Argon Injection Optimization in Continuous Slab Casting

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Objectives

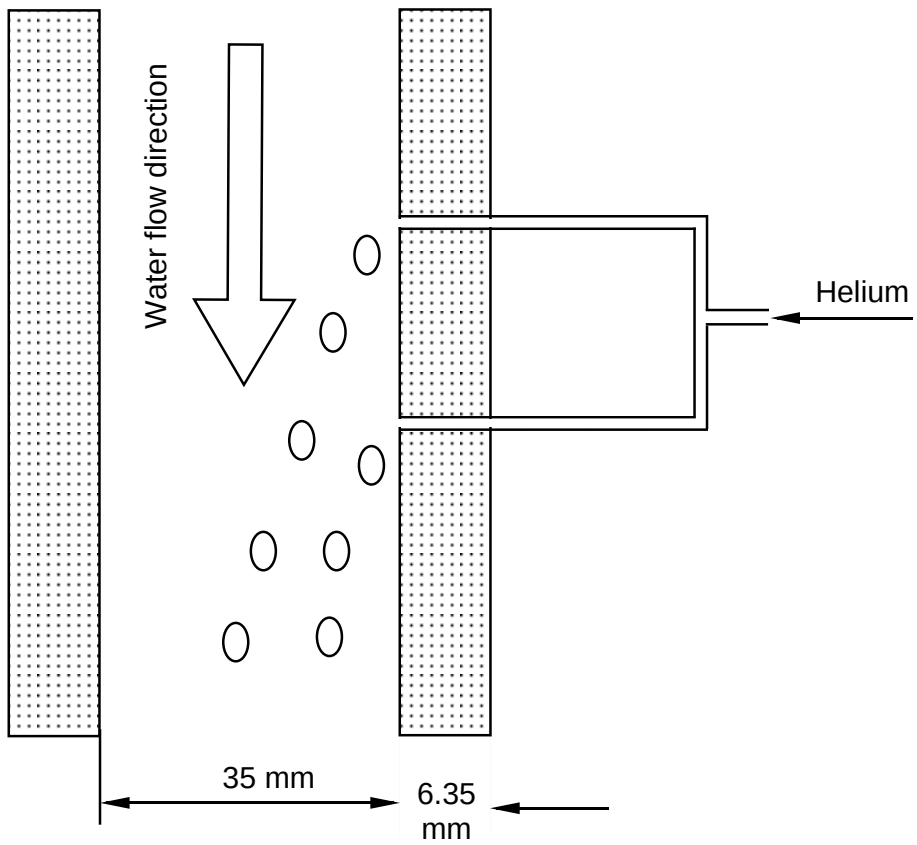
- Develop multiphase computational model to simulate the 3-D flow pattern of molten steel in the continuous casting mold with argon gas injection.

- Compare and evaluate differences between steel caster and scale water models.

- Estimate flow pattern (single roll, double roll, etc.) obtained in steel caster as a function of gas injection rate, steel throughput, mold width, and argon bubble size etc.

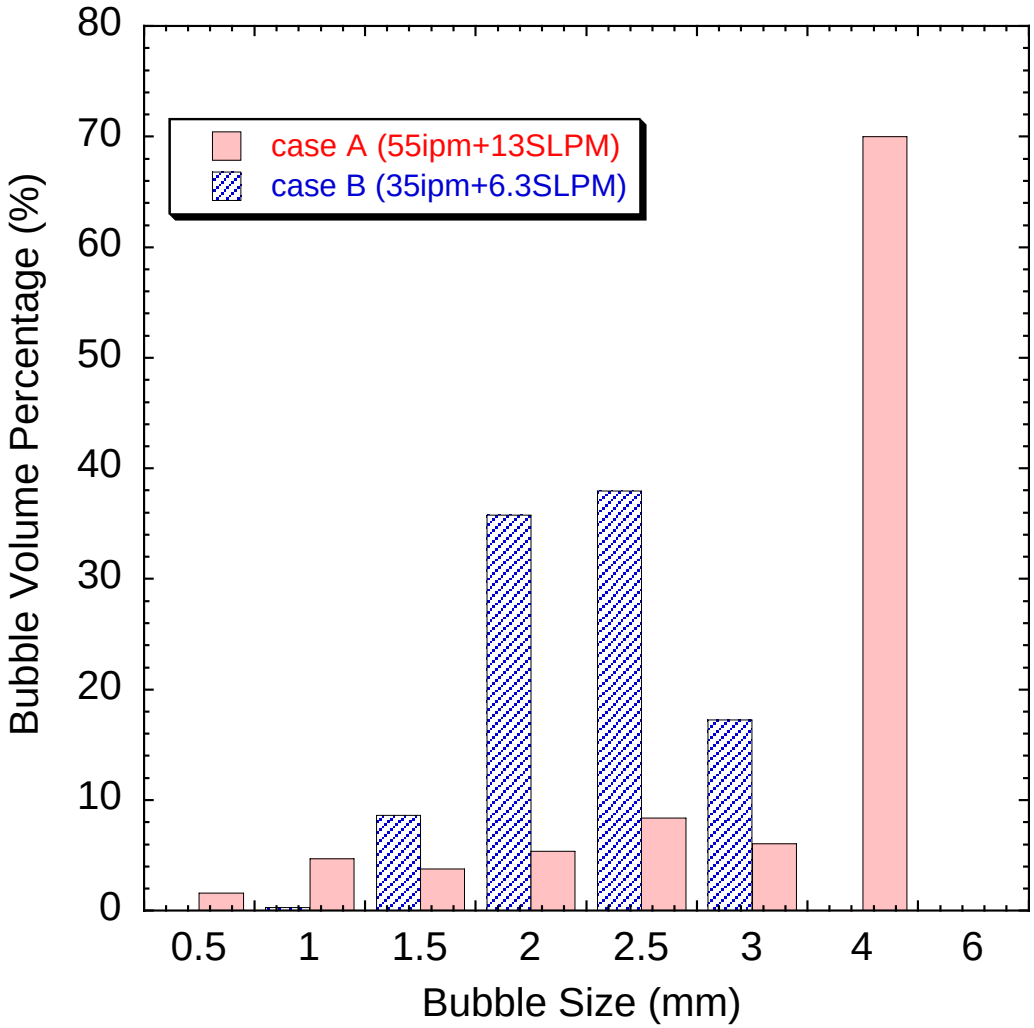
- Recommend practices related to argon gas injection optimization to improve steel product quality, especially as related to flow pattern.

