Effect of Argon Gas Distribution on Fluid Flow in the Mold Using Time-Averaged k-ε Models

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Objectives

- **Develop multiphase model to simulate the 3-D flow pattern of molten steel in the continuous casting mold with multisize-argon gas injection**
- **Validate model using water model & steel caster comparisons**
- **Estimate flow pattern (single roll, double roll, etc.) and gas penetration (contours) obtained in steel caster as a function of casting conditions (gas flow rate, gas volume fraction, argon bubble size, steel throughput, mold width, and SEN submergence depth)**
- **Recommend practices related to argon gas injection optimization to improve the flow pattern in continuous casting mold**

Contents

1. **Model Development**
2. **Model Validation**
3. **Parametric Study for the Steel Caster**

   - Steel throughput

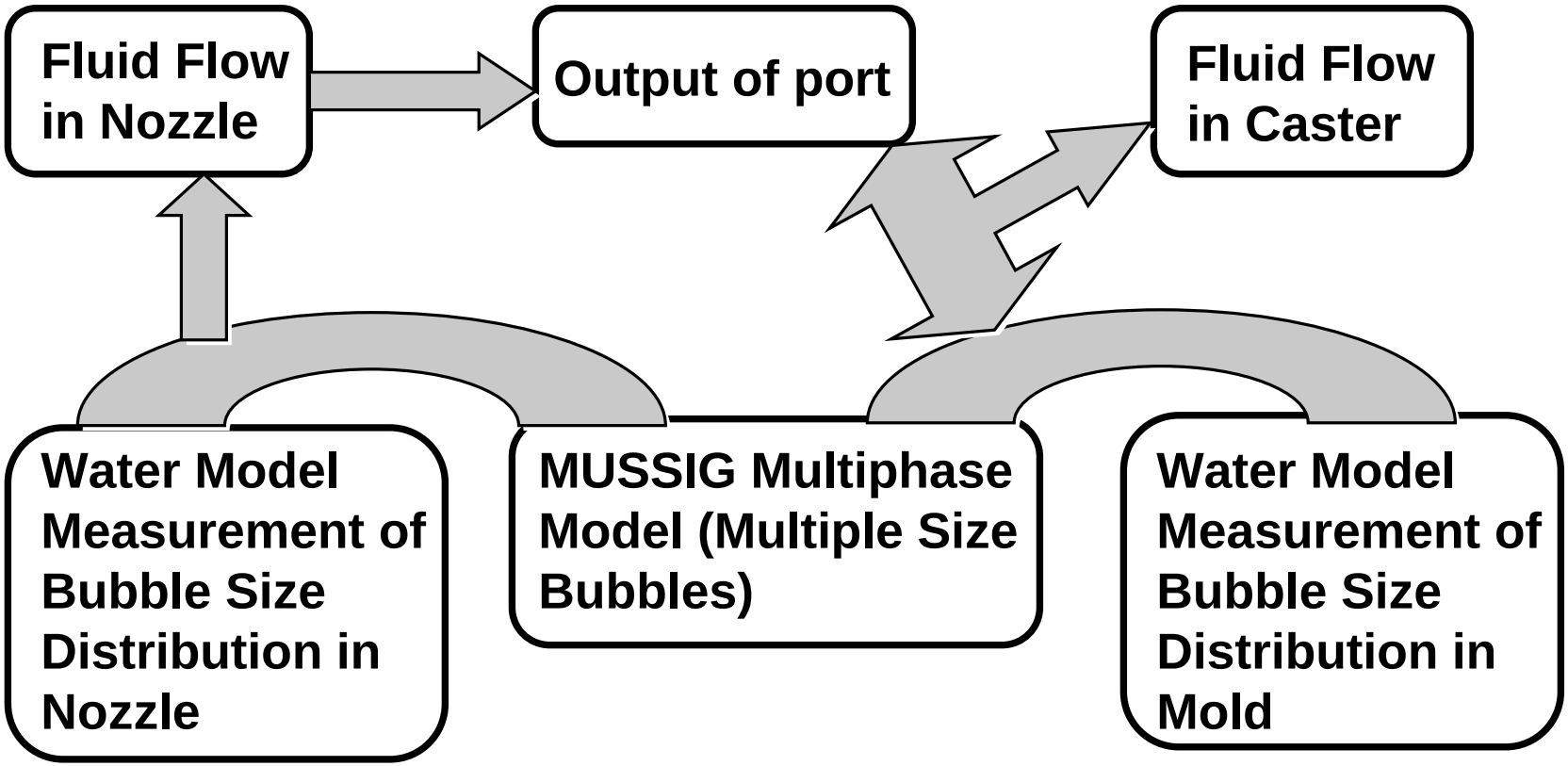
   - Gas volume fraction (gas flow rate)

   - Bubble size and its distribution

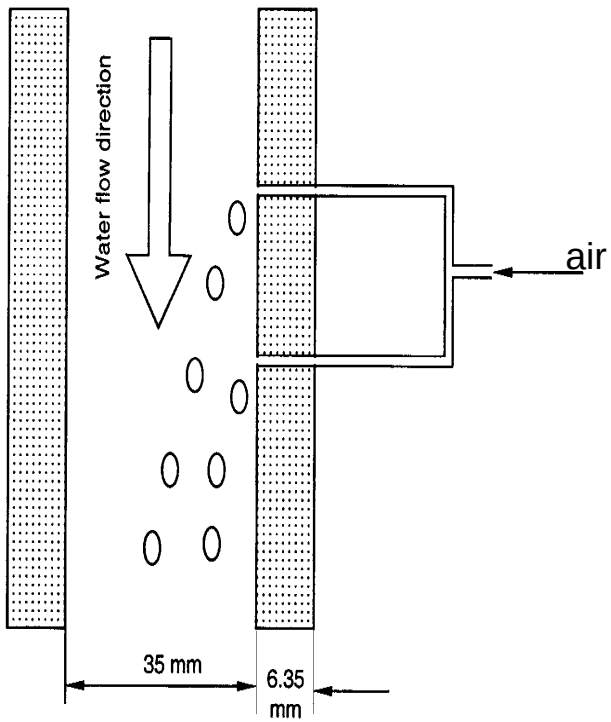
   - Slab width

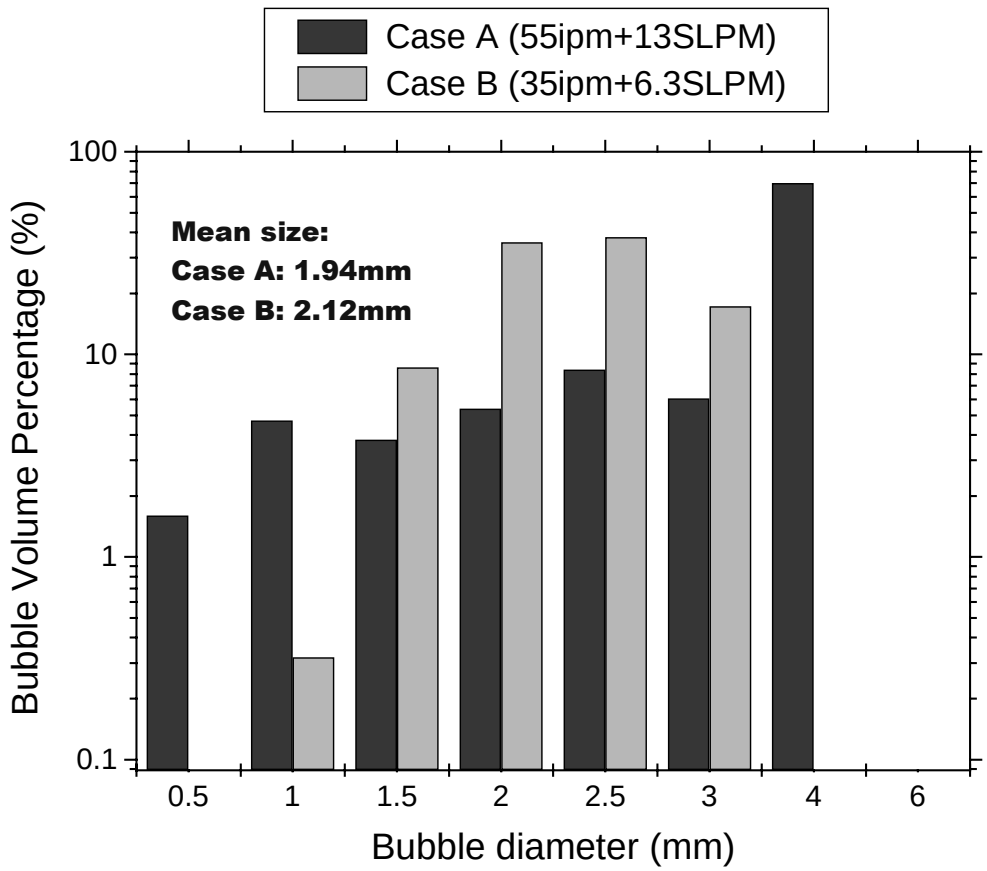
   - SEN submergence depth

Model-Calculation Steps



Bubble Size Distribution in Nozzle
(Bai's Double-needle Water Model Experiment)



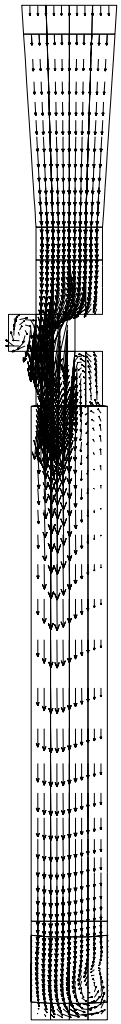


Liquid Velocity in the Nozzle (Case A)

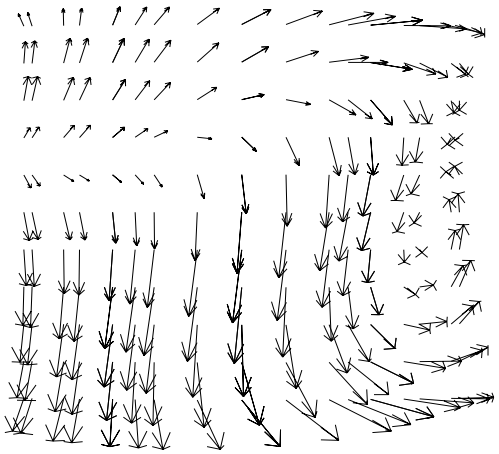
Conditions:

23.2 mm/s
13 SLPM
Gate open 58%

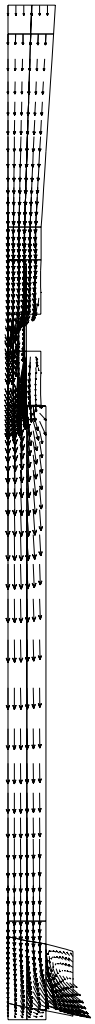
Mean bubble size: 1.94mm



Centerplane parallel to SEN port



Velocity at SEN port



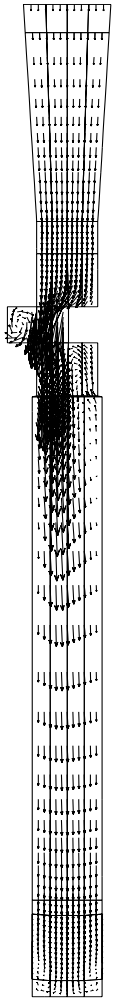
Centerplane perpendicular to SEN port

Liquid Velocity in the Nozzle (Case B)

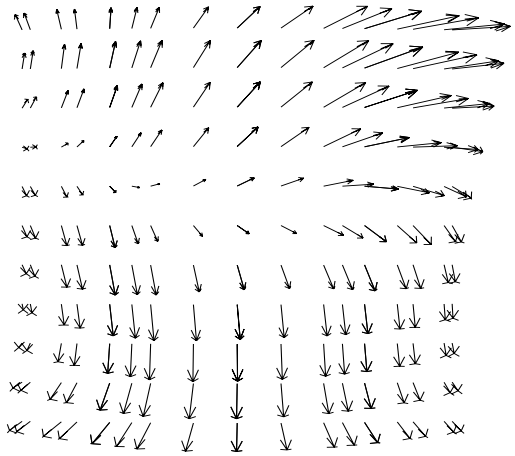
Conditions:

14.8 mm/s
13 SLPM
Gate open 50%

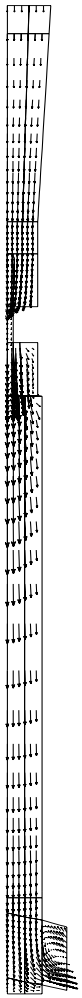
Mean bubble size: 2.12mm



Centerplane parallel to SEN port



Velocity at SEN port

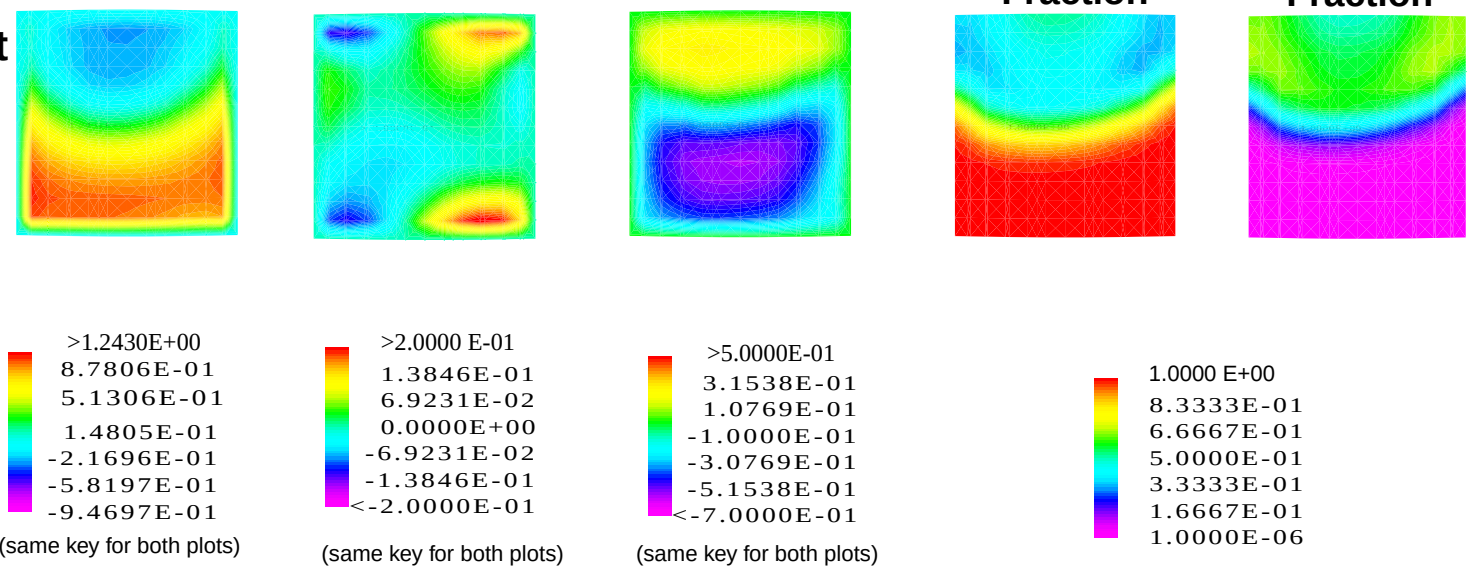


Centerplane perpendicular to SEN port

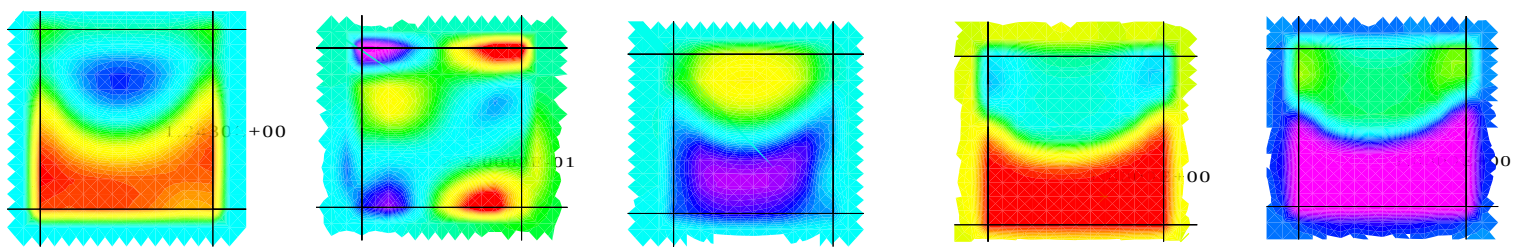
Data Transfer from Nozzle Simulation Output to Mold Simulation Input

