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Electromagnetic effects on multi-phase flow in the slab casting nozzle and mold

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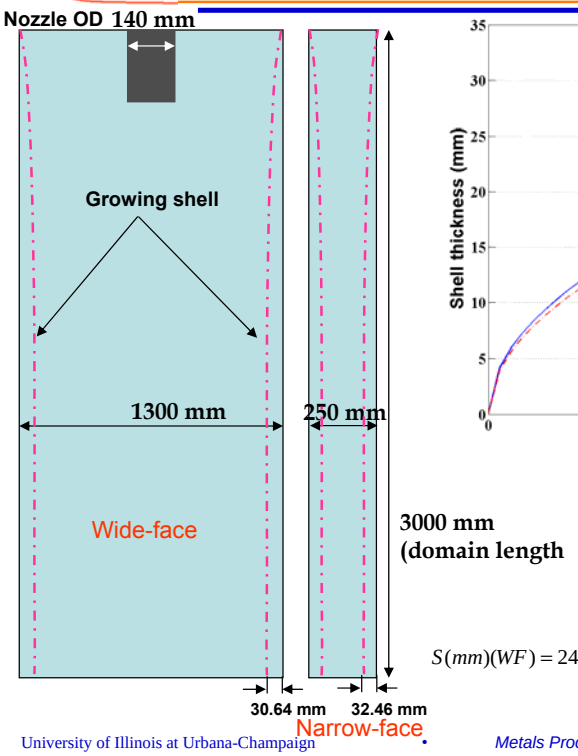
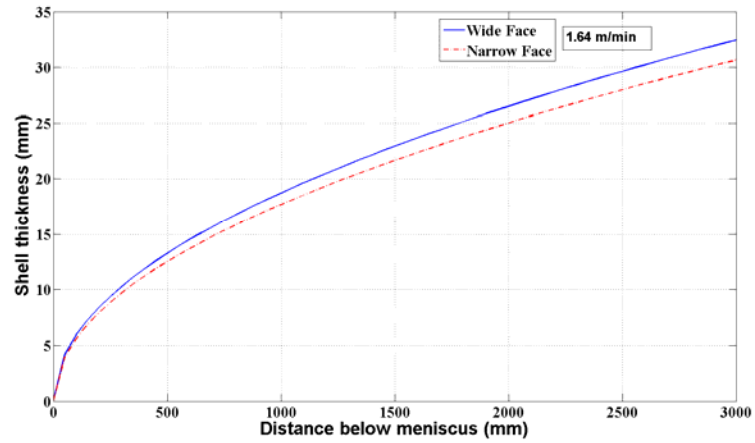
Project outline

- To investigate the effect of argon gas and magnetic field on turbulent nozzle & mold flow:
  - 3-D, turbulent, single-phase steel flow model
  - 3-D, turbulent, multiphase flow model (Eulerian-mixture & Eulerian-Eulerian models)
  - 3-D, Single-phase steel flow and multiphase steel-argon flow models with MHD (based on measured magnetic fields)
  - 3-D, VOF model to investigate the effect of slag-steel interface on single-phase steel flow
- Experiments were performed in real caster with Nail-board measurements (with & without magnetic field)
  - To measure free surface velocity at 10 locations along two lines parallel to wide faces at 55 mm from mid-plane
  - Surface level variations were also measured at same locations
- Perform one way coupled inclusion transport and entrapment studies. (with Rui Liu)
- Based upon knowledge gained from above modeling and experimental work, flow parameters will be fine tuned to optimize multiphase turbulent flow in real caster to minimize inclusion defects in the final steel product.

Mold schematic with dimensions and shell thickness along wide- and narrow faces





Shell thickness as a function of distance below meniscus (CON1D)

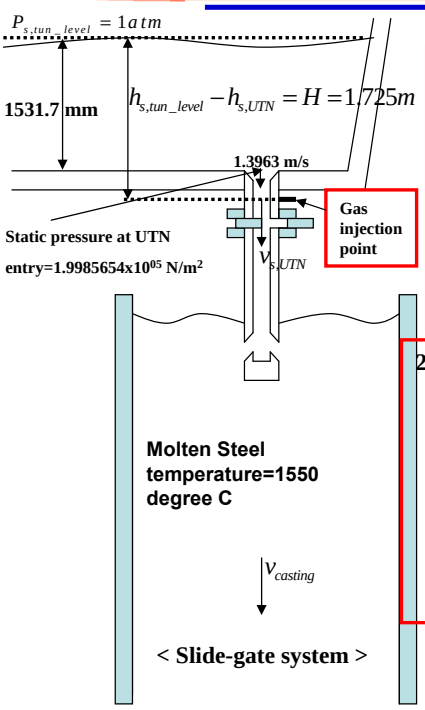
Ref: **Y. Meng and B.G. Thomas: Metall. Mater. Trans. B, 2003, vol. 34B, pp. 685–705.**

$$S(mm)(WF) = 24.0\sqrt{\frac{Z(mm)}{1000V_{casting}(m/\min)}} \quad S(mm)(NF) = 22.6\sqrt{\frac{Z(mm)}{1000V_{casting}(m/\min)}}$$