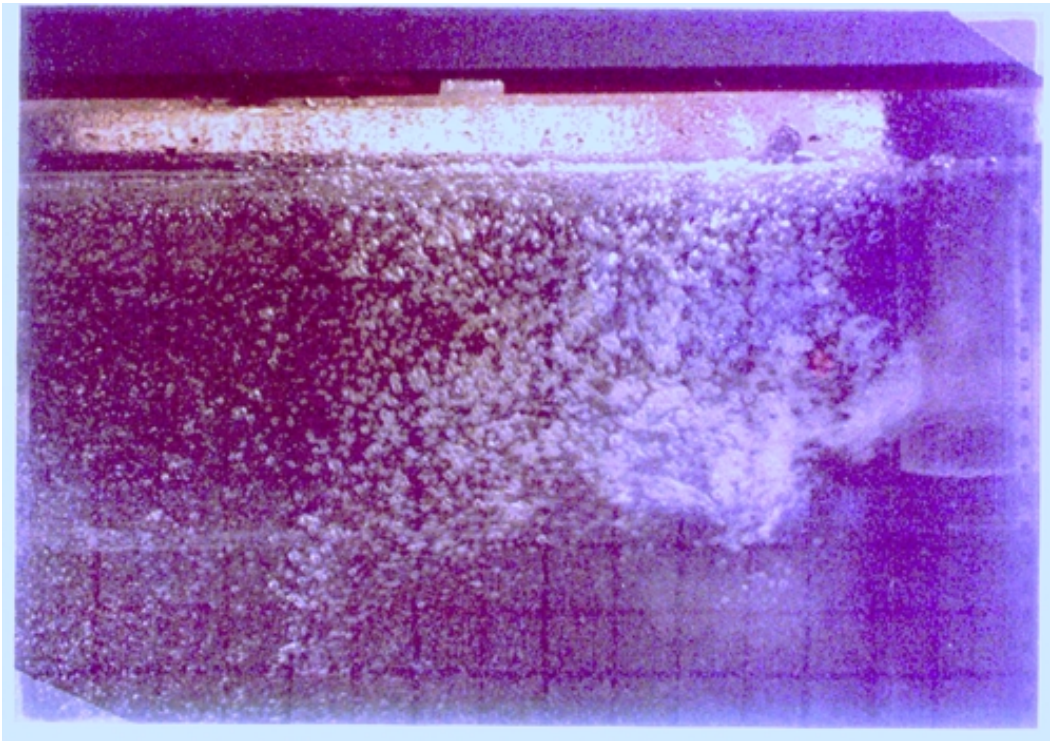
Bubble Size Investigation

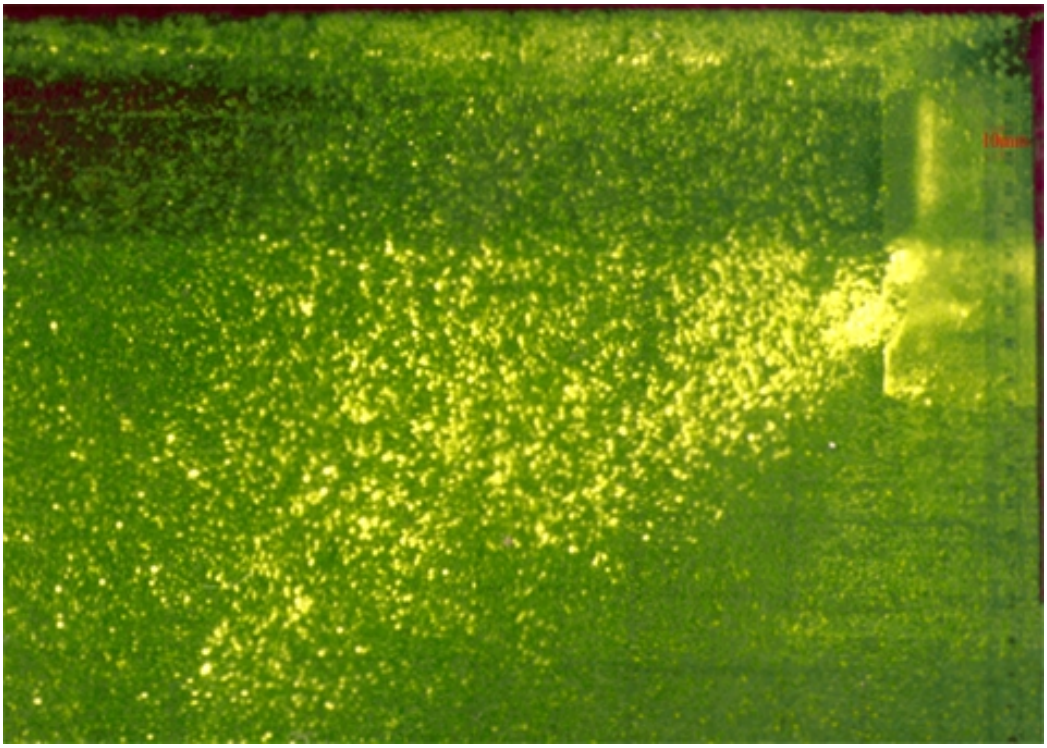


Double-needle experiment schematic

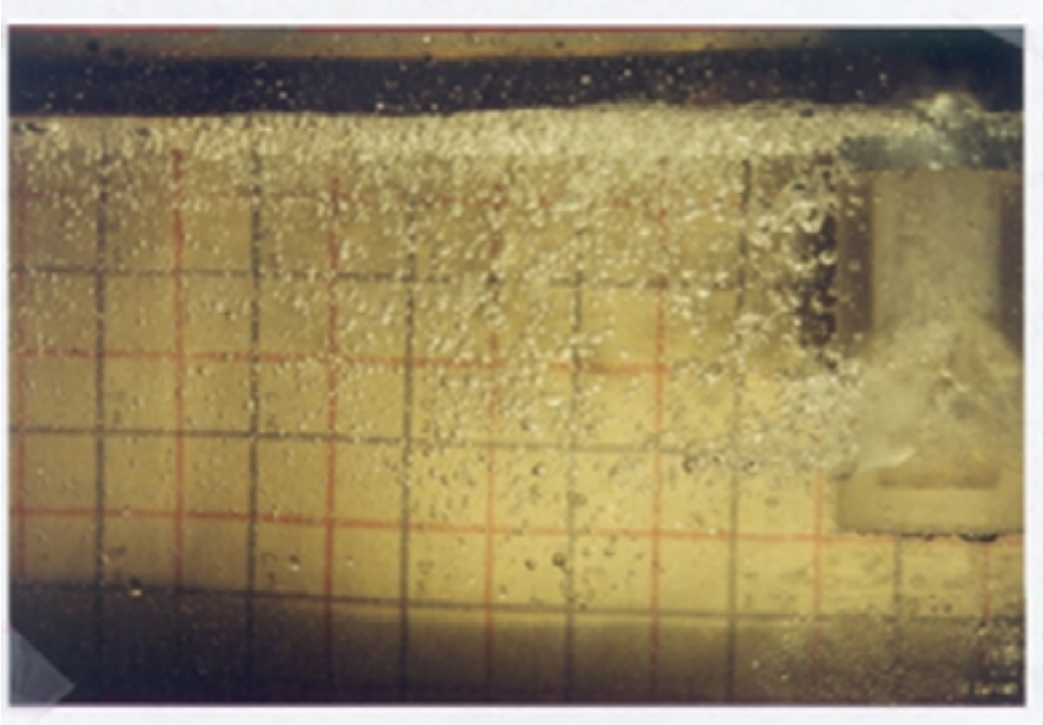
Bubble Size Investigation

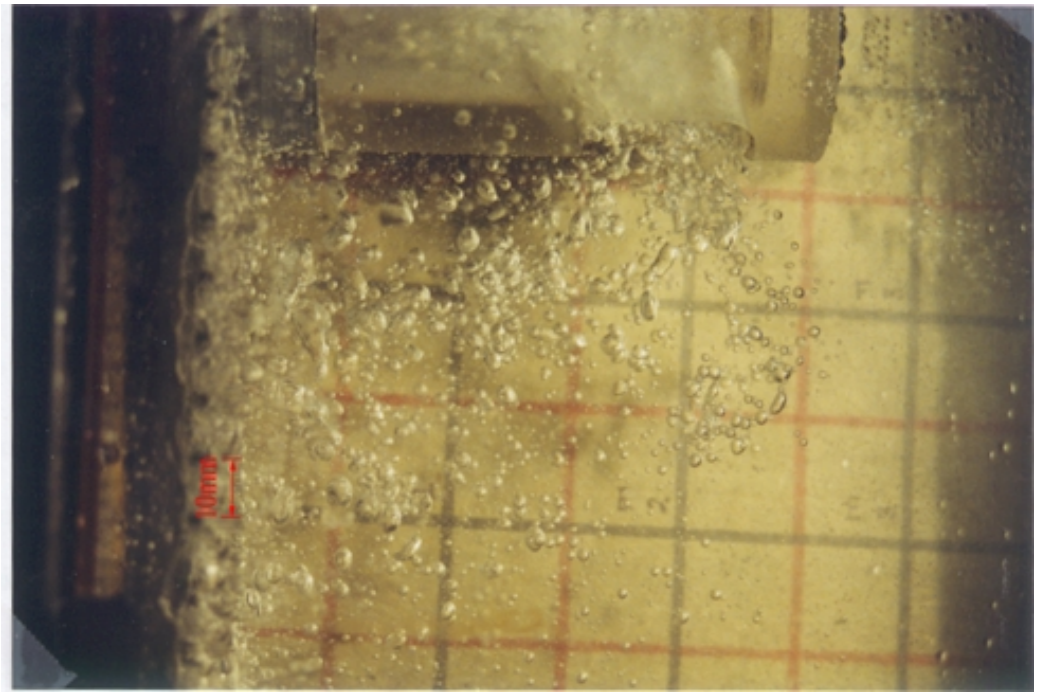






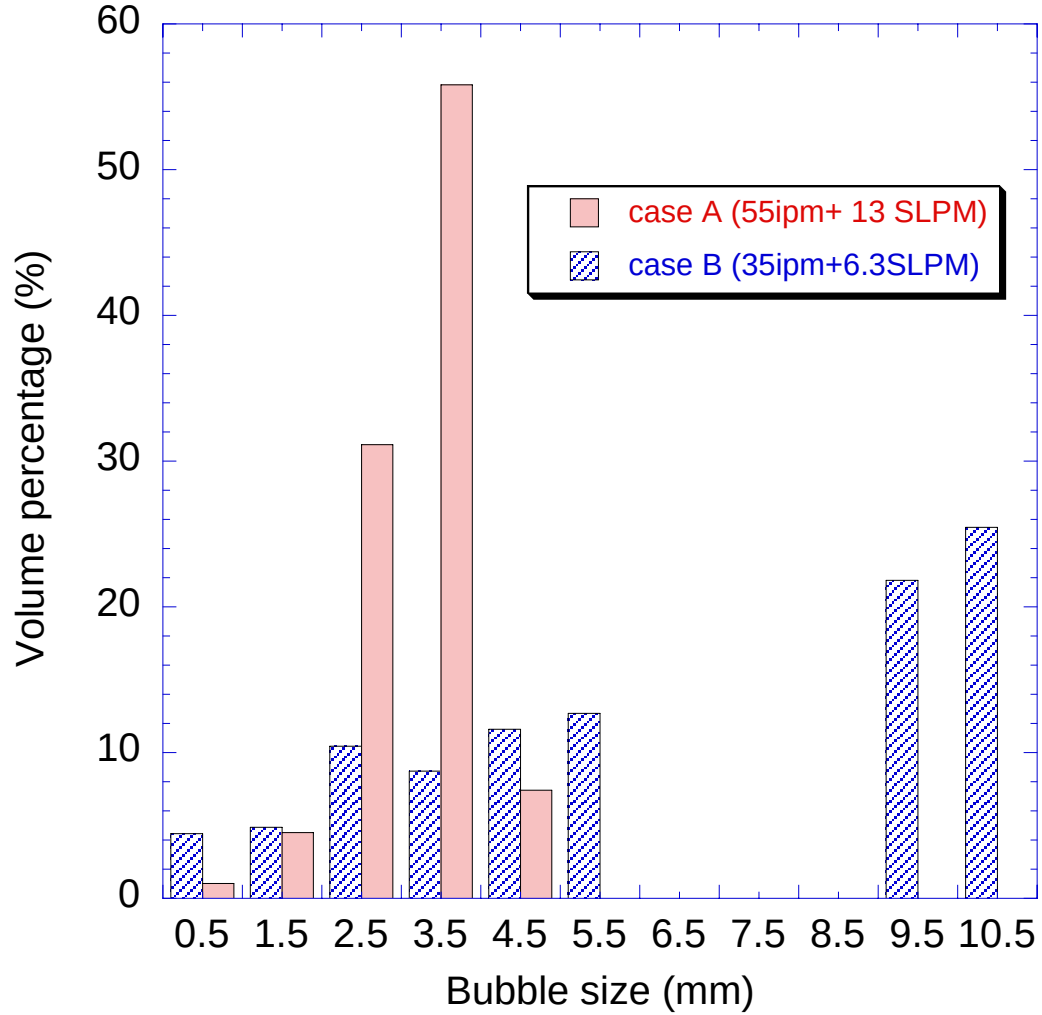
Bubble size in the water model
Case A (55ipm + 13 SLPM/ 11% hot gas)





Bubble size in the water model
Case B (35ipm + 6.3 SLPM/ 8.5% hot gas)

Bubble Size Investigation

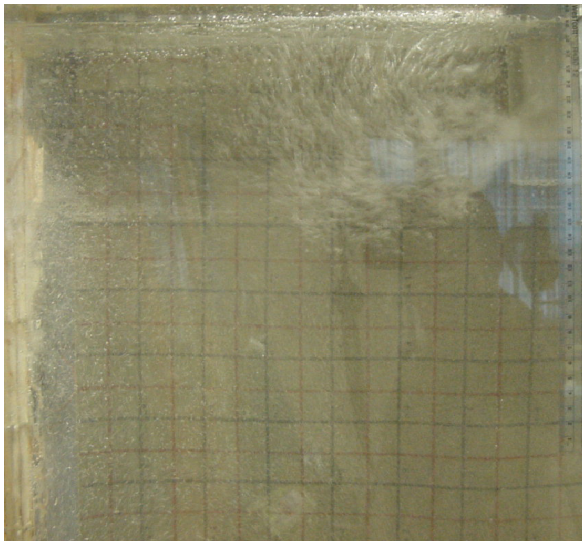


Parameters for water model for Case A (55 ipm+11% hot gas)

