Effect of argon gas distribution on fluid flow in the mold using timeaveraged K-ε model

Tiebiao Shi

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Outline

- MUSIG multiphase flow model
- Effect of submergence depth on flow pattern
- Investigation of the influence of bubble size on flow pattern switching in the continuous casting mold using MUSIG model
- Predict the jet deflection quantitatively in the multiphase flow

MUSIG Multiphase Flow Model

What is new with MUSIG Model ?

- Bubbles are divided into different size groups
- Bubbles are allowed to breakup and coalesce

Case No.	Inlet bubble size distribution									
	Size group (mm)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	
1	Vol. Fraction (%)		100							
2	Vol. Fraction (%)			100						
3	Vol. Fraction (%)				100					
4	Vol. Fraction (%)					100				
5	Vol. Fraction (%)								100	
6	Vol. Fraction (%)	25	40	35						
7	Vol. Fraction (%)						25	40	35	
8	Vol. Fraction (%)	10	11	12	13	13	14	14	13	
9	Size group (mm)	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	
	Vol. Fraction (%)	50							50	

Investigation of 9 cases using MUSIG model

	Casting speed =35 inch/min
	Gas injection rate =6.3 L/min
Mold Width	1854 mm
Mold Thickness	228 mm
Nozzle Submergence Depth (top surface to top of port)	120 mm
Nozzle Bore Inner Diameter	78 mm
Nozzle Port Height	78 mm
Nozzle Port Width	78 <i>mm</i>
Inlet Jet Height, L _h	50 mm
Inlet Jet Width, L_w	78 mm
Vertical Velocity in Nozzle	1.31 <i>m/s</i>
Nominal Vertical Angle of Port Edges	15° down
Inlet Jet Spread Angle	0°
Casting Speed, V _c	14.8 <i>mm/s</i>
Inlet Velocity, V _x	0.8766 <i>m/s</i>
Inlet Velocity, V_z	0.3018 <i>m/s</i>
Jet Angle at Inlet, α	19° down
Inlet Turbulent Kinetic Energy, K _o	$0.0502 \ m^2/s^2$
Inlet Turbulence Dissipation Rate, ϵ_{o}	$0.457 \ m^2/s^3$
Liquid Steel Density, ρ_1	$7020 \ kg/m^3$
Gas Density, ρ_{gas}	$0.559 \ kg/m^3$
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 <i>N/m</i>
Inlet Gas Flow Rate	0.0063 <i>m³/min</i>
Inlet Gas Volume Fraction, f_{gas}	8.5%
Average Gas Bubble Diameter, D_0	0.5-4.0 mm
Gravitational Acceleration, g	9.8 m/s^2

Other Modeling Parameters

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



Flow Domain

0.5 m/s

Case 1 (Inlet bubble distribution: 1.0mm 100%)



Case 2 (Inlet bubble distribution: 1.5mm 100%)



Case 3 (Inlet bubble distribution: 2.0mm 100%)



Case 4 (Inlet bubble distribution: 2.5mm 100%)



Case 5 (Inlet bubble distribution: 4.0mm 100%)



Case 6 (Inlet bubble distribution: 0.5mm 25% 1.0mm 40% 1.5mm 35%)



Case 7 (Inlet bubble distribution: 3.0mm 25% 3.5mm 40% 4.0mm 35%)



Case 8 (Inlet bubble distribution: 0.5mm 10% 1.0mm 11% 1.5mm 12% 2.0mm 13% 2.5mm 13% 3.0mm 14% 3.5mm 14% 4.0mm 13%)



Case 9 (Inlet bubble distribution: 0.5mm 50% 7.5mm 50%)



Gas Volume Fraction Contour for Uniform Size Cases



Gas Volume Fraction Contour for Size Distribution Cases

Relationship between gas volume fraction and bubble size for <u>Uniform Size Model</u>*



*Uniform Size Model was used in previous modeling. It does not allow breakup and coalescence of bubbles in the domain.