Process parameters

Casting speed	**1.64 m/min**
Steel flow rate	**533 LPM**
Argon gas injection rate	**9.2 SLM: STP (1 atm Pr and 273K)**
Nozzle inner diameter	**90 (at UTN top) to 80 (at bottom well) mm**
Nozzle outer diameter	**140 mm**
Nozzle height	**1330 mm**
Nozzle type and port angles	**Bifurcated type: 52 to 35 degree step angles at the top 45 degree port angle at the bottom**
Nozzle port area	**85 mm (height) x 80 mm (width) each**
Port to bore (at UTN top) area ratio	**2.13**
SEN depth	**178 mm**
Mold width	**1300 mm**
Mold thickness	**250 mm**
Domain width	**650 mm**
Domain thickness	**250 mm**
Domain length	**3000 mm**
Density (argon gas) **Density (molten steel)**	**0.55 kg/m3 (at gas gas injection pressure (1.99e05 N/m^2, &1550ºC) 0.30 kg/m3 (at SEN depth pressure (1.13e05 N/m^2, &1550ºC) 7020 kg/m3 (molten Steel temperature=1550ºC)**
Dynamic viscosity (argon gas) Dynamic viscosity (molten steel)	**7.42e-05 kg/m-s 0.006 kg/m-s**

Calculation of steel velocity and pressure at gas injection



1) Steel velocity in UTN (at gas injection point)

$$Q_{s,mold} = Q_{s,UTN}$$

$$v_{casting} \times w_m \times t_m = v_{s,UTN} \times \pi (R_{UTN})^2$$

$$v_{s,UTN} = \frac{v_{casting} \times w_m \times t_m}{\pi (R_{UTN})^2}$$

2) Estimated Steel pressure in UTN (at gas injection point)

$$P_{s,tun\_level} + \frac{1}{2}\rho_s v_{s,tun\_level}^2 + \rho_s g h_{s,tun\_level}$$

$$= P_{s,UTN} + \frac{1}{2}\rho_s v_{s,UTN}^2 + \rho_s g h_{s,UTN}$$

$$P_{s,UTN} = P_{s,tun\_level} + \rho_s g H - \frac{1}{2}\rho_s v_{s,UTN}^2$$

$Q_{s,mold}$	Steel flow rate in mold	
$Q_{s,UTN}$	Steel flow rate in UTN	
$v_{casting}$	Casting speed	1.64m/min
v_{s,tun_level}	Steel velocity at tundish level	0
$v_{s,UTN}$	Steel velocity in UTN	1.52 m/s
w_m	Width of mold	1300mm
t_m	Thickness of mold	250mm
R_{UTN}	Inner radius of UTN	43mm
P_{s,tun_level}	Pressure at tundish steel level	1atm
$P_{s,UTN}(abs)$	Pressure in UTN	$2.118x10^5 N/m^2$
ρ_s	Steel density	$7020 kg/m^3$
g	Gravity acceleration	$9.8 m/sec^2$
h_{s,tun_level}	Height of steel level in tundish	
$h_{s,UTN}$	Height of steel level in UTN (gas injection point)	
H	$h_{s,tun\_level} - h_{s,UTN}$	1725mm

Calculation of gas flow rate at gas injection point

SLM: STP (1 atm Pr and 273K)
Argon density=1.7837 kg/m³ @ STP
Argon density=0.55 kg/m³ @ injection, 1823 K(1550 °C)
Argon density=0.30 kg/m3 @ SEN depth, 1823 K(1550 °C)

$$Q_s = w_m \times t_m \times v_{cast}$$

$$\frac{Q_{g@STP}}{Q_g} = \frac{\rho_g}{\rho_{g@STP}} = \left(\frac{P_g}{P_{g@STP}}\right)\left(\frac{273}{T}\right)$$

$$\frac{Q_g}{Q_{g@STP}} = \left(\frac{P_{g@STP}}{P_{s,tun\_level} + \rho_s g H - \frac{1}{2}\rho_s v^2{}_{s,UTN}}\right)\left(\frac{T}{273}\right) = 3.2$$

Average argon gas % in nozzle:

$$F_g = \frac{Q_g \times 100}{w_m \times t_m \times v_{cast} + Q_g} = 5.22\%$$

F_g	Gas volume fraction	5.22%
Q_g	Gas flow rate	9.2SLPM(273K) 30LPM(1823K, i.e. at injection) 55LPM(1823K, i.e. at SEN depth)
Q_s	Steel flow rate	533LPM
w_m	Width of mold	1300mm
t_m	Thickness of mold	250mm
v_{cast}	Casting speed	1.64m/min
$v_{s,UTN}$	Steel velocity in UTN	91.75m/min
ρ_g	Gas density	
ρ_s	Steel density	$7020 kg/m^3$
p_g	Gas pressure	1atm
p_{s,tun_level}	Steel pressure at tundish steel level	1atm
g	Gravity acceleration	$9.8 m/sec^2$
H	Distance between tundish steel level and UTN	1725mm
T	Temperature	