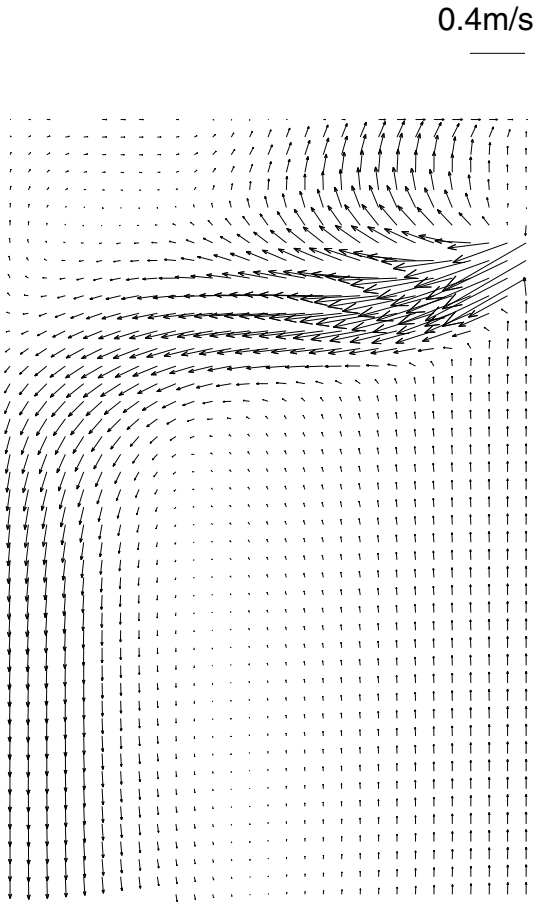
	Normal Conditions	Enlarged Slide Gate
Mold Width W (mm) x Thickness H (mm)	730 x 80	730 x 80
Mold Height (mm)	950	950
Nozzle Submergence Depth (top surface to top of port)	80	80
Nozzle Inner Diameter *(mm)*	31	31
Nozzle Port Width (mm) x Height (mm)	31 x 31	31 x 31
Jet Angle	30° down	30° down
Inlet Jet Spread Angle	0°	0°
Water Flow Rate Q_w *(SLPM)*	58.59 (15.5 GPM)	76.06 (20.1 GPM)
Equivalent Steel Casting Speed (ipm) $V_c = \frac{Q_w}{0.4 \times W \times 0.4 \times H \times \sqrt{0.4}}$	54.03	70.14
Gas Flow Rate *(SLPM, hot volume)*	7.43 (15.8 SCFH)	7.43 (15.8 SCFH)
Gas Volume Fraction (%)	11.3	8.9
Inlet Velocity, V_x *(m/s)*	0.571	0.724
Inlet Velocity, V_z *(m/s)*	0.330	0.418
Inlet Turbulent Kinetic Energy, K_o *(m^2/s^2)*	0.044	0.044
Inlet Turbulence Dissipation Rate, ε_o *(m^2/s^3)*	0.999	0.999
Water Density *(kg/m^3)*	1000	1000
Water Viscosity *(m^2/s)*	1×10^{-3}	1×10^{-3}
Gas Density *(kg/m^3)*	1.20	1.20
Gas Viscosity *(m^2/s)*	1.7×10^{-5}	1.7×10^{-5}
Average Bubble Diameter *(mm)*	2.590	2.590
Volume Fraction of 0.5 mm Bubble (%)	1.07	1.07
Volume Fraction of 1.5 mm Bubble (%)	4.53	4.53
Volume Fraction of 2.5 mm Bubble (%)	31.15	31.15
Volume Fraction of 3.5 mm Bubble (%)	55.83	55.83
Volume Fraction of 4.5 mm Bubble (%)	7.42	7.42
Breakup Coefficient	0.5	0.5
Coalescence Coefficient	0	0

Parameter for water model for Case B (35 ipm+8.5% hot gas)

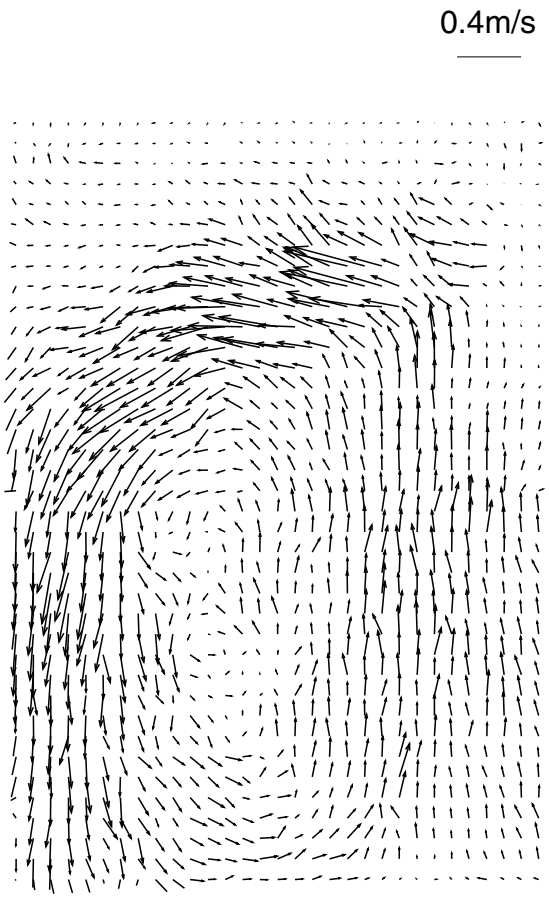
	Normal Conditions	Enlarged Slide Gate
Mold Width W (mm) x Thickness H (mm)	730 x 80	730 x 80
Mold Height *(mm)*	950	950
Nozzle Submergence Depth	80	80
Nozzle Inner Diameter *(mm)*	31	31
Nozzle Port Width (mm) x Height (mm)	31 x 31	31 x 31
Water Flow Rate *(SLPM)*	37.80 (10.0 GPM)	43.64 (11.54 GPM)
Equivalent Steel Casting Speed (ipm) $V_c = \frac{Q_w}{0.4 \times W \times 0.4 \times H \times \sqrt{0.4}}$	34.86	40.24
Gas Flow Rate *(SLPM, hot volume)*	3.71 (7.9 SCFH)	3.71 (7.9 SCFH)
Gas Volume Fraction (%)	8.9	7.8
Inlet Velocity, V_x *(m/s)*	0.358	0.410
Inlet Velocity, V_z*(m/s)*	0.207	0.237
Inlet Turbulent Kinetic Energy *(m^2/s^2)*	0.044	0.044
Inlet Turbulence Dissipation Rate *(m^2/s^3)*	0.999	0.999
Water Density *(kg/m^3)*	1000	1000
Water Viscosity *(m^2/s)*	1×10^{-3}	1×10^{-3}
Gas Density *(kg/m^3)*	1.20	1.20
Gas Viscosity *(m^2/s)*	1.7×10^{-5}	1.7×10^{-5}
Jet Angle	30° down	30° down
Inlet Jet Spread Angle	0°	0°
Average Bubble Diameter *(mm)*	2.43	2.43
Volume Fraction of 0.5 mm Bubble (%)	4.43	4.43
Volume Fraction of 1.5 mm Bubble (%)	4.90	4.90
Volume Fraction of 2.5 mm Bubble (%)	10.34	10.34
Volume Fraction of 3.5 mm Bubble (%)	8.73	8.73
Volume Fraction of 4.5 mm Bubble (%)	11.60	11.60
Volume Fraction of 5.5 mm Bubble (%)	12.71	12.71
Volume Fraction of 6.5 mm Bubble (%)	0	0
Volume Fraction of 7.5 mm Bubble (%)	0	0
Volume Fraction of 8.5 mm Bubble (%)	0	0
Volume Fraction of 9.5 mm Bubble (%)	21.83	21.83
Volume Fraction of 10.5 mm Bubble (%)	25.46	25.46
Breakup Coefficient	0.1	0.1
Coalescence Coefficient	0	0



Flow Picture of Water Model



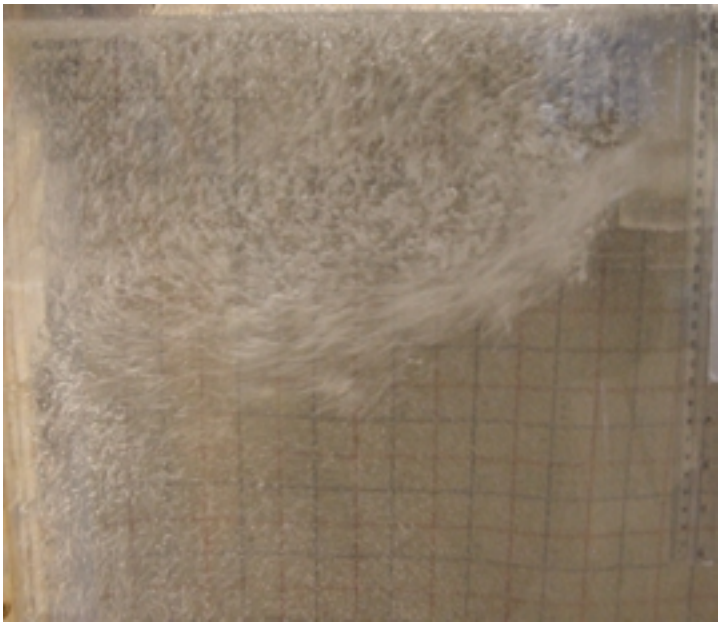
Simulation Result



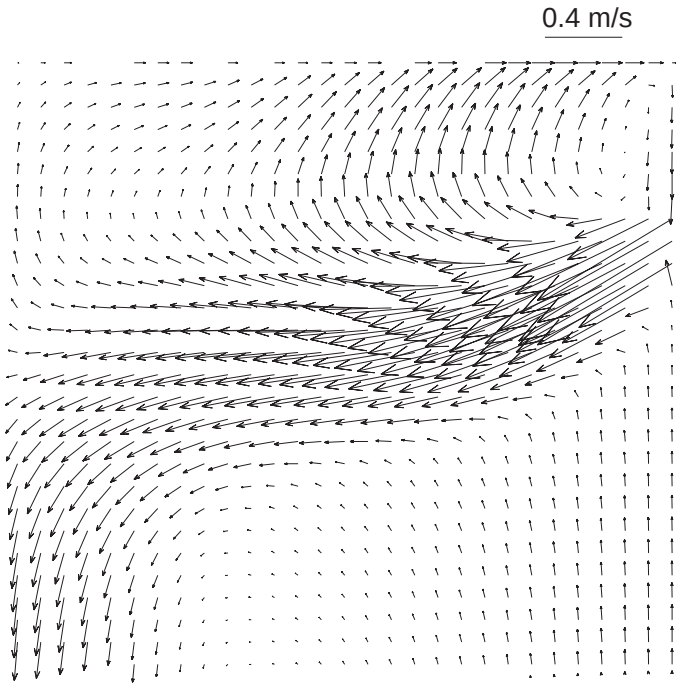
PIV Mesurements

Comparison of Velocity at centerplane between PIV measurements, simulation and eyeview