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Velocity vector comparison (center plane)



Gas volume fraction contour comparison (center plane)

Left: Uniform Size Model (bubble diameter 1.0mm) Right: MUSIG Model (Inlet bubble dstribution: 1.0mm uniform)

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Velocity vector comparison (center plane)



Gas volume fraction contour comparison (center plane)

Left: Uniform Size Model (bubble diameter 2.0mm) Right: MUSIG Model (Inlet bubble dstribution: 2.0mm uniform)



percentage of 0.5mm bubble in all bubbles



percentage of 1.0mm bubble in all bubbles



percentage of 2.0mm bubble in all bubbles

percentage of 4.0mm bubble in all bubbles

*above figures are all for volume fraction



Total gas volume fraction contour

Distribution of bubble sizes in the mold

(inlet bubble distribution: 2.0mm uniform)





percentage of 0.5mm bubble in all bubbles

percentage of 1.0mm bubble in all bubbles



percentage of 2.0mm bubble in all bubbles

*above figures are all for volume fraction

ubbles percentage of 4.0mm bubble in all bubbles



Total gas volume fraction contour

Distribution of bubble sizes in the mold

(inlet bubble distribution: 0.5mm bubble 50%, 7.5mm bubble 50%)

Observations

- Distributed-bubble-size MUSIG model has slightly different liquid and gas flow behavior than uniform bubble size model
- For MUSIG model, bubbles exert less lifting force on the liquid flow than uniform bubble size model perhaps due to coalescence and breakup of bubbles.
- The overall relationship between mean bubble size and flow pattern remains the same for both models.

Effect of submergence depth on flow pattern

- Model: MUSIG model
- Inlet bubble distribution: 2.0 mm uniform size
- Geometry and other parameters: Same as the previous 9 cases(see page 4).
 V_c =35 inch /min, Q_{gas}=6.3 l/min
- 4 cases with different submergence depth:
 4.2, 4.7, 5.2 and 6.5 inches

Velocity vector plots at center plane for different submergence depth

submergence depth=6.5 inch

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submergence depth=4.7 inch

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Velocity contour plots at center plane for different depth

submergence depth=5.2 inch



Conclusions

- With decreasing submergence depth, flow pattern is easier to be single roll. Changing from double roll to single roll causes a series of changes in other parameters.
- Effect of submergence depth on other important parameters will be analyzed in future research.

Investigation of the influence of bubble size on flow pattern switching in the continuous casting mold using MUSIG model

Two Cases

• Case A:

Casting Speed: 55 inch/min Gas Flow Rate: 13 Liter/min More pencil pipe defects

Case B: Casting Speed: 35 inch/min Gas Flow Rate: 6.3 Liter/min More sliver defects

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	Case A(13L/min,55"/min)	Case B(6.3L/min,35"/min)
Mold Width	1854 mm	
Mold Thickness	228 mm	
Nozzle Submergence Depth	120 mm	
(top surface to top of port)		
Nozzle Bore Inner Diameter	78 mm	
Nozzle Port Height	78 mm	
Nozzle Port Width	78 <i>mm</i>	
Inlet Jet Height, L _h	50 mm	50 mm
Inlet Jet Width, L_w	78 mm	
Vertical Velocity in Nozzle	2.05 m/s	1.31 <i>m/s</i>
Nominal Vertical Angle of Port Edges	15° down	
Inlet Jet Spread Angle	0°	
Casting Speed, V_c	23.2 <i>mm/s</i>	14.8 <i>mm/s</i>
Inlet Velocity, V _x	1.4127 <i>m</i> / <i>s</i>	0.8766 <i>m/s</i>
Inlet Velocity, V _z	0.4051 <i>m/s</i>	0.3018 <i>m/s</i>
Jet Angle at Inlet, α	16° down	19° down
Inlet Turbulent Kinetic Energy, K_o	$0.0502 \ m^2/s^2$	
Inlet Turbulence Dissipation Rate, $\epsilon_{\!\scriptscriptstyle o}$	$0.457 \ m^2/s^3$	
Liquid Steel Density, ρ_1	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 <i>N/m</i>	
Inlet Gas Flow Rate	$0.013 \ m^{3}/min$	0.0063 <i>m³/min</i>
Inlet Gas Volume Fraction, f_{gas}	11%	8.5%
Average Gas Bubble Diameter, D_o	2.0, 1.5 mm	2.0, 1.5 mm
Gravitational Acceleration, g	9.8 m/s^2	

Parameters in the modeling

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



Geometry for Case A and Case B

What is the bubble size at inlet ?

Deciding factors:

1) Vertical velocity in the nozzle: Case A: U=2.05 m/s Case B: U=1.31 m/s

2) Gas injection rate per pore*: Case A: Q_{gas}=2.17 ml/s Case B: Q_{gas}=1.05 ml/s

*Assuming at least 100 pores for gas injection in the nozzle

Relationship between Mean Bubble Diameter and Gas Flow Rate and Liquid Flow Velocity



*Above figure is rearranged from fig.3, Hua Bai and Brian G. Thomas,Met&Mat Trans.B, submitted in June, 2000

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How is bubble size distributed at inlet?