U **V** **W** **Liquid Volume Fraction** **Gas Volume Fraction**

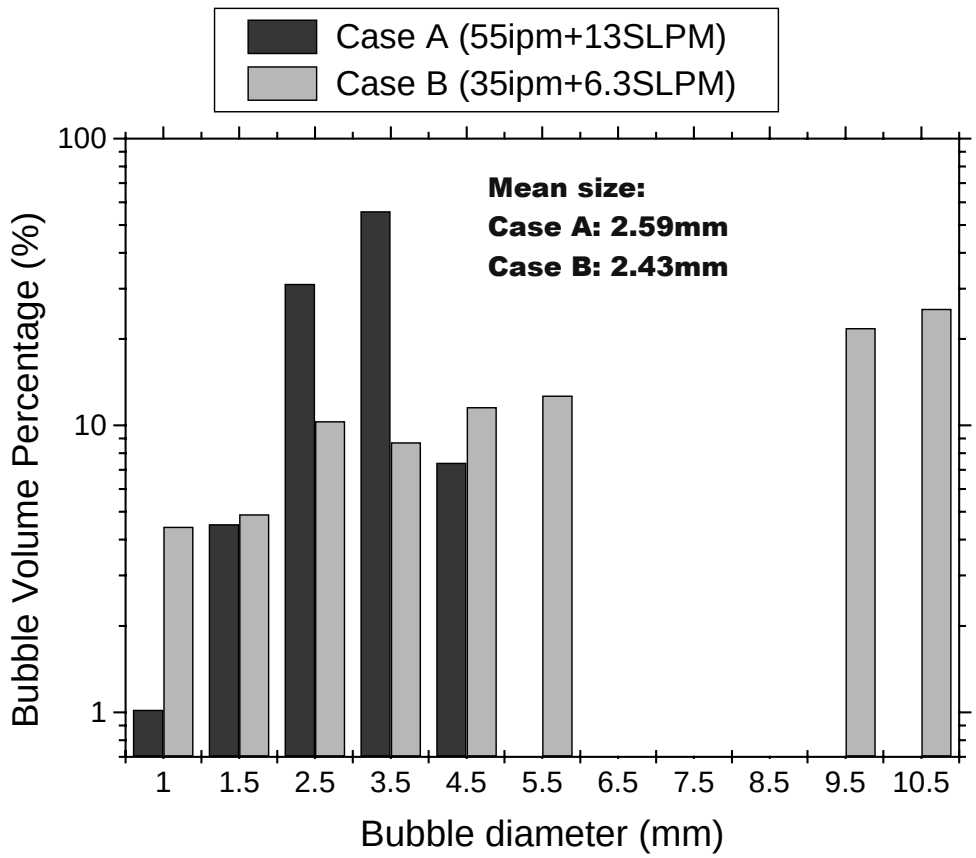
Nozzle Port Output by Nozzle Modeling



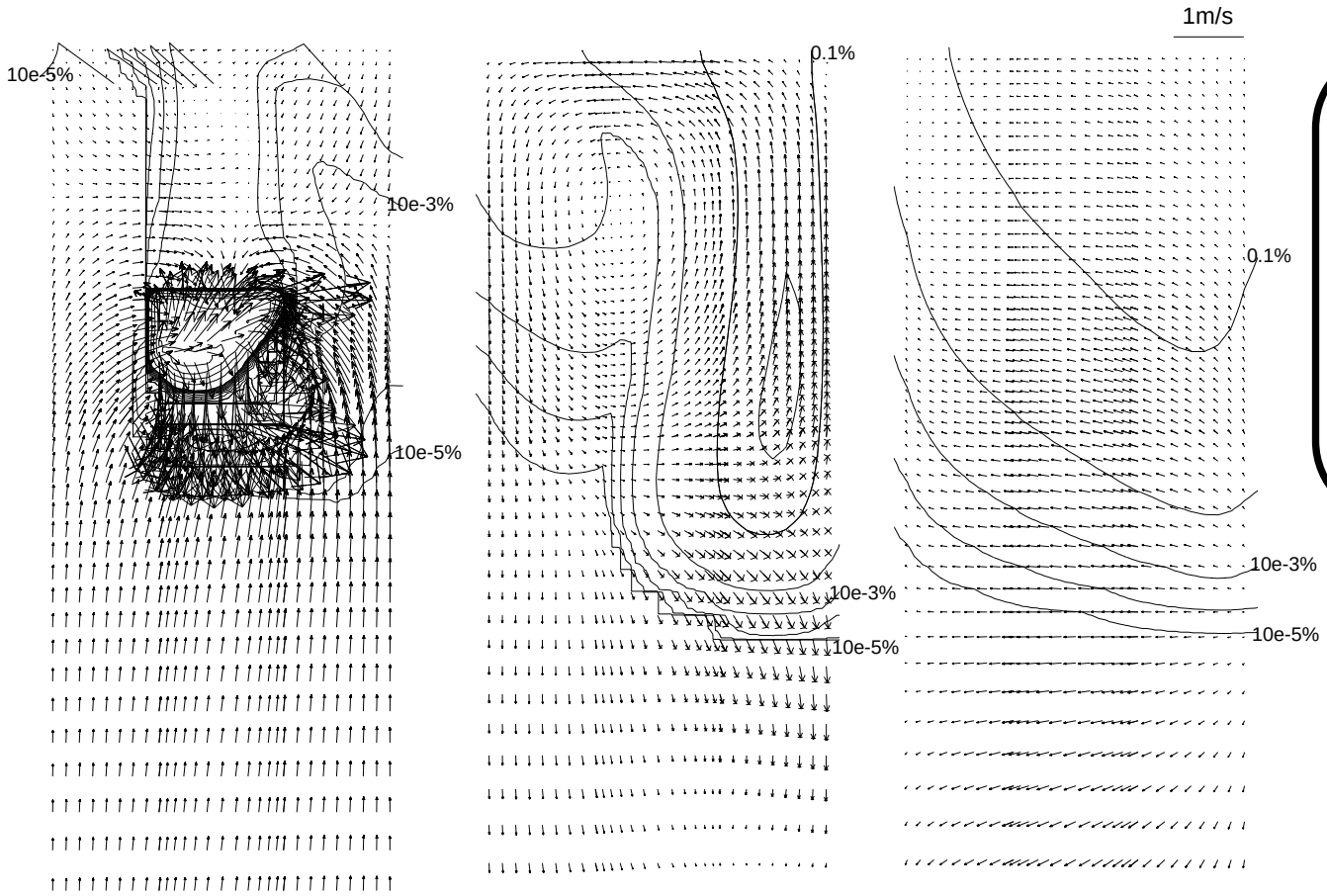
Real Caster Nozzle Port Input



Bubble Size Distribution in Mold (0.4 Scale LTV Water Model)



Steel Flow Pattern with Distributed Bubble Size (Case A)



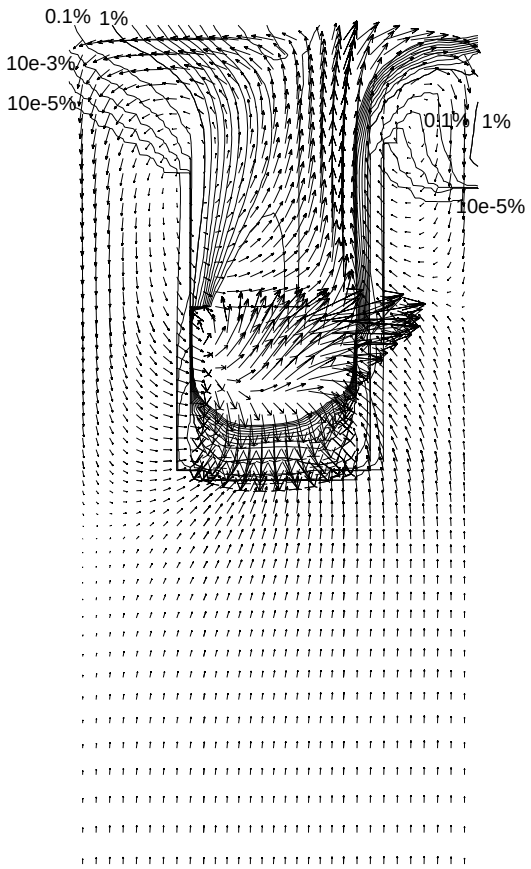
Slice at SEN Port

Centerplane betwen SEN and NF

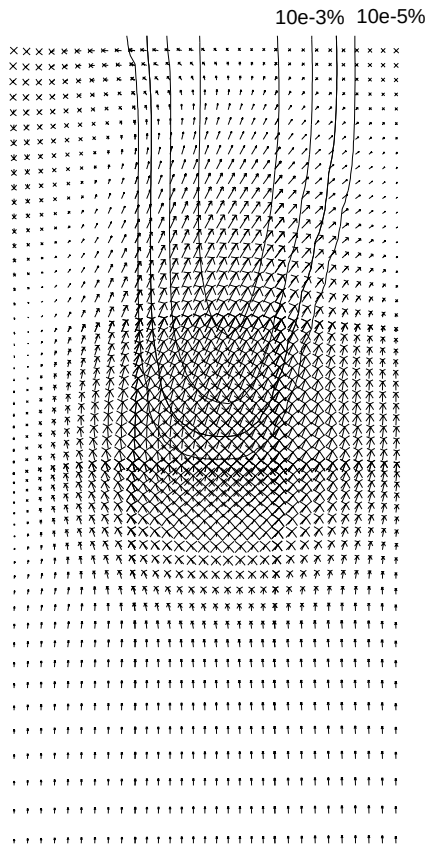
10 mm from Narrow Face

Conditions:
1854mm slab
23.2mm/s
(4.1 tonne/min)
13 SLPM
11%gas (hot)
2.59mm mean bubbles
(normal distribution)

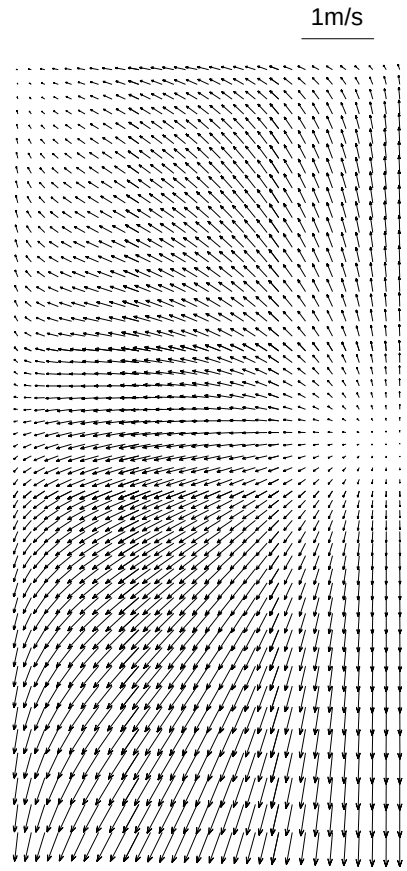
Steel Flow Pattern with Distributed Bubble Size (Case B)



Slice at SEN Port



Centerplane betwen SEN and NF



10 mm from Narrow Face

Conditions:
1854mm slab
14.8mm/s
(2.64 tonne/min)
6.3 SLPM
8.5%gas (hot)
2.43mm mean bubbles
(bi modal distribution)

Model Validation

	Case A	Case B
Casting Speed	55 inch/min	35 inch/min
Gas Flow Rate	13 SLPM	6.3 SLPM
Quality	More pencil pipe defects	More sliver defects

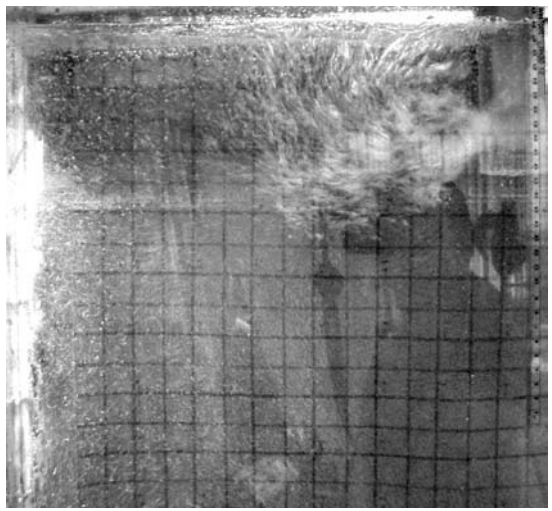
Parameters for Fluid Flow Calculation in Water Model

Cases	A (55ipm+11%hot gas)	B (35ipm+8.5%hot gas)
Mold Width W(mm) × Thickness H(mm)	730×80	
Mold Height (mm)	950	
Nozzle Submergence Depth (mm) (Top surface to top of port of SEN)	80	
Nozzle Inner Diameter	31	
Nozzle Port Width (mm) × Height (mm)	31 ×31	
Jet Angle	30° down	
Inlet Jet Spread Angle	0°	
Water Flow Rate Q_W *(SLPM)*	58.59 (15.5GPM)	37.80(10.0GPM)
Equivalent Steel Casting Speed (ipm)	54.03	34.86
Gas Flow Rate *(SLPM, hot volume)*	7.43 (15.8SCFH)	3.71(7.9SCFH)
Gas Volume Fraction (%)	11.3	8.9
Inlet Velocity, V_x *(m/s)*	0.571	0.358
Inlet Velocity, V_z *(m/s)*	0.33	0.207
Inlet Turbulent Kinetic Energy, k_o *(m^2/s^2)*	0.044	
Inlet Turbulent Turbulent dissipation rate , ε_o *(m^2/s^3)*	0.999	

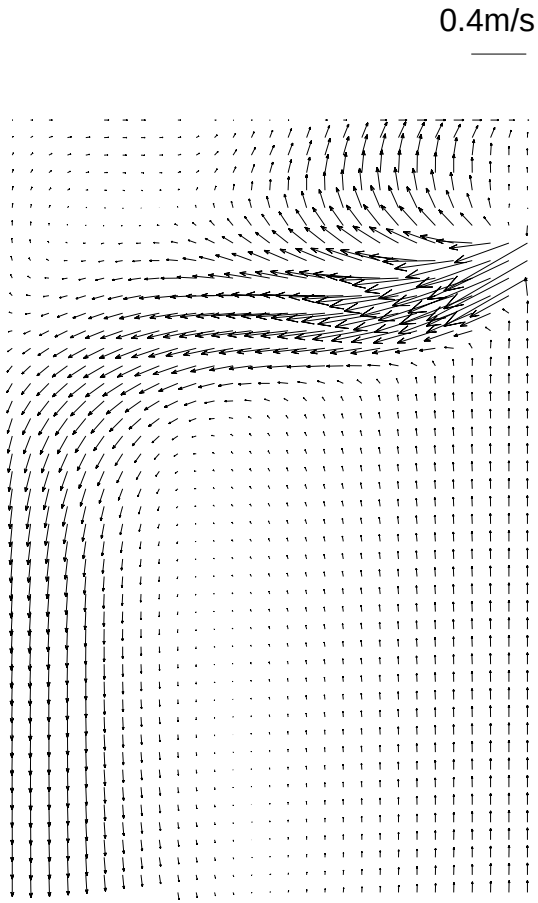
Parameters for Fluid Flow Calculation in Water Model (Cont.)

Cases	A (55ipm+11%hot gas)	B (35ipm+8.5%hot gas)
Water Density *(kg/m³)*	1000	
Water Viscosity *(kg/m³)*	1×10^{-3}	
Gas Density (*kg/m³*)	1.20	
Gas Viscosity (*kg/m³*)	1.7×10^{-5}	
Average Bubble Diameter (*mm)*	2.59	2.43
Volume Fraction of 0.5 mm Bubble (%)	1.07	4.43
Volume Fraction of 1.5 mm Bubble (%)	4.53	4.90
Volume Fraction of 2.5 mm Bubble (%)	31.15	10.34
Volume Fraction of 3.5 mm Bubble (%)	55.83	8.73
Volume Fraction of 4.5 mm Bubble (%)	7.42	11.60
Volume Fraction of 5.5 mm Bubble (%)	0	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 (%)	0	21.83
Volume Fraction of 10.5 mm Bubble (%)	0	26.46
Breakup Coefficient	0.5	0.1
Coalescence Coefficient	0	0

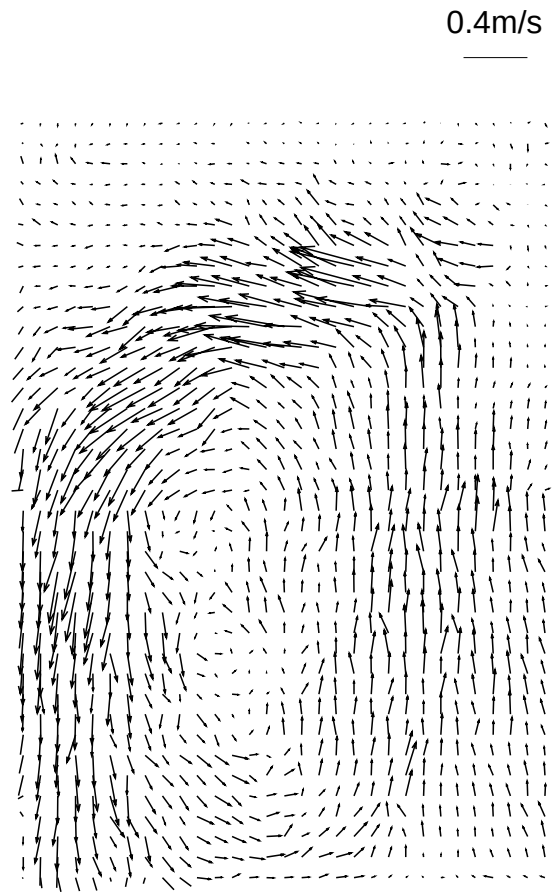
Velocity at Centerplane (Case A: 55ipm+13SLPM/11% hot gas)