(55 ipm+13SLPM/11% hot gas)



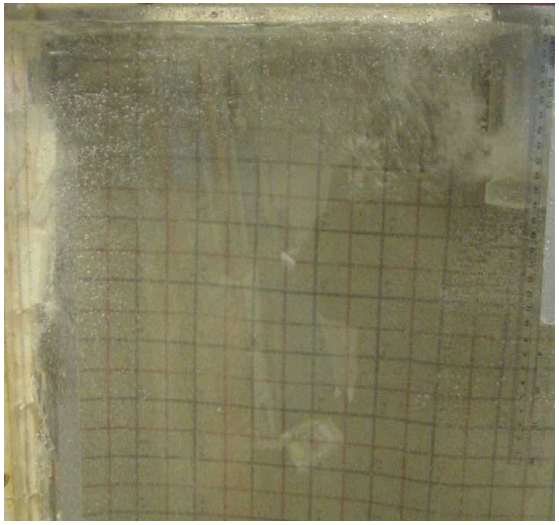
Flow Picture of Water Model (55ipm +11% gas)



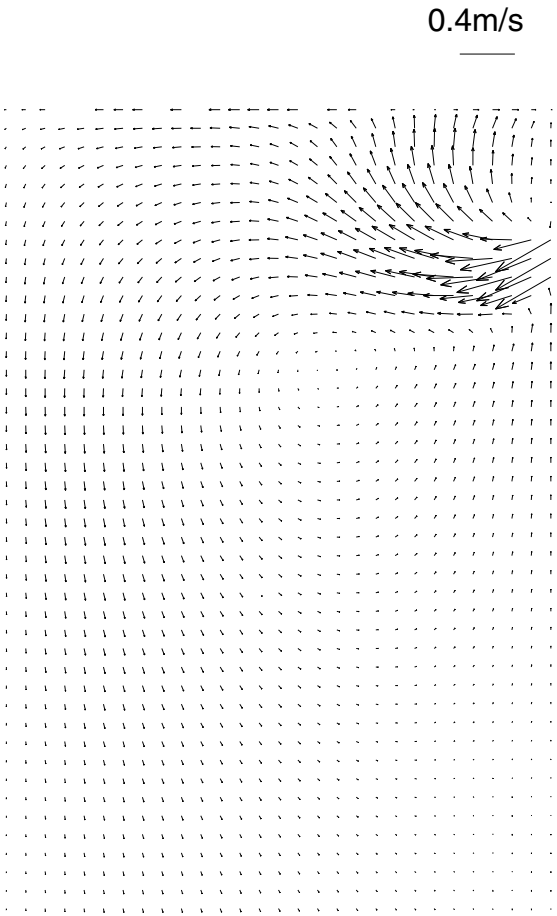
Liquid Velocity Vectors of Modeling (55ipm+11%gas)

Comparison of simulation and eyeviews
while adjusting liquid level with 15% increase in flow rate

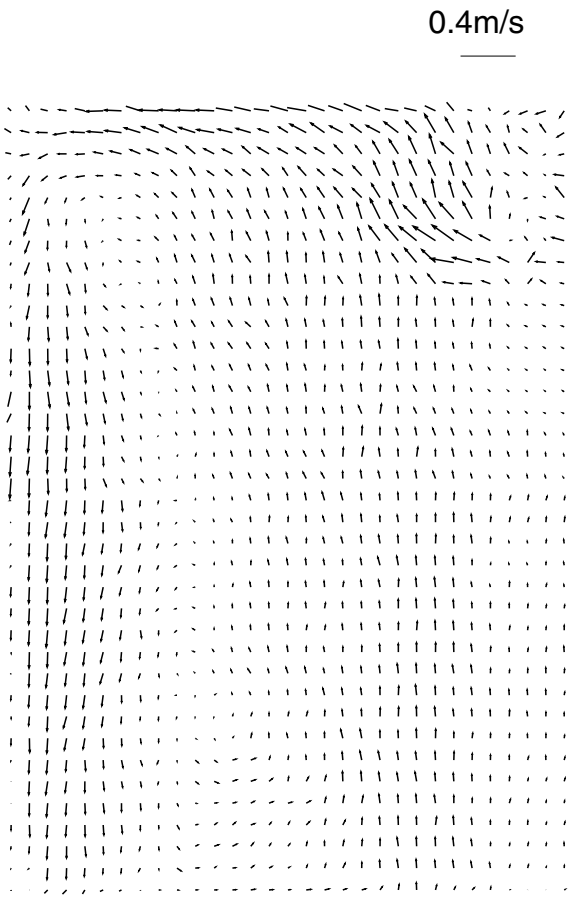
Case A (55 ipm + 13 SLPM/11% hot gas)



Flow Picture of Water Model



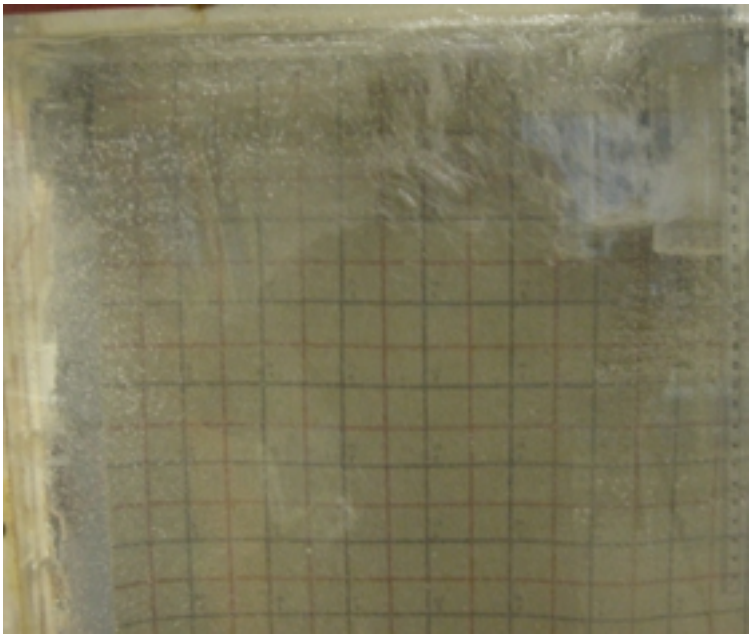
Simulation Result



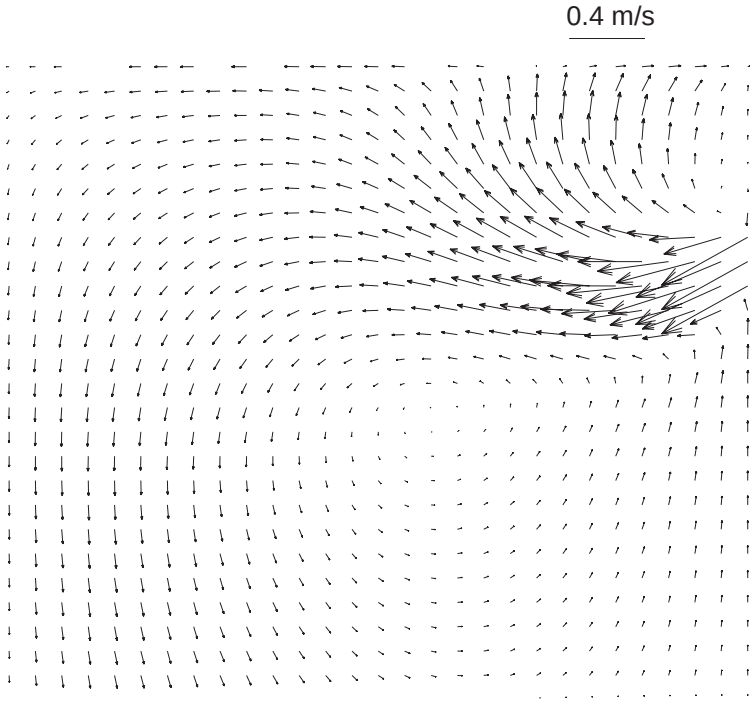
PIV Mesurements

Comparison of velocity at centerplane between PIV measurements, simulation and eyeview

(35 ipm+6.5SLPM/8.5% hot gas)



Flow Picture of Water Model (35ipm +8.5% gas)



Liquid Velocity Vectors of Modeling (35ipm+8.5%gas)

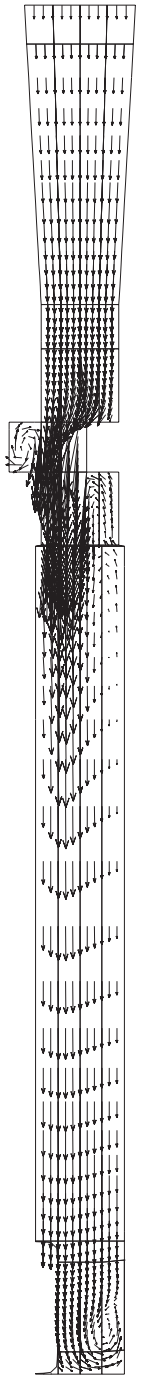
Comparison of simulation and eyeviews
while adjusting liquid level with 15% increase in flow rate

Case B (35 ipm + 6.3 SLPM/8.5% hot gas)