Calculation of gas velocity profile at UTN

< Gas flow rate near steel flow = Total gas flow rate calculated from gas profile >

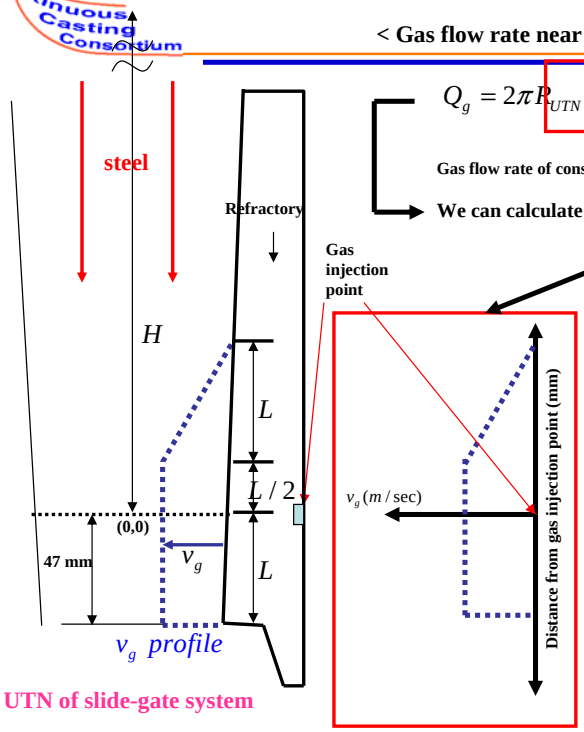
$$Q_g = 2\pi R_{UTN} \times \frac{3}{2} L \times v_g + 2\pi R_{UTN} \int_0^L v_g (1 - \frac{x}{L}) dx = 4\pi R_{UTN} L v_g$$

Gas flow rate of constant gas velocity part — Gas flow rate of linearly decreasing gas velocity part

We can calculate the gas velocity at injection point(v) by this equation

$$v_g(m/\sec) = 0.01928 (-47mm \le x < 23.5mm)$$

$$v_g(m/\sec) = 0.01928 \left(1.5 - \frac{x}{47}\right) (23.5mm \le x \le 70.5mm)$$



UTN of slide-gate system

Q_g	Gas flow rate	9.2SLPM(273K) 30LPM(1823K@ injection) 55LPM (1823 @SEN depth
v_g	Average gas velocity	
v_g	Vg (lower part of injection area)	0.01928 m/s (1823 K &@ injection) 0.036 m/s (1823K & @ SEN depth)
R_{UTN}	Inner radius of UTN	43mm
H	Distance between gas injection point and steel surface of UTN	1725mm
L	Distance between gas injection point and UTN bottom	47mm
x	Distance from gas injection point (mm)	

Computational models (single-phase)

(Flow in combined nozzle and mold)

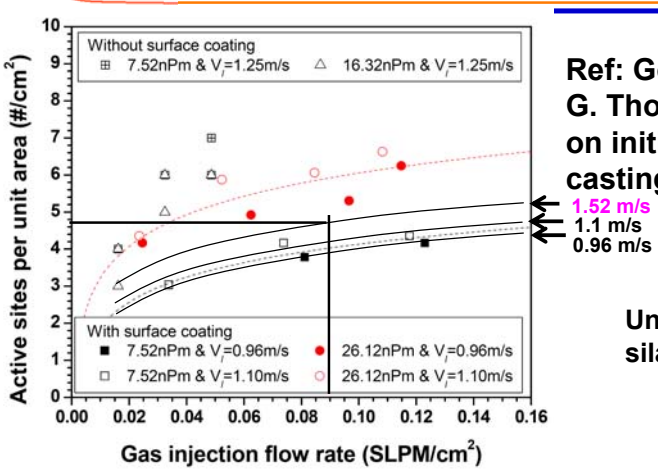
- Single-phase flow:
  - 3-D steady state Navier-stokes equations with mass conservation
  - RANS approach to model turbulence, k-ε turbulence model was used.
  - Mass and momentum sink terms to model shell solidification were implemented using a User-Defined Function (UDF).

- VOF (volume of fluid) model for slag-steel interface:
  - VOF model has been used without any argon gas injection to track steel-slag interface.
  - Energy equation was solved in slag layer and viscosity of the slag was considered to be a function of temperature. Within steel a constant temperature of 1550 degree C was considered.
  - RANS approach with k-ε turbulence model was used.
  - Mass and momentum sink terms to model shell solidification were implemented using a User-Defined Function (UDF).