Flow Picture of Water Model

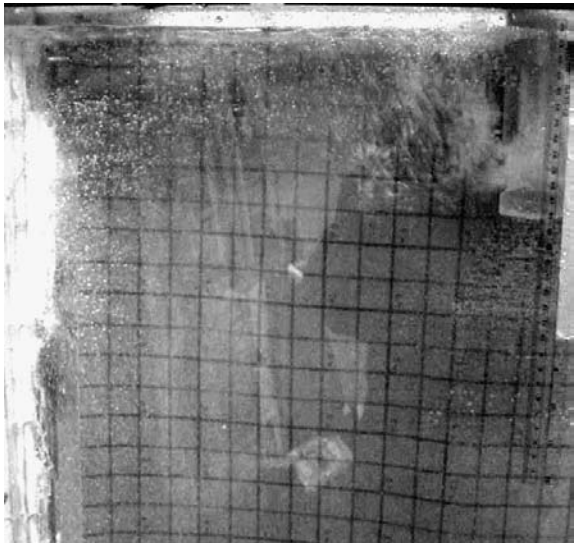


***K-ε* Simulation Results**

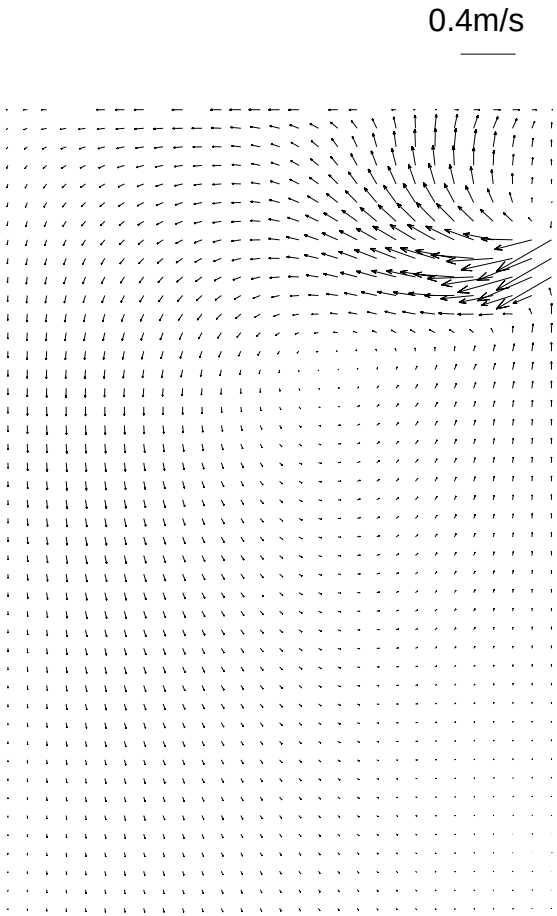


PIV Measurements

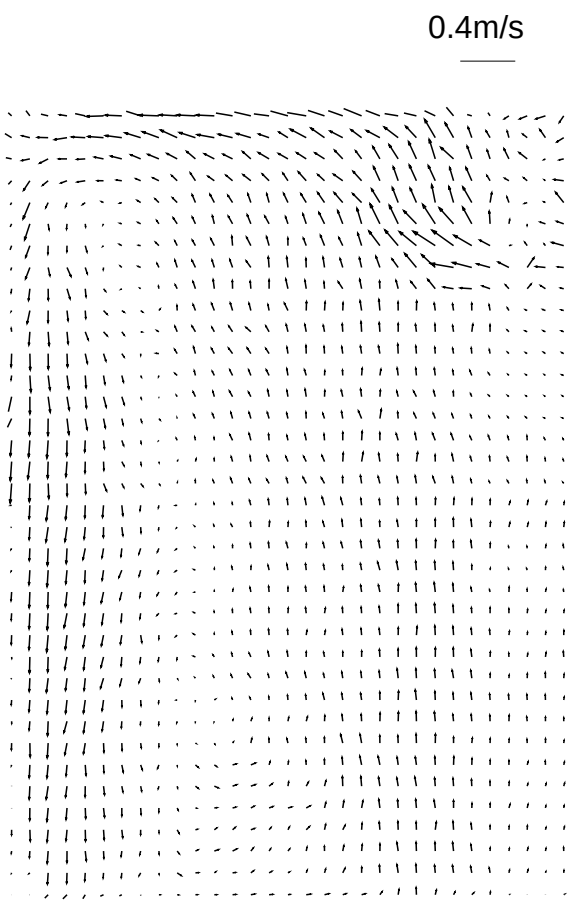
Velocity at Centerplane (Case B: 35ipm+6.5SLPM/8.5% hot gas)



Flow Picture of Water Model



***K-ε* Simulation Results**



PIV Measurements

Parameters for the Real Caster Modeling

Mold Width W(mm) $\times$ Thickness H(mm)	1854 $\times$228
Mold/Domain Height (mm)	3000
Nozzle Bore Inner Diameter (mm)	78
Nozzle Port Width (mm) $\times$ Height (mm)	78 $\times$78
Nominal Vertical Angle of Port Edges	15° down
Liquid Steel Density *(kg/m^3)*	7020
Liquid Steel Molecular Viscosity *(kg.m s)*	0.0056
Gas Density (*kg/m^3*)	0.27
Gas Viscosity (*kg/m s)*	7.42×10^{-5}
Surface Tension Coeff. (Steel-Argon) *(N/m)*	1.192
Gravitational Acceleration *(m/s^2)*	9.8

Parameters for the Real Caster Modeling

	Cast A (13SLPM, 55ipm)	**Case B** (6.3SLPM, 3.5 ipm)
Nozzle Submergence Depth *(mm)*	165	165
Vertical Velocity in Nozzle *(m/s)*	2.05	1.31
Casting Speed (*mm/s*)	23.2	14.8
Inlet Steel Flow Rate *(m^3/min)*	0.584	0.376
Throughput *(tonne/min)*	4.10	2.64
Inlet Gas Flow Rate *(SLPM)*	13	6.3
Inlet Gas Volume Fraction *(%)*	11	8.5
Average Gas Bubble Diameter *(mm)*	2.59	2.43

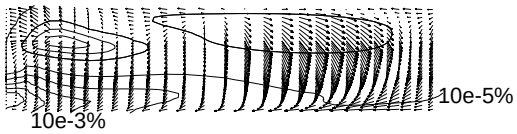
Differences between Steel Caster and Water Model

1. Increasing the dimensions by a factor of 2.5 to simulate the full-scale geometry ;
2. Increasing the inlet velocity by a factor of $(2.5)^{1/2}$ (to simulate the actual casting speed rather than the velocities in the water model, which were scaled down according to the standard modified Froude criterion);
3. Replacing the domain bottom with a pressure boundary condition;
4. Changing the bubble distribution
5. Changing the liquid properties
6. Nozzle geometry slight change and simulated with 3D model

Fluid Flow in Steel Caster (Case A)

Bubble mean size: 2.59mm
Normal distribution

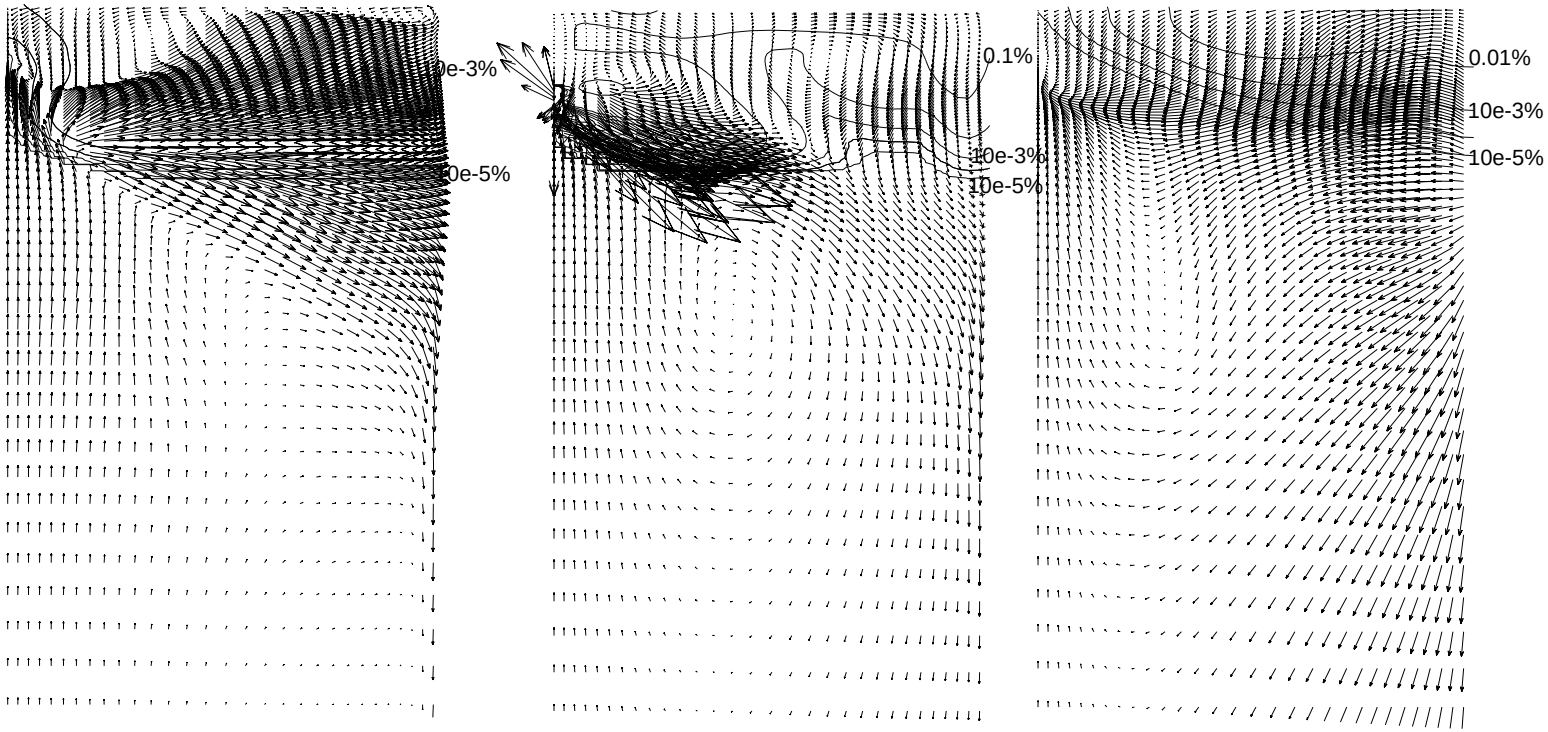
10 mm below Meniscus



Casting conditions:

1.854 m slab
23.2 mm/s
13 SLPM
11% Gas (hot)

1m/s



10 mm from Inner Wide Face

Centerplane between Wide Faces

10 mm from Outer Wide Face

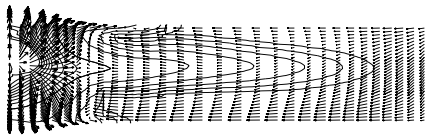
Fluid Flow in Steel Caster (Case B)

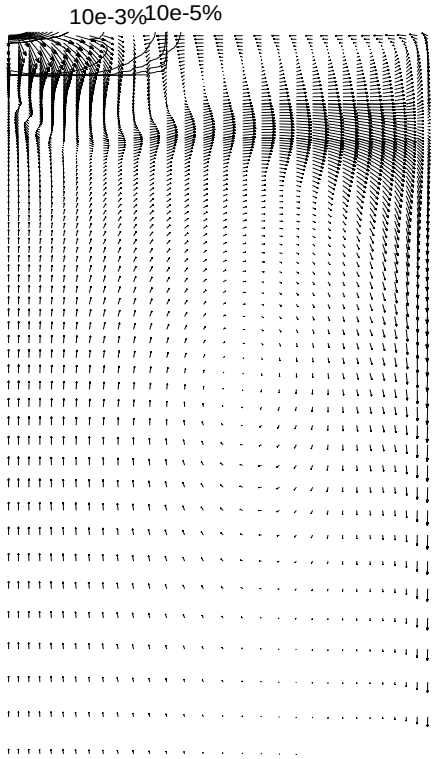
Bubble mean size: 2.43mm
Bi modal distribution

Casting conditions:

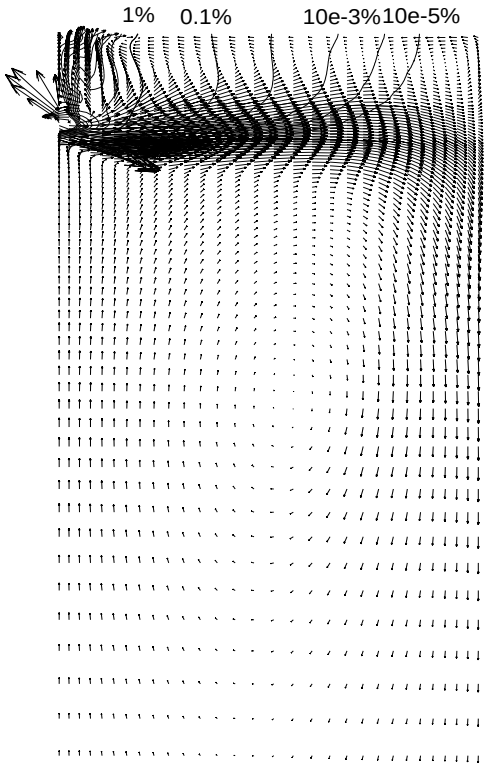
1.854 m slab
14.8 mm/s
6.3 SLPM
8.5% Gas (hot)

10 mm below Meniscus

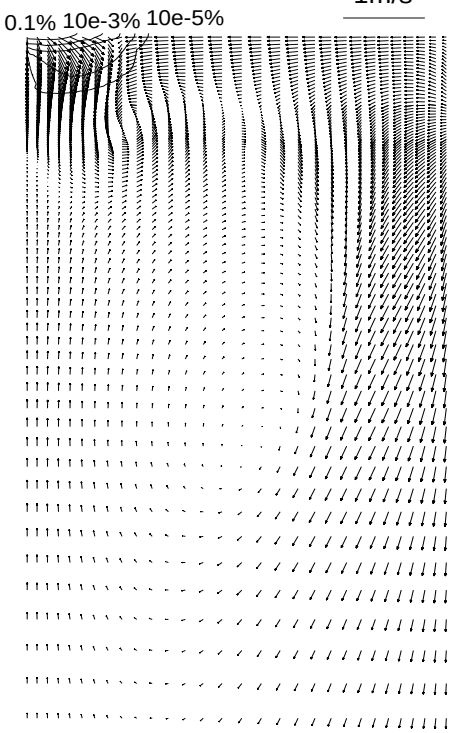




10 mm from Inner Wide Face

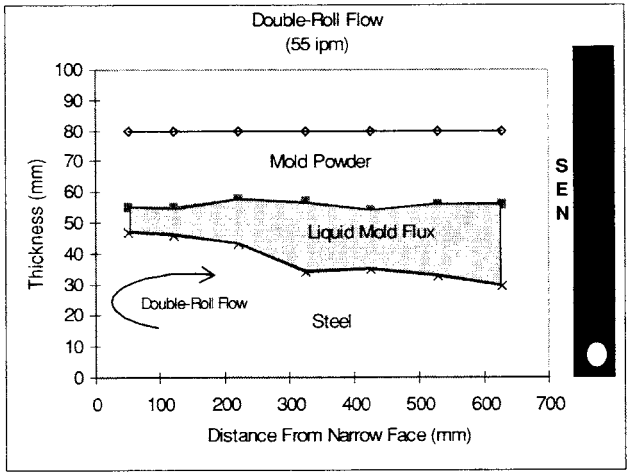


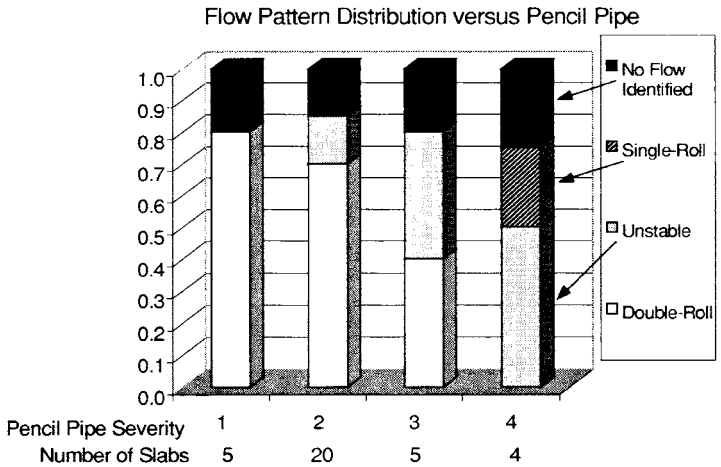
Centerplane between Wide Faces



10 mm from Outer Wide Face

MFC Measurement of Flow Pattern in Steel Caster





Case A, 11% gas: Normally double roll.

Almost Case B: Mostly double roll but experiencing some flow pattern switching.

M. B. Assar, P. H. Dauby and G. D. Lawson. Opening then black box: PIV and MFC measurements in a continuous caster mold. 83rd Steelmaking Conference Proceedings, P397-411

Comparison between Water Model and Steel Caster

Case A			
Water model		**Steel Caster**	
PIV measurement	Single roll	MFC measurement	Normally double roll
k-ε calculation (CFX)	Single roll	k-ε calculation (CFX)	Computer flow closer to double roll than a single roll

Case B			
Water model		**Steel Caster**	
PIV measurement	Single roll	MFC measurement	Mostly double roll but experiencing some flow pattern switching
k-ε calculation (CFX)	Single roll	k-ε calculation (CFX)	Slight double roll flow

Parametric Study

Effects of

- **Steel throughput**
- **Gas volume fraction (gas flow rate)**
- **Bubble size and its distribution**
- **Slab width**
- **SEN submergence depth**

Results of

- **Flow pattern**
- **Gas Penetration**

Steel Caster Modeling Cases

Case No.	Steel Flow rate		Slab width (m)	Casting speed		Gas volume fraction (%)	Gas flow rate (SLPM)	Bubbles		Flow pattern
	tonne/ min	ton/min		Steel density 7020kg/m^3	Steel density 7700kg/m^3			Mean size (mm)	Size distribution	
1	1.65	1.815	1.016	0.0169m/s (40 ipm)	0.0154m/s (36.4ipm)	33	20.9			Single
2	1.65	1.815	1.016			27	15.7			Single
3	1.65	1.815	1.016			23	12.7			Double
4	1.65	1.815	1.016			21	11.3			Double
5	1.65	1.815	1.016			19	9.9			Double
6	2.14	2.354	1.321			25	18.3			Single
7	2.14	2.354	1.321			18.6	12.6			Double
8	2.14	2.354	1.321			17	11.3			Double
9	2.6	2.86	1.6			17	13.7			Complex
10	2.6	2.86	1.6			15	11.8			Complex
11	2.6	2.86	1.6			9	6.6			Double
12	2.64	2.906	1.854	0.0148m/s (35ipm)	0.0134m/s (31.8ipm)	16.4	13.3	2.43	Bi modal	Single
13	2.64	2.906	1.854			8.5	6.3	2.43	Bi modal	Double
14	2.64	2.906	1.854			11	8.4	2.43	Bi modal	Double
15	2.64	2.906	1.854			6.77	4.9	2.43	Bi modal	Double

Steel Caster Modeling Cases (Cont.)