Parameters in the real caster modeling

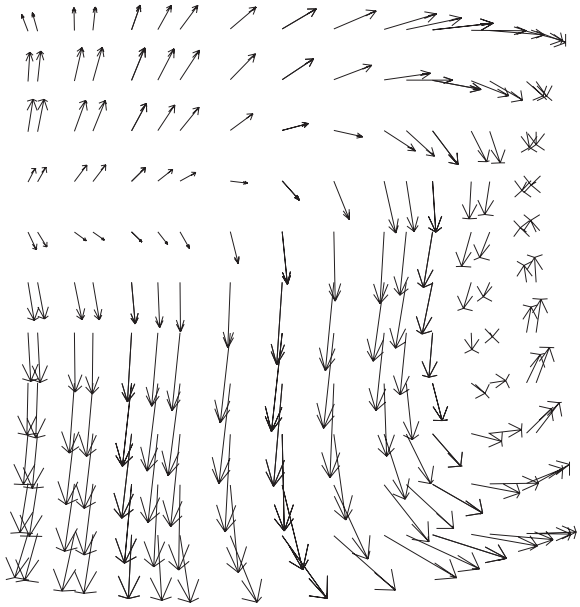
	Case A (13 SLPM, 55 ipm)	Case B (6.3SLPM /13SLPM, 35 ipm)
Mold Width	1854 *mm*	
Mold Thickness	228 *mm*	
Nozzle Submergence Depth (top surface to top of port)	165 *mm*	
Nozzle Bore Inner Diameter	78 *mm*	
Nozzle Port Height	78 *mm*	
Nozzle Port Width	78*mm*	
Vertical Velocity in Nozzle	2.05 *m/s*	1.31 *m/s*
Nominal Vertical Angle of Port Edges	15° down	
Inlet Jet Spread Angle	0°	
Casting Speed, V_c	23.2 *mm/s*	14.8 *mm/s*
Liquid Steel Density, ρ_l	7020 kg/m^3	
Gas Density, ρ_{gas}	0.27 kg/m^3	
Steel Laminar (Molecular) Viscosity, μ_o	0.00560 *kg/m s*	
Gas Vescosity, μ_{gas}	7.42E-5	
Surface Tension Coeff. (Steel-Argon)	1.192 *N/m*	
Inlet steel flow rate	0.584 m^3/min	0.376 m^3/min
Throughput (ton/min)	4.10	2.64
Inlet Gas Flow Rate	13 *SLPM*	6.3*SLPM* /13 *SLPM*
Inlet Gas Volume Fraction, f_{gas}	11%	8.5%
Average Gas Bubble Diameter, D_o	2.59 *mm*	2.43 mm
Gravitational Acceleration, g	9.8 m/s^2	

*Blank in second column is the same as the first column.

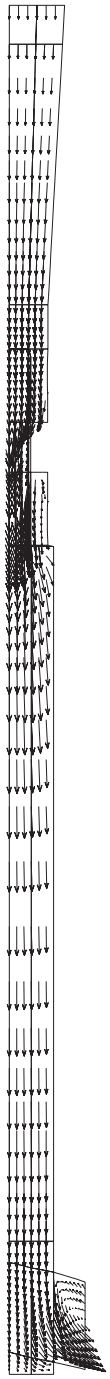


Conditions:

55 ipm
13 SLPM
Gate open 58%



Velocity at SEN port



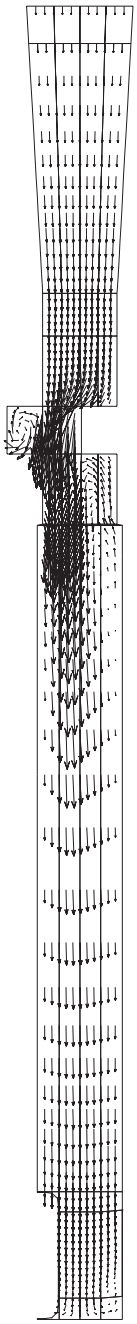
Centerplane parallel to SEN port

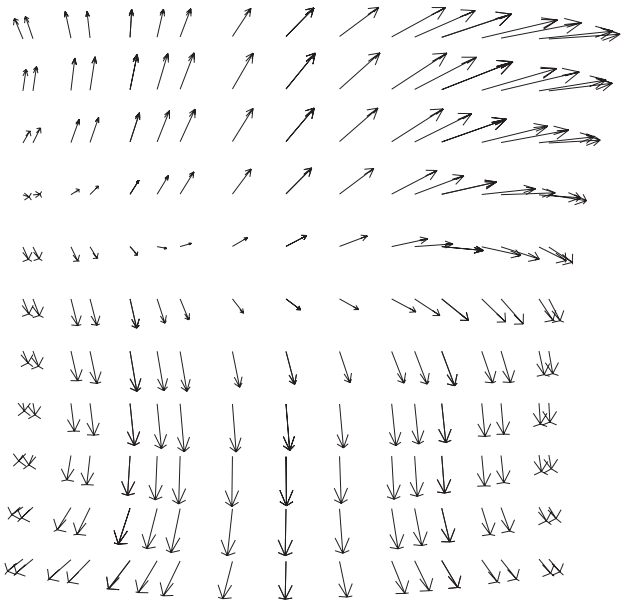
Centerplane perpendicular to SEN port

Liquid velocity in the nozzle (Case A)

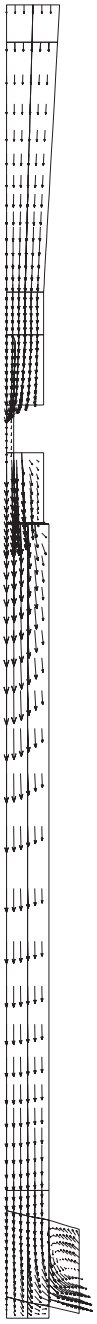
Conditions:

35 ipm
13 SLPM
Gate open 50%





Velocity at SEN port



Centerplane parallel to SEN port

Centerplane perpendicular to SEN port

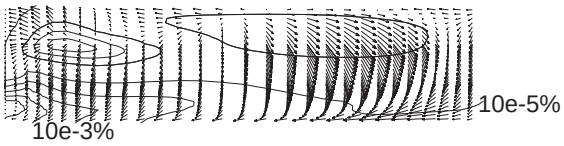
Liquid velocity in the nozzle (Case B)

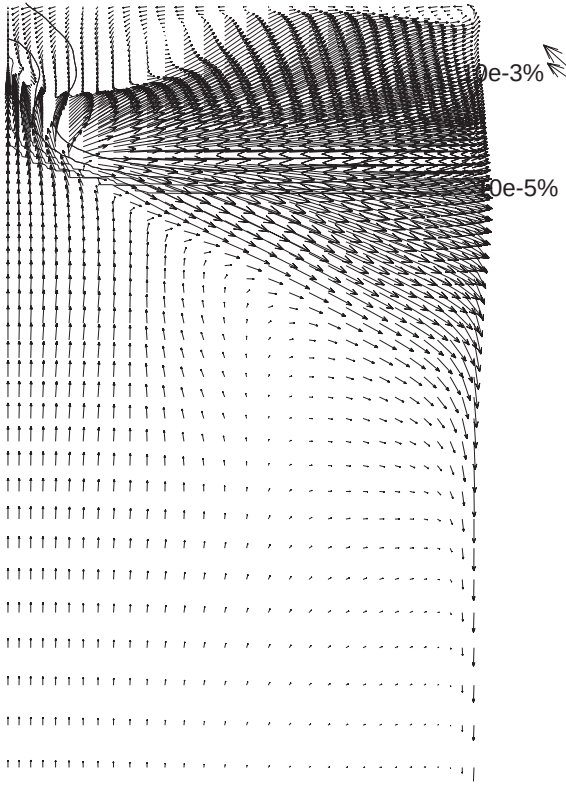
Casting conditions:

73" slab
55 ipm
13 SLPM
11% Gas (hot)

