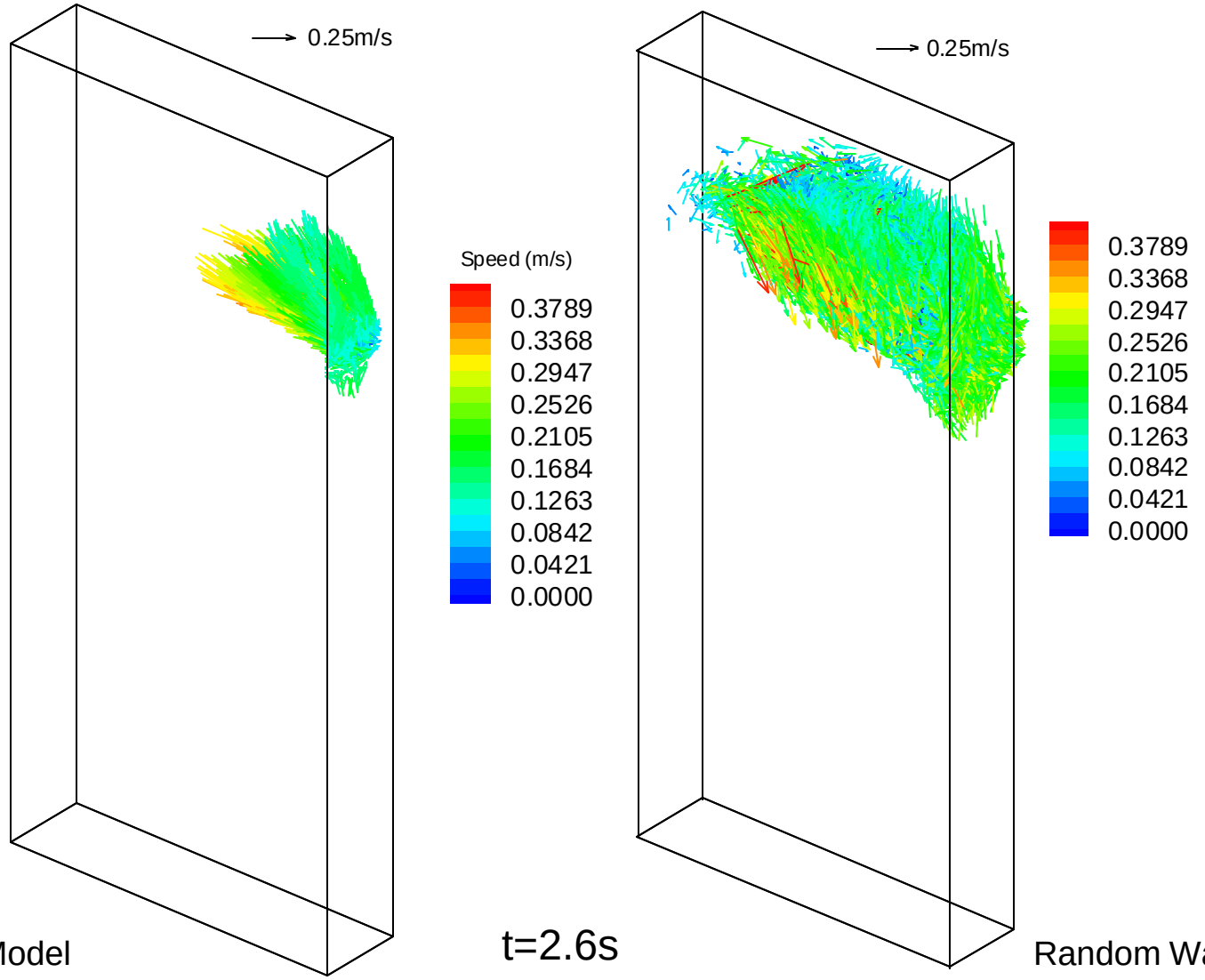
Streamline Model

t=1.6s



Random Walk Model

Particle Velocities Distribution

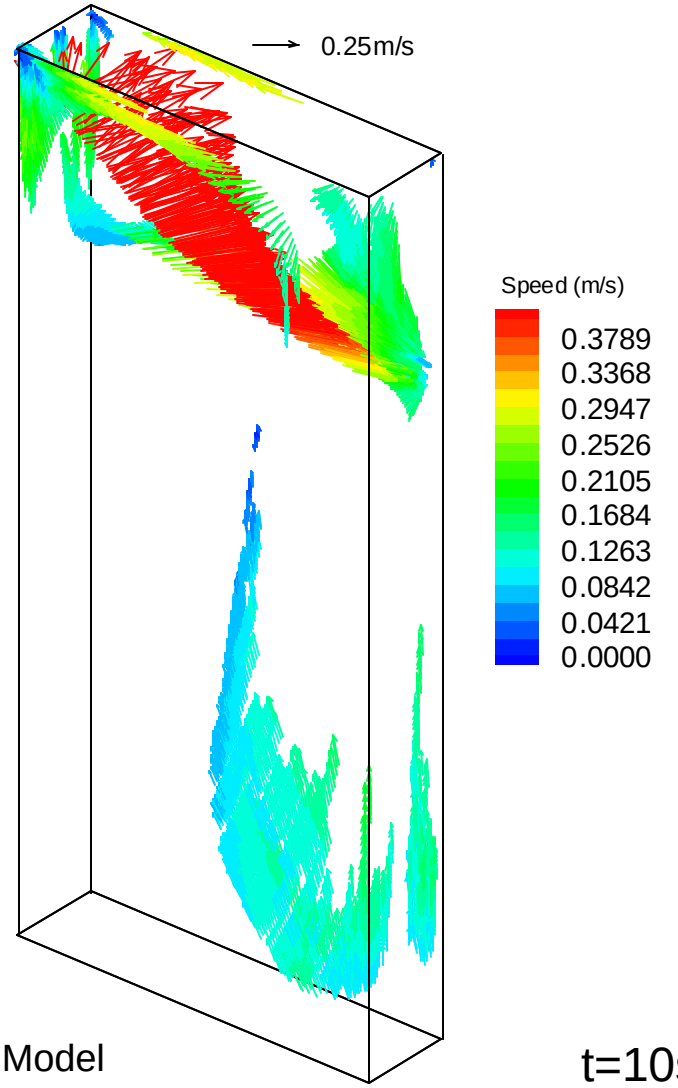


Streamline Model

t=2.6s

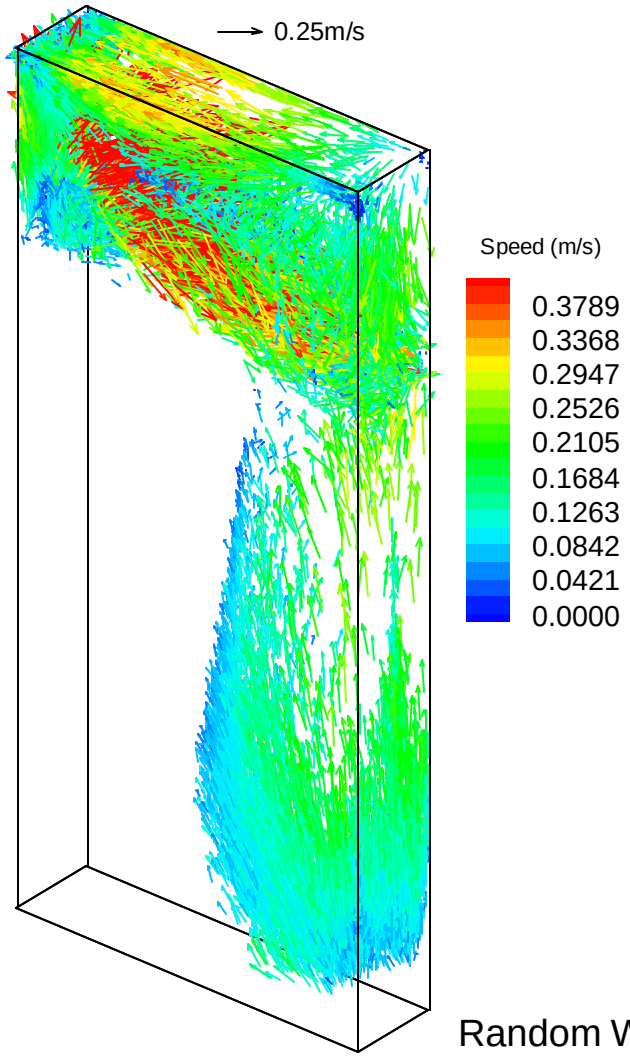
Random Walk Model

Particle Velocities Distribution



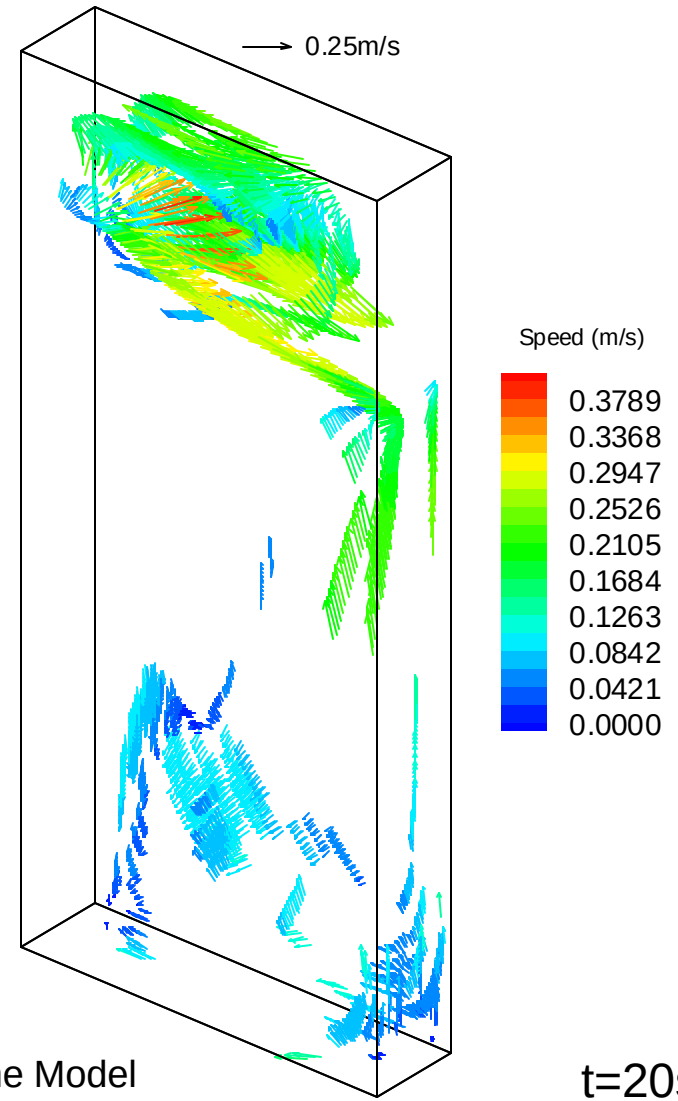
Streamline Model

t=10s



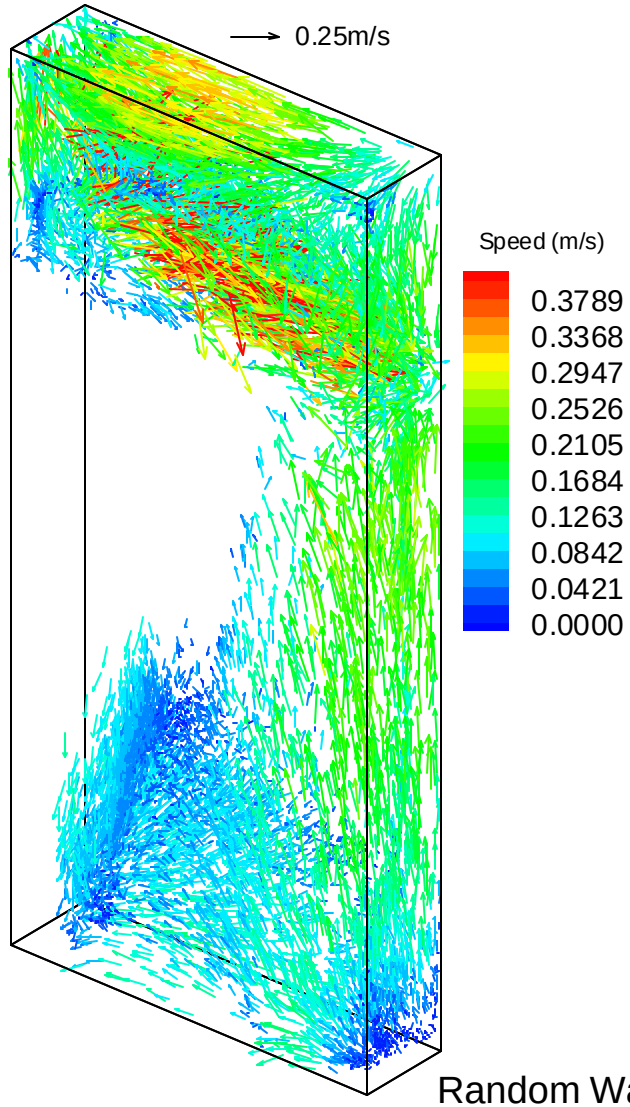
Random Walk Model

Particle Velocities Distribution



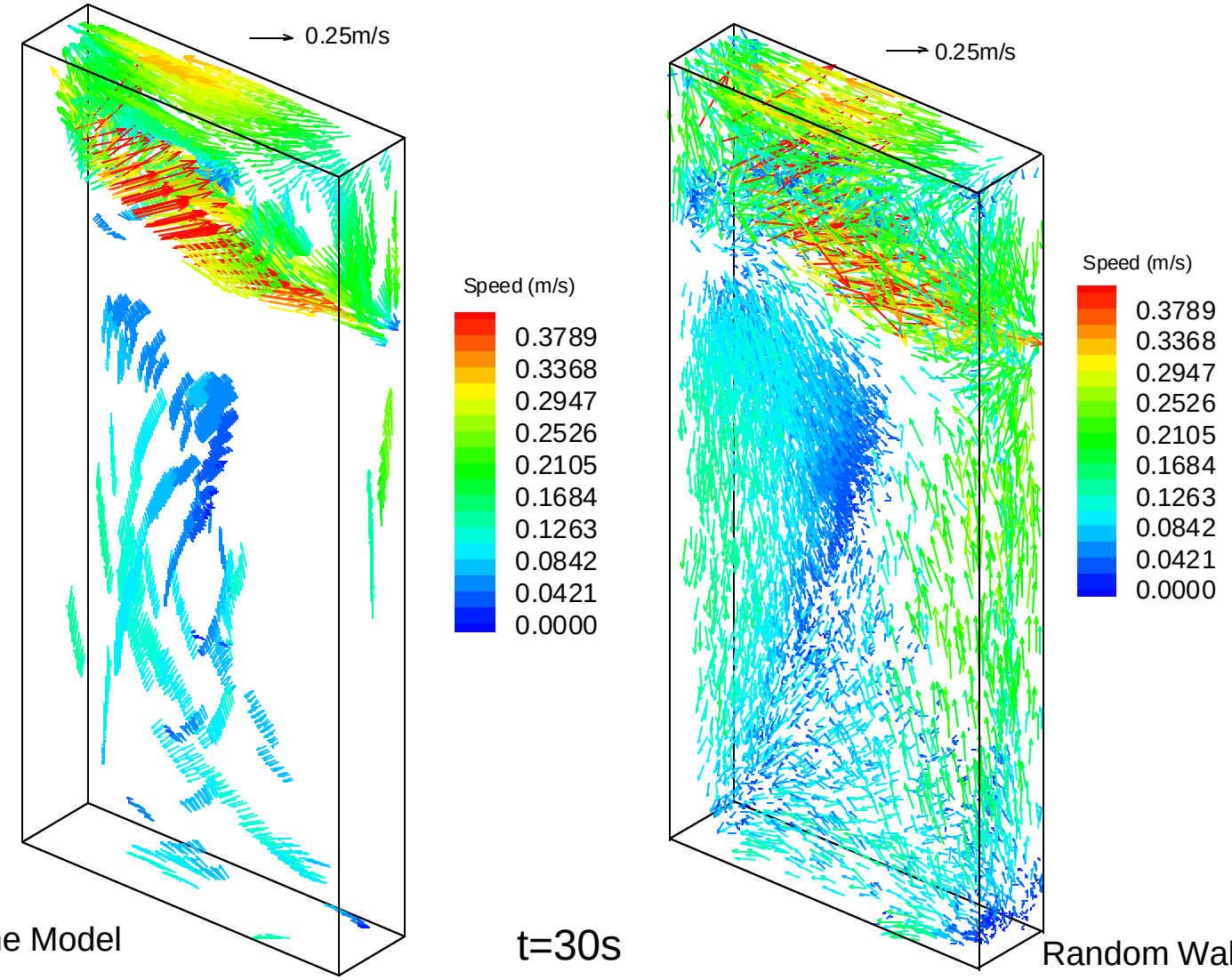
Streamline Model

t=20s



Random Walk Model

Particle Velocities Distribution

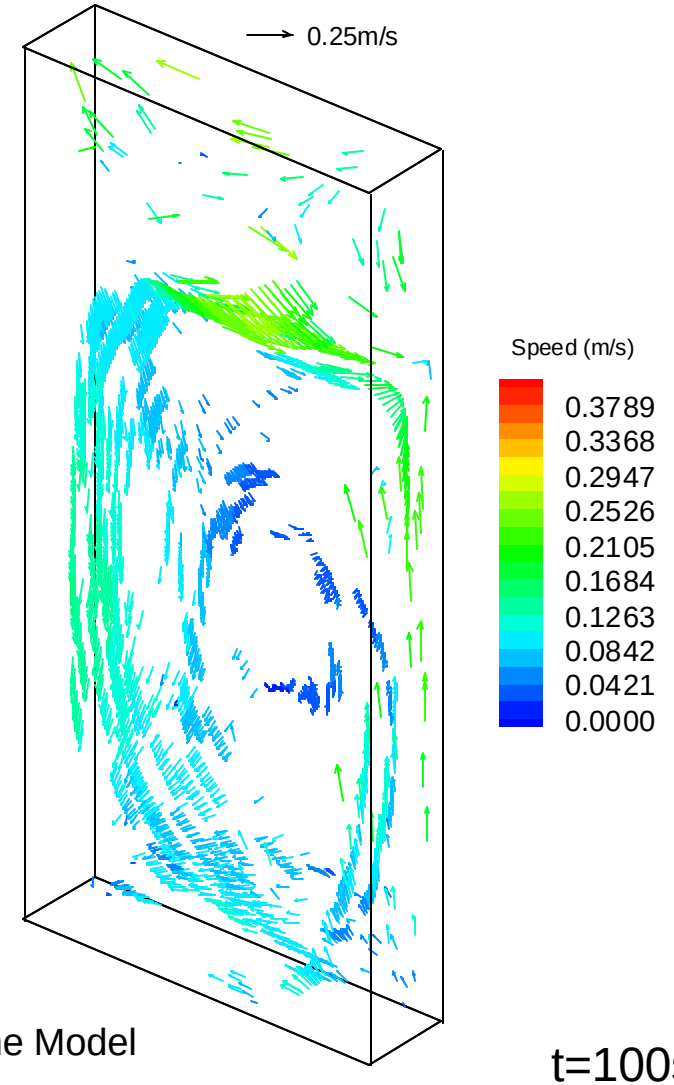


Streamline Model

t=30s

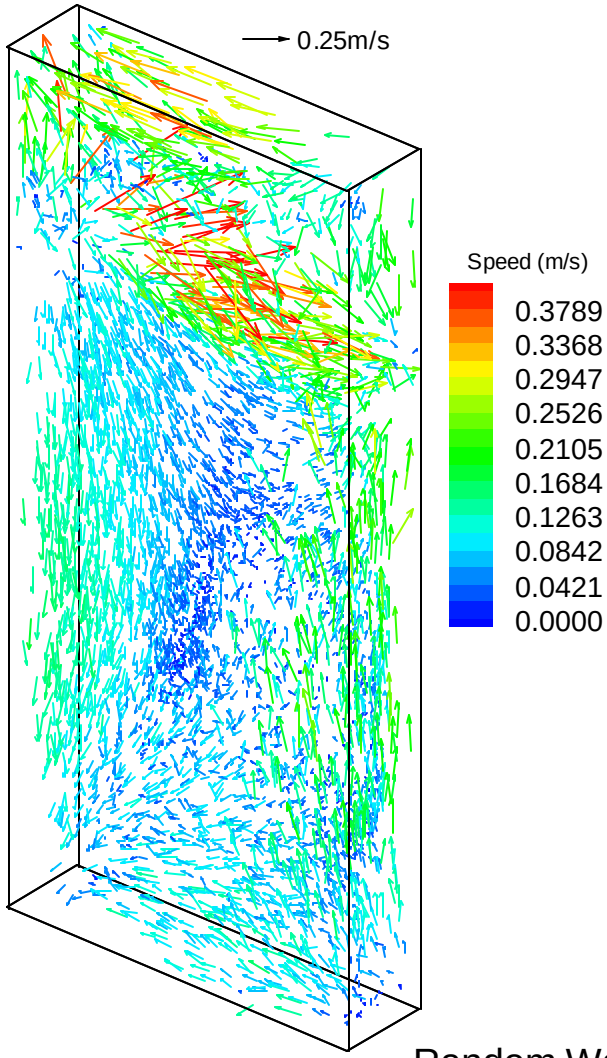
Random Walk Model

Particle Velocities Distribution



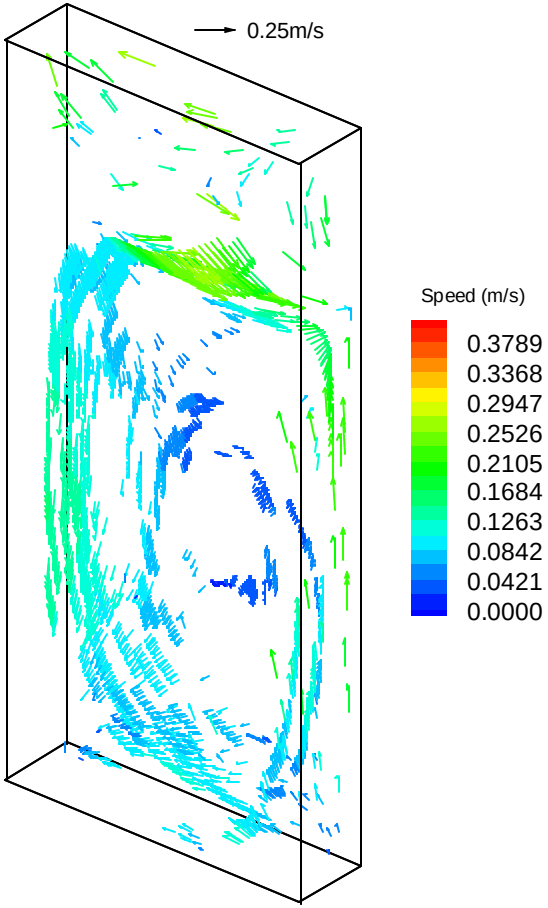
Streamline Model

t=100s

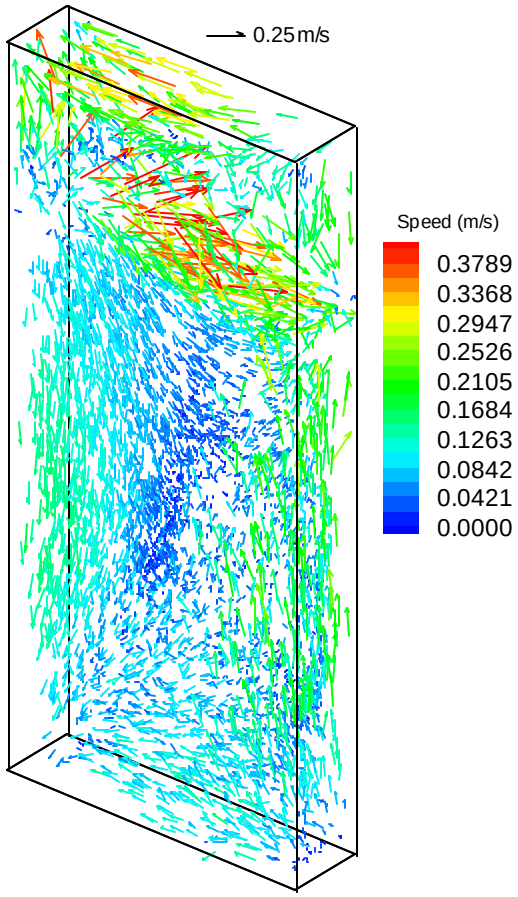


Random Walk Model

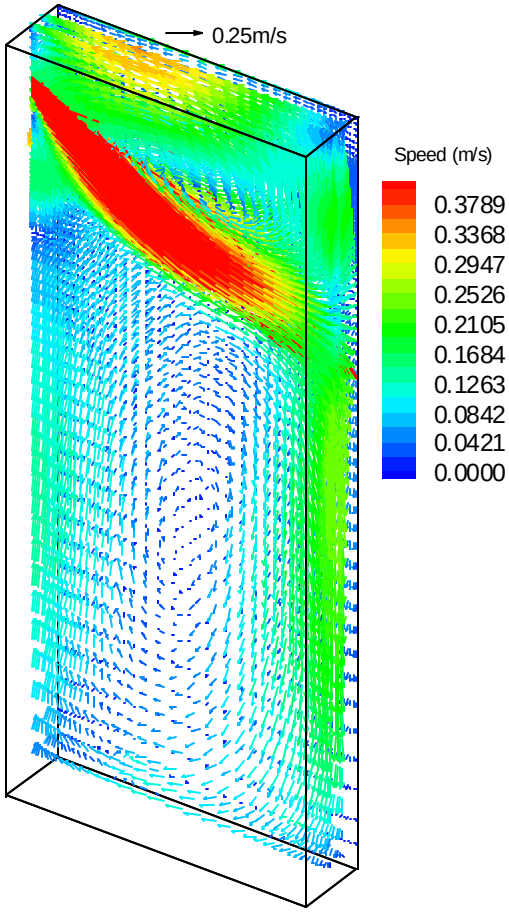
Compare of Particle Velocities and Fluids Flow Velocities



Particle velocities (Streamline Model, 100s)

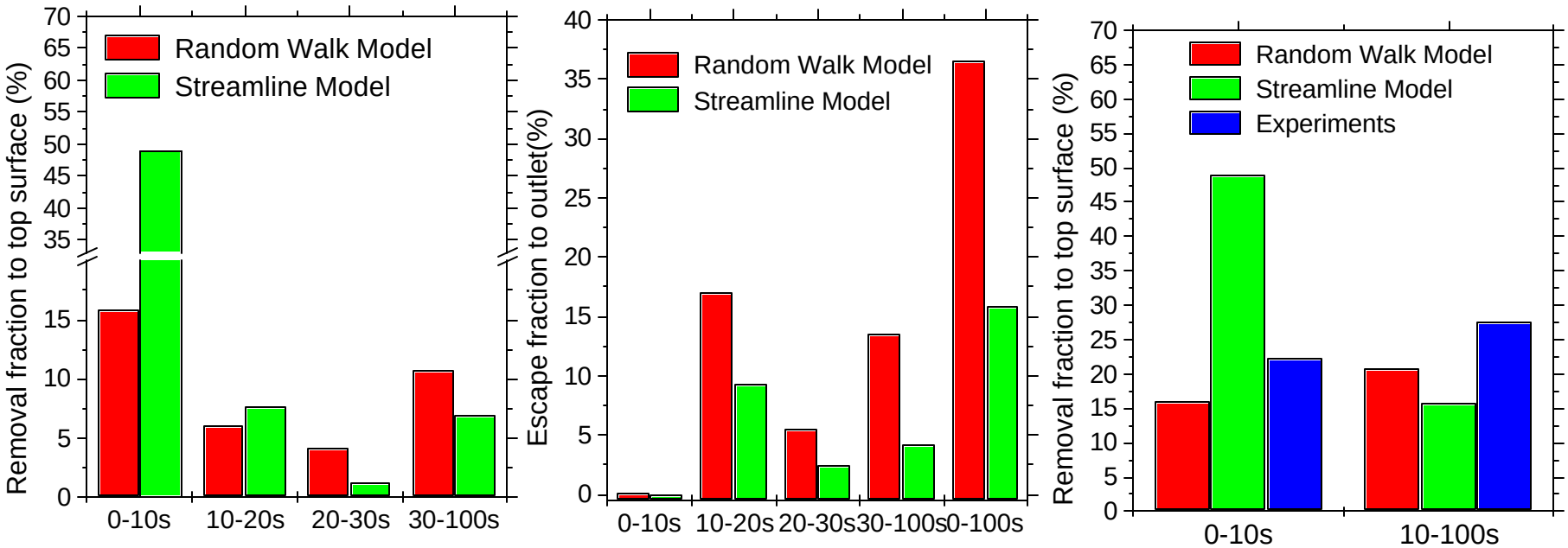


Particle velocities (Random Walk Model, 100s)



Fluid flow velocities (steady)

Particle Escape Fraction



Conclusions:

Random walk model is better than streamline model to predict the inclusions motion in mold because considering the effect of turbulence fluctuation. (In 100s, Random walk model: 37% removal; Streamline model: 65%; Experiments: 50%)

Comparison between Different Turbulence Models

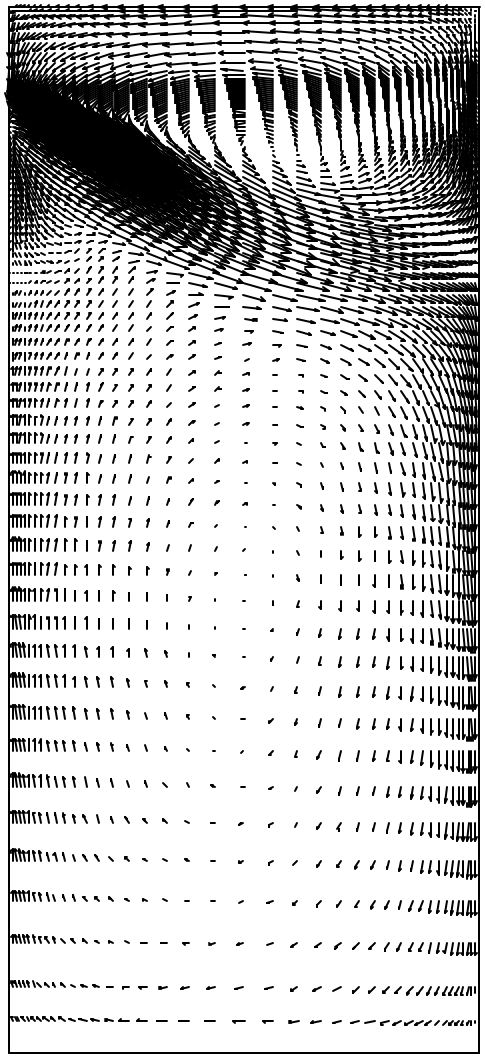
Non-uniform inlet condition

1. Large Eddy Simulation (LES)
2. Reynolds Stress Model (RSM)
3. ***k-e*** Two Equation Model

Uniform inlet condition

1. ***k-e*** Two Equation Model

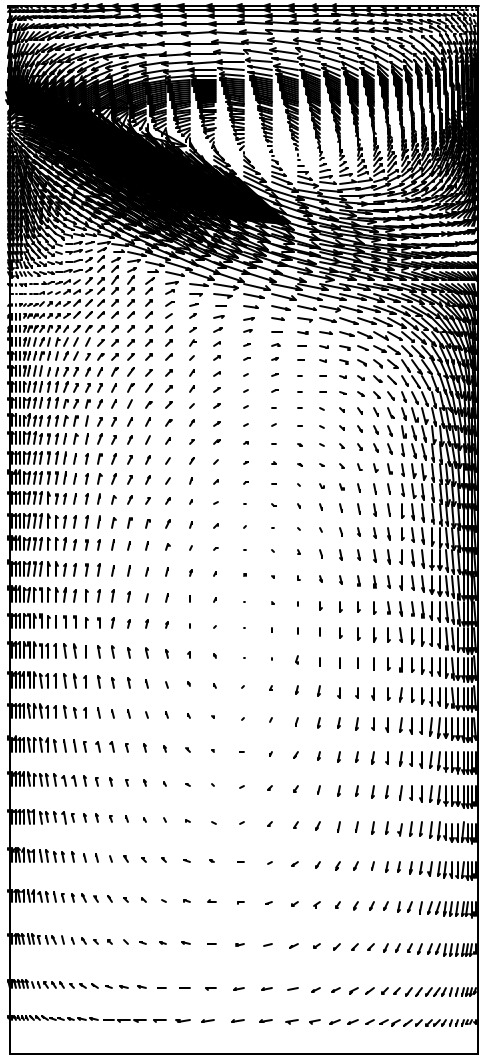
Comparison between Uniform Inlet and Non-Uniform Inlet (*k-e* Model)



scale: ⟶ 0.5m/s

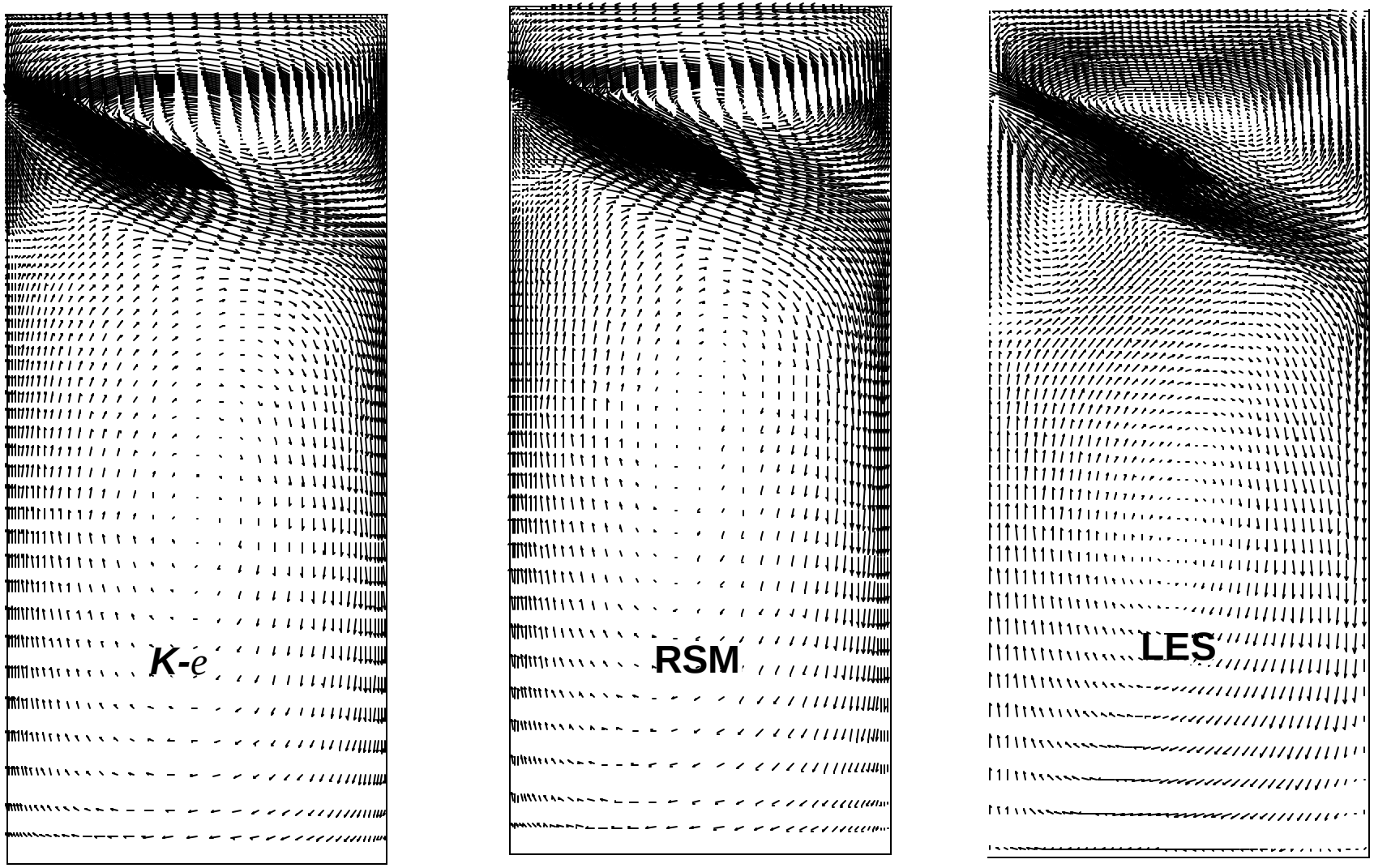
Uniform inlet
Vx=1.191594 m/s
Vy=-0.5512596 m/s
Vz=-0.001 m/s
k=0.0832 m^2/s^2
e=1.057863 m^2/s^3

Non-uniform inlet
From LES Simulation



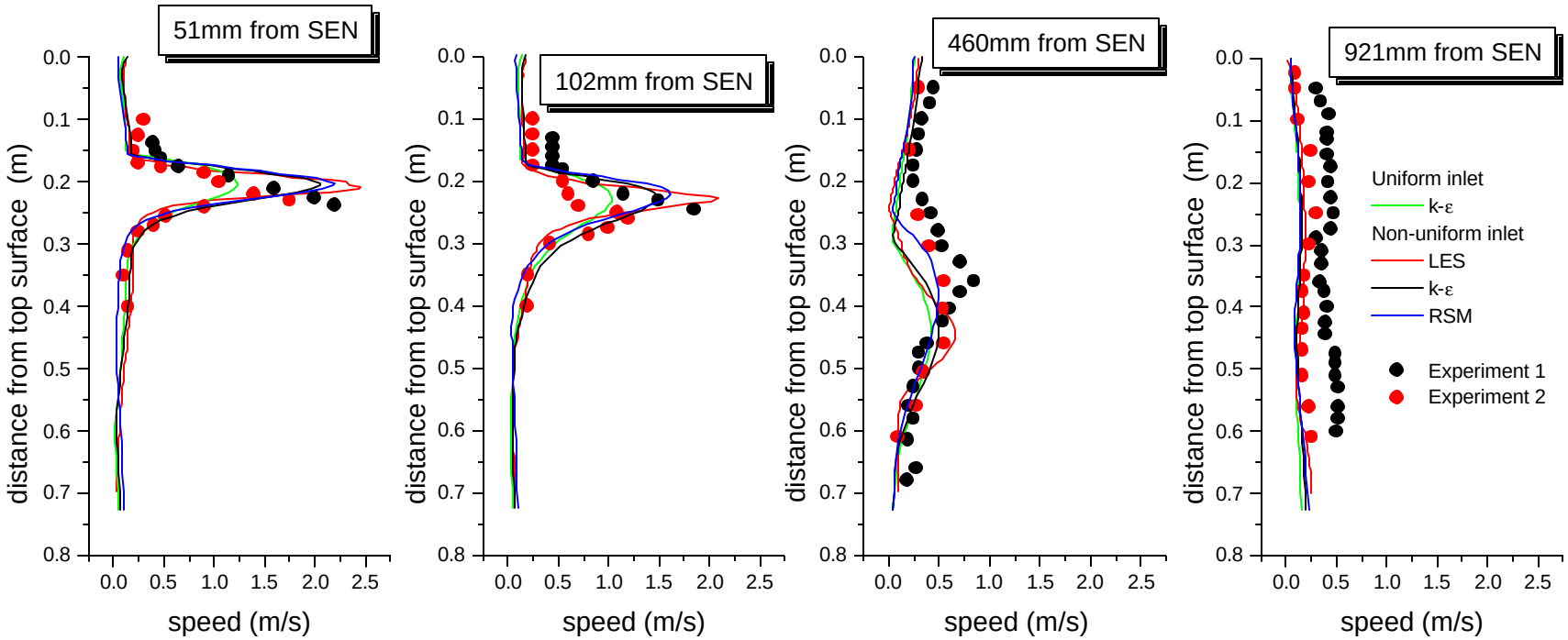
scale: ⟶ 0.5m/s

Comparison between Different Turbulence Models (Non-Uniform Inlet Condition)



scale: ⟶ 0.5m/s scale: ⟶ 0.5m/s scale: ⟶ 0.5m/s

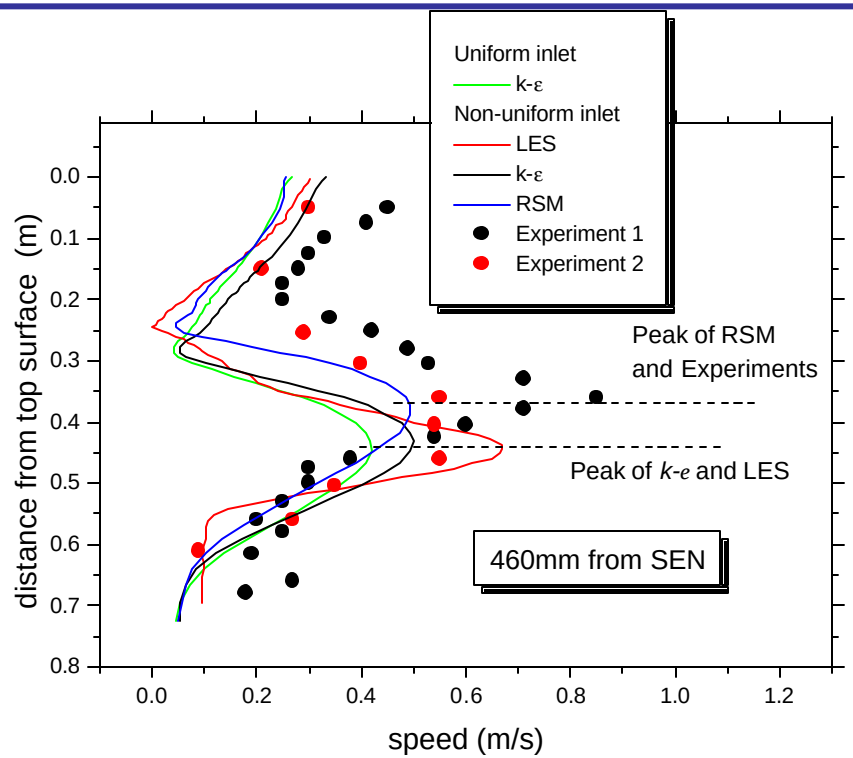
Speed along Four Vertical Lines by Different Turbulence Models and Measurement



Conclusion:

Uniform inlet *k-e* underpredicts velocity peaks.