Case No.	Steel Flow rate		Slab width (m)	Casting speed		Gas volume fraction (%)	Gas flow rate (SLPM)	Bubbles		Flow pattern
	tonne/ min	ton/min		Steel density 7020kg/m^3	Steel density 7700kg/m^3			Mean size (mm)	Size distri -bution	
16	4.1	4.51	1.854	0.023m/s (55ipm)	0.021m/s (50ipm)	18	23.1			Single
17	4.1	4.51	1.854			16	20.0			Single
18	4.1	4.51	1.854			11	13.0	2.59	normal	Complex
19	4.1	4.51	1.854			11	13.0	2.59	normal	Sin/com
20	4.1	4.51	1.854			5.7	6.4	2.59	normal	Complex
22	4.1	4.51	1.854			3.7	4.0	2.59	normal	Double
21	2.64	2.91	1.854	0.0148m/s (35ipm)	0.0134m/s (31.8ipm)	11.0	8.4	2.59	normal	Single
23	2.64	2.91	1.854			5.7	4.0	2.59	normal	Single
24	2.64	2.91	1.854			8.6	6.3	2.59	normal	Single
25	2.64	2.91	1.854			3.7	2.6	2.59	normal	Complex
26	3.0	3.30	1.854	0.0168m/s (40ipm)	0.0153 (36.4ipm)	4.9	4.0	2.59	normal	Sin/com
27	3.0	3.30	1.854			7.8	6.5	2.59	normal	Single
30	3.0	3.30	1.854			2.7	2.1	2.59	normal	Com/sin
28	2.64	2.91	1.854	0.0148m/s (35ipm)	0.0134m/s (31.8ipm)	1.9	1.3	2.59	normal	Complex
29	2.64	2.91	1.854			1.2	0.8	2.59	normal	Com/dou

Effect of Steel Throughput on Flow Pattern

Conclusion:

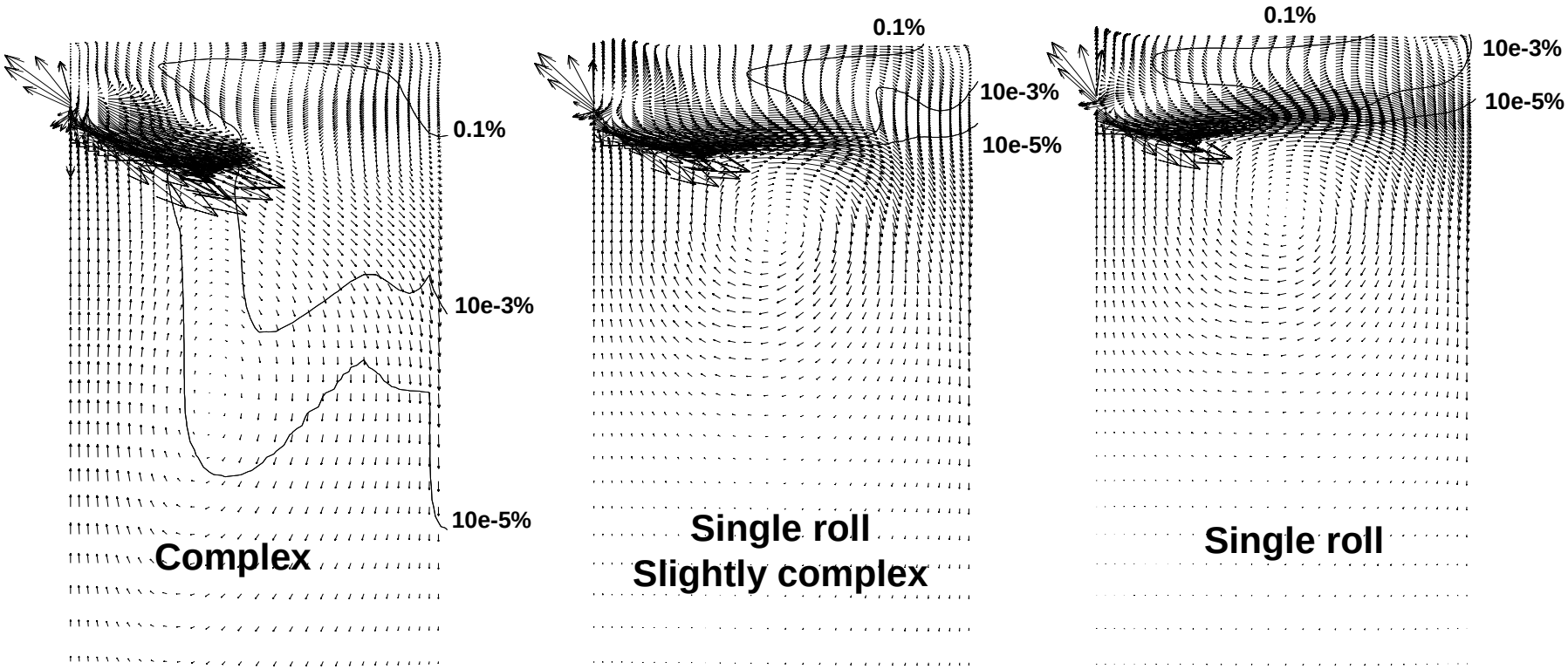
Lower steel throughput tends to generate more single roll and generally less gas penetration.

Effect of Steel Throughput on Flow Pattern

Conditions:
1.854 m slab
23.2mm/s
(**4.1tonne/min**)
6.4 SLPM
5.7% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
16.8mm/s
(**3.0tonne/min**)
4 SLPM
5% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
14.8mm/s
(**2.64tonne/min**)
4 SLPM
5.7% Gas
2.59mm bubble(normal)

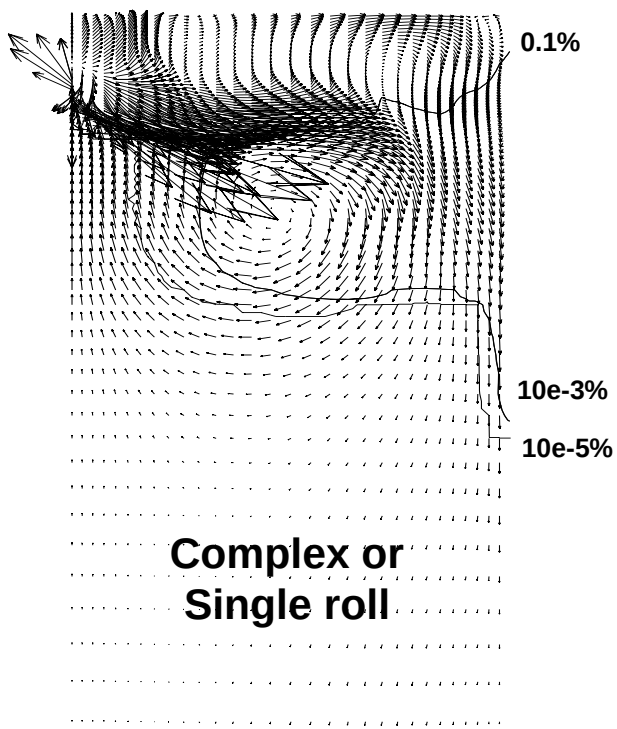


Case20 **Case26** **Case23**

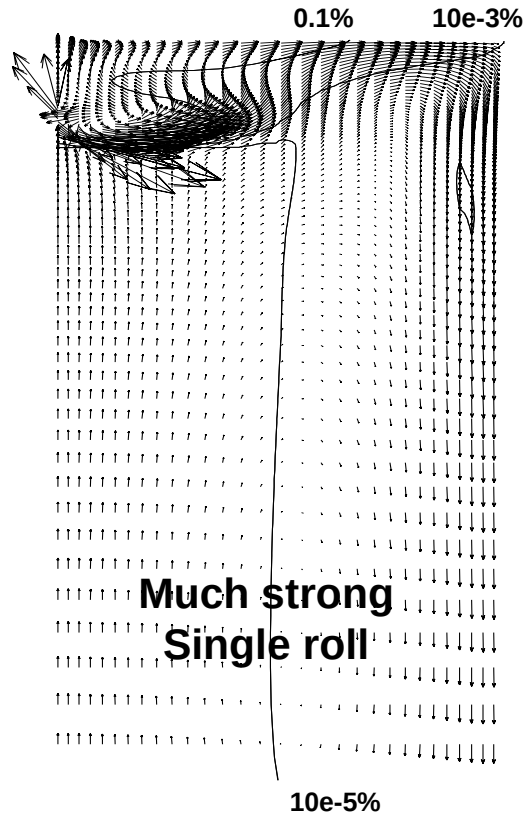
Effect of Steel Throughput on Flow Pattern

Conditions:
1.854 m slab
23.2mm/s
(**4.1tonne/min**)
13 SLPM
11% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
14.8mm/s
(**2.64tonne/min**)
8.37 SLPM
11% Gas
2.59mm bubble(normal)



Case18

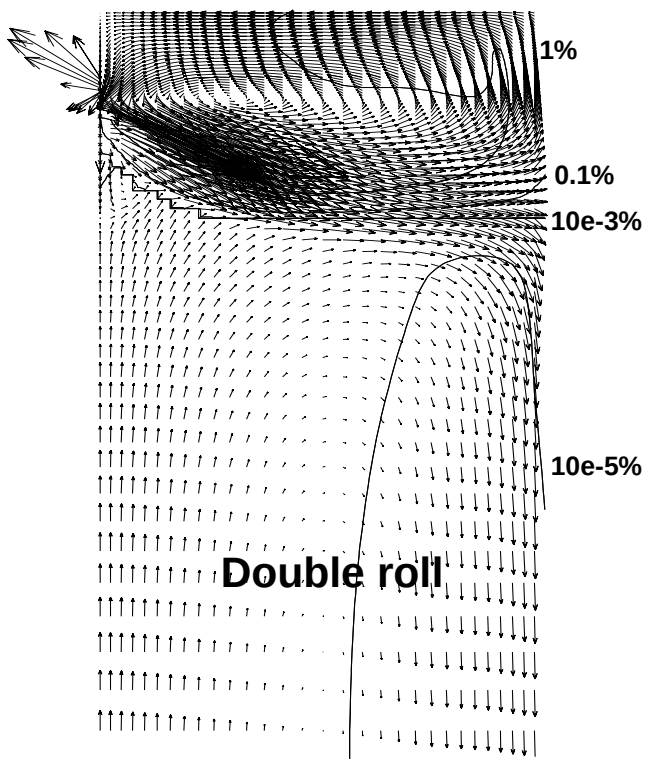


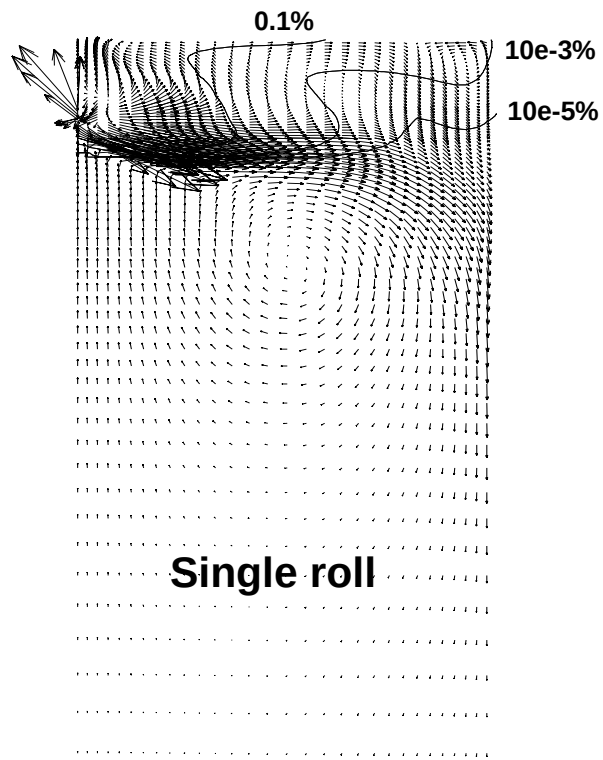
Case21

Effect of Steel Throughput on Flow Pattern

Conditions:
1.854 m slab
23.3mm/s
(**4.1tonne/min**)
4 SLPM
3.7% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
14.8mm/s
(**2.64tonne/min**)
2.6 SLPM
3.7% Gas
2.59mm bubble(normal)





Case22 **Case25**

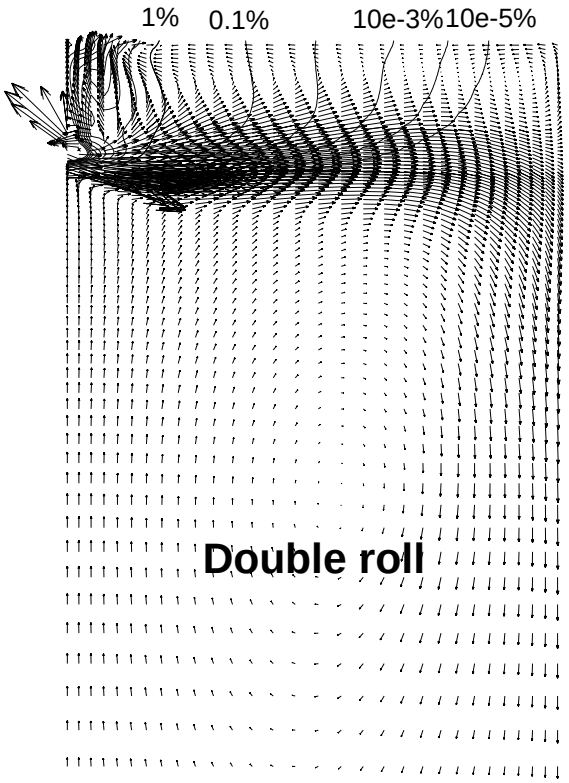
Effect of Gas Volume Fraction on Gas Penetration Depth

Conclusion:

1. **For the same flow pattern, either single roll (case21, 23 and 24) or complex flow pattern (case29, 28 and 25) or double roll (case13 and 14), increasing gas volume fraction makes a deeper gas penetration.**
2. **When this causes the flow pattern to change then there is no clear effect of gas volume fraction on gas penetration depth (case 18, 20 and 22).**
3. **Double roll generally appears to have less penetration than single roll**

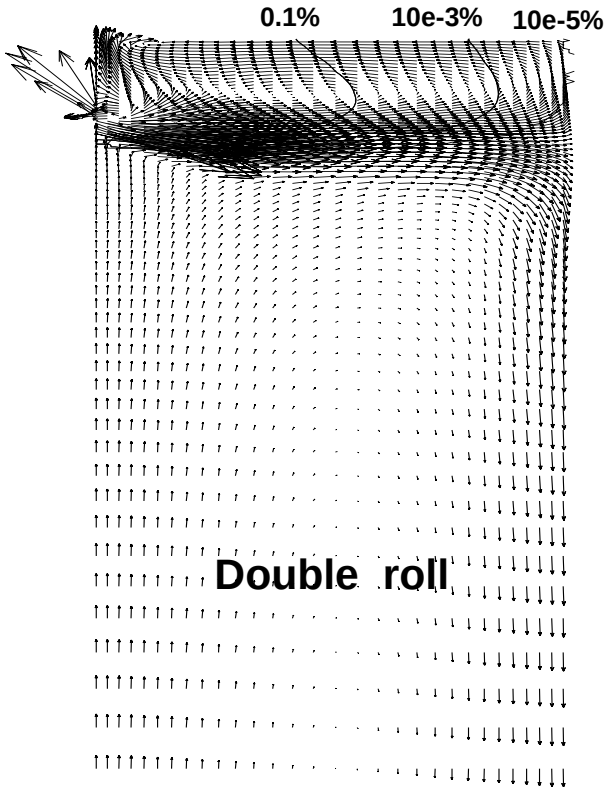
Effect of Gas Volume Fraction on Gas Penetration Depth

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
6.3 SLPM
8.5% Gas
2.43mm bubble(bi modal)



Case13

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
8.4 SLPM
11% Gas
2.43mm bubble(bi modal)