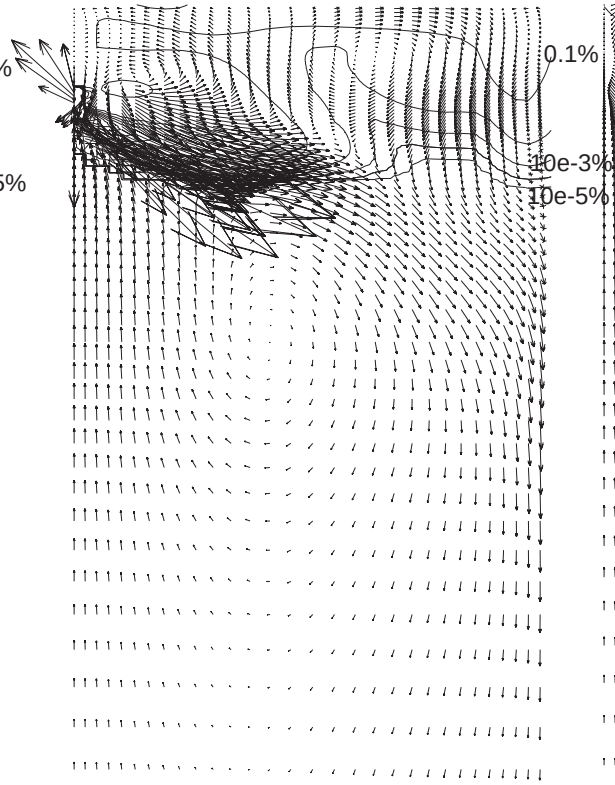
1m/s

10 mm below Meniscus

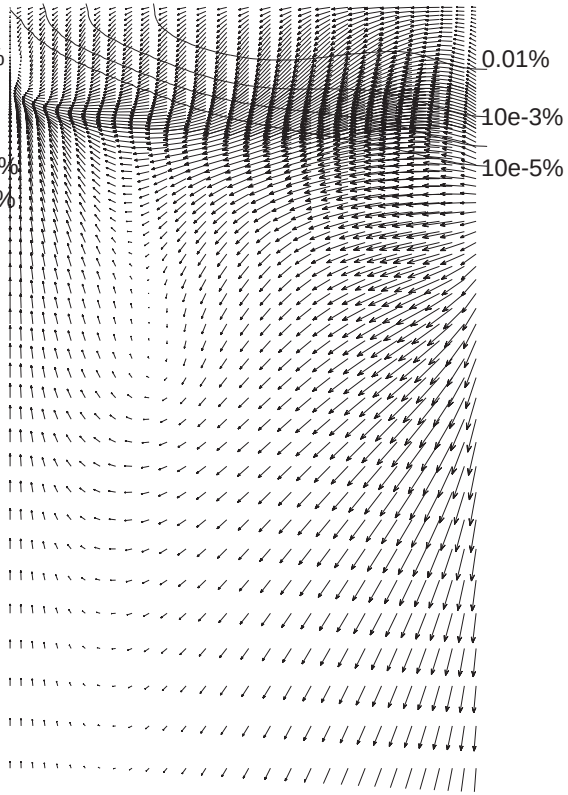




10 mm from Inner Wide Face



Centerplane between Wide Faces

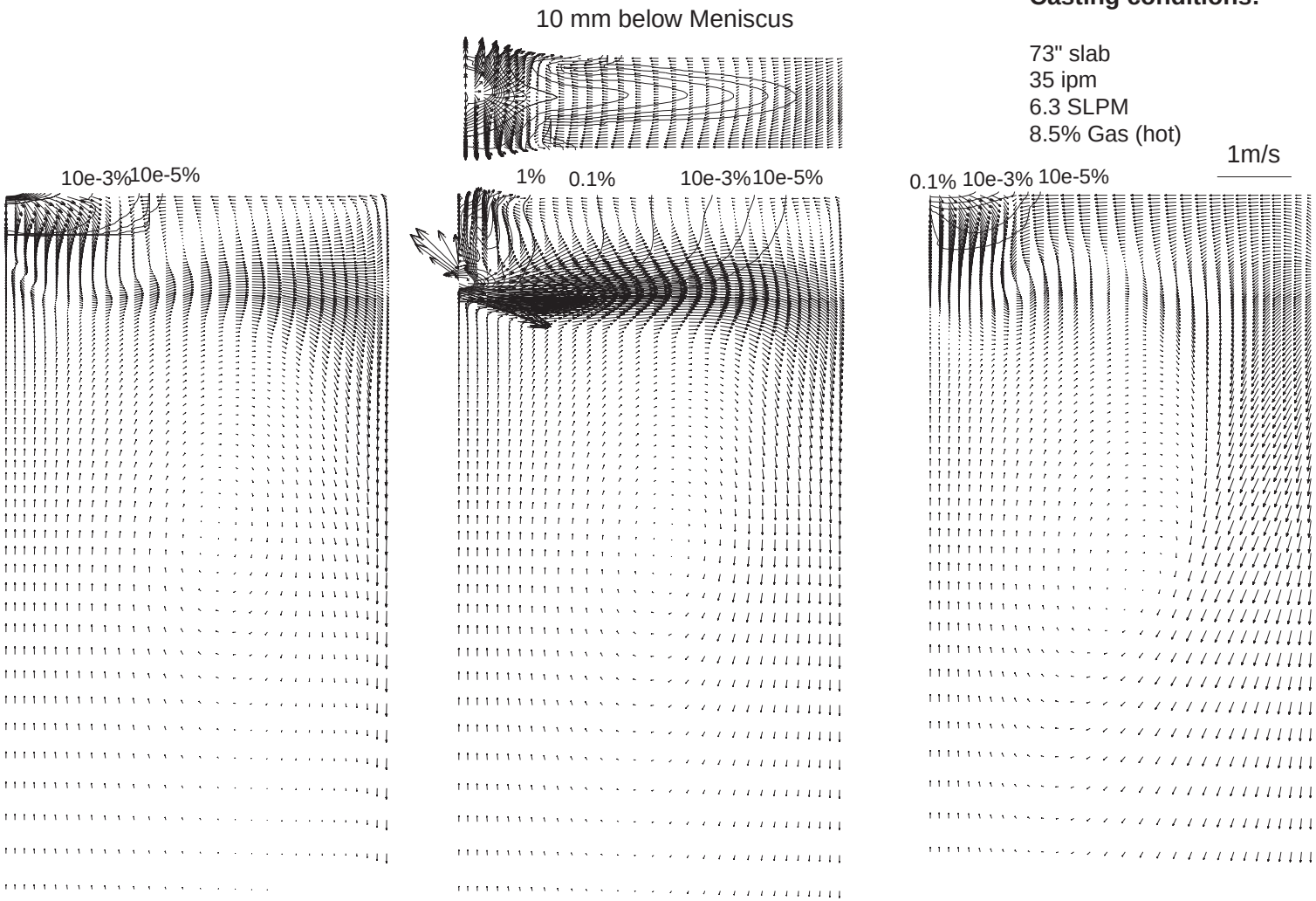


10 mm from Outer Wide Face

Steel flow pattern calculated using CFX with distributed bubble size (2.59mm mean)

Casting conditions:

73" slab
35 ipm
6.3 SLPM
8.5% Gas (hot)



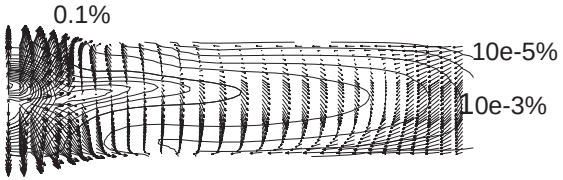
10 mm from Inner Wide Face

Centerplane between Wide Faces

10 mm from Outer Wide Face

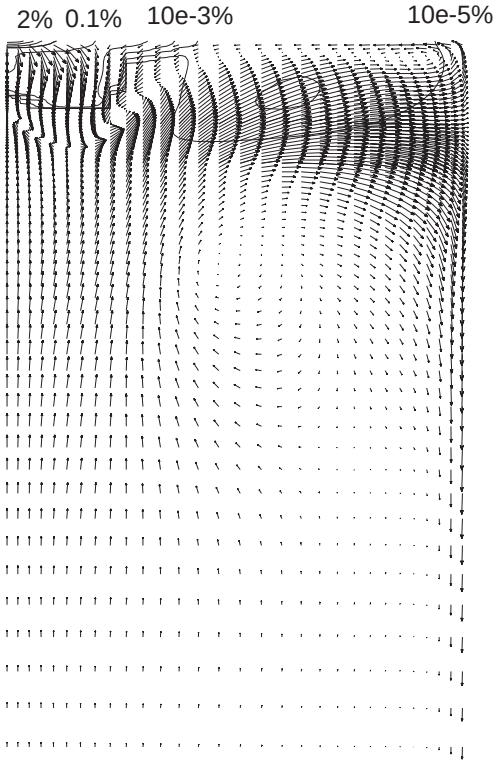
Steel flow pattern calculated using CFX with distributed bubble size(2.43 mm mean)

10 mm below Meniscus

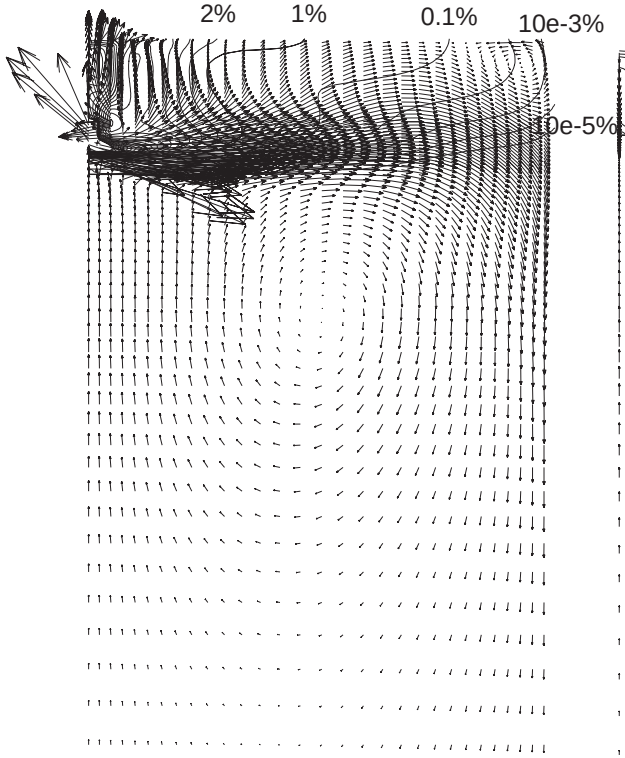


Casting conditions:

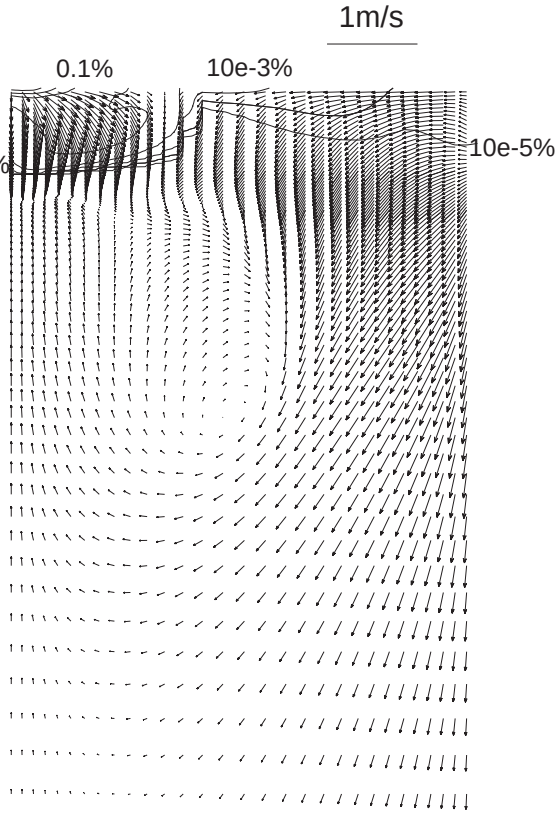
73" slab
35 ipm
13 SLPM
16.4% Gas (hot)