Multiphase computational models (combined nozzle & mold)

- Multiphase flow:
  - Gas was injected at UTN based upon gas velocity profile shown in previous slides using a UDF.
  - This gas was removed by creating mass, and momentum sink in the cells below free surface.
  - Eulerian-Eulerian model (E-E model)
    - Two sets of governing equations for the field variables (i.e. mass, x-,y- and z- momentum equations for each phase).
    - Two-equation mixture k-ε model for turbulence
    - Schiller-Naumann drag formulation for steady phase coupling after modifying it for three-way coupling (i.e. bubble-bubble fluid dynamic interaction) using a UDF.
  - Eulerian-Mixture model (E-M model)
    - One set of governing equation for the field variables (i.e. mass, x-, y- and z-momentum equation for mixture phase).
    - Volume-fraction equation and algebraic relative velocity expression for gas phase
    - Assuming smaller response time of gas bubbles in steel, relative velocity expression was simplified to terminal velocity and after modifications with three way coupling effect was implemented using a UDF.

Mean Bubble diameter: Active sites per unit area in porous refractory for gas injection



Ref: Go Gi Lee, Seon-Hyo Kim and Brian G. Thomas, "Effect of refractory properties on initial bubble formation in continuous casting nozzles", 2009 (In progress)

Uncoated and coated (with siloxane and silane solution) MgO refractory

Important Findings: Active sites per unit area increases with increasing argon gas injection, permeability, down-ward liquid velocity and decreasing contact angle (i.e lower sites in steel-argon system).

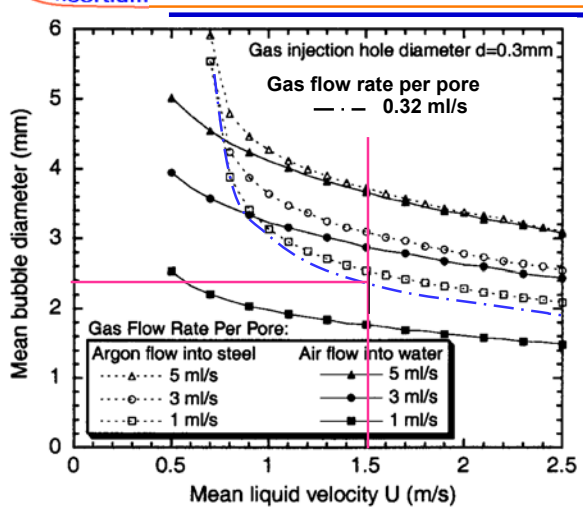
Motivations: Higher contact angle case of surface coating in air-water system is expected to closely imitates higher surface tension steel-argon system.

Mean bubble diameter: Steel-argon vs water-air analogy

- Water model experiments have been used to measure active sites per unit area in surface coated Mgo refractory.

- Because of the higher contact angle in steel-argon systems (~100 degree), they behave much like water-air system with surface coated porous refractory.

Mean bubble diameter: In steel-argon system predicted by H. Bai and B. G. Thomas (2001)



Ref: Hua Bai and Brian G Thomas, "Bubble formation during horizontal gas injection into downward-flowing liquid", Metallurgical and materials Transactions B, Volume 32, Number 6/ December, 2001

2.4 mm mean bubble diameter

-Analytical model was developed and verified in water-air experiments.

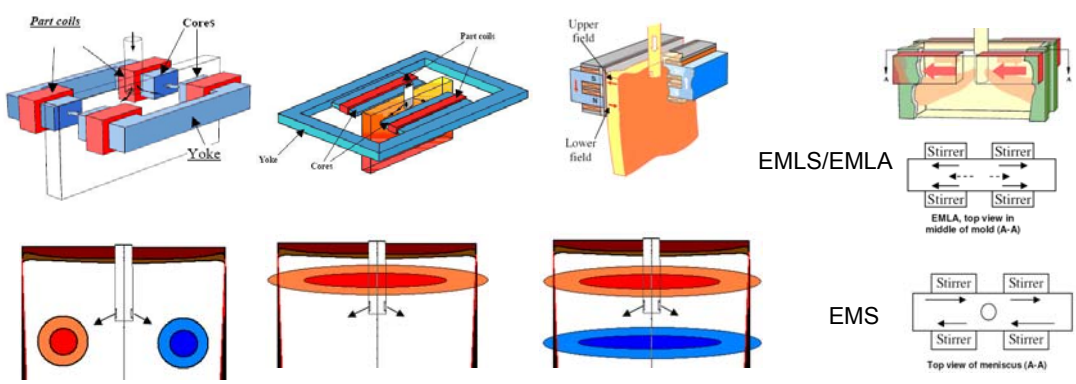
-Analytical model was further extended to be used to predict average bubble size in steel-argon system.

-Mean bubble diameter was found independent of injection hole size.