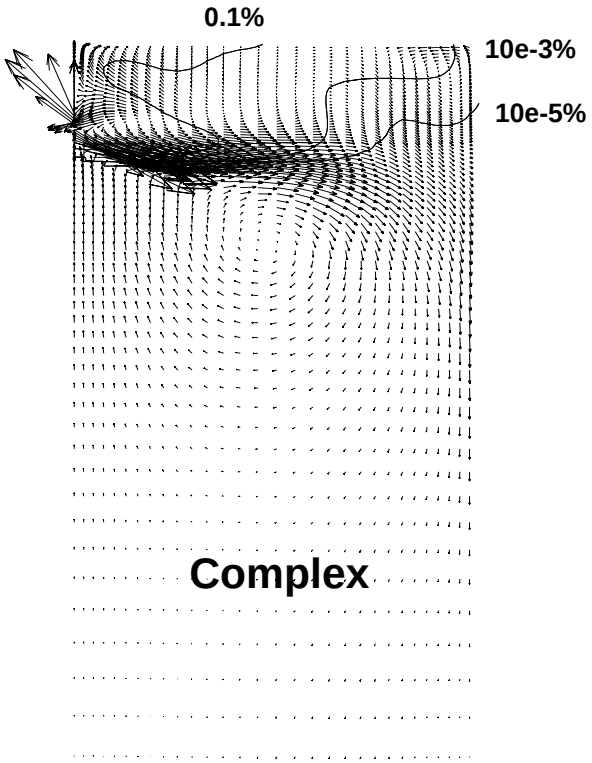
Case14

Effect of Gas Volume Fraction on Gas Penetration Depth

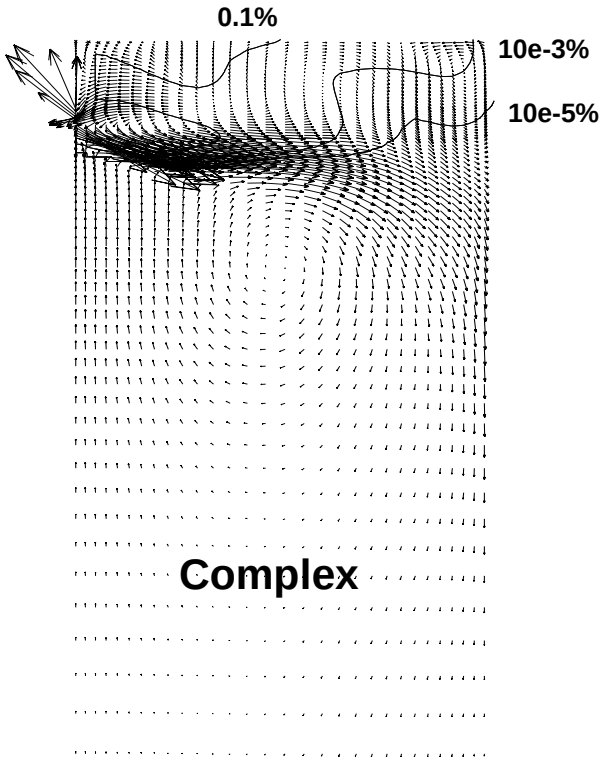
Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
0.83 SLPM
1.2% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
1.3 SLPM
1.9% Gas
2.59mm bubble(normal)

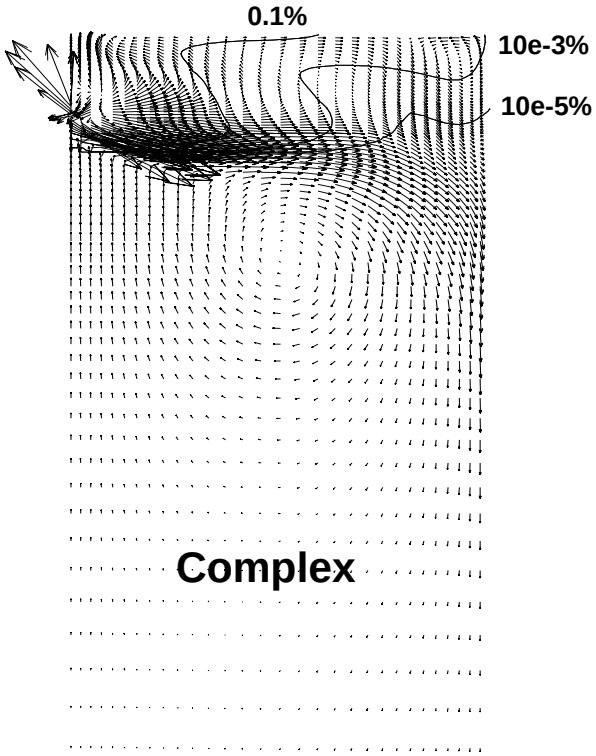
Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
2.6 SLPM
3.7% Gas
2.59mm bubble(normal)



Case29



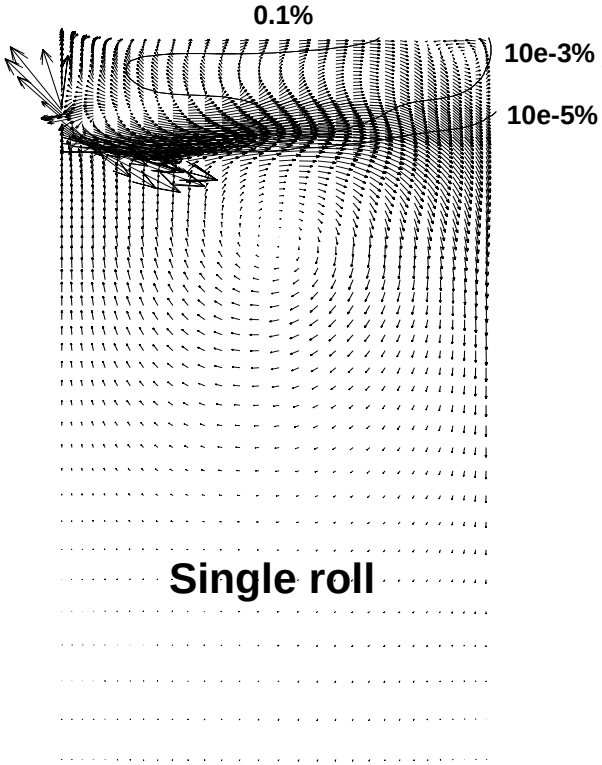
Case28



Case25

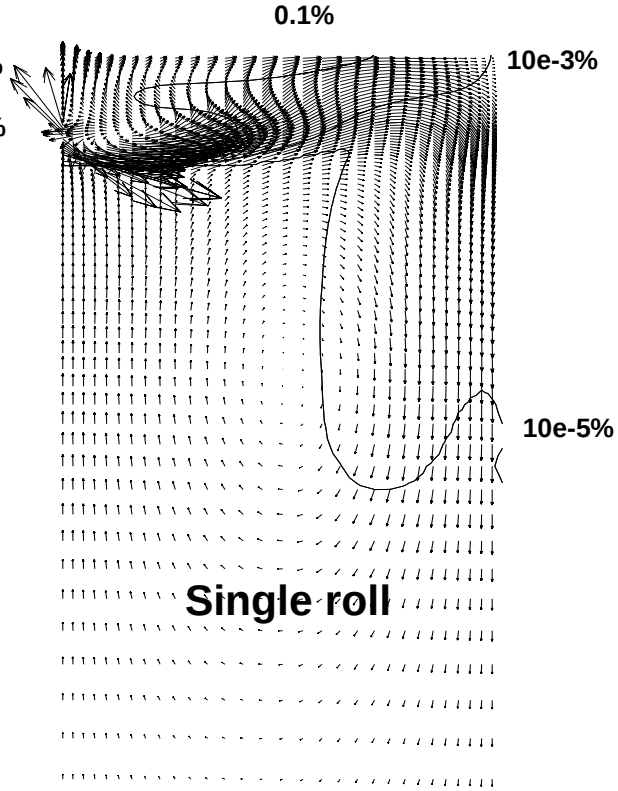
Effect of Gas Volume Fraction on Gas Penetration Depth

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
4 SLPM
5.7% Gas
2.59mm bubble(normal)



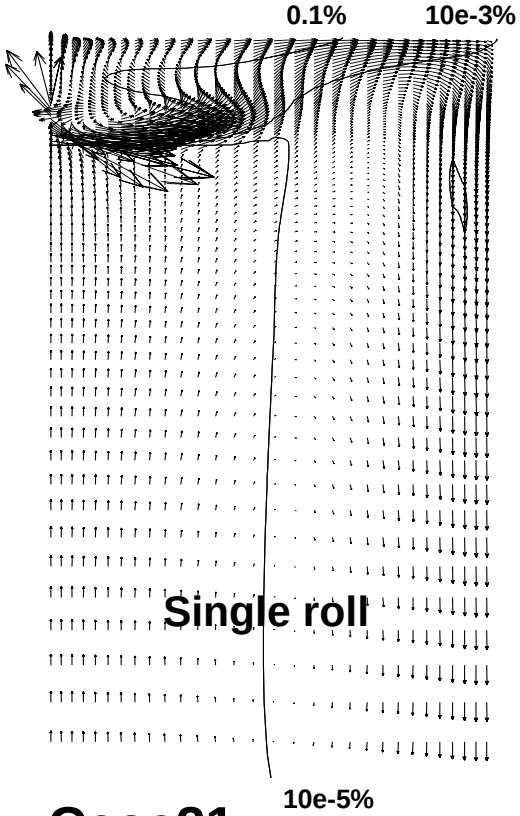
Case23

Conditions:
1.854 m slab
14.8mm/s
(2.64onne/min)
6.3 SLPM
8.5% Gas
2.59mm bubble(normal)



Case24

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
8.37 SLPM
11% Gas
2.59mm bubble(normal)



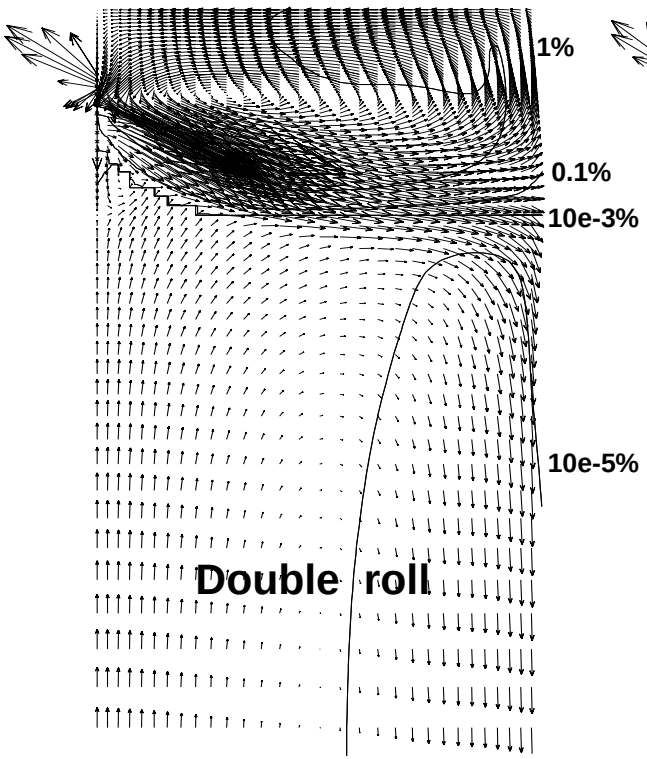
Case21

Effect of Gas Volume Fraction on Gas Penetration Depth

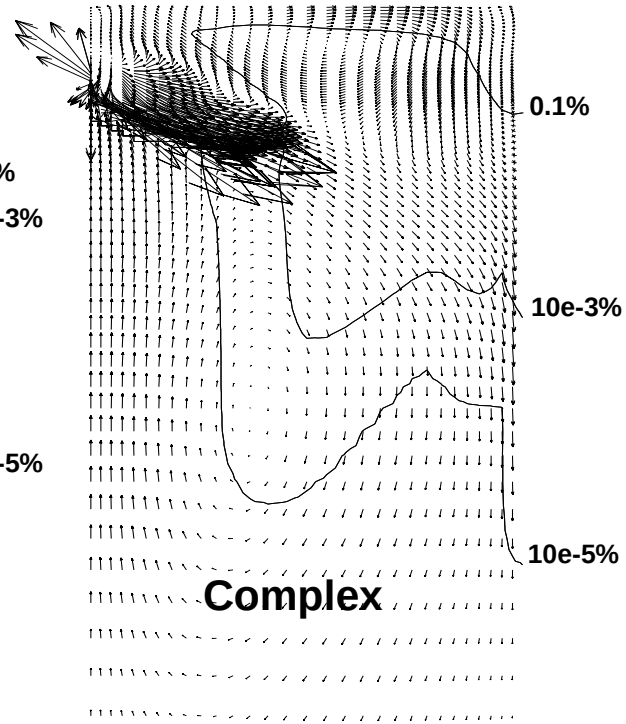
Conditions:
1.854 m slab
23.3mm/s
(4.1tonne/min)
4 SLPM
3.7% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
23.2mm/s
(4.1tonne/min)
6.4 SLPM
5.7% Gas
2.59mm bubble(normal)

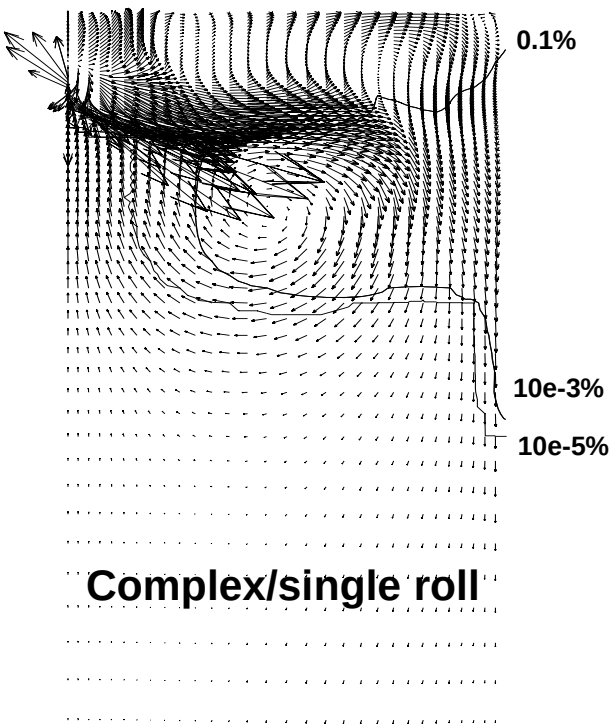
Conditions:
1.854 m slab
23.2mm/s
(4.1tonne/min)
13 SLPM
11% Gas
2.59mm bubble(normal)



Case22



Case20



Case18

Effect of Gas Volume Fraction on Flow Pattern

Conclusion:

1. Successively decreasing gas volume fraction, the flow pattern will change from single roll to complex flow pattern and then to double roll.

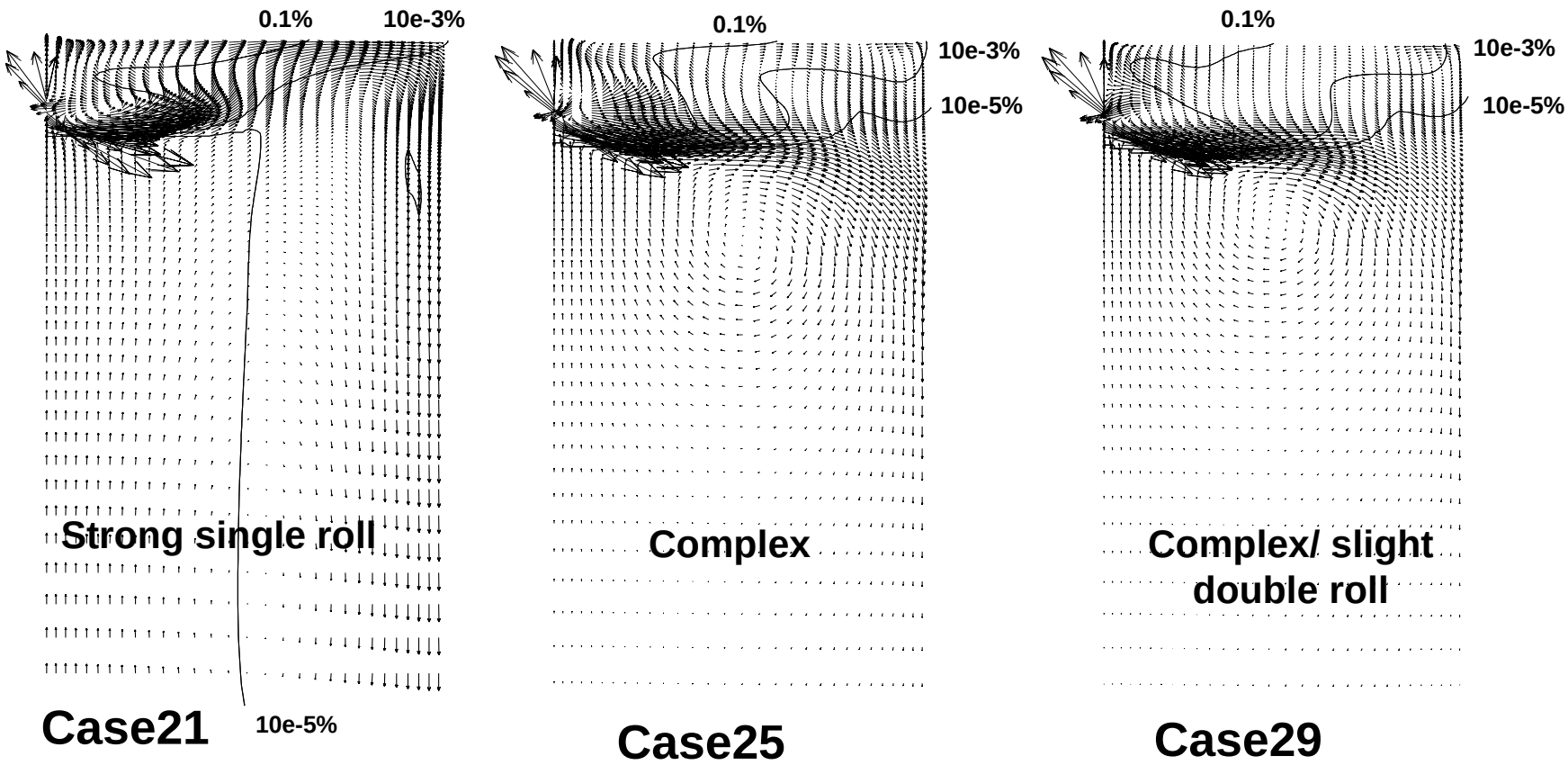
2. Lower gas volume fraction tends to a double roll flow pattern.