10 mm from InnerWide Face



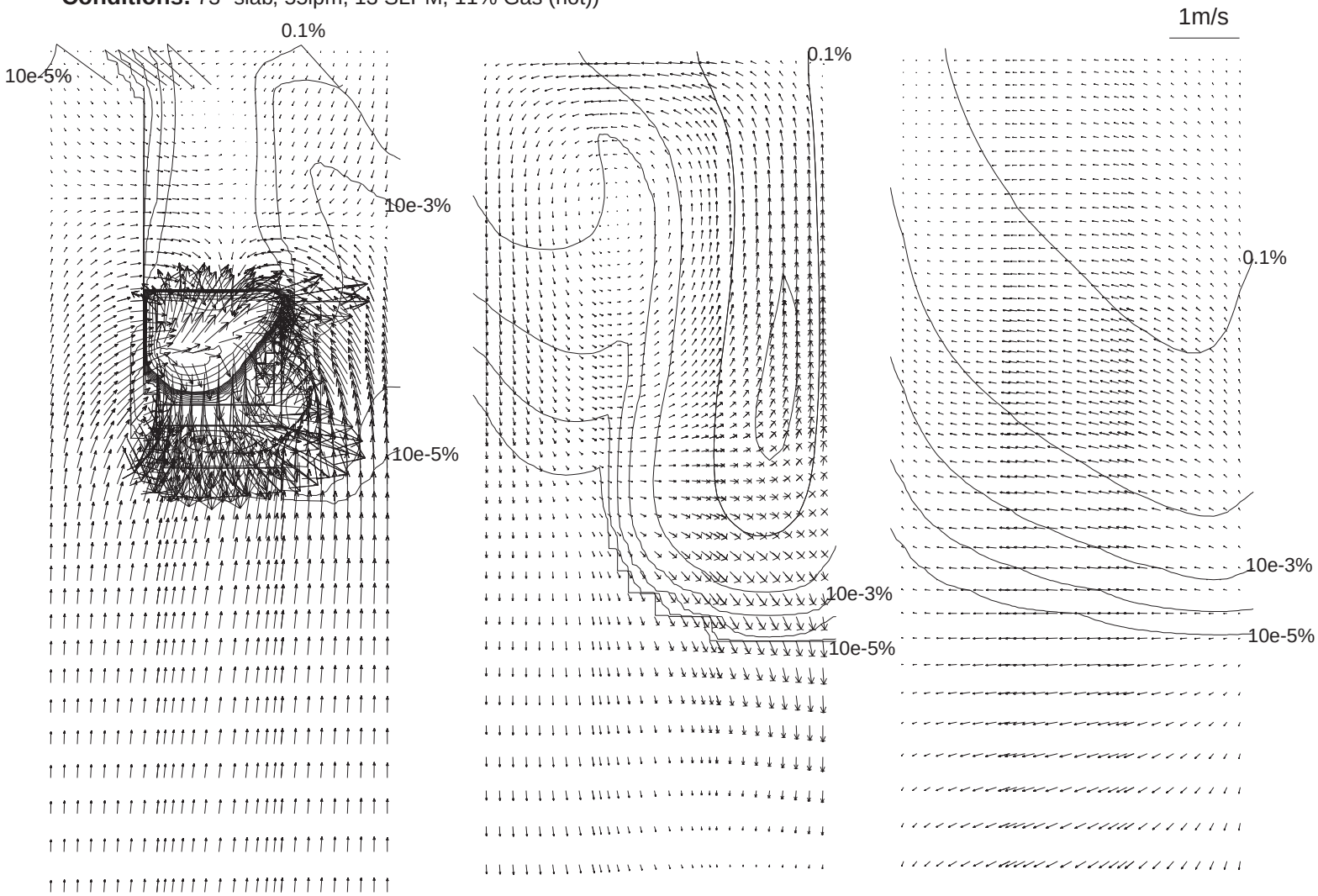
Centerplane between Wide Faces



10 mm from Outer Wide Face

Steel Flow pattern calculated using CFX with distributed bubble size(2.43 mm mean)

Conditions: 73" slab, 55ipm, 13 SLPM, 11% Gas (hot))



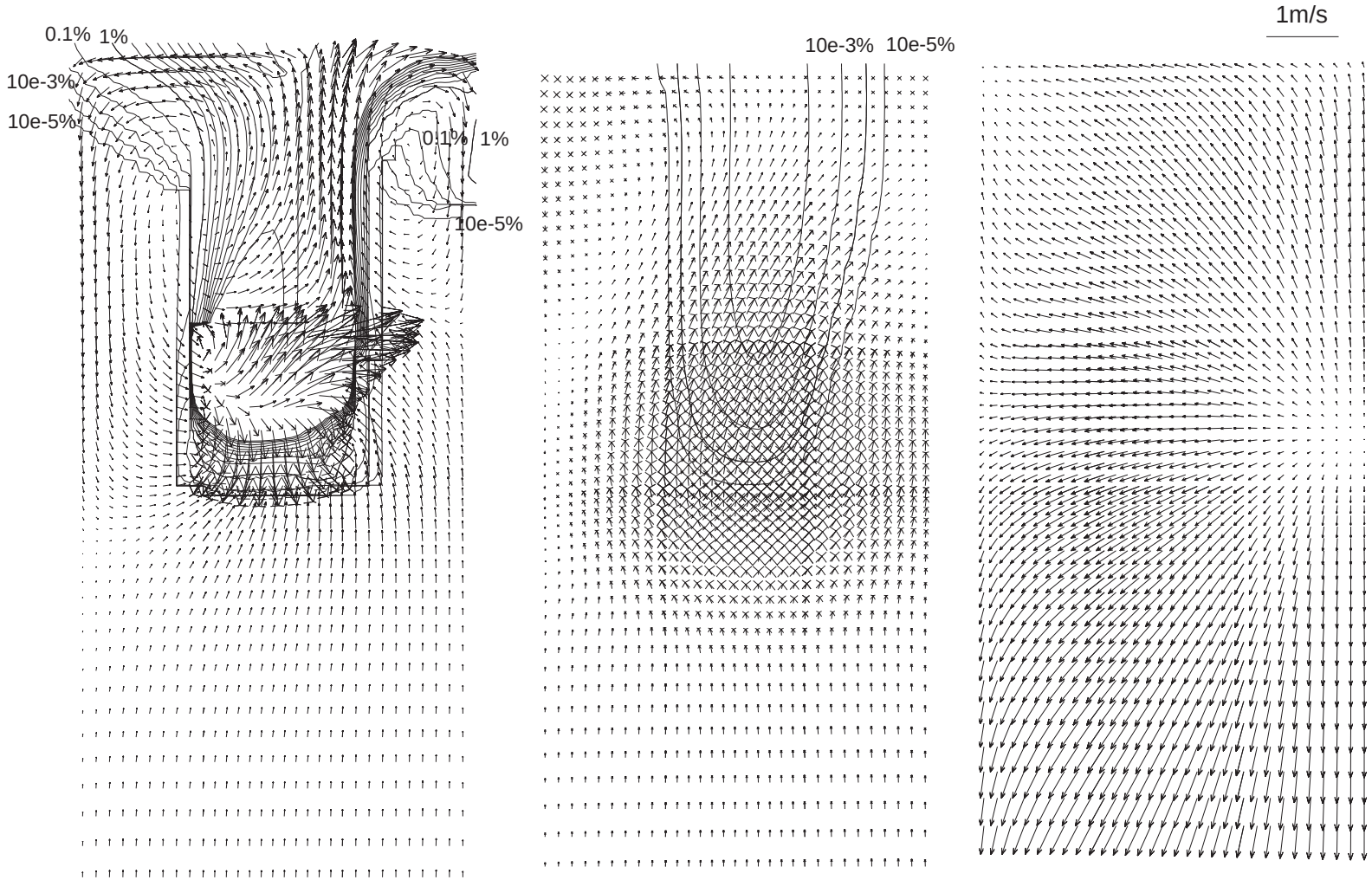
Slice at SEN Port

Centerplane betwen SEN and NF

10 mm from Narrow Face

Steel flow pattern calculated using CFX with distributed bobble size(2.59 mm mean)

Conditions: 73" slab, 35ipm, 6.3 SLPM, 8.5% Gas (hot))



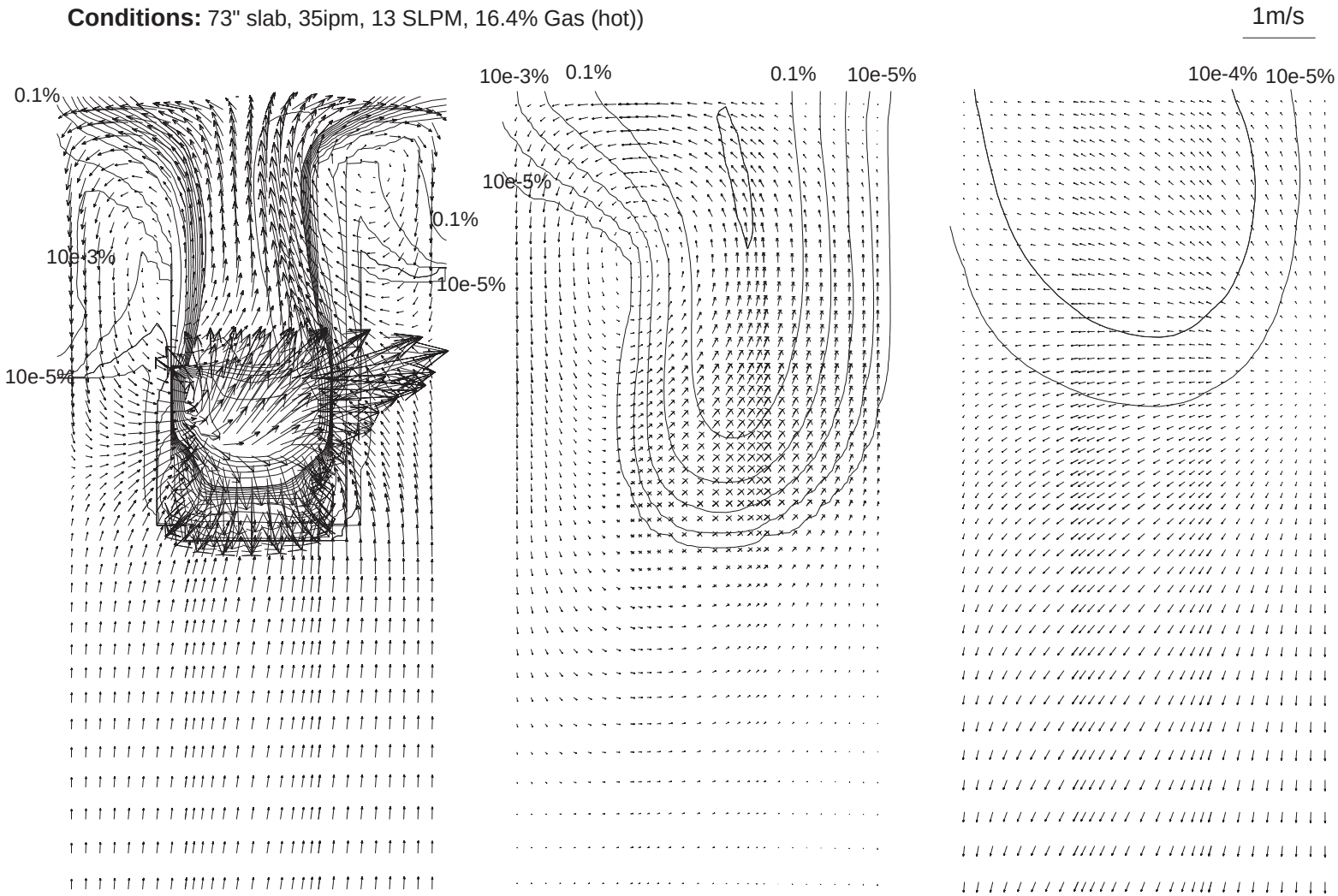
Slice at SEN Port

Centerplane betwen SEN and NF

10 mm from Narrow Face

Steel flow pattern calculated using CFX with distributed bobble size(2.43 mm mean)

Conditions: 73" slab, 35ipm, 13 SLPM, 16.4% Gas (hot))