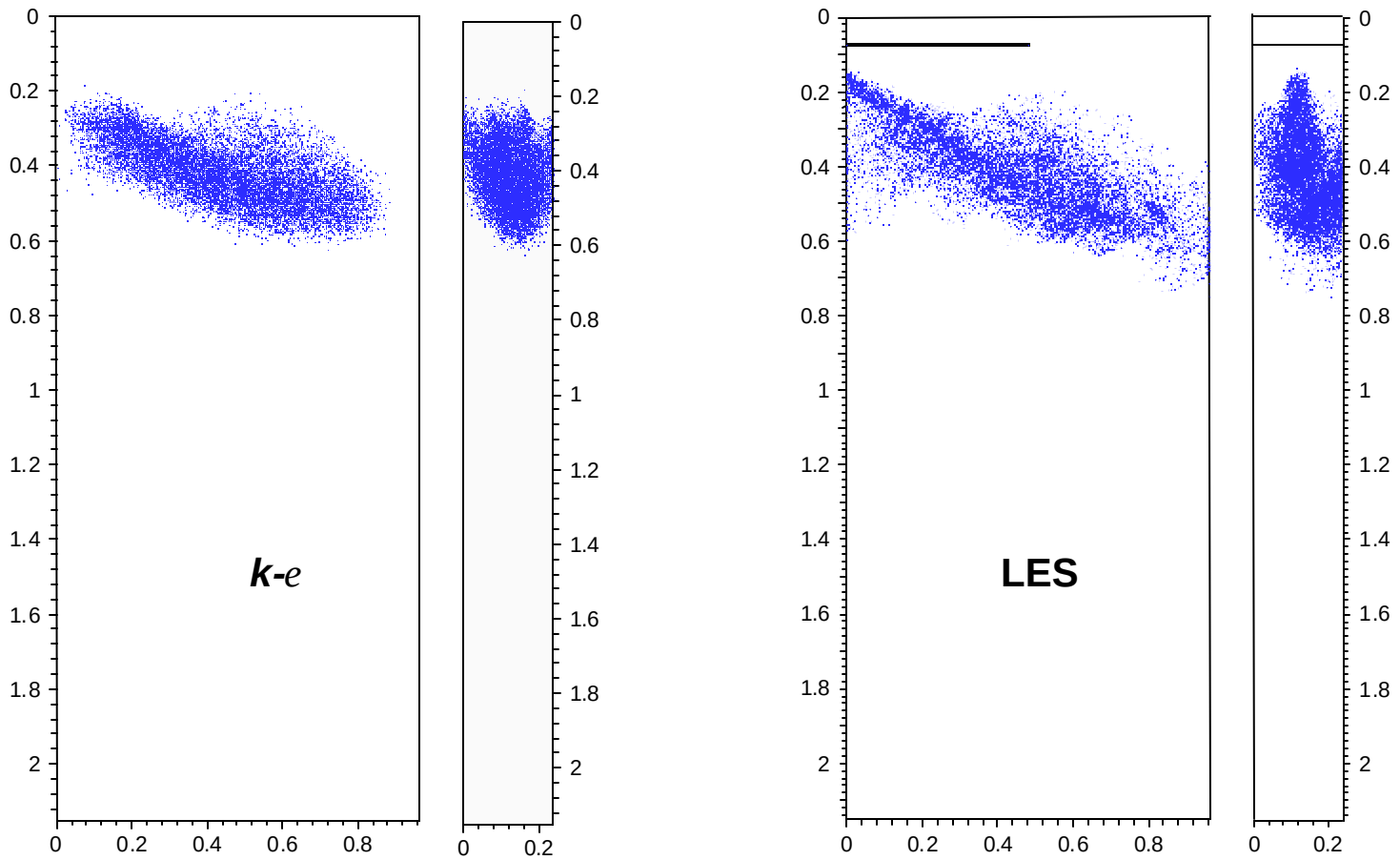
Enlargement of the Speed the line of 460mm from SEN on the central wide section



Conclusion:

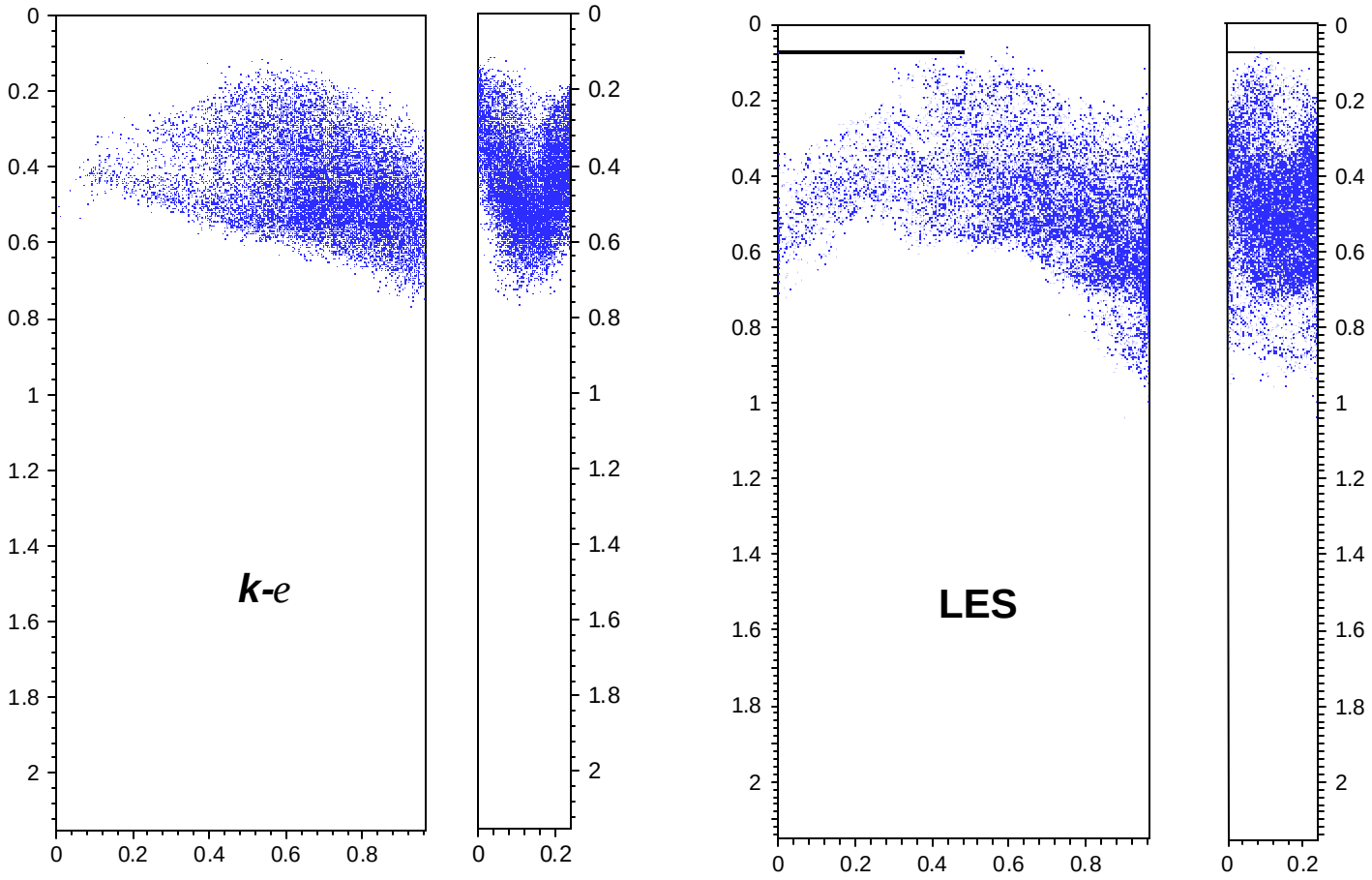
RSM model has slightly better prediction on the position of the peak for the line 460mm from SEN on the central wide section.

Particle Distribution by *k-e* and LES



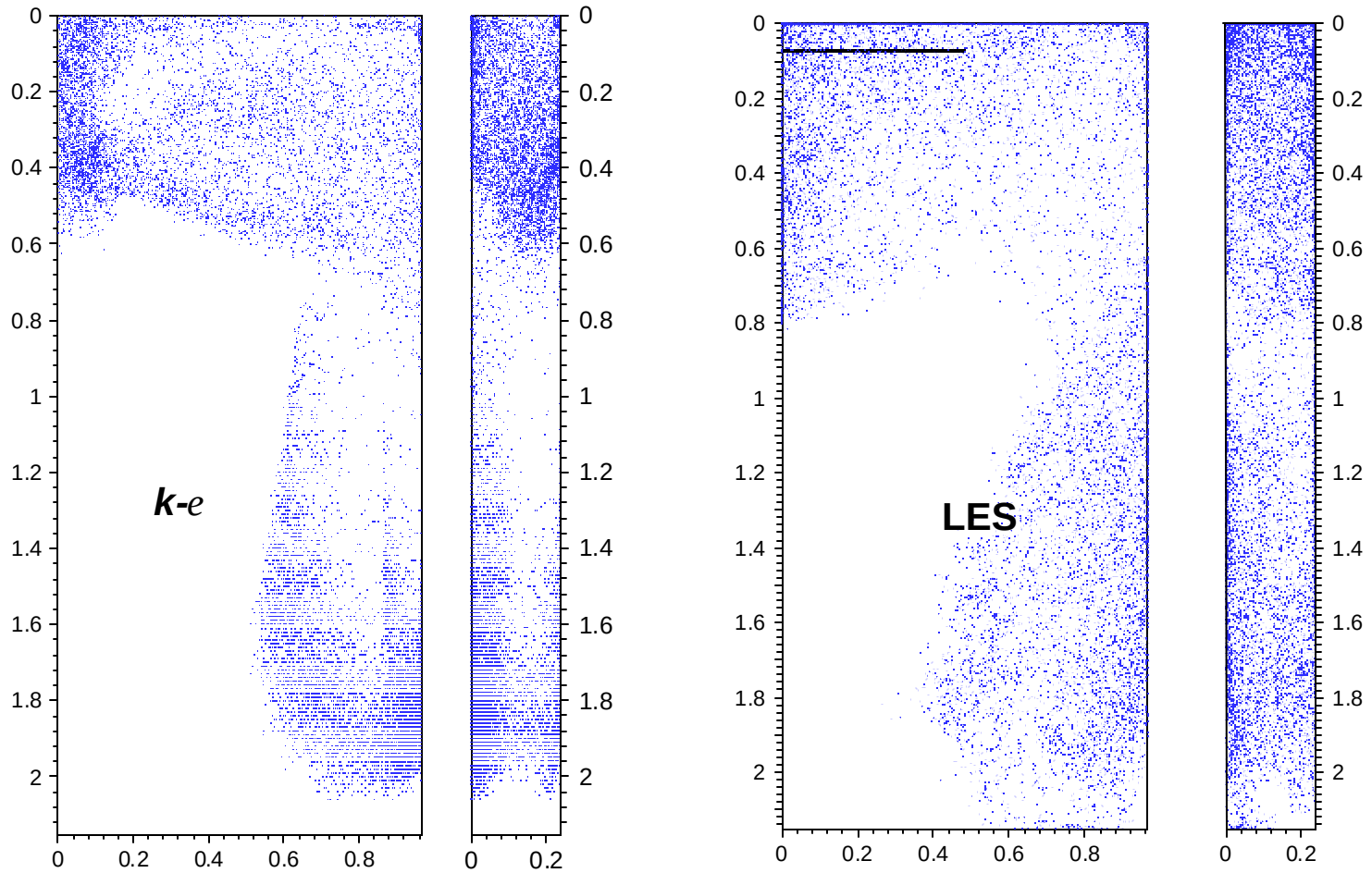
t=1.6s

Particle Distribution by *k-e* and LES



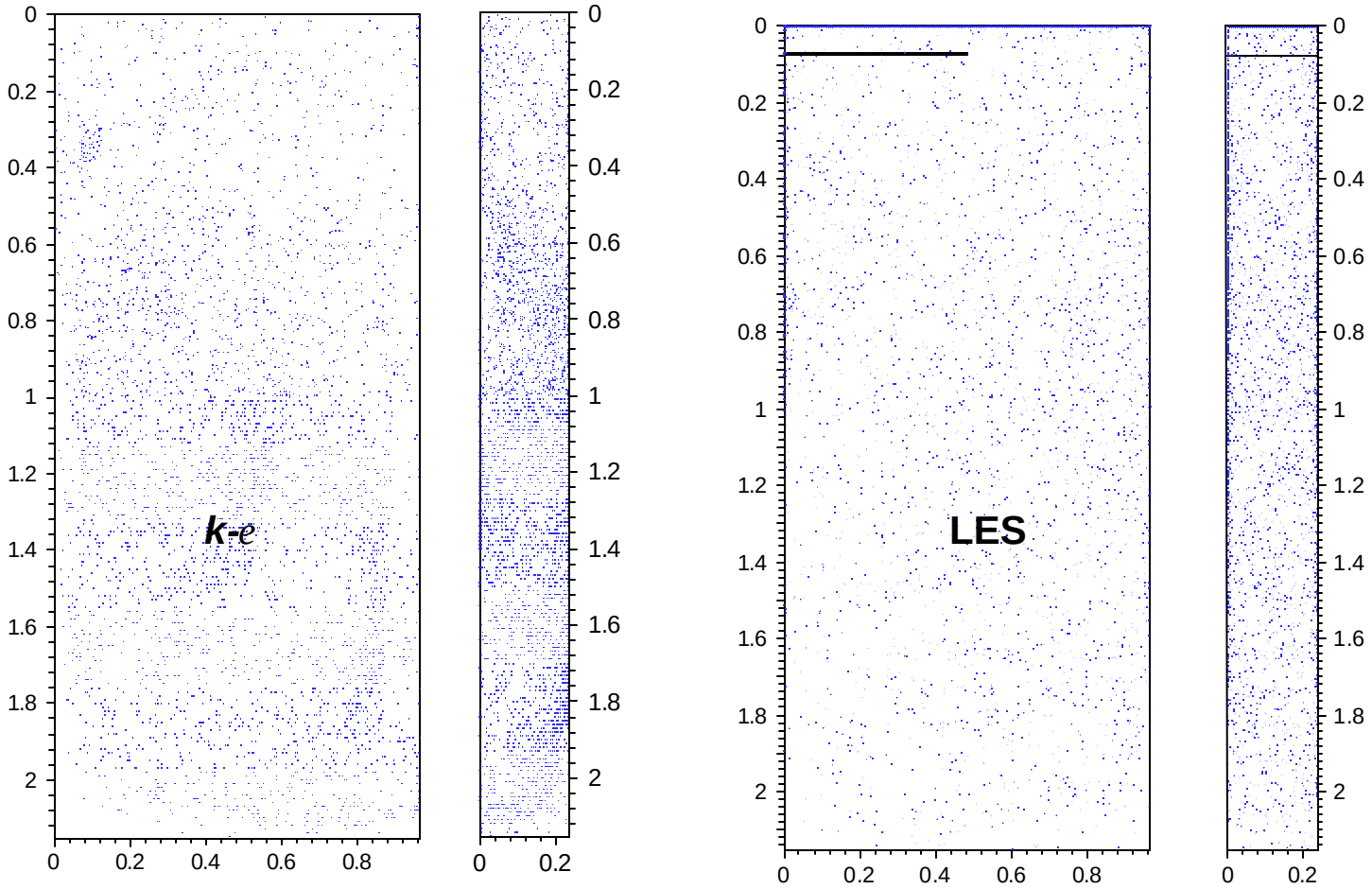
t=2.6s

Particle Distribution by *k-e* and LES



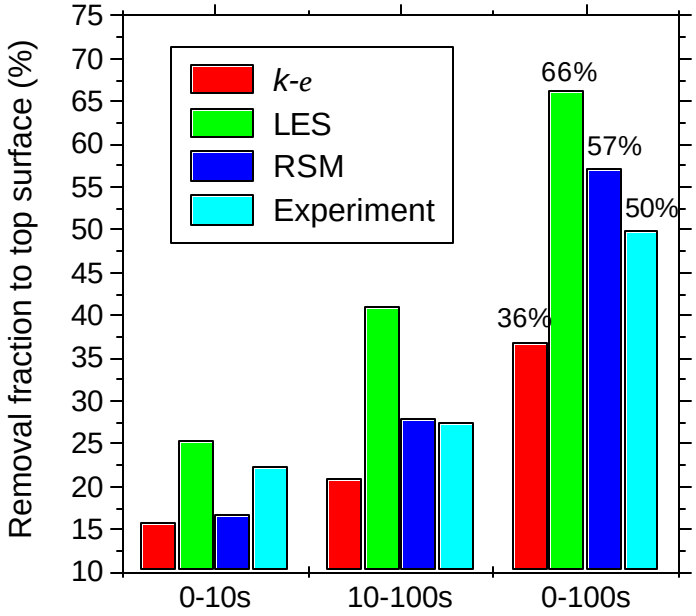
t=10s

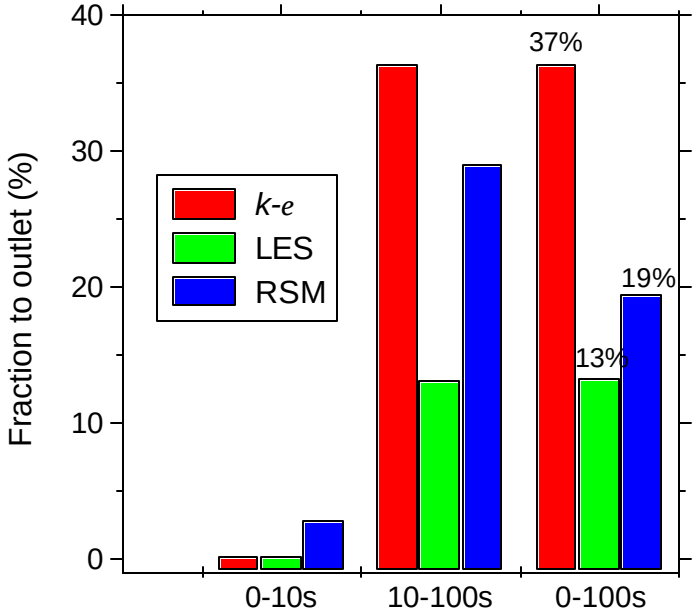
Particle Distribution by *k-e* and LES



t=100s

Particle Escape Fraction





Conclusion:

- **RSM model has a best prediction of particle removal fraction compared to the experiments results.**
- **LES model overpredicts particle removal fraction and *k-e* far underpredicts particle removal fraction.**

Computation Time Consuming

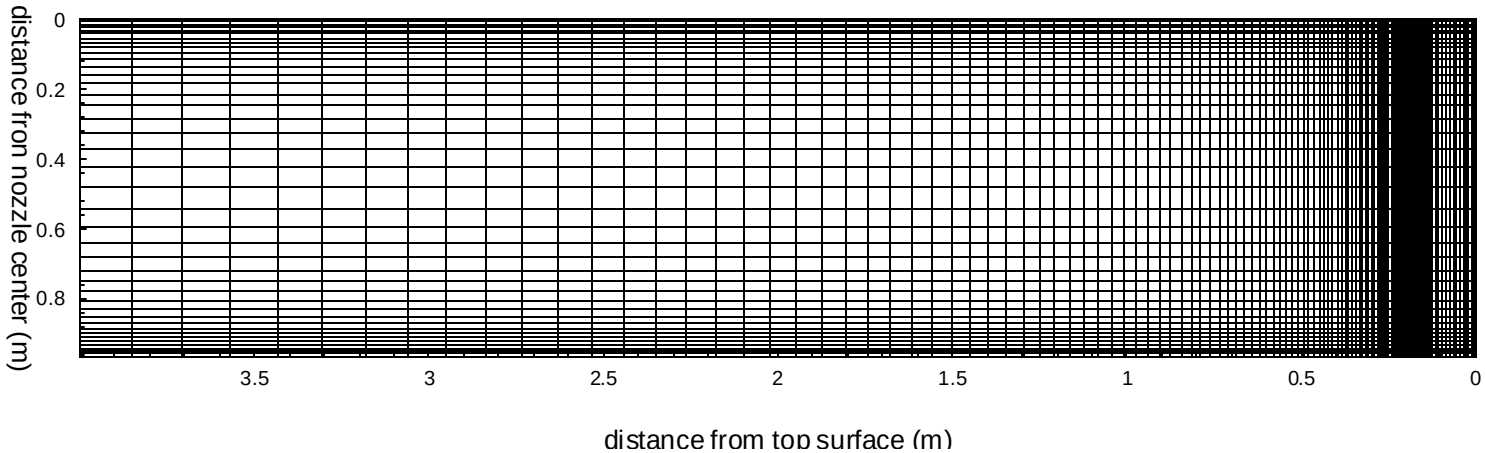
- **LES: more than 20 days**
- **To reach a residual of 10^{-6} as convergence criterion, the computation time are as follows:**
  - **RSM: 43 hours**
  - ***k-e*: 11 hours**

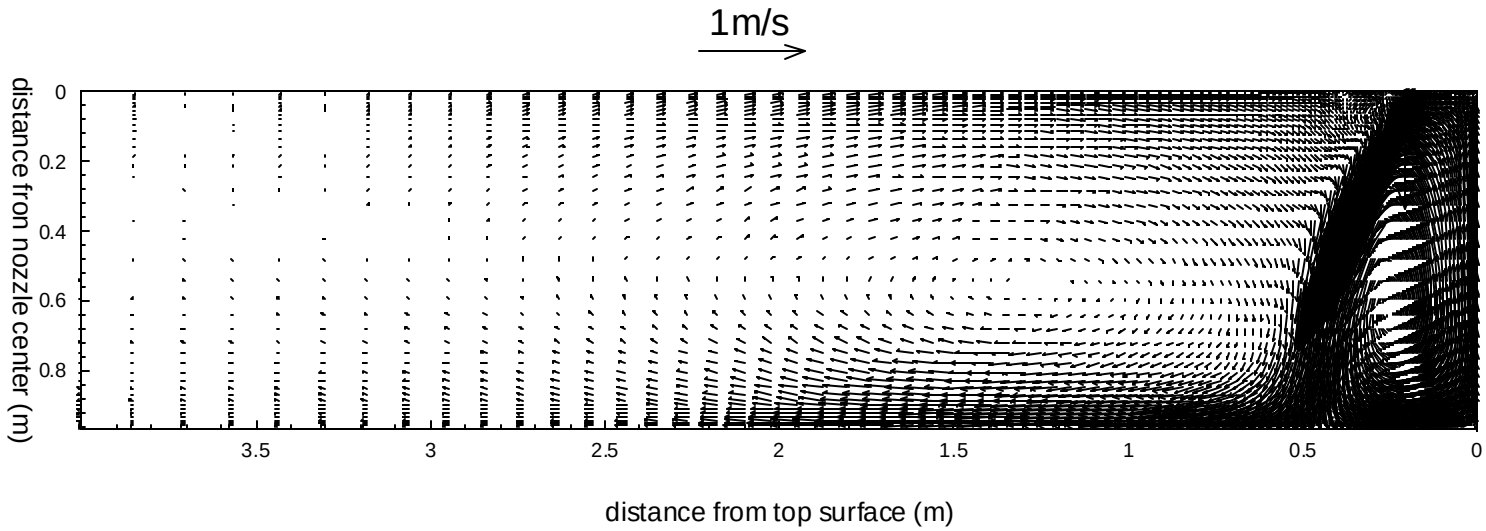
Fluid Flow and Inclusion Behavior in Steel Caster (Random Walk *k*-e)

Experimental and Simulation Parameters

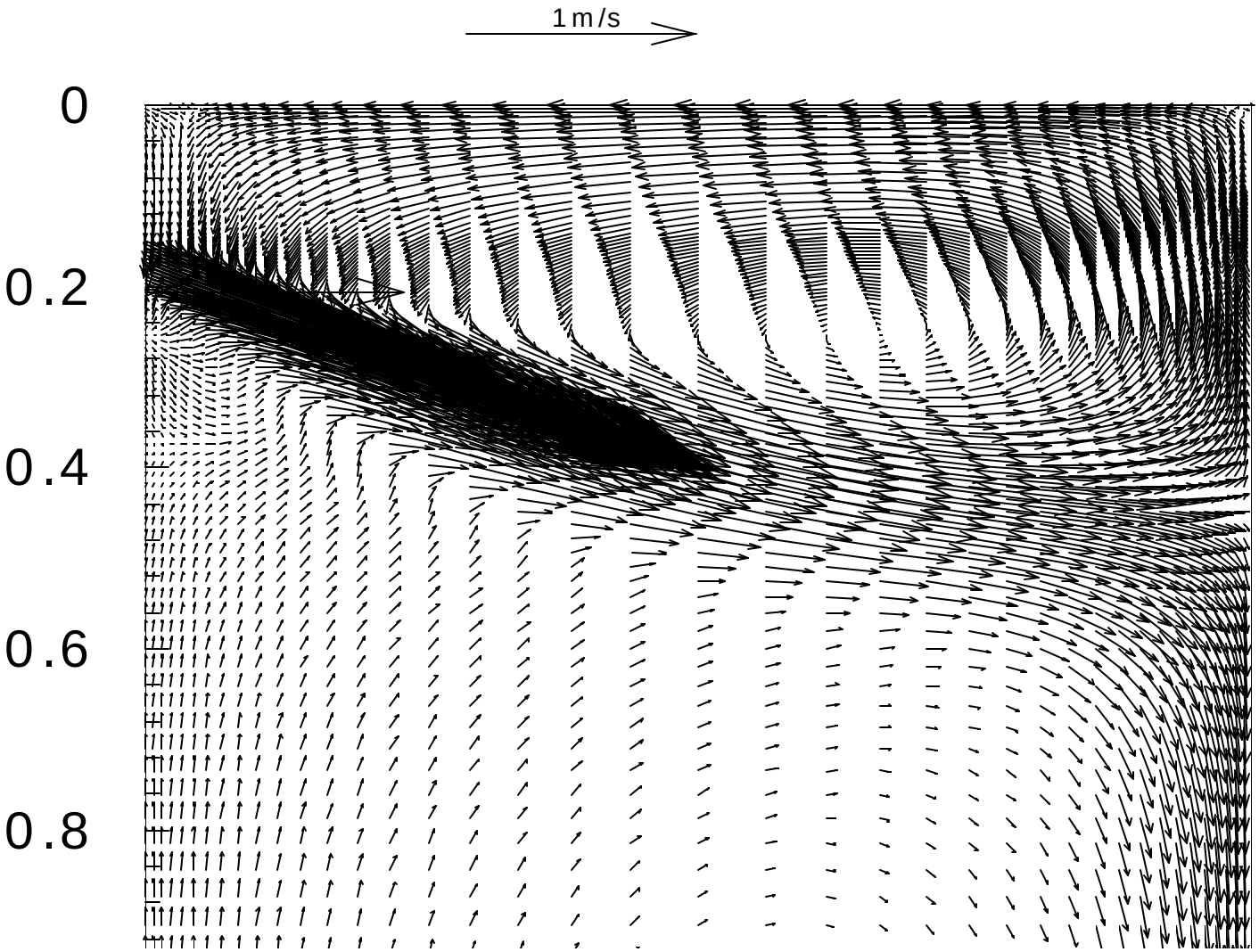
	Simulation
Nozzle port size/ Inlet port size (x×y) (m)	0.051×0.056
Nozzle angle	25°
Inlet jet angle	25°
Submergence depth (m)	0.150
Mold/Domain height (m)	**4**
Mold/Domain width (m)	1.83
Mold/Domain thickness (m)	0.238
Average inlet flow rate (m^3/s)	0.00344
Casting speed (m/s)	0.0152
Fluid density (kg/m^3)	**7020**
Fluid kinetic viscosity (m^2/s)	**0.954×10^{-6}**
Particle size (diameter) (μm)	**300, 100, 50, 25**
Particle density (kg/m^3)	**2700**
Inlet condition	LES pipe simulation results
Turbulence model	*k-e*
Inclusion motion model	Random walk model
Boundary condition for inclusions	Escape from top surface and open bottom, reflect from other faces