Deciding factor*: liquid flow velocity

U >1.9 m/s, Mode III, mixture of large and small bubbles

U <1.4 m/s, Mode II, relatively uniform-sized bubbles

*see Hua Bai's thesis

Measured relationship between bubble size, distribution and mode and gas flow rate and liquid flow velocity



*Above figure is rearranged from fig.3, Hua Bai and Brian G. Thomas, Met&Mat Trans.B, submitted in June, 2000

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Estimation of average bubble size and size distribution at inlet

	Case A	Case B
	(55inch/min,13l/min)	(35inch/min,6.31/min)
Liquid Flow Rate(Q _{liq} ,m ³ /s)	9.81	6.26
Velocity in Nozzle(V,m/s)	2.05	1.31
Largest Gas Flow Rate Per	2.17	1.05
Pore(ml/s)		
Estimated Mean Bubble	1.8-2.58	2.0-2.55
Diameter(mm)		
Bubble Formation Mode	III	Π

How is bubble size distributed at inlet for Case A and Case B

- Water model experiments were conducted under similar conditions corresponding to those of Case A and Case B
- The mean bubble diameter is calculated as:

$$D_{avg} = 2 * \sqrt[3]{3 * (\sum_{i=1}^{n} (N_i * V_i) / \sum_{i=1}^{n} N_i) / 4 / \pi}$$

Schematic of two-needle water model for bubble size distribution investigation



University of Illinois at Urbana-Champaign M

Metals Processing Simulation Lab

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Bubble Size Distribution Investigation

Diameter	<1.0	1.0	1.5	2.0	2.5	3.0	3.0-	>5.0	Photo
of bubbles(mm)							5.0		Frame No.
Data Set #1	4	3	1	1	0	1	1	0	159
Data Set #2	2	0	0	0	0	0	1	0	219
Data Set #3	0	0	0	1	1	0	1	0	265
Data Set #4	2	1	1	0	1	0	1	0	285
Data Set #5	2	2	1	0	1	0	0	0	315
Data Set #6	3	2	0	0	0	1	2	0	368
Data Set #7	0	1	1	0	0	0	2	0	397
Data Set #8	3	2	0	1	0	0	1	0	532
Data Set #9	2	1	1	0	1	0	2	0	631
Data Set #10	1	2	0	1	0	0	2	0	668
Total Number	19	14	5	4	4	2	13	0	
Total Volume	3.73	11.00	8.84	12.57	19.63	14.14	163.3	0	
(mm^3)									
Volume %	1.6	4.72	3.79	5.39	8.42	6.06	70	0	

Case Bubble A (Q_{air}=1.2ml/s,U_{water}=1.92 m/s, Mode III)

*total volume=233.21 mm³

**total number of bubbles=61

*** mean bubble diameter=1.94 mm

**** The diameter of big bubbles(3.0mm<d<5.0mm) is difficult to measured due to the large distortion of big bubbles. An average diameter of 4.0mm is assumed for these big bubbles falls between 3.0mm and 5.0 mm.

Bubble Size Distribution Investigation

Diameter	<1.0	1.0	1.5	2.0	2.5	3.0	>3.0	Photo
of bubbles(mm)								Frame No.
Data Set #1	0	0	2	5	4	2	0	141
Data Set #2	0	0	3	4	2	3	0	177
Data Set #3	0	0	1	7	3	0	0	211
Data Set #4	0	0	2	7	3	1	0	246
Data Set #5	0	1	6	4	4	0	0	286
Data Set #6	0	0	2	3	6	2	0	341
Data Set #7	0	1	3	7	3	0	0	380
Data Set #8	0	0	2	8	4	2	0	444
Data Set #9	0	0	1	6	5	0	0	481
Data Set #10	0	0	2	5	4	2	0	522
Total Number	0	2	24	56	38	12	0	
Total Volume	0	2.09	56.55	234.57	248.71	113.1	0	
(mm^3)								
Volume %	0	0.32	8.63	35.81	37.97	17.27	0	

Case Bubble B	$B(Q_{gas}=1.3ml/s,$	U _{water} =1.3m/s, Mode II)
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*total volume=655.02 mm³

**total number of bubbles=132

*** mean bubble diameter=2.12mm

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Bubble Size Distribution by Number



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Bubble Size Distribution by Volume



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Mold flow simulation - Mode II bubble size distribution

- From bubble size distribution investigation, it is known that bubble size distribute over a small range near the mean bubble diameter
- What is the difference if one uniform size is set as the inlet bubble size instead of a small range of bubble sizes?