Slice at SEN Port

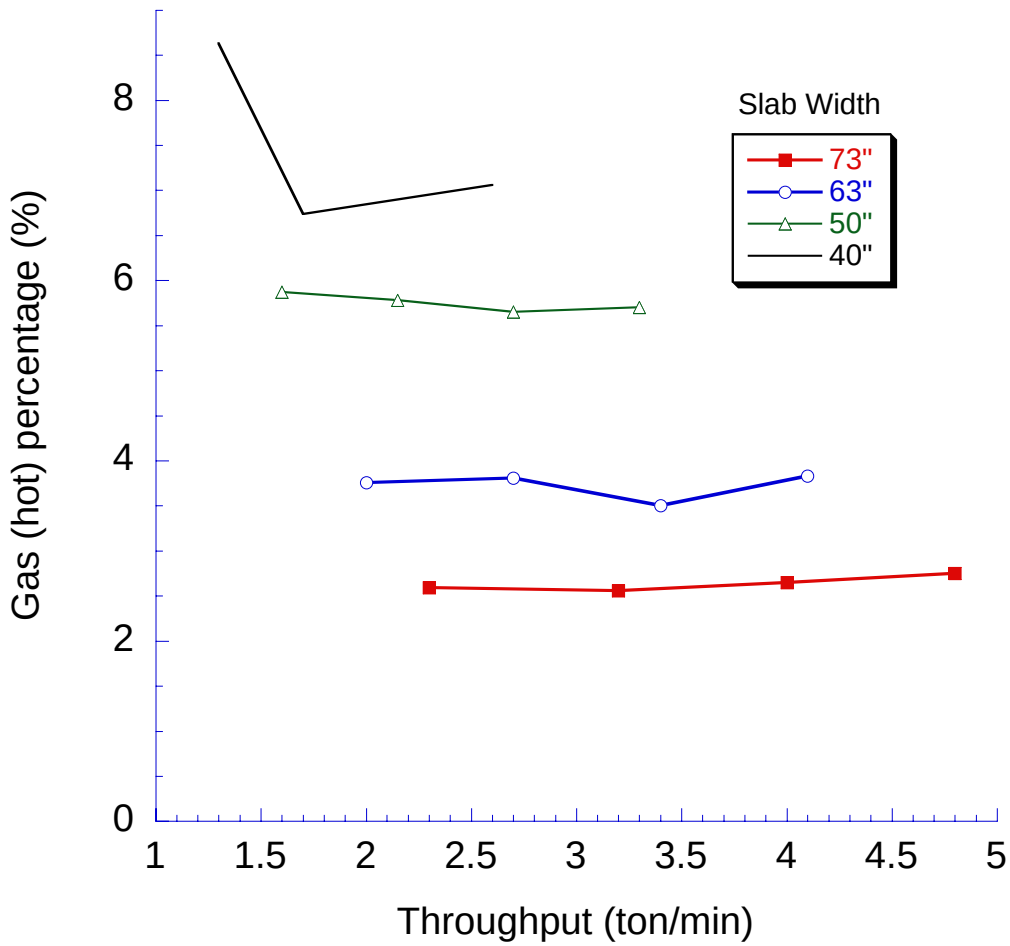
Centerplane betwen SEN and NF

10 mm from Narrow Face

Steel flow pattern calculated using CFX with distributed bobble size(2.43 mm mean)

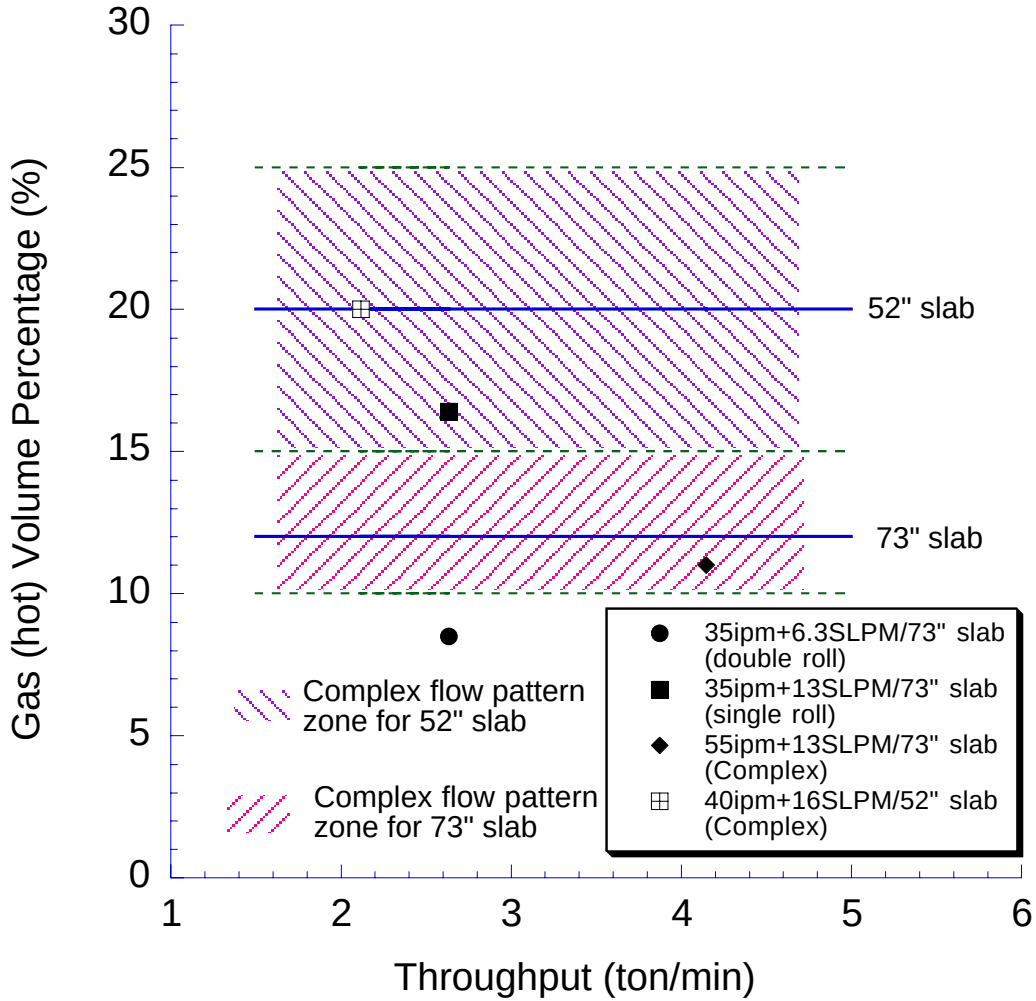
Flow Pattern Identification

(Water Model ,Modified from M. Assar, P. Dauby and G. Lawson)



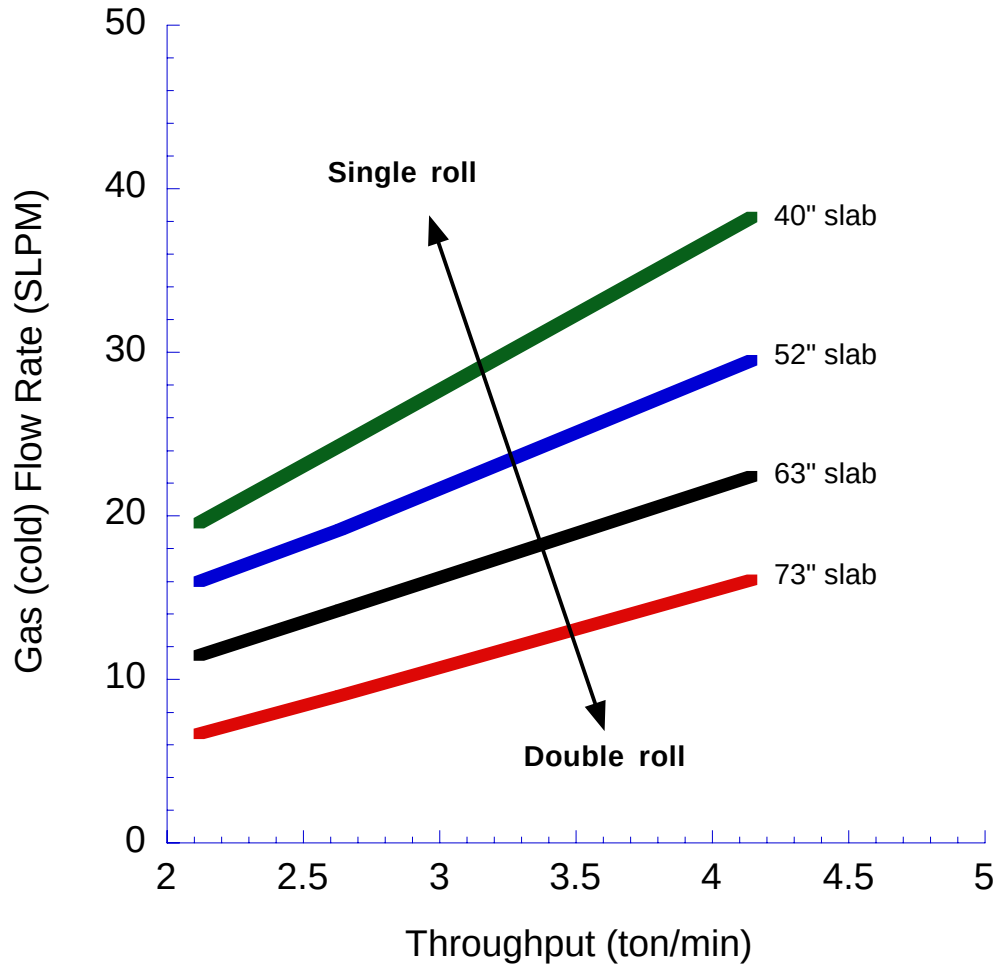
Flow Pattern Identification

(Real Caster)



Flow Pattern Identification

(Real Caster)



Recommendations

- Do not inject argon into the lowest pressure locations in the nozzle. These low pressure regions will attract large gas flow rates locally, leading to large gas pockets and potential flow instabilities.

- Ramp the casting speed back up slowly after a ladle change to minimize unstable transient flow.

- Change submergence gradually and try to arrange for the deeper submergence depths to occur the wider slabs and shallower for narrow slabs.

Recommendations

- Optimal argon injection depends on width, casting speed, and submergence depth. Vary argon injection rate with throughput, width, and submergence depth.

- Keep argon injection *below* the levels recommended for stable double roll flow.

- When casting speed drops severely, cut argon to zero or minimal flow rate. Argon should be needed to prevent nozzle clogging due to air aspiration in these conditions; very little gas is needed to maintain a constant gas percentage; and bubble size might grow severely.

Further Work

- Further study is recommended using the mathematical models to quantify the conditions which lead to defects and then to fully quantify the flow patterns which lead to safe conditions through subsequent parametric studies.

- Further study is also needed of gas flow through the refractory relative to pressure drops in the nozzle in order to understand how the gas exits into the nozzle.

Acknowledgements

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