Mean bubble diameter: Calculations (using Bai et al(2001) and Lee et al's(2009) formulations)

- Gas injection flow rate per unit area(SLM/cm^2, considering A=πxD_{UTN}x2.5L) =9.2 SLM*(3.2LM/SLM)/317.45 cm^2=0.09 LM/cm^2
- Average down-ward liquid velocity at gas injection in UTN =1.52 m/s
- Permeability of MgO porous refractory 7.52 nPm
- Based upon GG Lee et al (2009), for a given gas flow rate (0.09 SLPM/cm^2), permeability (7.52nPm) and downward liquid velocity (1.52 m/s), active sites per cm^2=4.7 (see fig on slide-11 for reference).
- Total active sites in porous refractory in gas exiting region= 4.7x317.45=1492
- Gas flow rate per pore at injection temperature and pressure=490(ml/s)/1492sites=0.32 ml/s
- Using Bai et al's formulations, for known mean downward liquid velocity (1.52m/s) and gas flow rate per pore (0.32 ml/s), we can get mean bubble diameter=2.4 mm (see fig in slide-13 for more details).

Various types of electo-magnetic mold flow control systems showing hardware and field shape



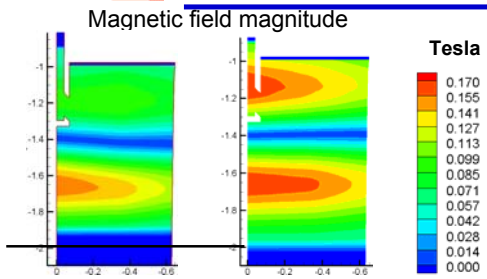
(a) Local EMBr (b) Ruler EMBr (c) Double ruler EMBr (d) Moving field

MHD computational flow model

- Magnetic induction method:
  - Solves an induced magnetic field transport equation
  - Induced magnetic field is used to calculate induced current and Lorentz force
  - Lorentz force is used as a source term in momentum equations
  - MHD simulations have been performed with single-phase and multiphase Eulerian-mixture model.

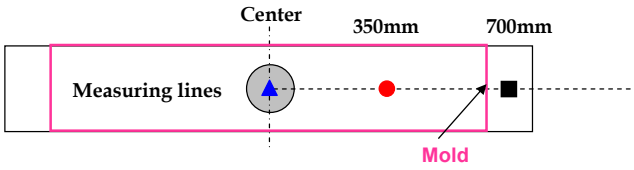
Measured and applied magnetic field in simulations

Magnetic field magnitude



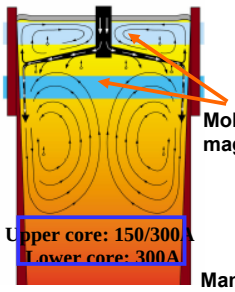
U:150A, L:300A

U:300A, L:300A



Front-view

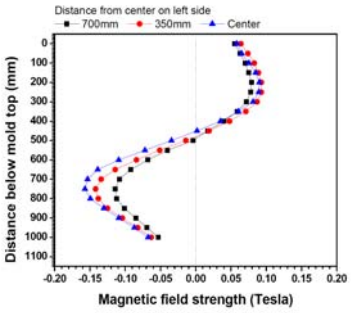
With FC Mold



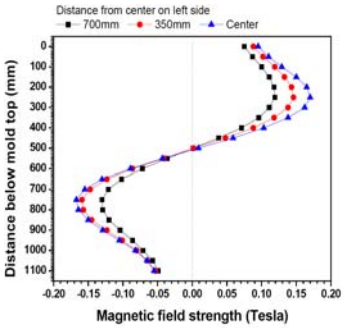
Measured and applied magnetic field

Mold showing double magnetic field rulers

Manufactured by ABB



U:150A, L:300A

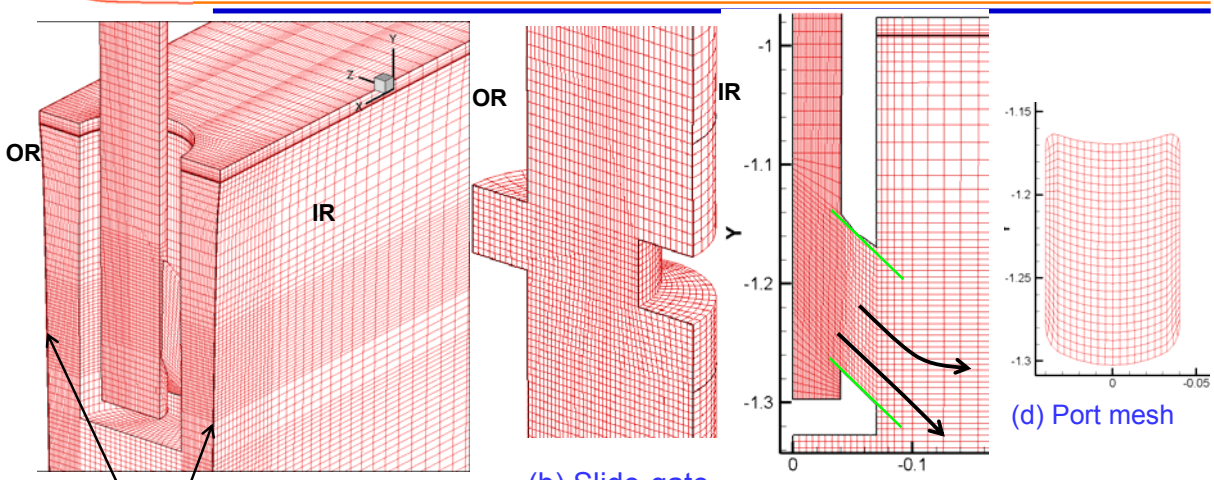


U:300A, L:300A

Computational domain and convergence (nozzle and mold combined)