Mesh and Velocity Distribution at Central Face

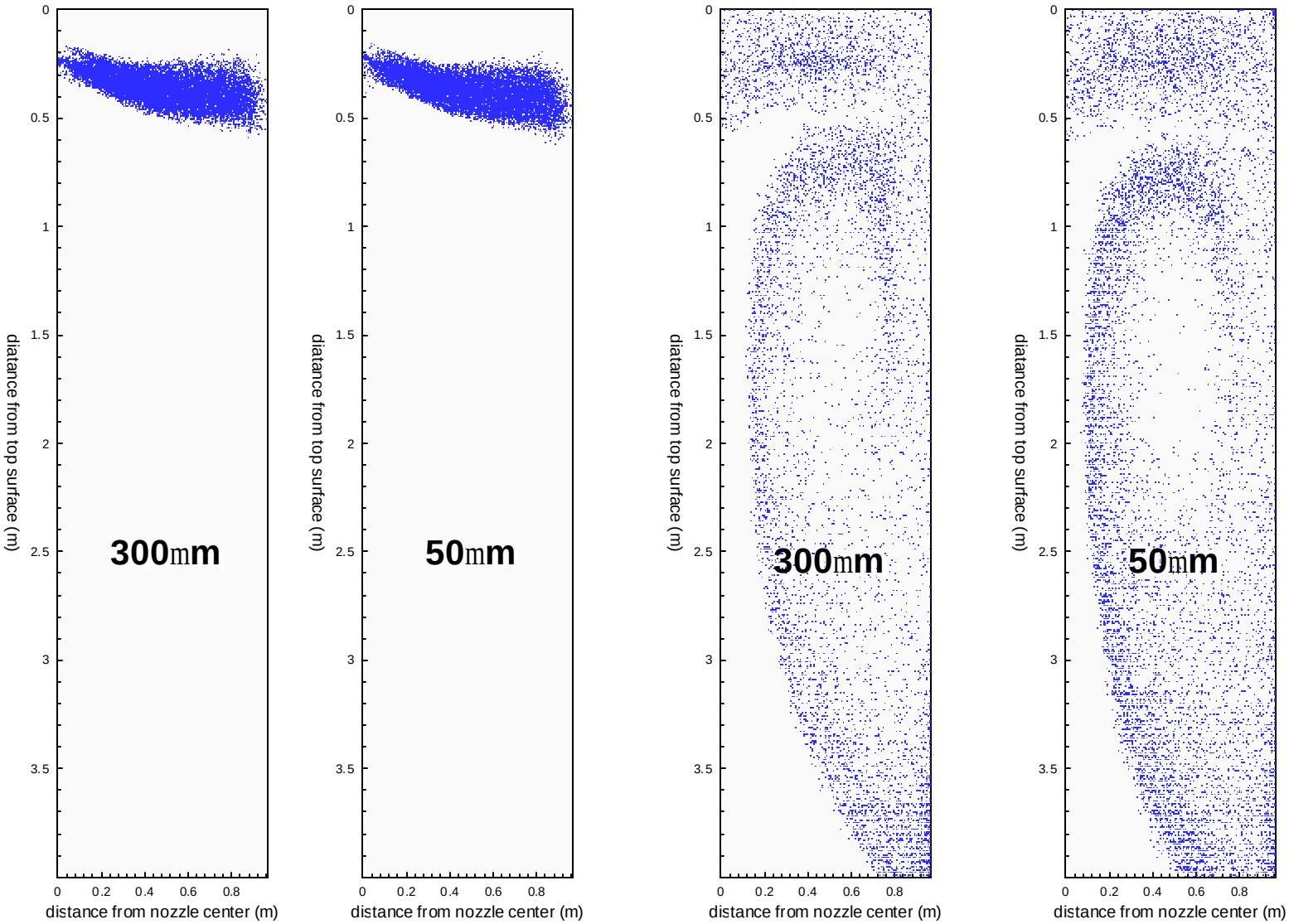




Magnified Velocity Distribution on Central face

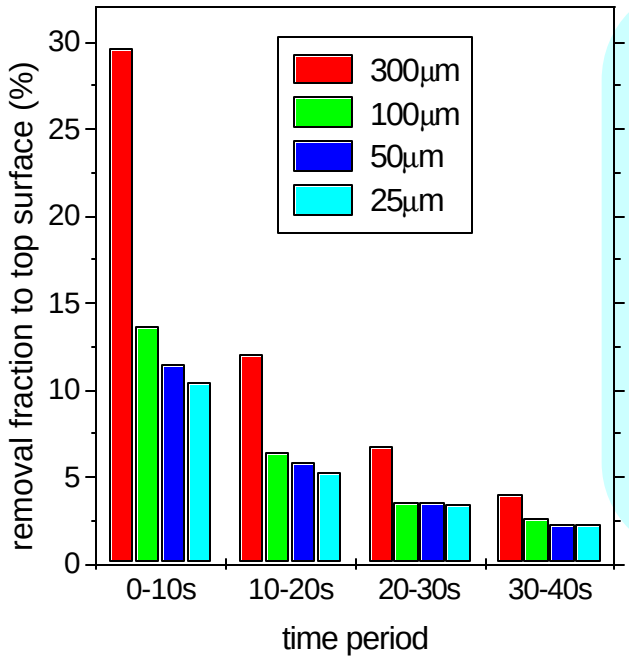


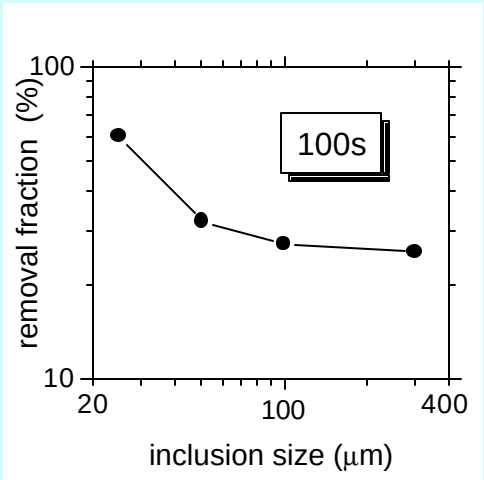
Different Size Particle distribution

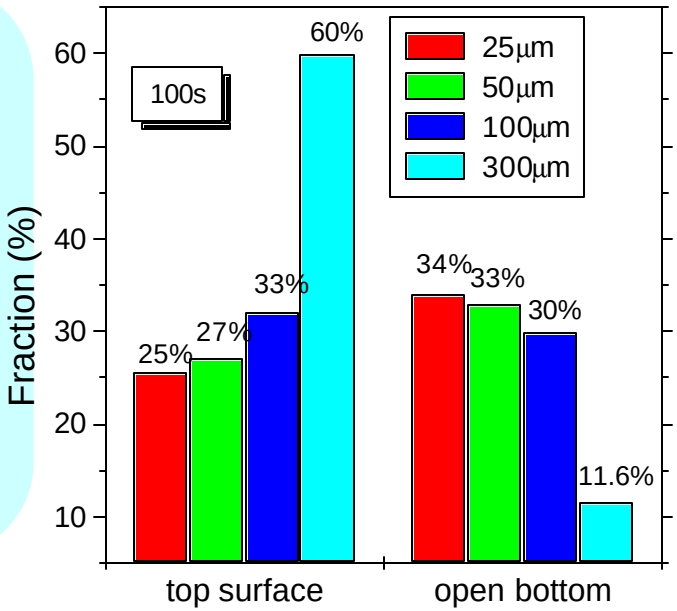


1.6s **40s**

Escape Fraction for Different Size Inclusions



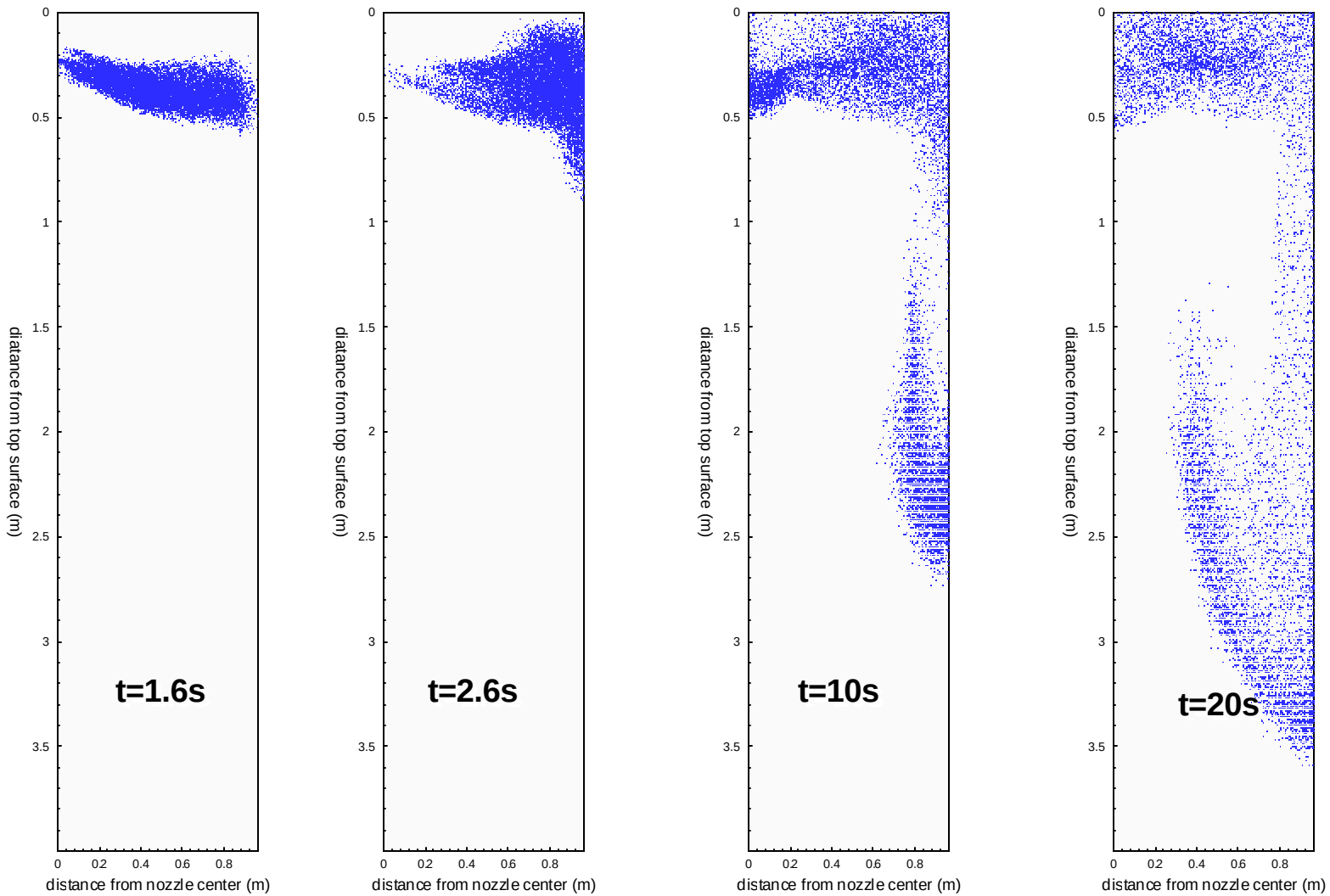




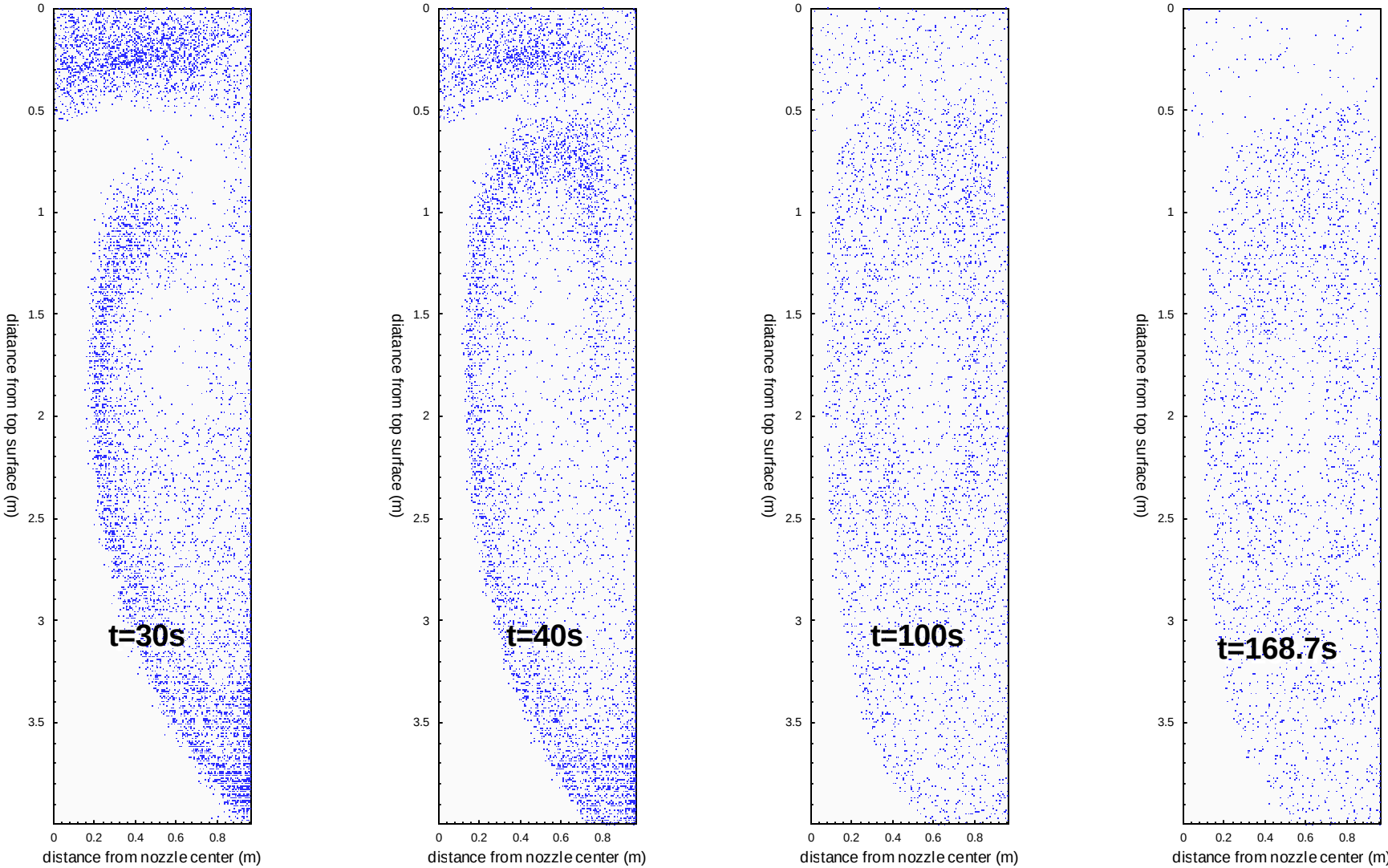
Conclusions:

- **With increasing size, inclusion removal to the top surface becomes easier.**
- **Smaller inclusions are much easily transported by the flow out of the bottom.**

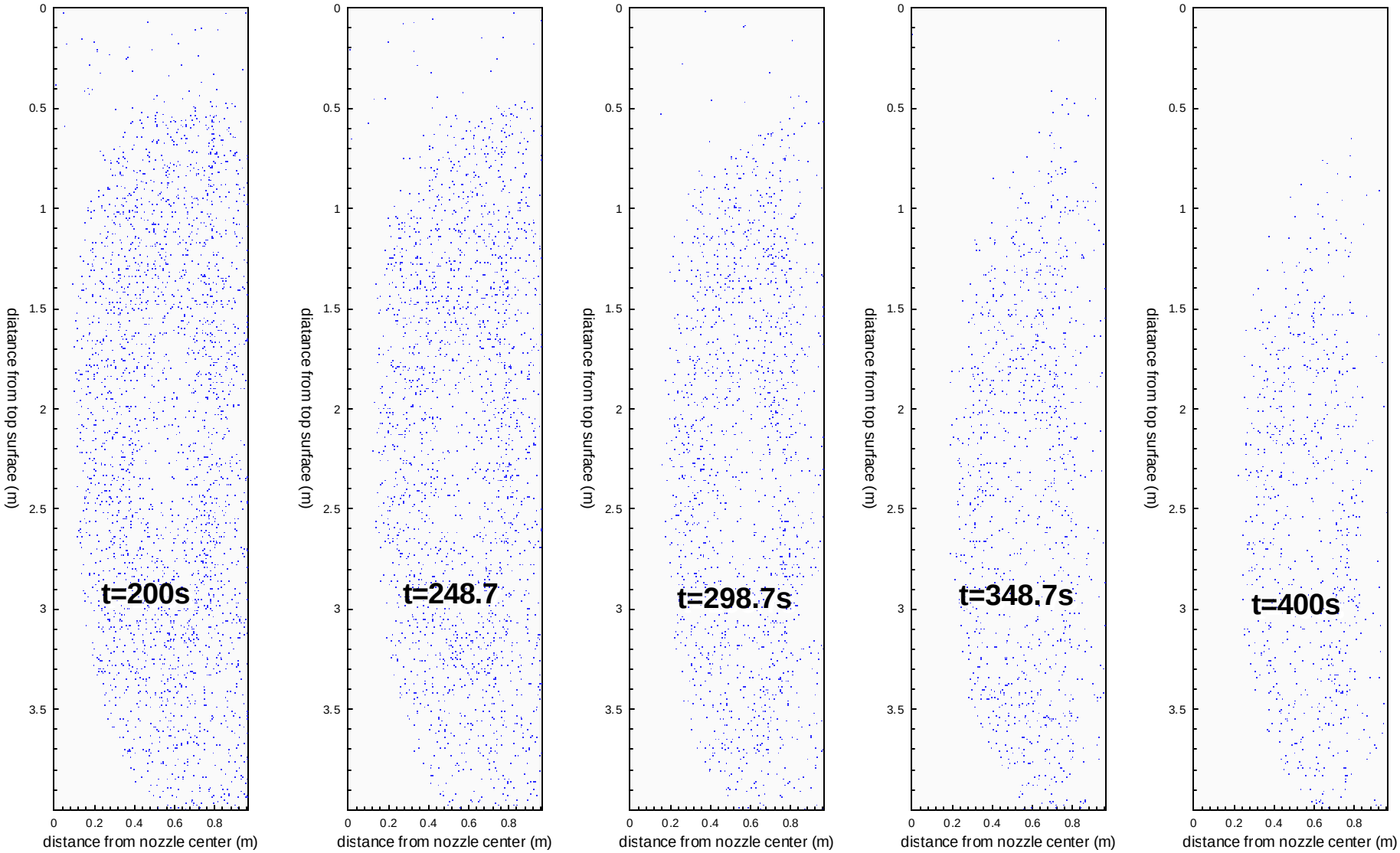
300㎛ Inclusion Distribution with Time Increasing



300㎛ Inclusion Distribution with Time Increasing



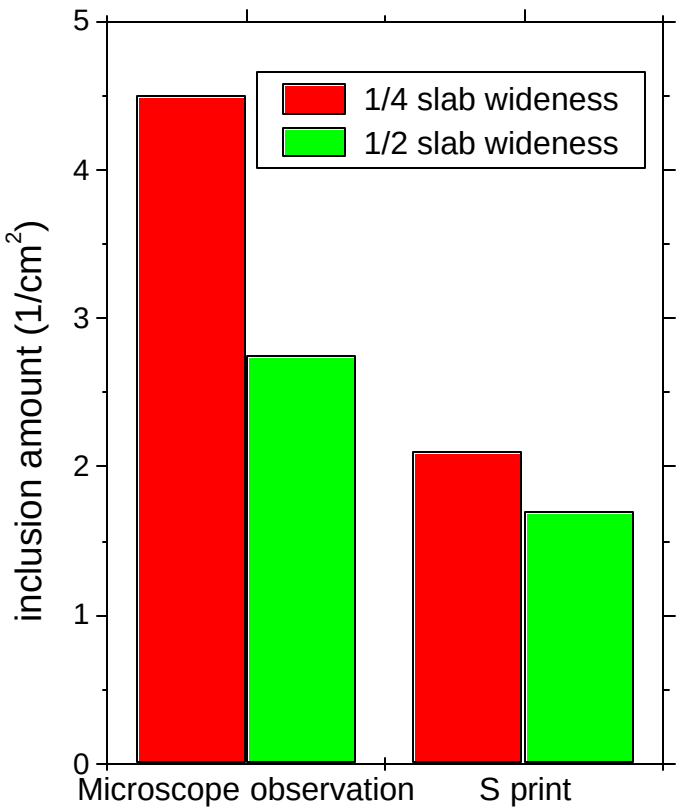
300㎛ Inclusion Distribution with Time Increasing



Conclusion about Inclusion Distribution along Slab Wideness

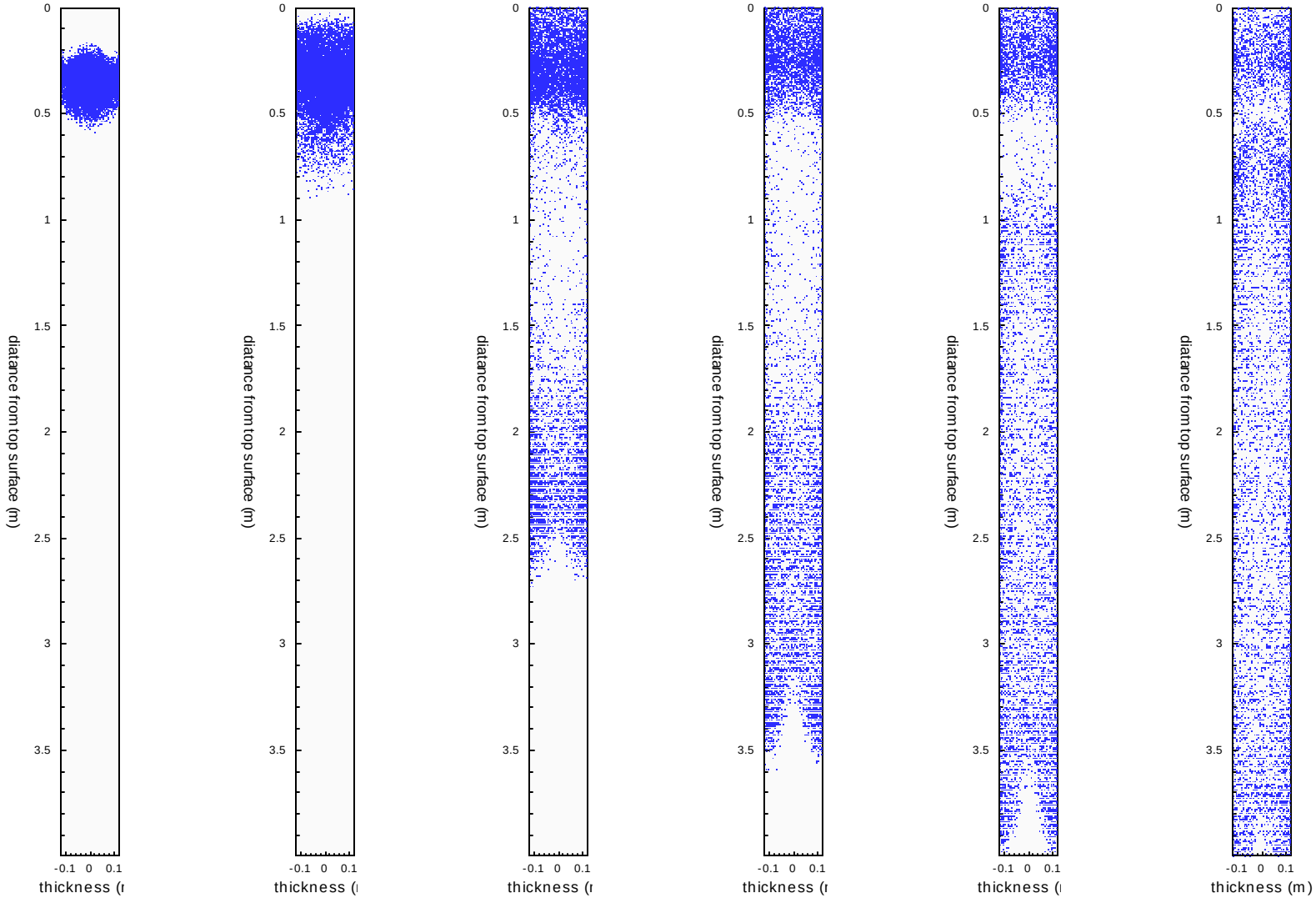
Conclusion from simulation:

Inclusion amount at the center of mold is less than that at other places.



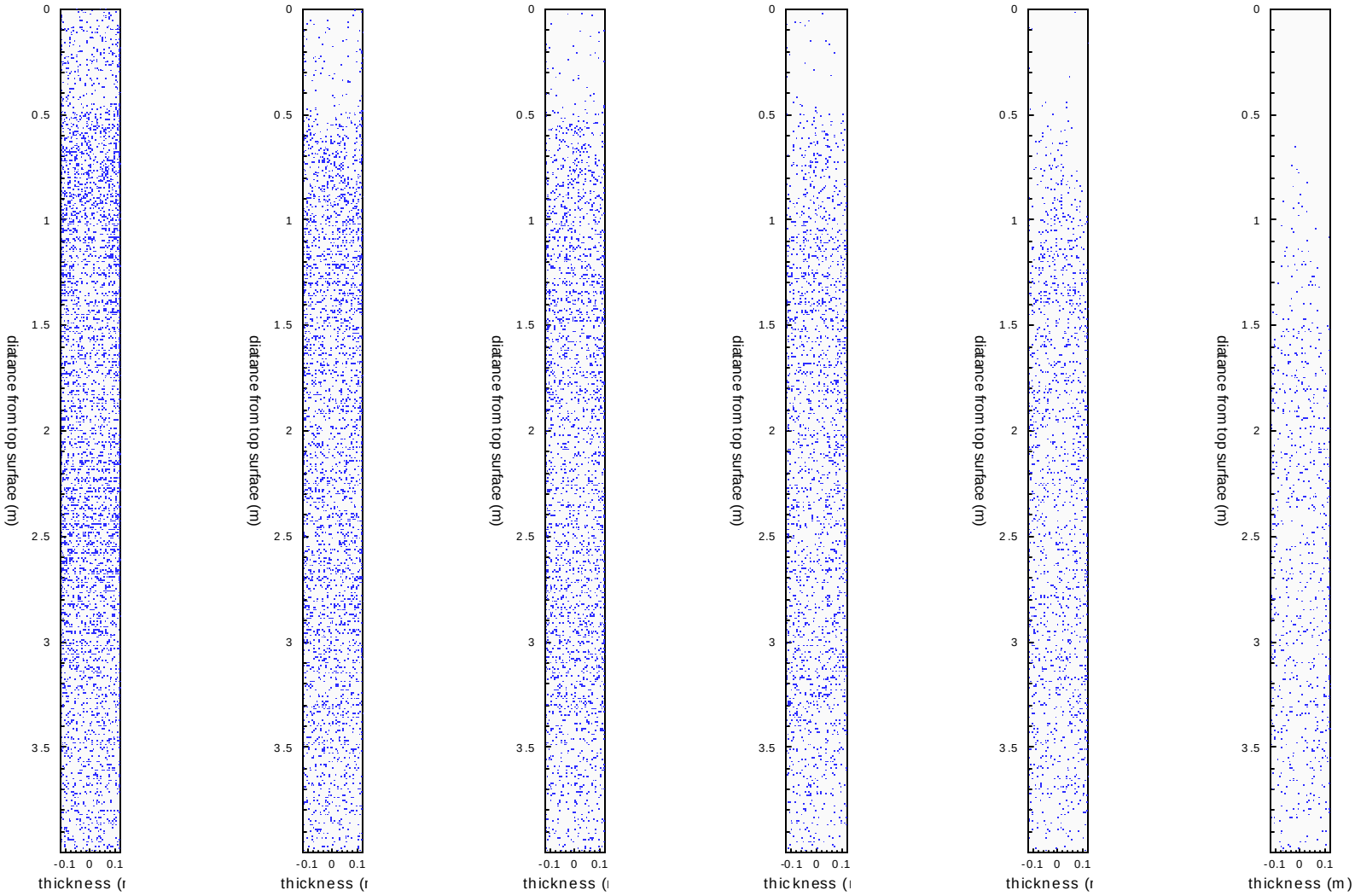
Proof from industrial experiments

300mm Inclusion Distribution with Time Increasing



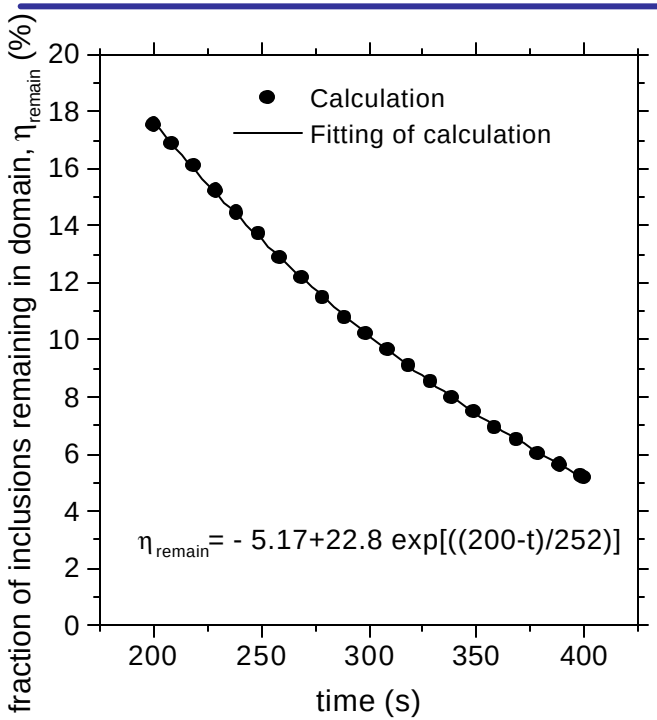
t=1.6s t=2.6s t=10s t=20s t=30s t=40s

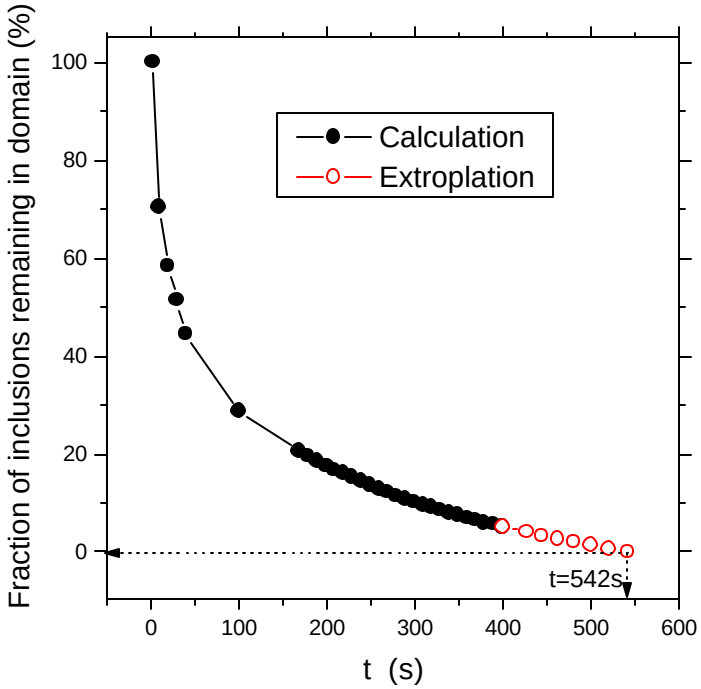
300㎛ Inclusion Distribution with Time Increasing