Effect of Gas Volume Fraction on Flow Pattern (Low Throughput)

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
8.37 SLPM
11% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
2.6 SLPM
3.7% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
0.83 SLPM
1.2% Gas
2.59mm bubble(normal)

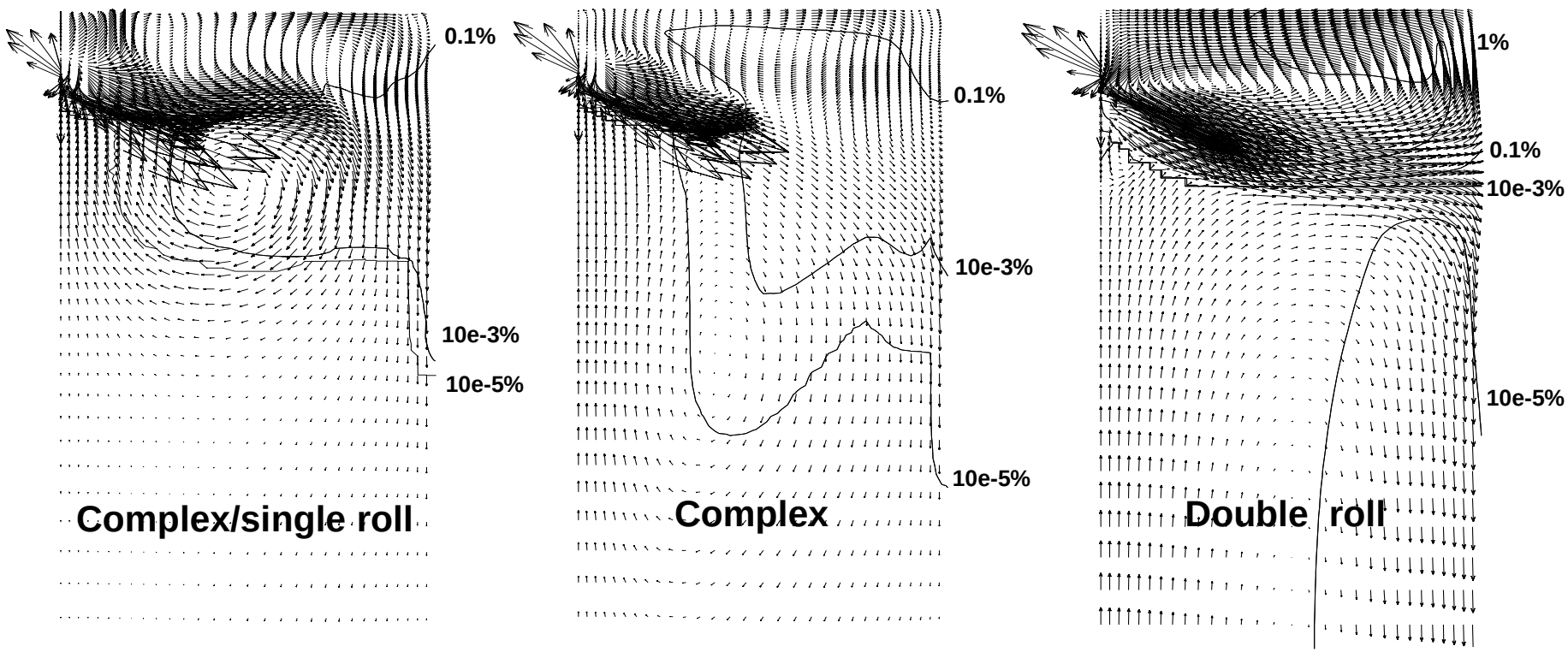


Effect of Gas Volume Fraction on Flow Pattern (High Throughput)

Conditions:
1.854 m slab
23.2mm/s
(4.1tonne/min)
13 SLPM
11% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
23.2mm/s
(4.1tonne/min)
6.4 SLPM
5.7% Gas
2.59mm bubble(normal)

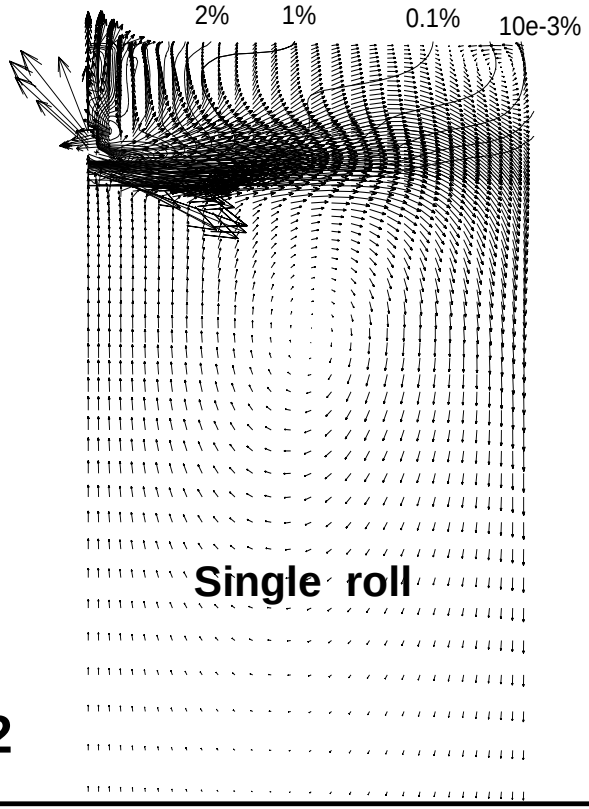
Conditions:
1.854 m slab
23.3mm/s
(4.1tonne/min)
4 SLPM
3.7% Gas
2.59mm bubble(normal)



Case18 **Case20** **Case22**

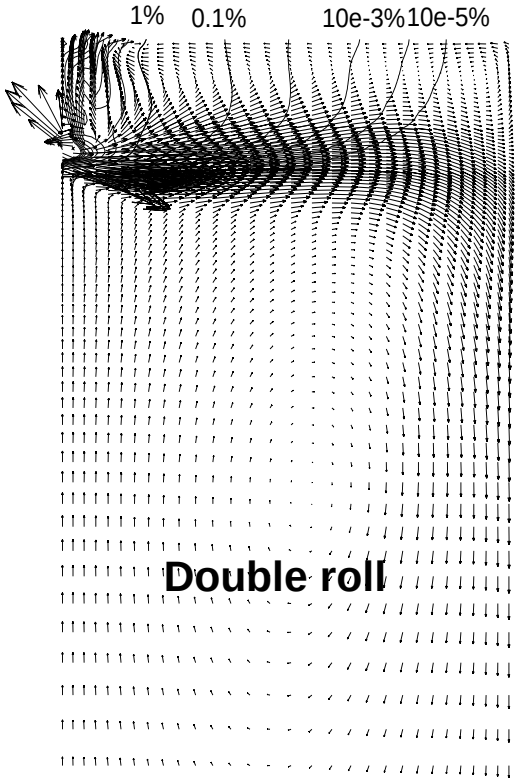
Effect of Gas Volume Fraction on Flow Pattern (Bi Modal Bubble Distribution)

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
13.4 SLPM
16.4% Gas
2.43mm bubble(Bi modal)



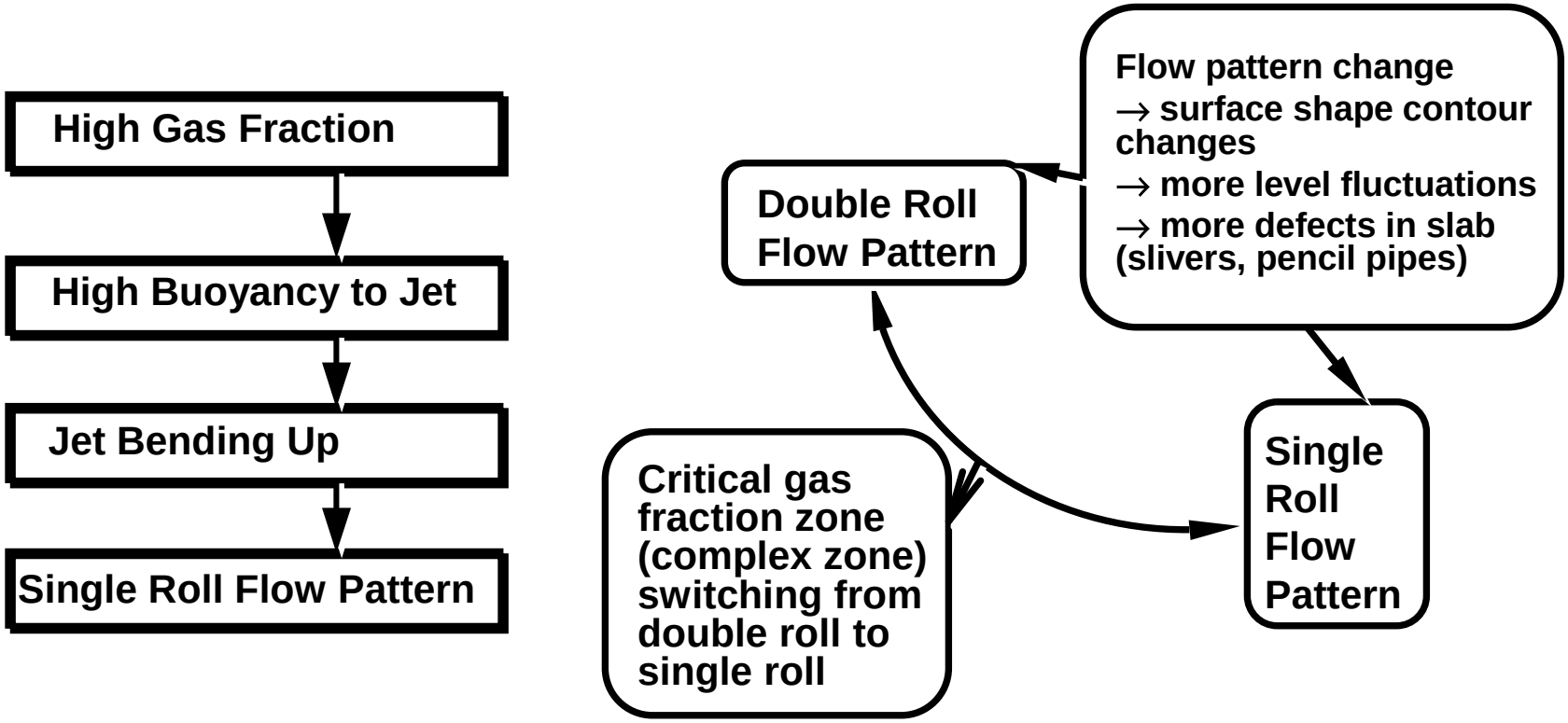
Case12

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
6.3 SLPM
8.5% Gas
2.43mm bubble(Bi modal)



Case13

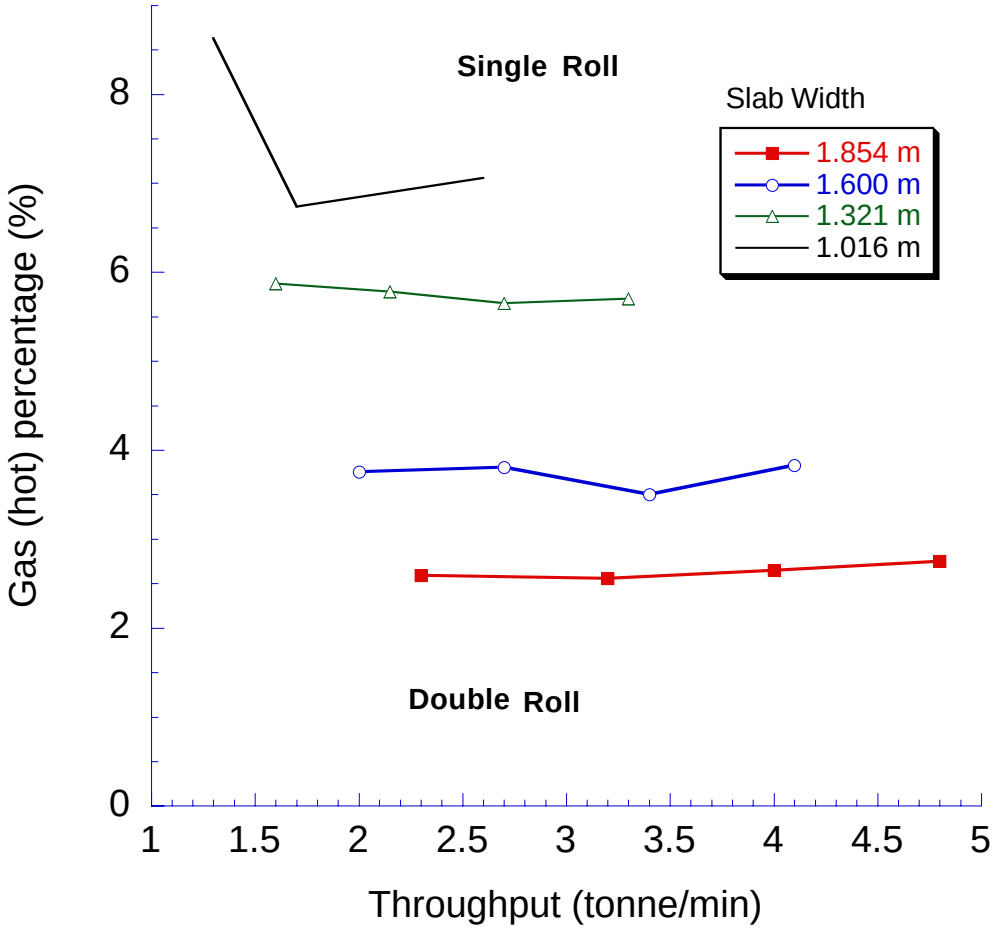
Effect of Gas Volume Fraction on Flow Pattern



<u>Conclusion</u>: Gas fraction should be kept stable and away from complex zone to give a stable flow pattern.

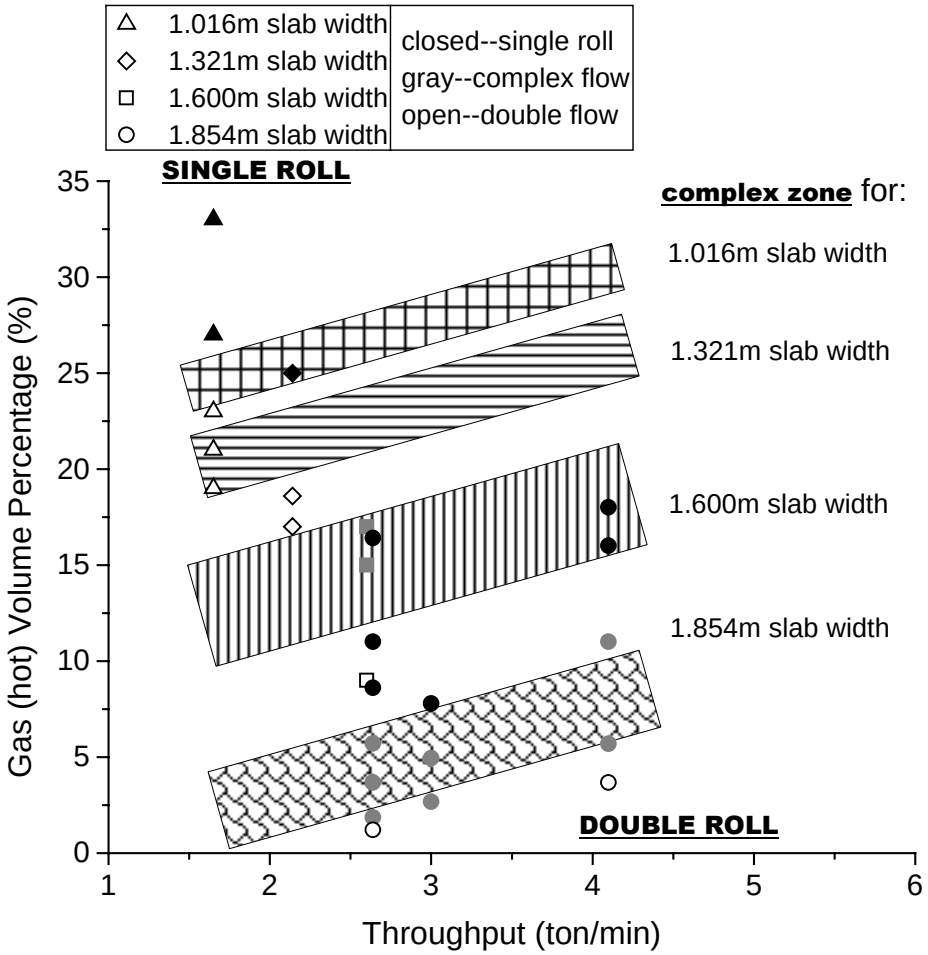
Flow Pattern Identification (Water Model)