- Combined computational domain of nozzle and mold was created assuming right-left symmetry. (right half is taken) (next slide)
- 0.50 million hexa-cells were used in the computational domain to model turbulent nozzle and mold flow.
- Domain was modified based upon shell profile and sink elements (mass and momentum) of 1 mm thickness were created close to shell in the molten steel domain to incorporate the effect of shell solidification.
- In steel-argon multiphase simulations, sink elements of again 1mm thickness were created just below the free-surface to remove the argon gas which is injected at UTN.
- In VOF simulations to model the effect of steel-slag interface, a 15 mm thickness of slag was considered.
- Convergence was pursued in almost all cases until scaled residuals were reduced to 10^{-4}.

Combined nozzle and mold mesh (0.50 Million hexa-cells)



(a) Combine nozzle & mold

(b) Slide-gate

(c) Front view close-up at SEN outlet port

(d) Port mesh

Sink elements created to model the effect of shell-solidification

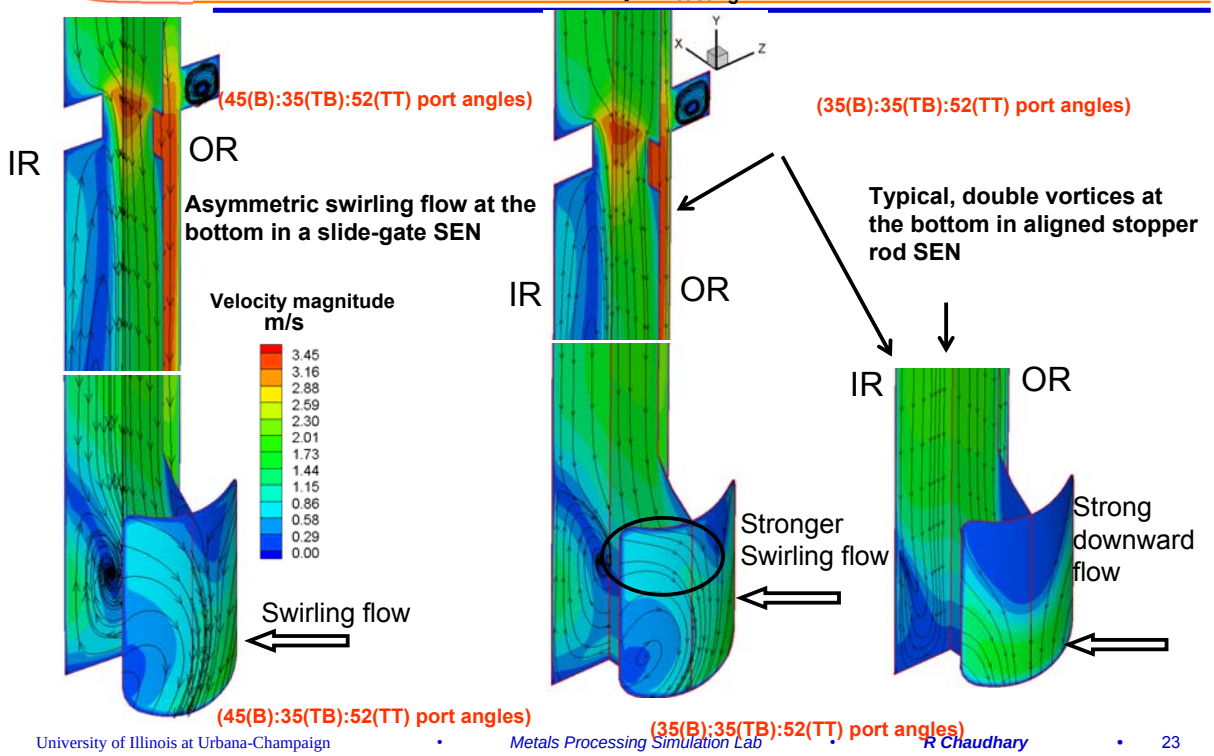
Boundary conditions

- At UTN top (i.e. tundish bottom), velocity inlet boundary condition for steel was applied as per the casting speed and correspondingly calculated flow rate.
- Bottom of mold was taken at constant pressure outlet (0 gauge Pa).
- Shell boundary was moved downward with casting speed.
- Top free-surface of the mold was taken no-slip boundary since it imitates effect of high viscosity slag on steel flow.
- In multiphase steel-argon simulations, gas was injected at UTN based upon a calculated velocity profile and given flow rate.
- In VOF simulations, top surface of the molten slag (i.e. sintered layer) was assumed no-slip at 1145 degree C. Slag (front, back, right) walls were given temperature boundary condition with temperature linearly changing from 1550 degree C to 1145 degree C. Slag touching the outer Nozzle was assumed insulated.