t=100s t=168.7s t=200s t=248.7s t=298.7s t=400s

Removal of 300mm Inclusions with Time Increasing

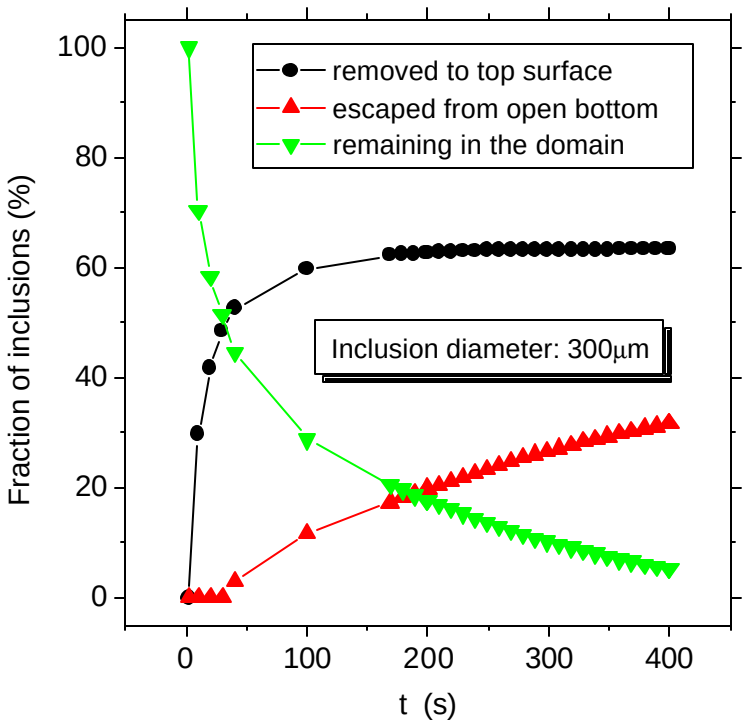


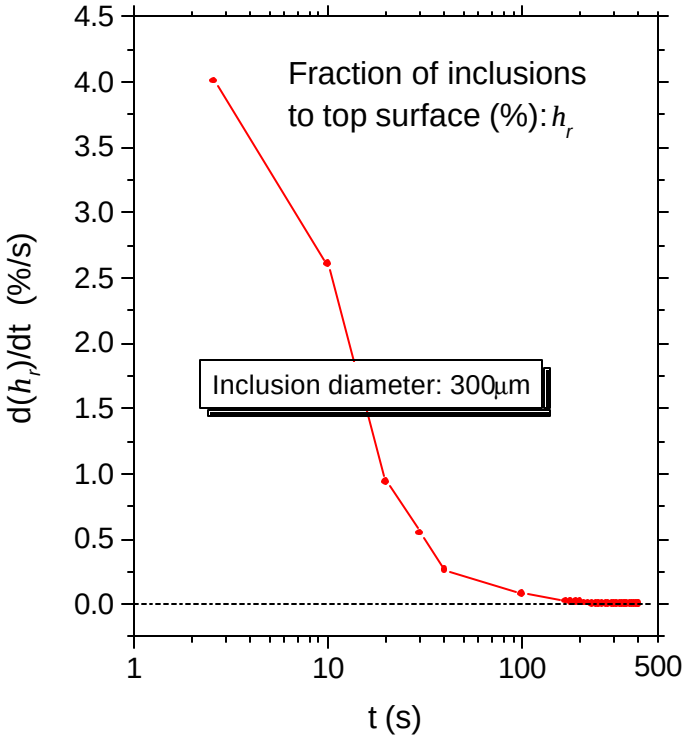


Conclusions

- Inclusions require about 10min to leave the domain of mold region (4m).
- The total removal fraction to top surface is 63%, escape fraction to open bottom is 37%.
- In 10 min, the casting length is 8.24m, but the domain is 4m. So if ignoring the inclusions entrapment to solidified shell, the steel in the domain will become dirty more and more with time increasing

Removal of 300㎛ Inclusions with Time Increasing





Conclusions:

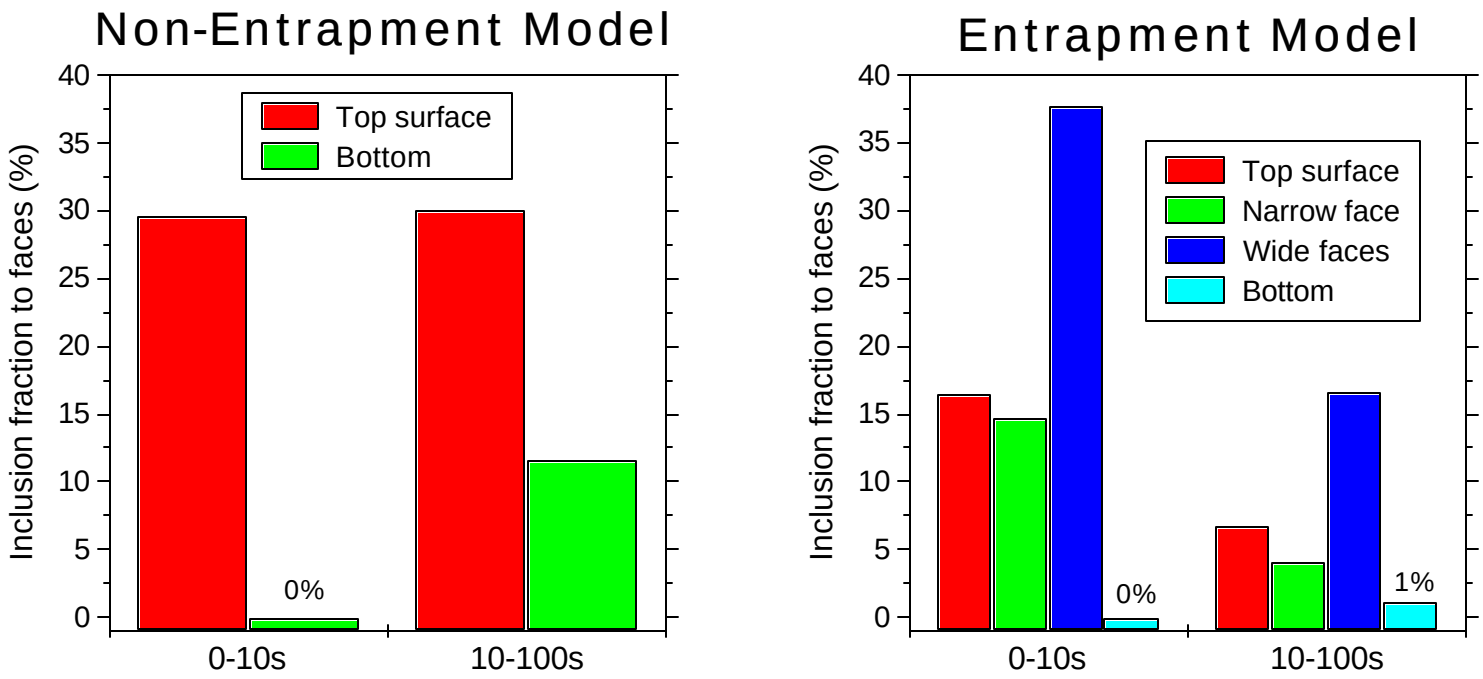
- **After t=270s, inclusions removal to top surface becomes less than 0.5%.**
- **At t=270s, the cast length is 4.1m, which is similar with domain length.**

Effect of Inclusion Entrapment to Solidified Shell

- **Non-Entrapment Model:** previous simulations assume that if inclusions collide with solidified shell, they will be reflected.

- **Entrapment Model:** if inclusions collide with solidified shell, they will be entrapped.

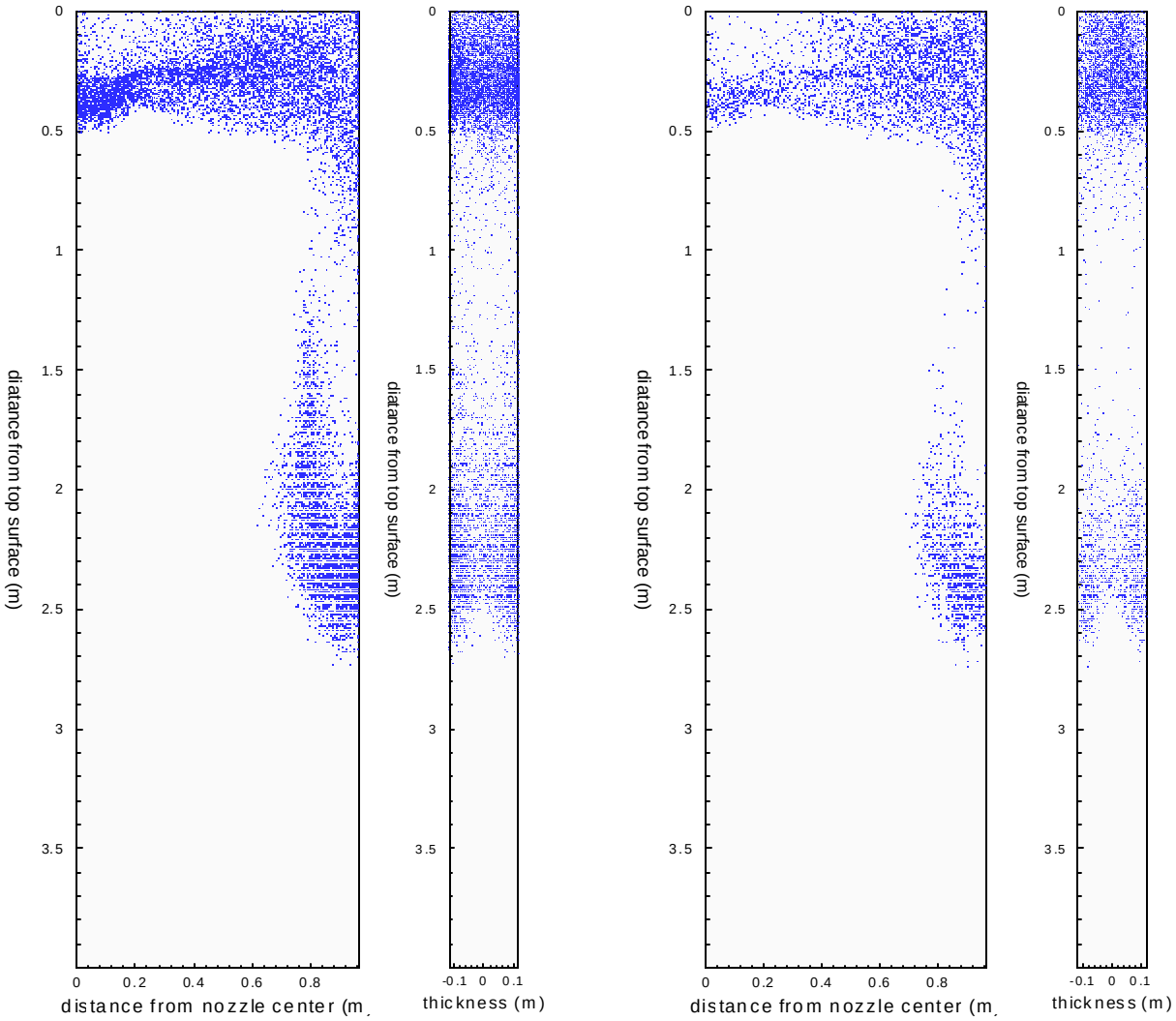
Effect of Inclusion Entrapment to Solidified Shell (100s)



Entrapment Model: **Top surface: 23%, entrapped to wide faces: 54%, narrow face: 19%, flow away from bottom: 1%, remain in domain: 3% (Total escape in 100s: 97%)**

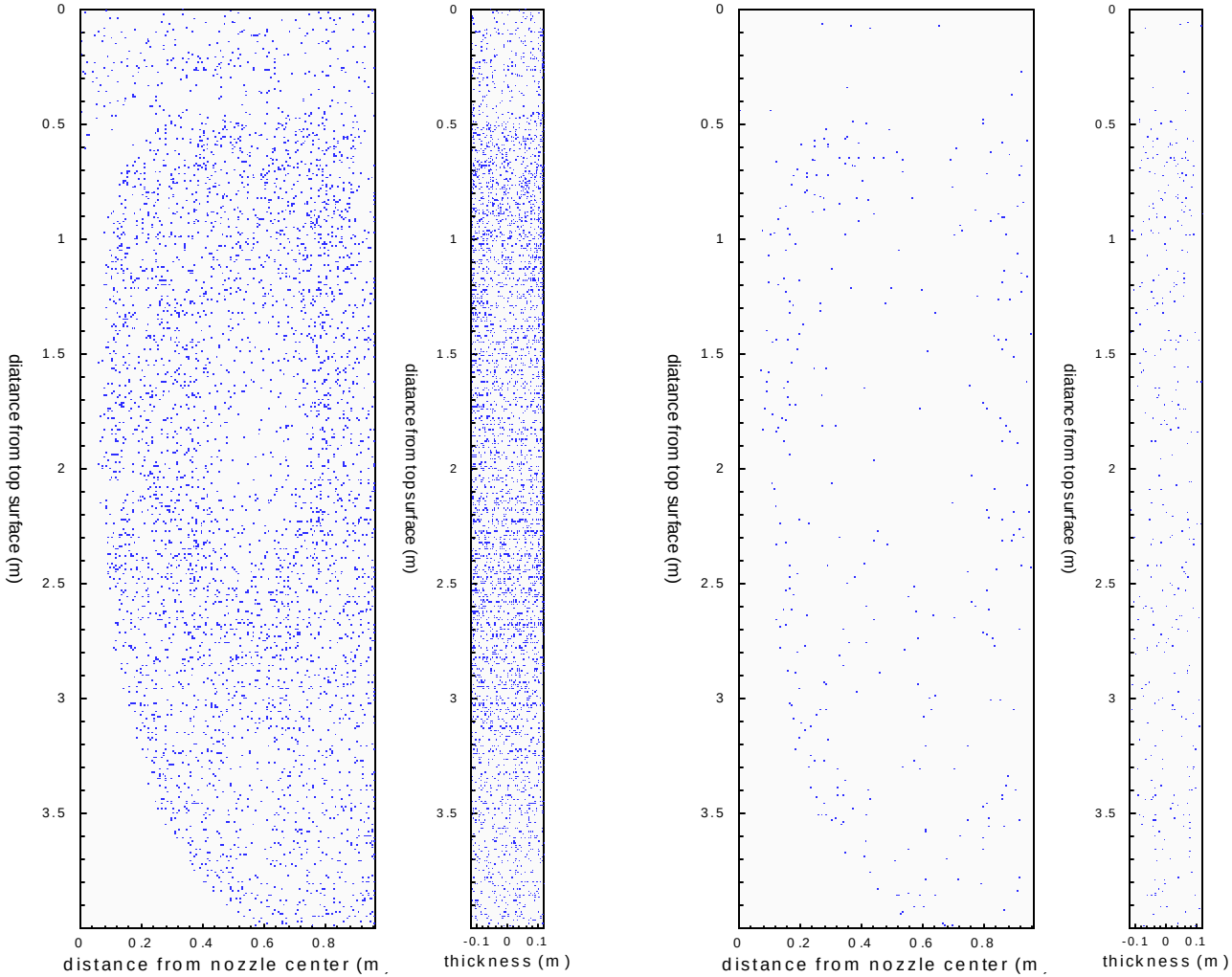
Non-Entrapment model: **Top surface: 60%, flow away from bottom: 12%, remain in domain: 28% (Total escape in 100s: 72%)**

Inclusion Distribution (10s)



Non-entrapment model **Entrapment model**

Inclusion Distribution (100s)



Non-entrapment model **Entrapment model**

The Accuracy of the Similarity Criterion of Stokes Velocity for the Particle Motion in Water and in Liquid Steel

The Accuracy of the Similarity of the Particle Motion between Water and Liquid Steel ¾ Stokes Velocity

	Steel Caster	Water Model
Mold Geometry	Same (The previous water model case)	
Outlet	Two holes on lower part of one wide face	
Density (kg/m^3)	7020	998
Viscosity (m^2/s)	0.954×10^{-6}	1.0×10^{-6}
Particle size	473 μm	3.8mm
Particle density (kg/m^3)	2700	988

$$V_s = \frac{(r - r_P)d_P^2}{18m} g$$

The Stokes velocity of the particles in water is the same as that of the inclusions in liquid steel. (V_s=0.0786m/s)