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



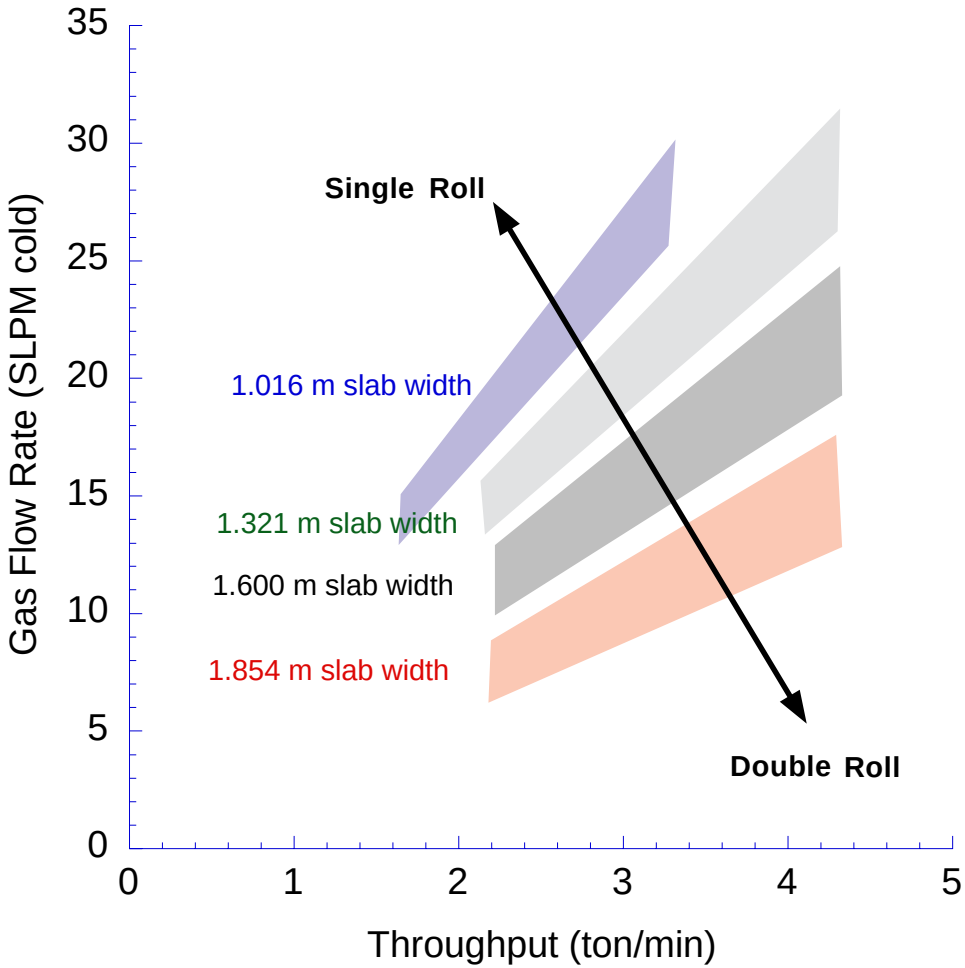
M. B. Assar, P. H. Dauby and G. D. Lawson. Opening then black box: PIV and MFC measurements in a continuous caster mold. 83rd Steelmaking Conference Proceedings, P397-411

Flow Pattern Identification (Real Caster)
— Gas (Hot) Volume Fraction and Steel Throughput



Note: The points for the cases with 2.43 mm mean size bi modal bubbles are deleted.

Flow Pattern Identification (Real Caster) — Effect of Gas Flow Rate (Approx.)



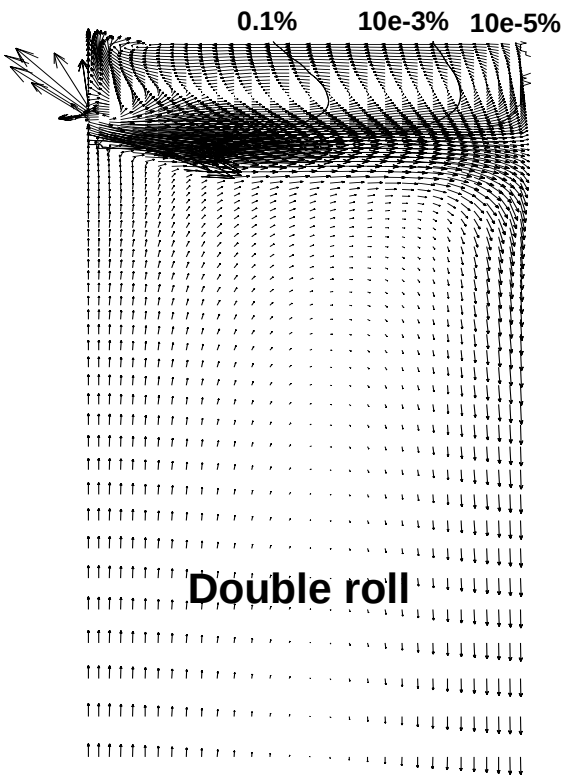
Effect of Bubble Size Distribution on Flow Pattern

Conclusion:

With other conditions same, the bi modal bubble distribution tends to double roll and the normal distribution tends to single roll.

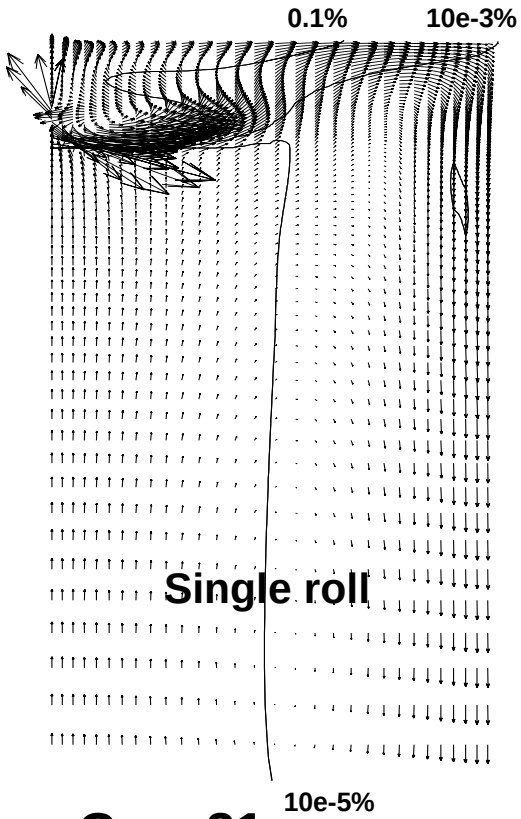
Effect of Bubble Size Distribution on Flow Pattern

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
8.4 SLPM
11% Gas
2.43mm bubble(bi modal)



Case14

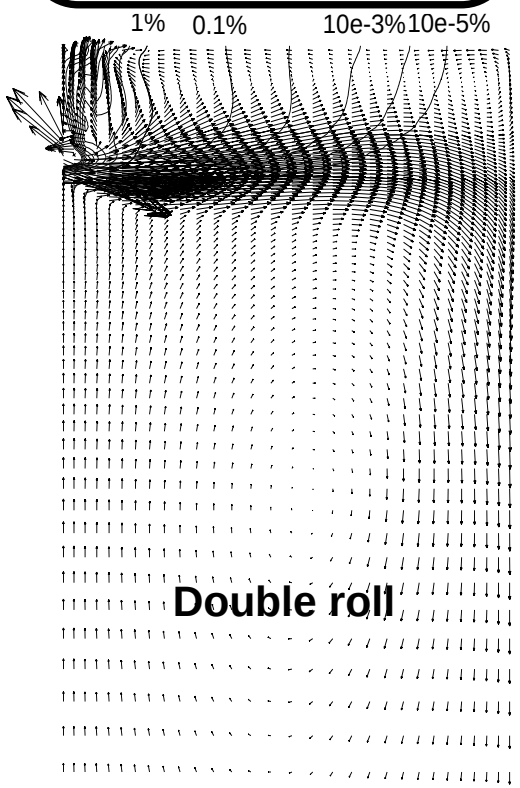
Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
8.37 SLPM
11% Gas
2.59mm bubble(normal)



Case21

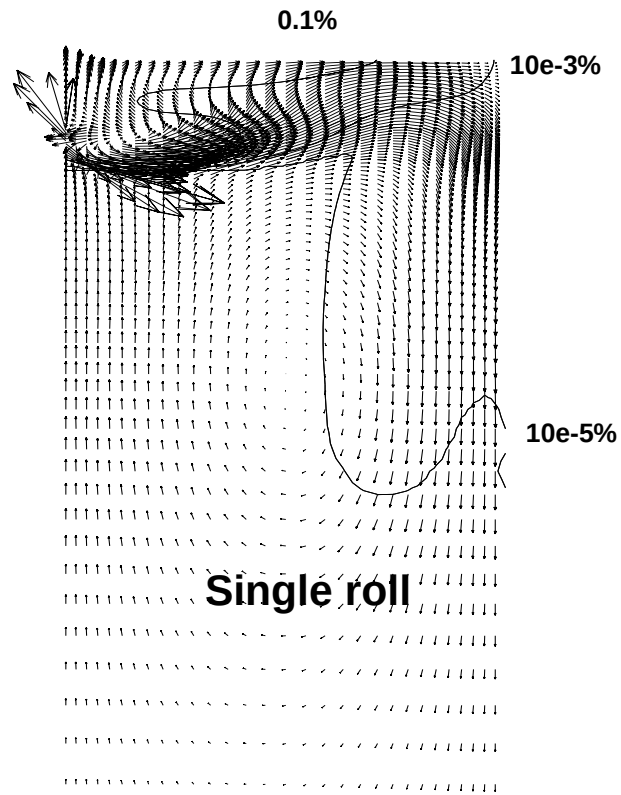
Effect of Bubble Size Distribution on Flow Pattern

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
6.3 SLPM
8.5% Gas
2.43mm bubble(bi model)



Case13

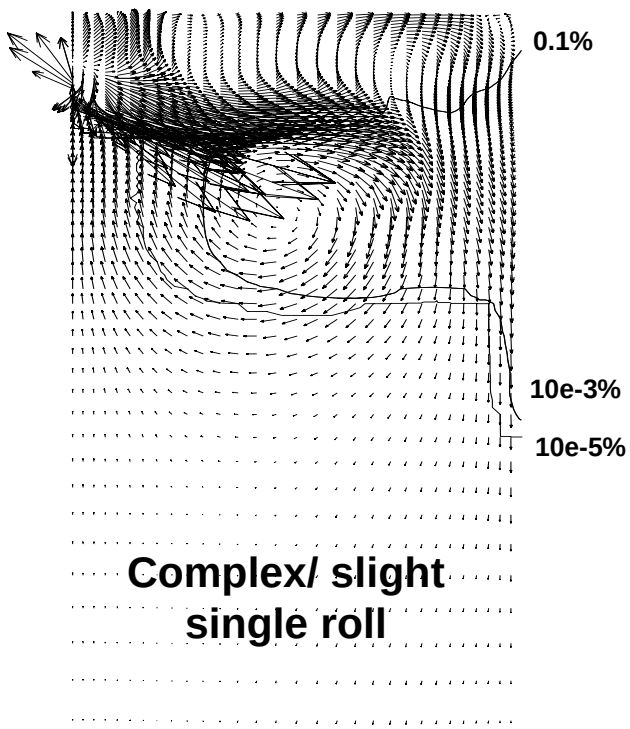
Conditions:
1.854 m slab
14.8mm/s
(2.64onne/min)
6.3 SLPM
8.5% Gas
2.59mm bubble(normal)



Case24

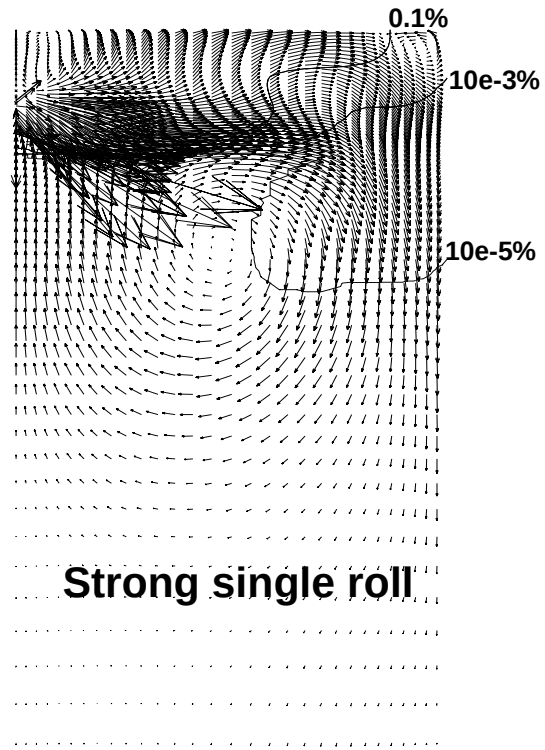
Effect of Bubble Size on Flow Pattern

Conditions:
1.854 m slab
23.2mm/s
(4.1tonne/min)
13 SLPM
11% Gas
2.59mm bubble(normal)



Case18

Conditions:
1.854 m slab
23.2mm/s
(4.1tonne/min)
13 SLPM
11% Gas
3.69mm bubble(normal)



Case19

Factors Affecting Gas Penetration

Conclusion:

Assuming that shallower gas penetration leads to fewer internal defects, the following conclusion can be derived:

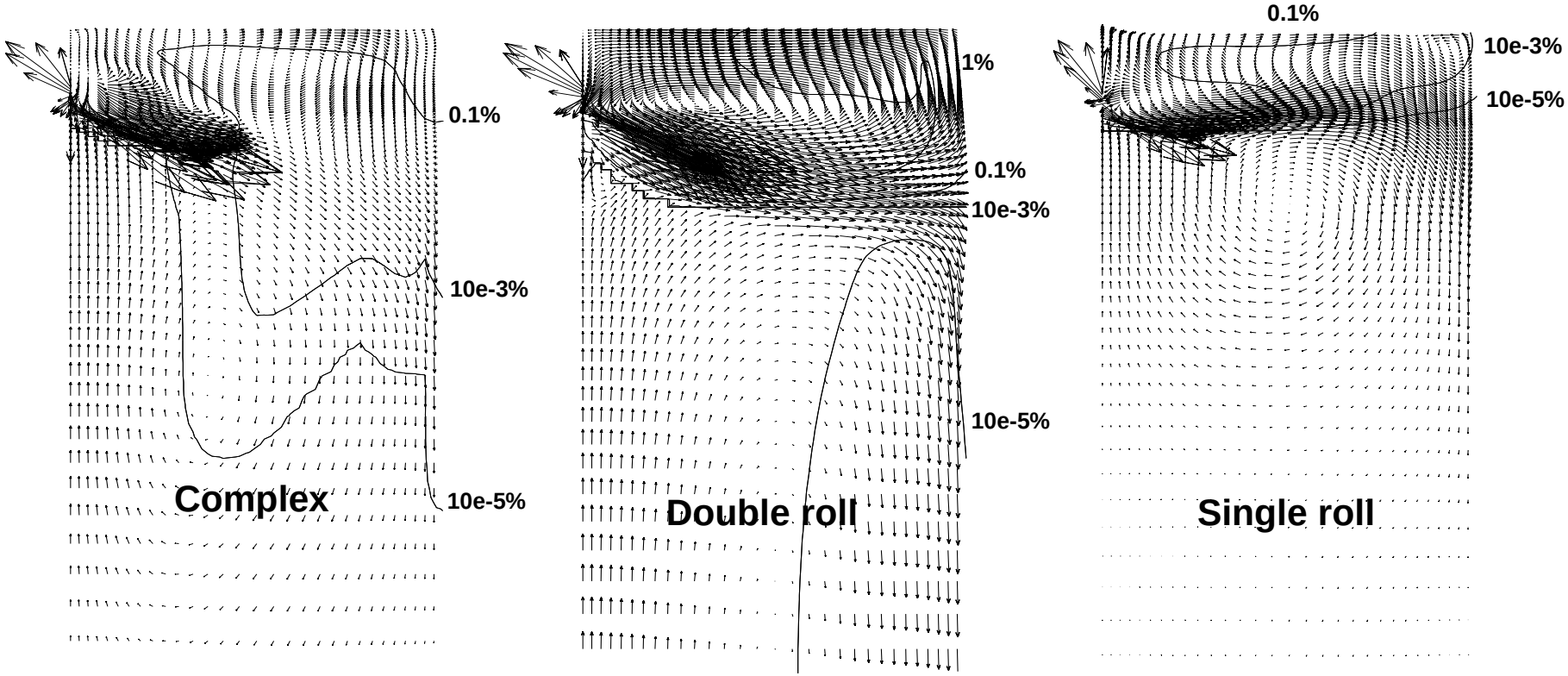
Smaller steel throughput and larger gas volume fraction (case23) has less internal defects than either case20 (larger steel throughput and larger gas volume fraction) or case22 (larger steel throughput and smaller gas volume fraction).