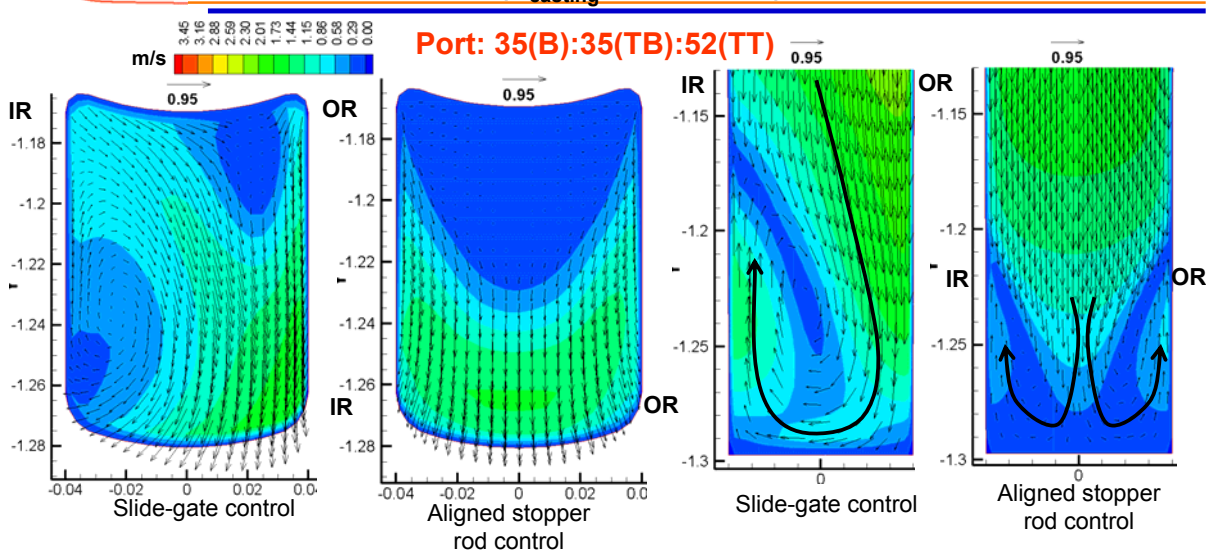
Various cases modeled with their labels and process parameters

Case no	**Case label**	Model type	Magnetic field	Bubble size (mm)	Gas flow rate (LPM)	Bubble-bubble interaction correction	Bottom port angle (º)
1.	**NOFC_SINGLE**	Single-phase	no	NA	NA	NA	45
2.	**NOFC_SINGLE_35**	Single-phase	no	NA	NA	NA	35
3.	**150A_SINGLE**	Single-phase	U:150A, L:300A	NA	NA	NA	45
4.	**300A_SINGLE**	Single-phase	U:300A,L:300A	NA	NA	NA	45
5.	**NOFC_2.4_30_EM_BB**	E-M	no	2.4	30	yes	45
6.	**150A_2.4_30_EM_BB**	E-M	U:150A, L:300A	2.4	30	yes	45
7.	**300A_2.4_30_EM_BB**	E-M	U:300A, L:300A	2.4	30	yes	45
8.	**NOFC_2.0_30_EE_NOBB**	E-E	no	2.0	30	no	45
9.	**NOFC_2.4_30_EE_BB**	E-E	no	2.4	30	yes	45
10.	**NOFC_2.4_55_EM_BB**	E-M	no	2.4	55	yes	45

Single-phase steel flow in SEN (45(B):35(TB):52(TT) and 35(B):35(TB):52(TT) degree port angled nozzles) ($V_{casting}$=1.64 m/min)



Steel flow at SEN bottom and port in aligned stopper rod and slide-gate SEN (single-phase: steel flow) ($V_{casting}$=1.64 m/min)