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1.0mm bubble 100%

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0.5mm 25%-1.0mm40%-1.5mm35%

Velocity vector plots Case B(35inch/min, 6.3l/min)



1.0mm bubble 100%



0.5mm 25%-1.0mm40%-1.5mm35%

Velocity contour plots Case B(35inch/min, 6.3l/min)

How does the flow pattern change when mean bubble size is near the lower bound of estimated size range ?

- Flow pattern in the mold changes from single roll to double roll with increasing mean bubble size*
- The estimated mean bubble diameter: Case A: 1.8-2.58 mm Case B: 2.0-2.55 mm

*

• Four cases set up for Case A and Case B:

Run I: mean bubble diameter=2.0 mm, Case A Run II: mean bubble diameter=2.0 mm, Case B Run III: mean bubble diameter=1.5 mm, Case A Run IV: mean bubble diameter=1.5 mm, Case B

see "effect of gas bubble size on fluid flow in continuous casting mold", Tiebiao Shi, 1999 winter report

Bubble size distribution at inlet

		Cas	se A		Case B								
Diameter	Ru	n I	Rur	n III	Ru	n II	Run IV						
(mm)	Number	Volume	Number	Volume	Number	Volume	Number	Volume					
	Fraction	Fraction	Fraction	Fraction	Fraction	Fraction	Fraction	Fraction					
	%	%	%	%	%	%	%	%					
0.5	66	2.09	5	0.52	0	0	0	0					
1.0	22	5.56	4	3.35	0	0	0	0					
1.5	4	3.76	0	0 0		100	0	0					
2.0	0	0	1	6.71	0	0	100	100					
2.5	4	17.39	1	13.10	0	0	0	0					
3.0	0	0	1	22.64	0	0	0	0					
3.5	0	0	0	0	0	0	0	0					
4.0	4	71.21	1	53.67	0	0	0	0					
Avg. Diameter		_				_							
(mm)	1.	.5	2.	.0	1	.5	2.0						

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Velocity Vector Plot Case A(55 inch/min, 13l/min, Dmean=2.0 mm, distributed bubbles)





Velocity Vector Plot Case B(35 inch/min, 6.3l/min, Dmean=2.0 mm, uniform bubbles)



Velocity Vector Plot Case A(55 inch/min, 13l/min, Dmean=1.5 mm, distributed bubbles)



Velocity Vector Plot Case B(35 inch/min, 6.3l/min, Dmean=1.5 mm, uniform bubbles)



percentage of 0.5mm bubble in all bubbles



percentage of 1.0mm bubble in all bubbles



percentage of 2.0mm bubble in all bubbles

percentage of 4.0mm bubble in all bubbles

*above figures are all for volume fraction



Total gas volume fraction contour

Distribution of bubble sizes in the mold

(Case B:Vc=35 inch/min,Qgas=6.3 l/min, inlet bubble distribution: 2.0mm uniform, Mode II)

Effect of mean bubble diameter variation (Case A)

Velocity Vector Plot (55 inch/min, 13l/min, Dman=2.0 mm)

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Velocity Vector Plot (55 inch/min, 13l/min, Dmen=1.5 mm



0.8 m/s

Effecy of mean bubble diameter variation (Case B)

Velocity Vector Plot (35 inch/min, 6.3l/min, Dmen=2.0 mm)

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Velocity Vector Plot (35 inch/min, 6.3l/min, Dman=1.5 mm)

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Effect of mean bubble diameter variation (Case A)



Horizontal velocity at 3mm below meniscus(55ipm,13l/min)

Tiebiao Shi

Effect of mean bubble diameter variation (Case B)



University of Illinois at Urbana-Champaign Metals Processing Simulation Lab

Tiebiao Shi

* Above plots are provided by LTV Steel



Real-time measurement of fiquid flow below meniscus

* Above plots are provided by LTV Steel



Real-time measurement of fiquid flow below meniscus

Flow-related Results

	Case A 1.5 mm bubble	Case A 2.0 mm bubble	Case B 1.5 mm bubble	Case B 2.0 mm bubble
Flow Pattern	Double Roll	Double Roll	Single Roll	Double Roll
Upper Eye Position (x, z) (mm)	(755,124)	(774,124)		(812,105)
Max. Surf. Velocity (m/s)	0.172	0.176	0.145	0.136
Max. Surf. Pressure (Pa)	488	491	366	368
Avg. Surf. Pressure (Pa)	294	300.17	195.75	184.92
Max. Surf. Level (mm)	4.40	4.33	3.86	4.15
Max. Surf. K (m ² /s ²)	1.70E-02	1.73E-02	1.15E-02	1.13E-02
Max. Surf. Fluctuation (mm)	6.05	6.16	4.09	4.02

* Assuming flux density is 2700 kg/m³, liquid steel density is 7200 kg/m³.