Factors Affecting Gas Penetration

Conditions:
1.854 m slab
23.2mm/s
(**4.1tonne/min**)
6.4 SLPM
5.7% Gas
2.59mm bubble(normal)

Conditions:
1.854 m slab
23.3mm/s
(**4.1tonne/min**)
4 SLPM
3.7% Gas
2.59mm bubble(normal)

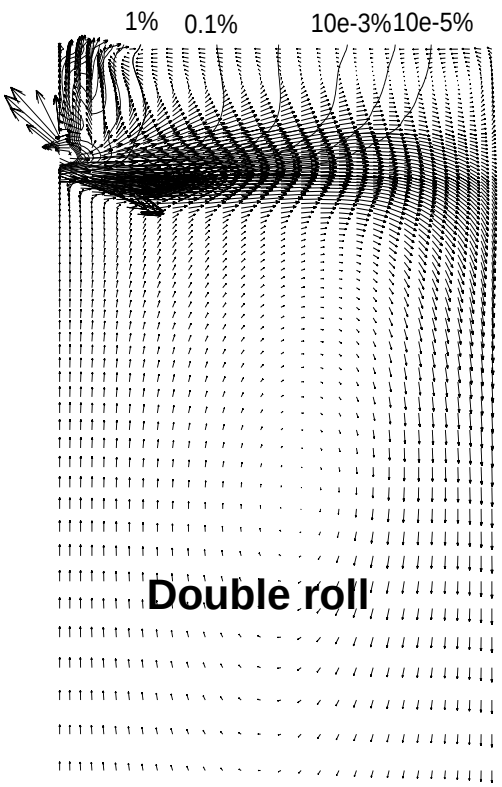
Conditions:
1.854 m slab
14.8mm/s
(**2.64tonne/min**)
4 SLPM
5.7% Gas
2.59mm bubble(normal)



Case20 **Case22** **Case23**

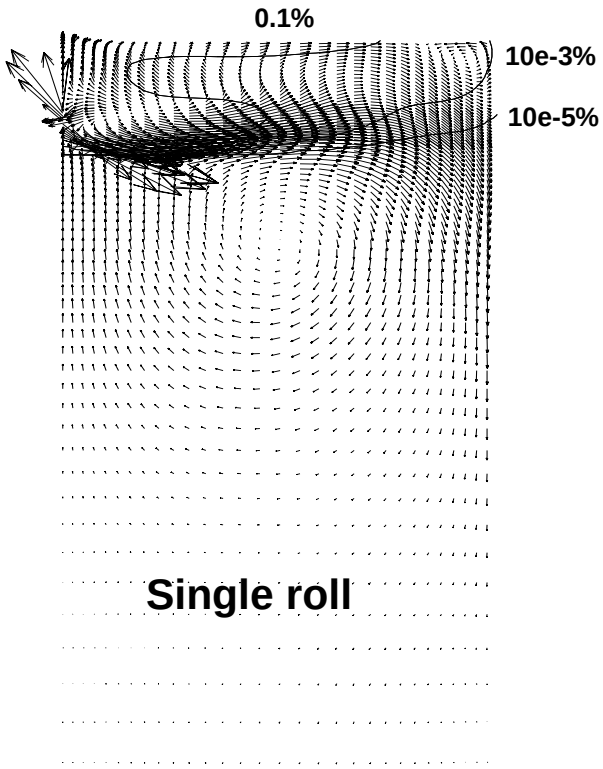
Best Case with the Lowest Gas Penetration Depth

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
6.3 SLPM
8.5% Gas
2.43mm bubble(bi model)



Case13

Conditions:
1.854 m slab
14.8mm/s
(2.64tonne/min)
4 SLPM
5.7% Gas
2.59mm bubble(normal)



Case23

Conclusion:

Lower gas penetration depth for:

1. Double roll flow pattern

2. Lower steel throughput

Effect of Slab Width on Flow Pattern

Deceasing of Slab Width

↓

Decreasing of the Distance between Nozzle Port and Narrow Face

↓

Jet Having Less Time to Be Lifted

↓

Tending to Double Roll Flow Pattern

<u>Conclusion</u>: Keeping casting speed and gas fraction constant, decreasing slab width is likely to have a double roll flow pattern in caster, with accompanying better stability and less gas penetration and defects.

Effect of SEN Submergence Depth on Flow Pattern

Increasing Submergence Depth

↓

Increasing the Distance from Jet to Top Surface

↓

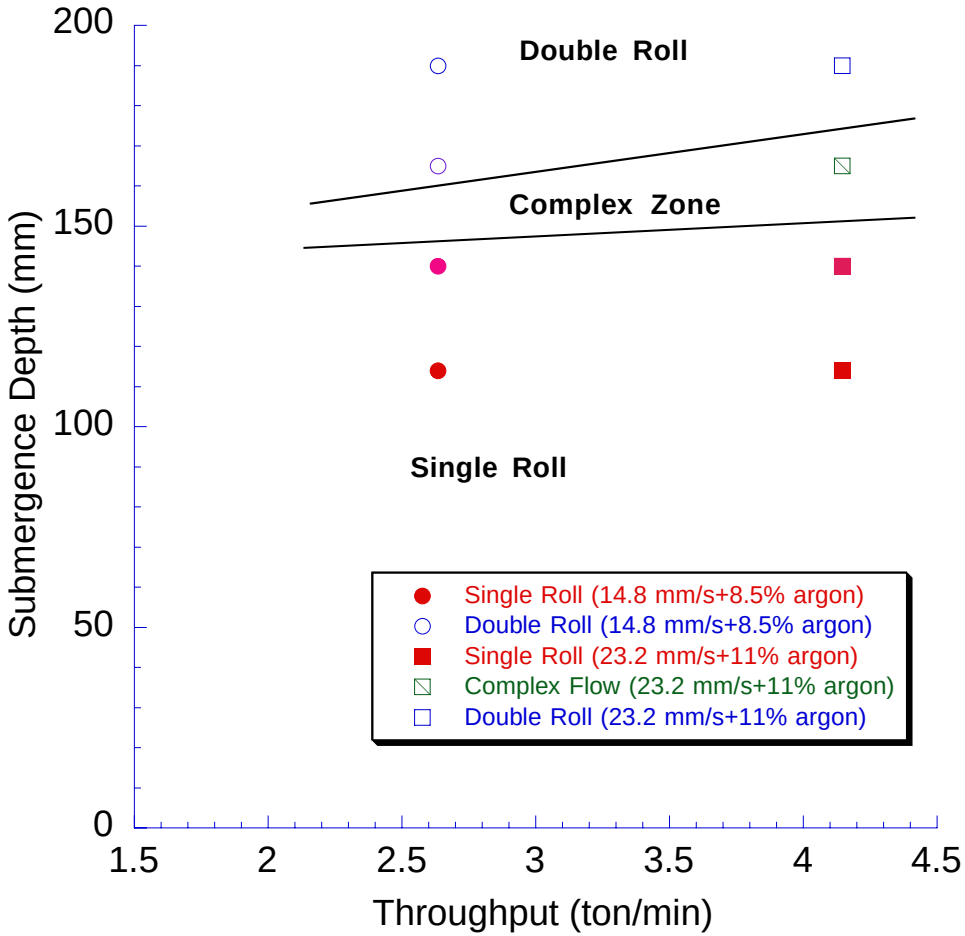
More Difficult for the Bent Jet Reaching the Top Surface

↓

Tending to a Double Roll

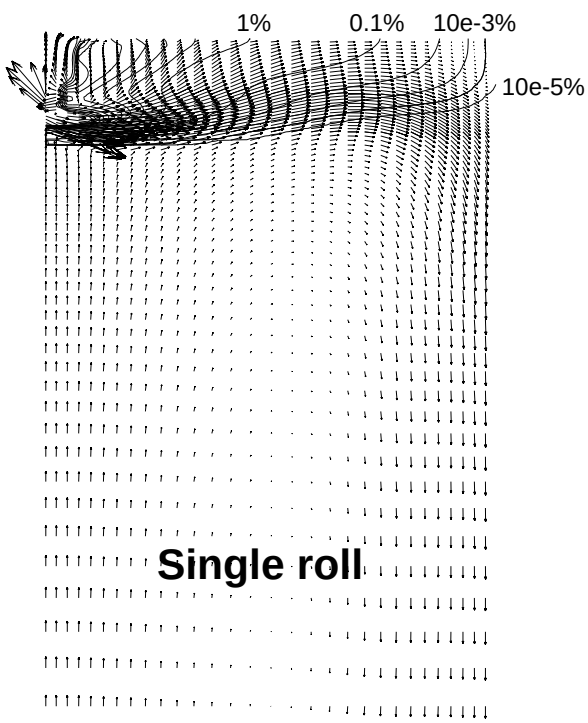
<u>Conclusion</u>: For a given gas fraction and throughput, increasing submergence depth more likely generates double roll.

Flow Pattern Identification (Real Caster)
— Effect of SEN Submergence Depth

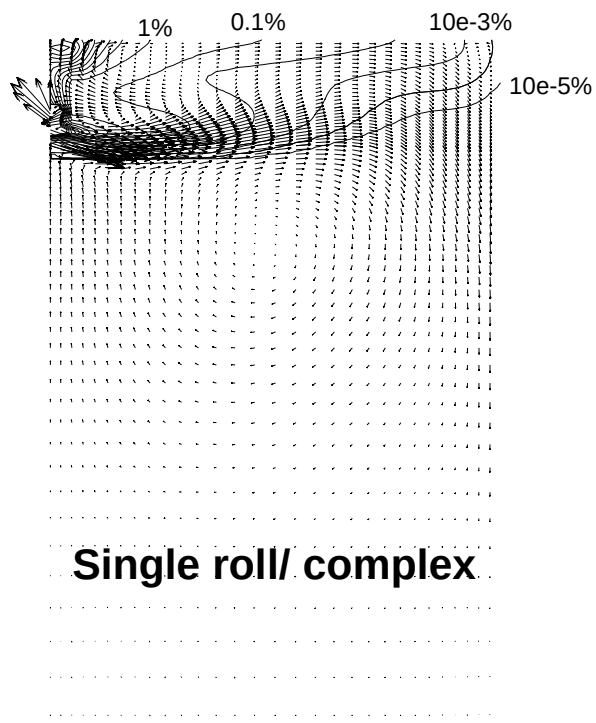


Computed Velocity at Centerplane with Different SEN Submergence

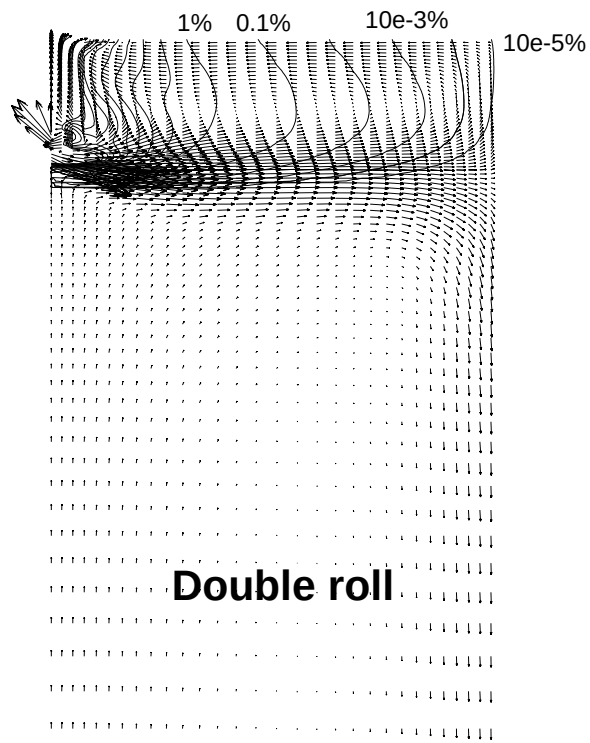
Conditions: 1854mm slab, 14.8mm/s, 8.5%gas (hot)



submergence depth 114 mm (4.5 inch)



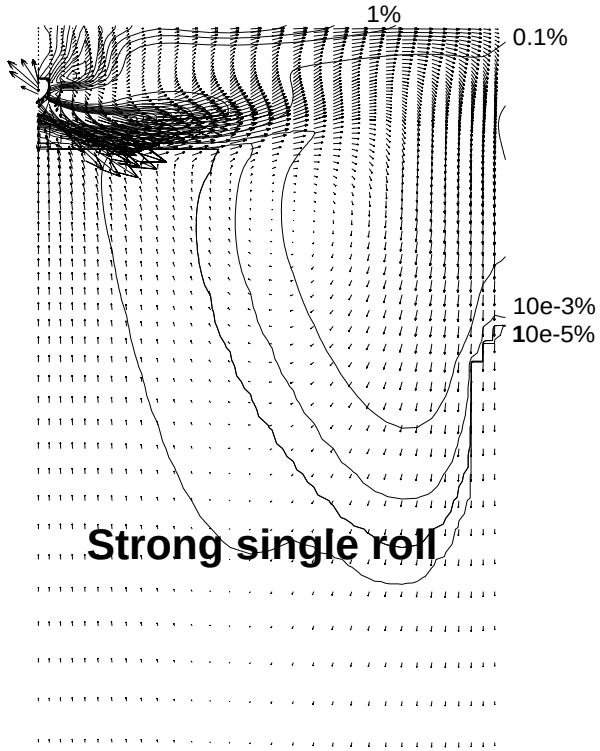
submergence depth 140 mm (5.5 inch)



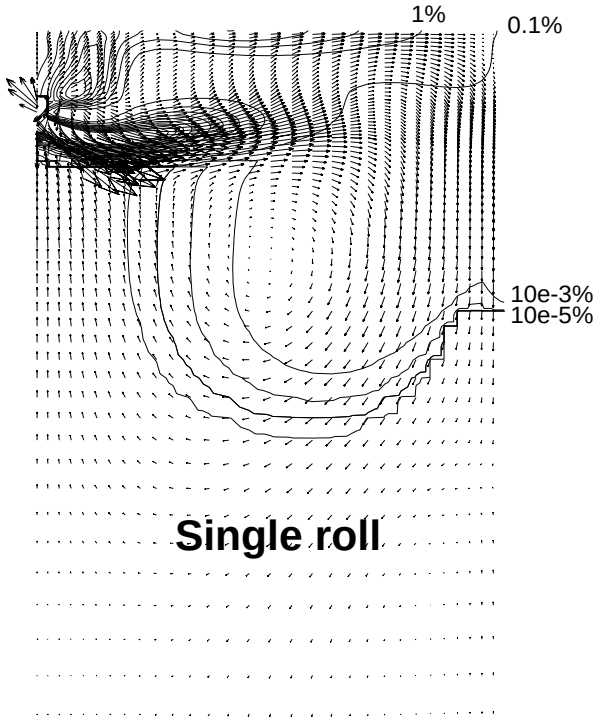
submergence depth 190mm (7.5 inch)

Computed Velocity at Centerplane with Different SEN Submergence

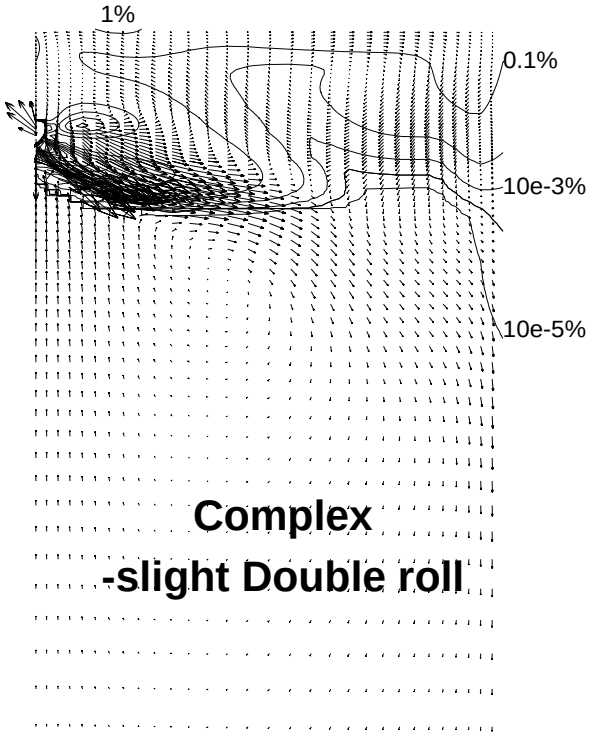
Conditions: 1854mm slab, 23.2mm/s, 11%gas (hot)



submergence depth 114mm (4.5 inch)



submergence depth 140 mm (5.5 inch)



submergence depth 190 mm (7.5 inch)

Conclusions

1. Computational simulation and measurements show that the flow pattern in the steel caster is sometimes very different from that in a scale water model and the steady, multiphase k-ε computation can match both. The main reason for this difference is the reduced scale of water model combined with the Froude-based velocity scaling criterion used to choose the water model flow rates.
2. Flow pattern changes during continuous casting, leads to surface contour changes and accompanying level fluctuations and defects, so should be avoided
3. Gas flow rate, casting speed, gas volume fraction, mold width, SEN submergence depth all change the fluid flow pattern. Optimal argon injection depends on all of these factors.
4. Lower steel throughput generates less gas penetration and tends to more single roll.

Conclusions

5. For the same flow pattern, increasing gas volume fraction causes deeper gas penetration. Double roll flow pattern generally has less penetration than single roll. When flow pattern changes, the effect of gas volume fraction on is unclear.

6. Decreasing gas volume fraction tends to change the flow pattern from single roll to complex flow pattern and then to double roll.

7. With other conditions constant, the bi modal bubble distribution tends to double roll and the normal bubble distribution tends to single roll.

8. The least gas penetration depth is found with double roll flow pattern and lower steel throughput.

9. For a given gas fraction and steel throughput, increasing submergence depth tends to generate double roll.

Further Work

1. **Validate and extend the current findings.**
2. **Improve the multiphase fluid flow model with multiple size bubbles. Quantitatively Investigate the function of bubble breakup and coalescence on the fluid flow and compared with measurements.**
3. **Quantify the conditions which lead to defects such as pencil pipes and then quantify the flow patterns which lead to safe conditions through subsequent parametric studies by the developed mathematical models.**
4. **Further study on gas flow behavior in the industrial nozzle.**