Particle Stokes Terminal Rising Velocity in Liquid

Force balance on particle: Drag force=gravitational force

For $\mathrm{Re}_p < 1$

$$\frac{1}{2} C_D r u_P^2 A_P = (r_P - r) g \frac{1}{6} p d_P^3$$

$$C_D = \frac{24}{\mathrm{Re}_P}$$

$$V_s = \frac{(r - r_P) d_P^2}{18m} g$$

V_S: Stokes velocity, m/s

r, r_p, liquid and particle density, kg/m^3

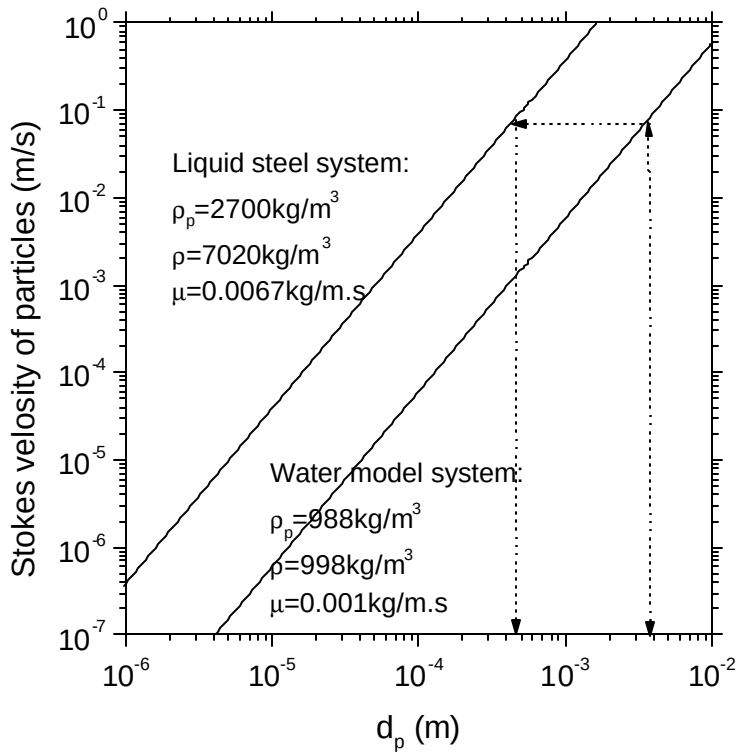
d_p, particle diameter, m

m, liquid viscosity, kg/m.s

g, gravitational acceleration, m/s^2

A_p: Intersection area of particle, m^2

Particle Stokes Terminal Rising Velocity in Liquid



$$V_s = \frac{(r - r_P) d_P^2}{18m} g$$

V_S: Stokes velocity, m/s

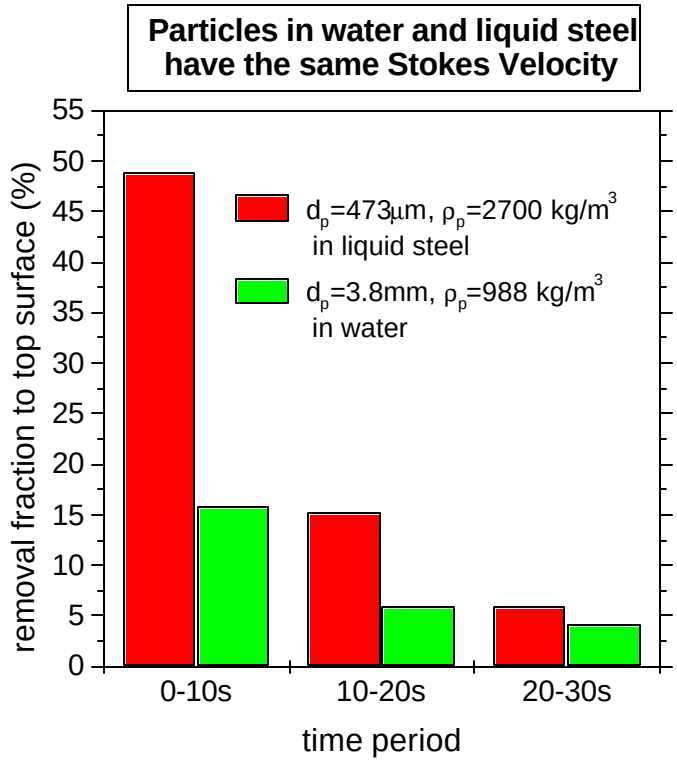
r, r_p, liquid and particle density, kg/m^3

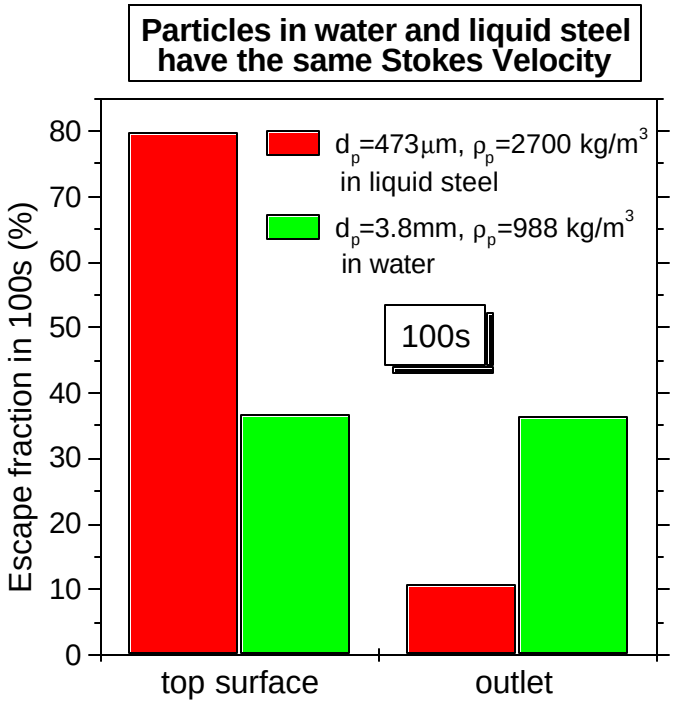
d_p, particle diameter, m

m, liquid viscosity, kg/m.s

g, gravitational acceleration, m/s^2

Comparison Between Liquid Steel and Water Model





The difference of particle removal fraction in water and liquid steel shows that the Stokes rising velocity is not a reasonable criterion for matching the particle behavior in water with inclusion behavior in liquid steel.

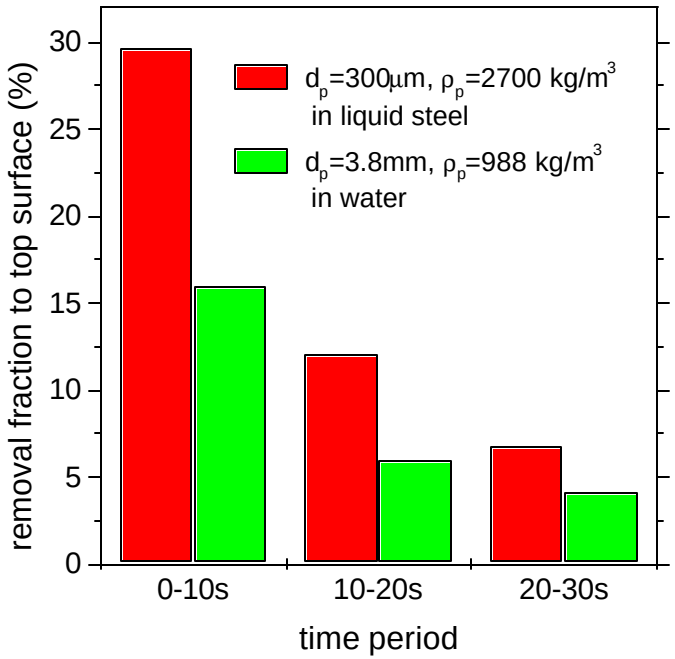
Comparison Between Liquid Steel and Water Model

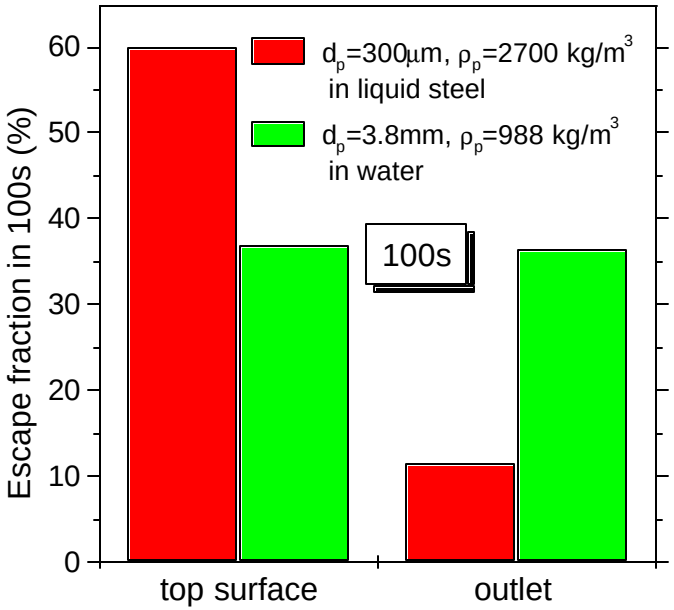
Steel caster: Previous Steel caster case (length : 4m, open bottom as outlet)

Water Model: Previous Water Model (length:2.152m, two holes at under part of wide face as outlet)

Stokes Velocity: Inclusions in steel ¾ 0.0316m/s

Particles in water ¾ 0.0786m/s





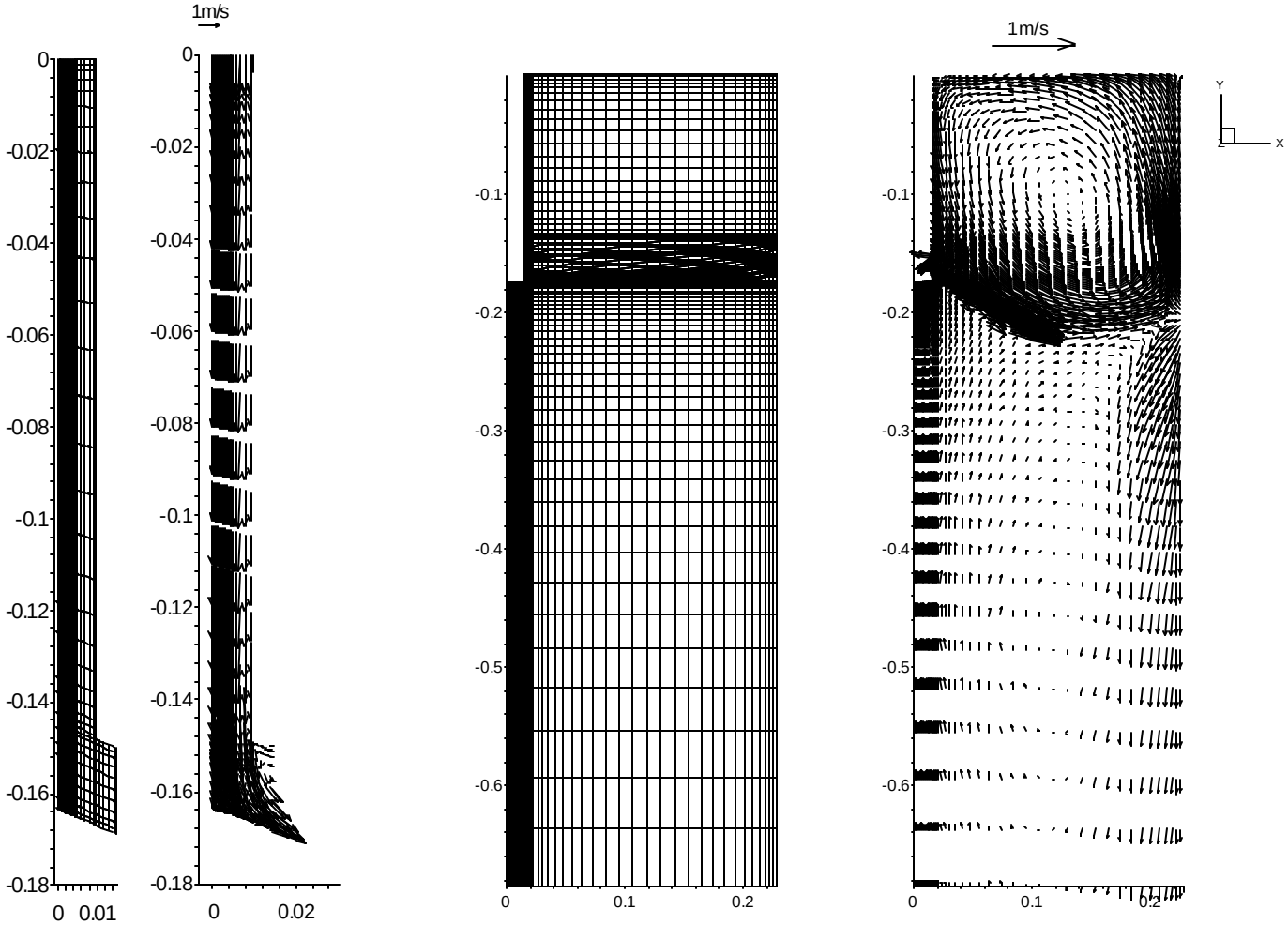
Pressure on the Top Surface and Level Fluctuation of Mold

Experimental and Simulation Parameters[1]

	Experiment
Nozzle inner diameter (m)	0.0195
Nozzle outer diameter (m)	0.0295
Nozzle port size/ Inlet port size (x×y) (m)	0.0175×0.0175
Nozzle angle	20° downward
Inlet jet angle	25° downward
Submergence depth (m)	0.150
Mold/Domain height (m)	0.686
Mold/Domain width (m)	0.457
Mold/Domain thickness (m)	0.059
Average inlet flow rate (m^3/s)	4.67×10^{-4}
Casting speed (m/s)	0.0173
Fluid density (kg/m^3)	1000
Fluid kinetic viscosity (m^2/s)	1.0×10^{-6}
Inlet condition (Nozzle)	Uniform inlet velocity and *k, e*
Top oil density	918

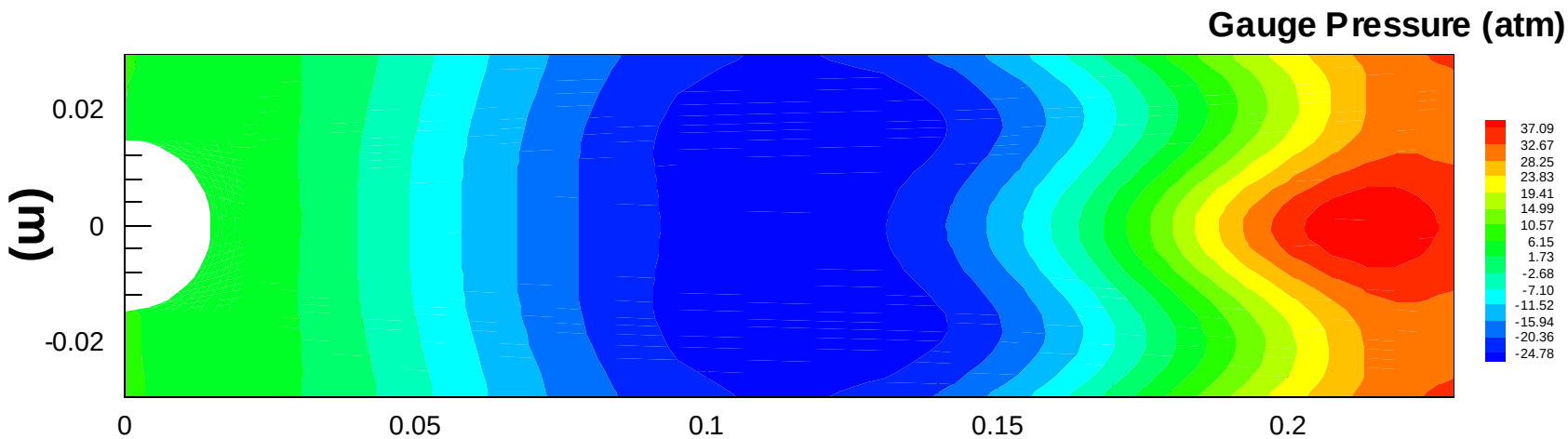
[1] J. Anagnostopoulos and G. Bergeles. Metall. Mater. Trans. B., Vol.30B, 1999, p1095-1105

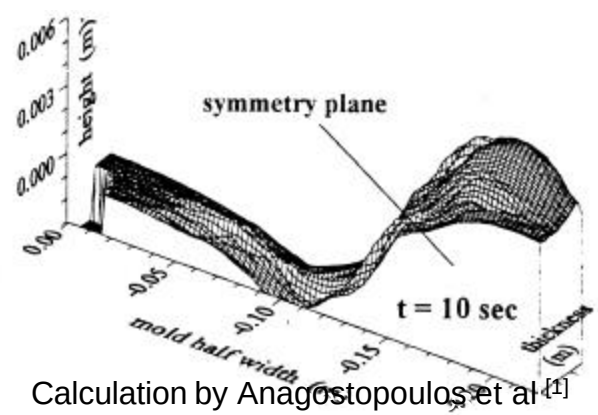
Mesh and Velocity Distribution



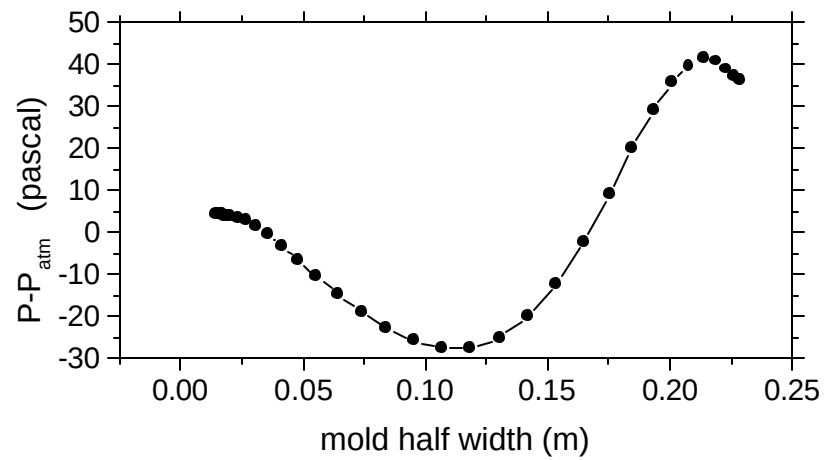
Nozzle **Mold**

Calculated Pressure Distribution at Top Surface and Measured Surface Level





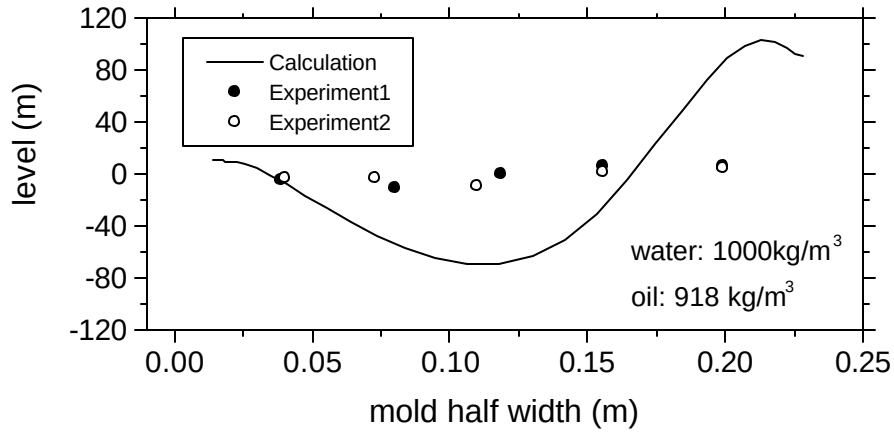
Calculation by Anagostopoulos et al [1]

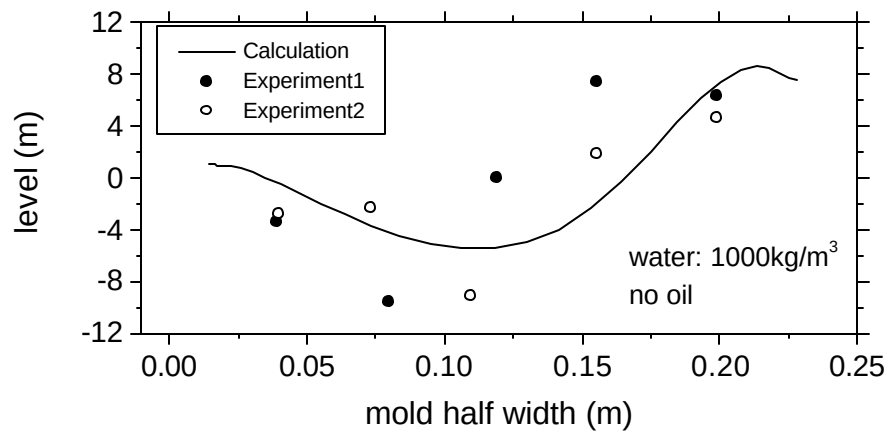


[1] J. Anagnostopoulos and G. Bergeles. Metall. Mater. Trans. B., Vol.30B, 1999, p1095-1105