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- Bubble size has great influence on flow pattern. Small bubbles cause more lift of the jet, so small bubbles tend to cause single roll flow while large bubbles tend to cause double roll flow
- For the same mean bubble size, uniform-sized bubbles are more likely to cause a single roll flow than distributed bubble sizes.

- There might be a critical mean bubble size(CMBS) which triggers the flow pattern changing from double roll to single roll in the mold. Below CMBS, flow pattern is single roll. Above CMBS, flow pattern is Double Roll.
- Uniform-sized bubbles have larger CMBS than sizedistributed bubbles. Multiphase flow with uniform-sized bubbles(case B) might be more likely to suffer flow pattern instability and cause surface quality problems. Flow with size-distributed bubbles has a better chance to remain stable in flow pattern.

 Inlet bubble sizes distributed over a small range around the mean have a similar influence on the flow pattern as uniform-sized bubbles of the mean bubble size.

Predict the Jet Deflection Quantitatively in the Multiphase Flow

University of Illinois at Urbana-Champaign Metals Processing Simulation Lab

Tiebiao Shi

Can we predict the jet deflection quantitatively in the real caster ?

 According to Iguchi's study*, there is a relation lying between jet vertical deflection and distance from inlet:

 $y_c/(r_v^*d_{ni})=0.02\{x/(r_v^*d_{ni})\}^{1.8}$

where y_c is the vertical deflection, x is the horizontal distance from inlet, d_{ni} is the diameter of the inlet.

 r_v is defined as:

$$r_{v} = \overline{u_{0}} / [gQ_{g} / (d_{ni}\overline{u_{0}})]^{1/2}$$

*M.Iguchi, N.Kasai, Met&Mat Trans.B, June 2000, Vol.31B, p455

	Q _w =5.0 LPM	Q _w =7.5 LPM
Mold Height	$Q_{air}=8.0 \text{ ml/s}$	$Q_{air}=8.0 \text{ ml/s}$
	500 mm	
Mold Width	300 mm	
Mold Thickness	150 mm	
Inlet Hole Diameter	9 mm	
Outlet Hole Diameter	9 mm	
Water Viscosity	0.001 kg/(ms)	
Air Viscosity	1.7E-05 kg/(ms)	
Water Density	1000 kg/m^3	
Air Density	1.2 kg/m^3	
Surface Tension Coefficient (Water-Air)	0.073 N/m	
Water K	$0.044 \text{ m}^2/\text{s}^2$	
Water ϵ	$0.999 \text{ m}^2/\text{s}^3$	
Water Flow Rate	83.33 ml/s	125.0 ml/s
Gas Flow Rate	8.0 ml/s	8.0 ml/s
Flow Inlet Velocity	1.884 m/s	2.091 m/s
Bubble Size Range	100 µm-5mm	
Gas volume Fraction	8.76%	6.02%

Parameters used in Iguchi water experiment

Assumed Bubble Size Distribution

Bubble Size	Volume Fraction
0.1 mm	1%
1.1 mm	13%
2.1 mm	17%
3.1 mm	20%
4.1 mm	24%
5.1 mm	25%

Geometry



0.5 m/s



 $Q_w=5.0$ l/min, $Q_{air}=8.0$ ml/s

Velocity vector plot at center plane





Qw=7.5 l/min, Qair=8.0 ml/s

Velocity vector plot at center plane



Air volume fraction contour (Qw=7.5 LPM Qair=8.0 ml/s) Modeling Result

Comparison of gas distribution in the upper mold between water experiment and modeling

Jet deflection for two cases in Iguchi's water experiment



Q_w=5.0 l/min, Q_{air}=8.0 ml/s



Simulation results for different cases



Relation between Jet Deflection and Distance from Inlet

University of Illinois at Urbana-Champaign

Metals Processing Simulation Lab

Tiebiao Shi

 Model matches Iguchi's experiment but is 10 times larger in deflection. The equation from simulation result is:

 $y_c/(r_v^*d_{ni})=0.2\{x/(r_v^*d_{ni})\}^{1.8}$

• Above equation is valid over range:

$$4 < r_v < 24$$

 $0.7 < x / (r_v * d_{ni}) < 5$