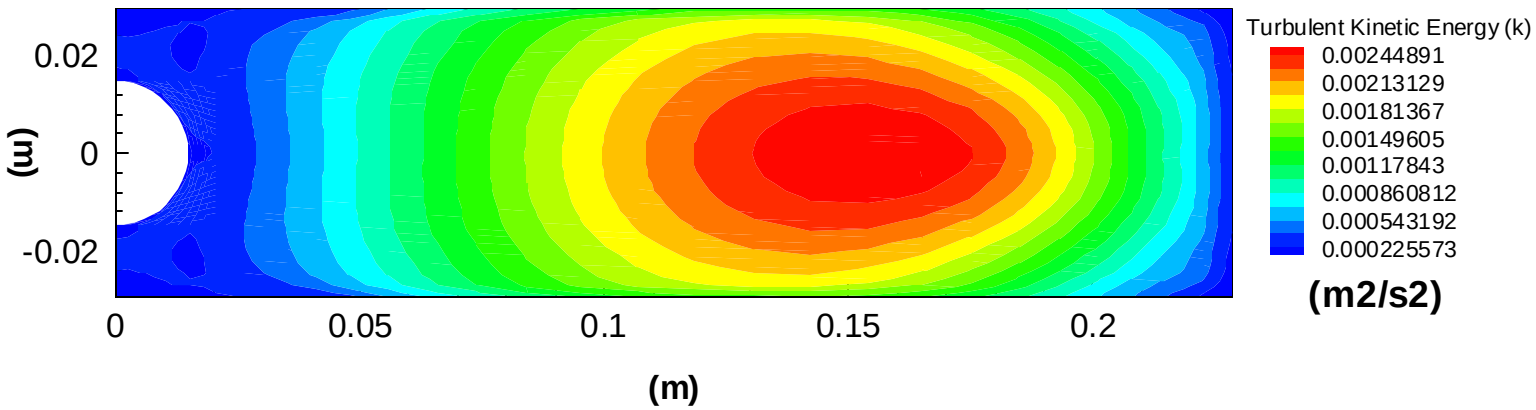
Mold Surface Level Calculated from Pressure at Center Line along Width direction on Top Surface

$$\text{Level} = \frac{2(p - p_{atm})}{(r_{water} - r_{oil})g}$$



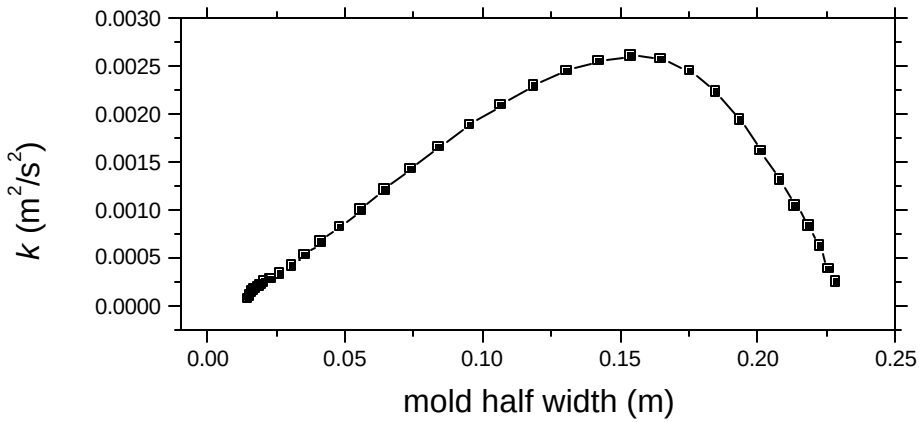


Turbulence Energy Distribution at Top Surface

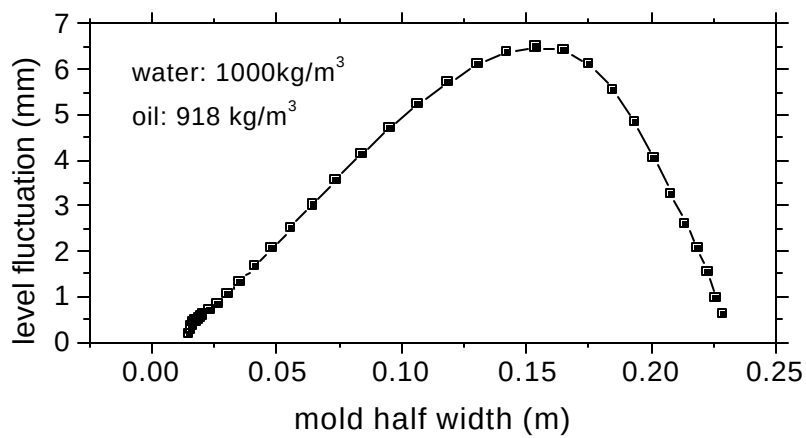


Level Fluctuation Calculated from Turbulence Energy at Center Line along Width direction on Top Surface

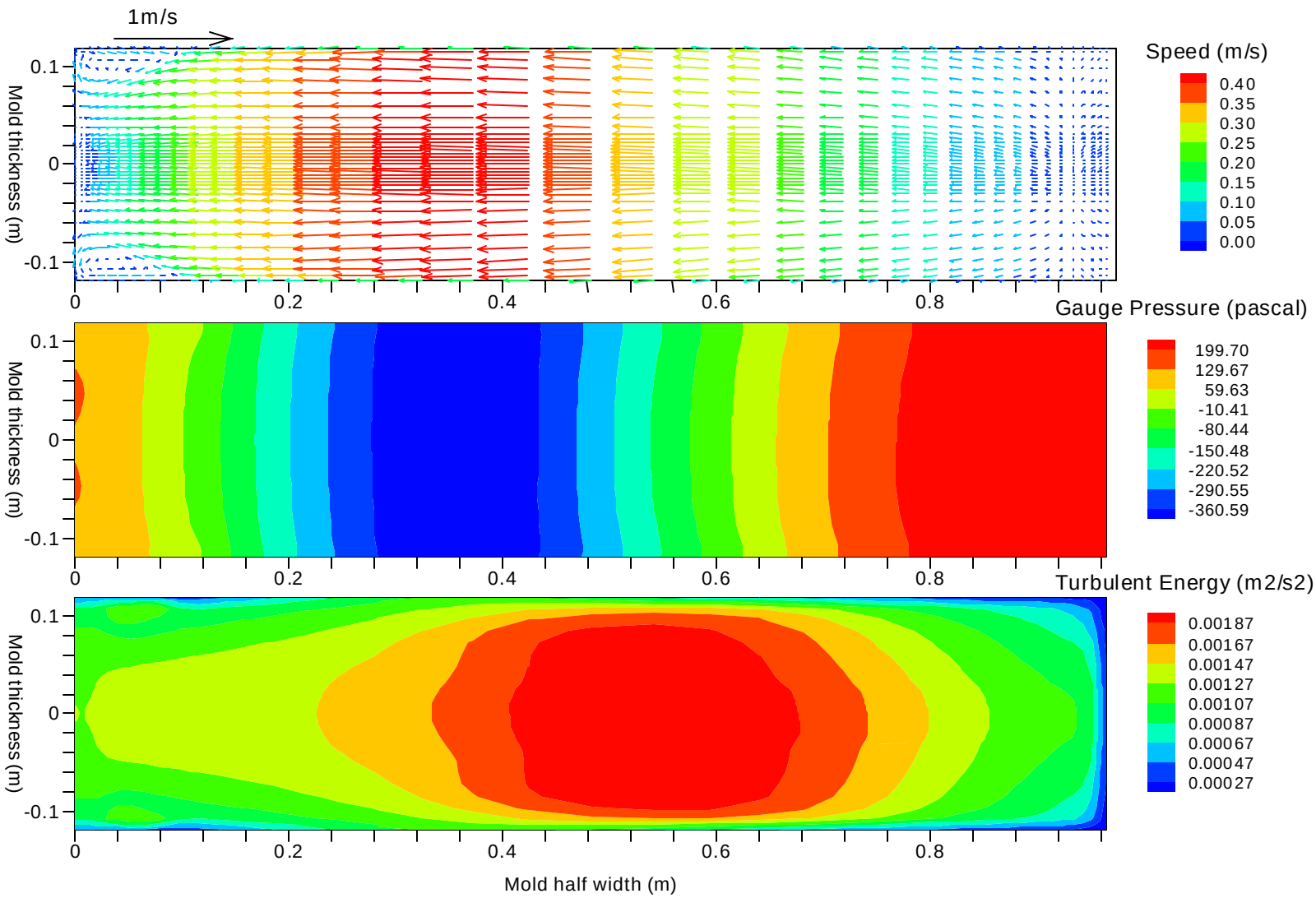
$$Level\ Fluctuation = \frac{2 r_{water} k}{(r_{water} - r_{oil}) g}$$



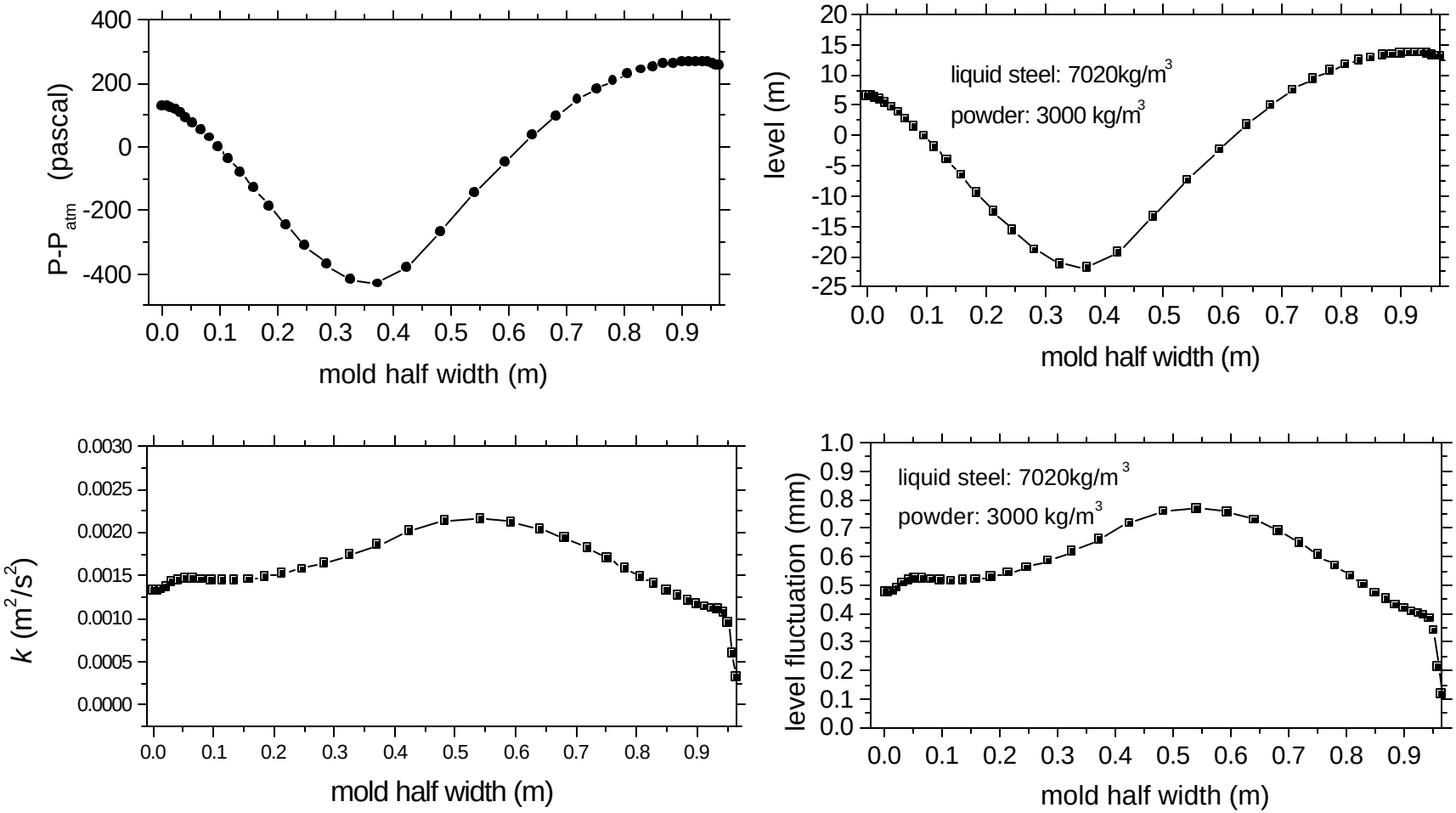
X. Huang, B.G.Thomas "Modeling Transient Flow Phenomena in Continuous Casting of Steel", in *35th Conference of Metallurgist*, 23B, C. Twigge-Molecey eds, (Montreal, Canada: CIM, 1996), 339-356



Velocity, Pressure, Turbulent Energy at Top Surface for the Former Liquid Steel System

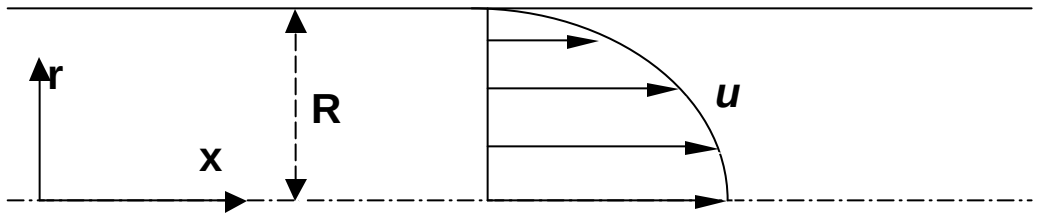


Calculated Surface Level and Its Fluctuation for the Liquid Steel System



Velocity, Turbulence Energy and Its Dissipation Rate for a Full-Developed Pipe Flow

Velocity Distribution along Radial Direction[1]



$$\frac{u}{u_{\max}} = \left(1 - \frac{r}{R}\right)^{\frac{1}{n}}$$

$$n = 2.81\,\mathrm{Re}^{0.084}$$

$$u_{x,\max} = \frac{(n+1)(2n+1)}{2n^2}\bar{u}_x$$

$$\mathrm{Re} = \frac{\bar{u}D}{n}$$

u: velocity in x axial direction

u_{max}: maximum value of u

Re: *Reynolds number*

R: radius of pipe

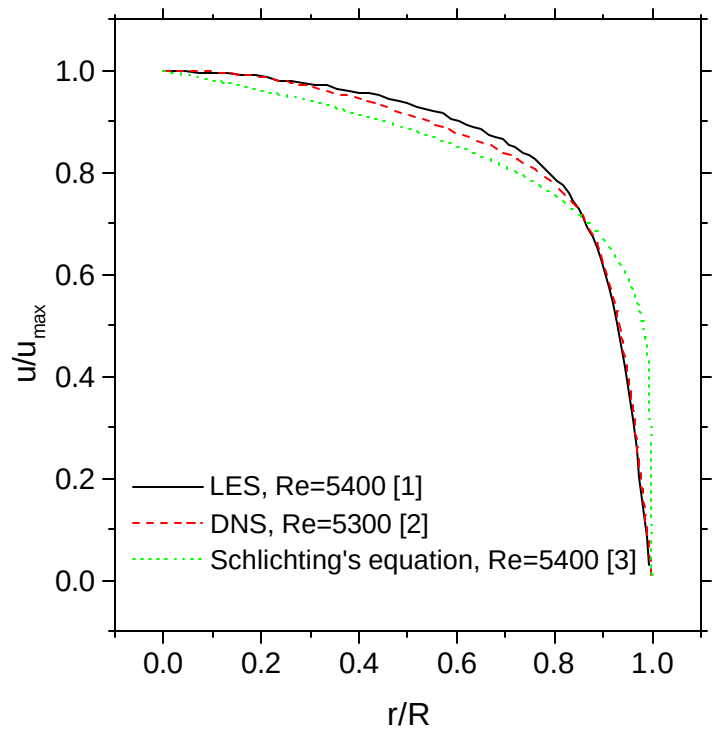
$\bar{u}$: average velocity along radial direction

n: power of velocity distribution

r: distance along radial direction

[1] H. Schlichting. Boundary-Layer Theory, 1979, 7th ed., p599

Velocity Distribution along Radial Direction



[1] Bin Zhao's LES simulation
[2] J. G. M. Eggels et al. J. Fluid Mech. (1994), Vol.268, pp175-209
[3] H. Schlichting. Boundary-Layer Theory, 1979, 7th ed., p599

Turbulence Energy and Its Dissipation along Radial Direction

$$\frac{k}{u^{*2}} = \left(\frac{u_{\max}}{u^*}\right)^2 \frac{C_m^{-1/2}}{n^2}\left(0.14 - 0.08\left(\frac{r}{R}\right)^2 - 0.06\left(\frac{r}{R}\right)^4\right)^2 \left(1 - \frac{r}{R}\right)^{\frac{2(1-n)}{n}}$$

$$\frac{e}{u^{*3}/D} = \frac{2}{n^3}\left(\frac{u_{\max}}{u^*}\right)^3 \left(0.14 - 0.08\left(\frac{r}{R}\right)^2 - 0.06\left(\frac{r}{R}\right)^4\right)^2 \left(1 - \frac{r}{R}\right)^{\frac{3(1-n)}{n}}$$

k: turbulence energy

e: turbulence energy dissipation rate

u: shear velocity at wall*

u_{max}*: maximum value of u*

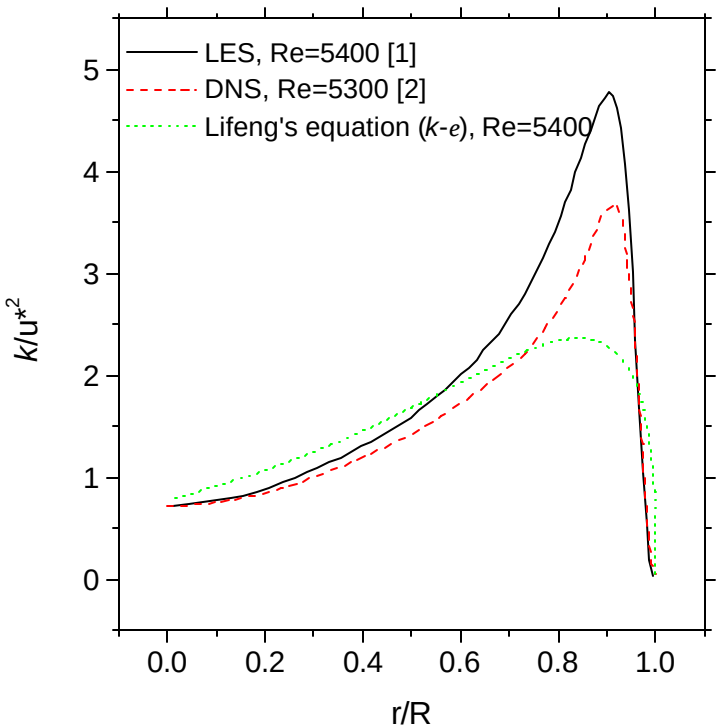
D: *diameter of pipe*

R: radius of pipe

n: power of velocity distribution

r: distance along radial direction

Turbulence Energy Distribution along Radial Direction



[1] Bin Zhao's LES simulation
[2] J. G. M. Eggels et al. J. Fluid Mech. (1994), Vol.268, pp175-209

Conclusions

1. **For the fluid flow calculation in a full scale water model, uniform inlet *k-e* underpredicts velocity peaks. With non-uniform inlet condition, all of *k-e* , RSM and LES turbulence models have good agreement with experiment measurement. However, RSM model has slightly better prediction at some places, and *k-e* model takes least time consuming.**
2. **For the particle motion, random walk model is better than streamline model because considering the effect of turbulence fluctuation.**
3. **It is concluded that entrapment of inclusions to walls has very strong effect to inclusion removal. The suitable entrapment model needs further development.**
4. **For the particle motion in full scale water model, RSM model has a best prediction of particle removal fraction compared to the experimental results. LES model overpredicts and *k-e* far underpredicts.**

Conclusions

5. **From the calculation of inclusion removal in steel caster (*k-e* , random walk and without consideration of entrapment to walls), with increasing size, inclusion removal to the top surface becomes easier. Inclusions require about 10min to leave the domain of mold region (4m), and the total removal fraction to top surface is 63%, escape fraction to open bottom is 37%. After t=270s, inclusions removal to top surface becomes less than 0.5%.**
6. **The difference of particle removal fraction in water and liquid steel shows that the Stokes rising velocity is not a reasonable criterion for matching the particle behavior in water with inclusion behavior in liquid steel.**
7. **The top surface level and its fluctuation can be approximately estimated from the calculated pressure distribution for the flat top surface.**
8. **The developed models for the velocity and turbulence energy distribution for a full-developed pipe flow agree well with LES and DNS simulation.**

Further Investigations

1. **The transient fluid flow simulation for the steel caster mold.**
2. **The suitable entrapment model of inclusion to the solidified shell.**
3. **The inclusions collision and coagulation simulation and its contribution to inclusion size growth and removal.**
4. **The interaction between inclusions and bubbles and its contribution to inclusion motion (removal) from mold.**