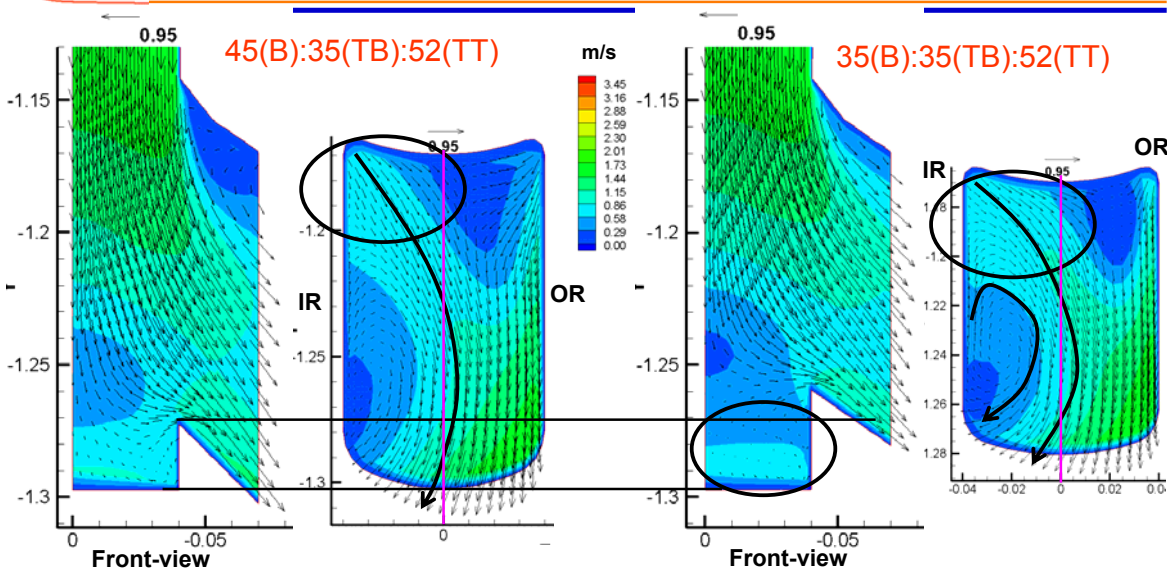


>>As expected, aligned stopper-rod gives two opposite rotating vortices compared to one in slide-gate type control.

>>Slide-gate gives swirling flow because of single vortex at bottom well.

>>Flow from stopper-rod SEN port is directed downward and therefore giving more reverse flow in the top region.

Steel velocity at ports in slide gate nozzle with 45(B):35(TB):52(TT) and 35(B):35(TB):52(TT) port angles (single-phase: steel flow) ($V_{casting}$=1.64 m/min)

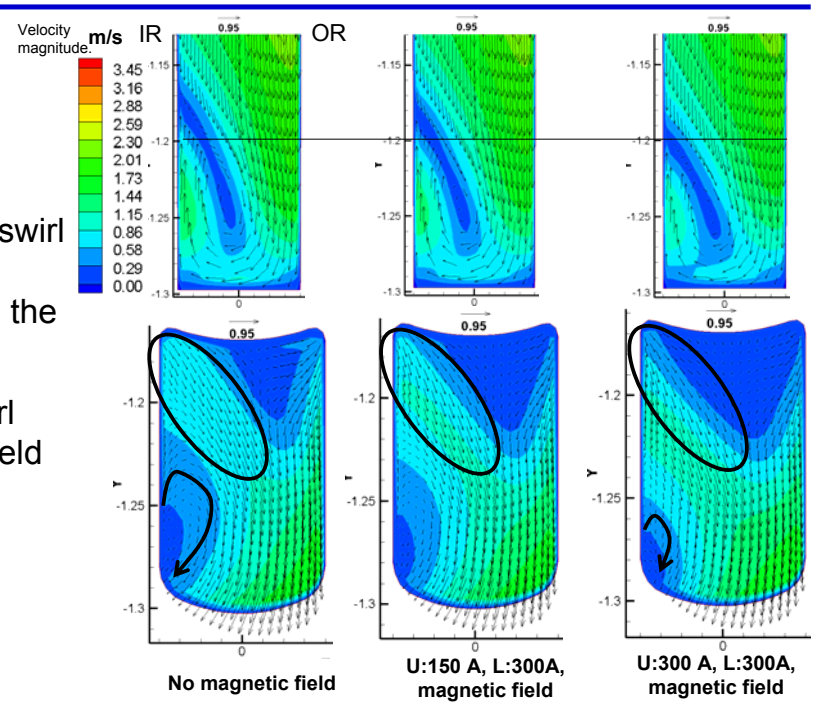


>>More stagnation region at the bottom with 35(B):35(TB):52(TT) compared to 45(B):35(TB):52(TT)
>>35(B):35(TB):52(TT) SEN being slightly more close to square gives higher swirling flow.
>> Less reverse flow on the top of port in 35(B):35(TB):52(TT) nozzle.
>> Qualitatively, both nozzles give same flow patterns at the port.

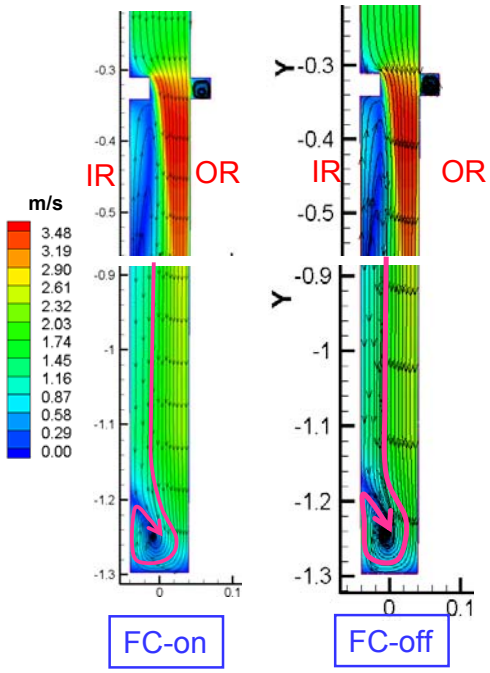
Comparison of port and bottom well velocity with and without magnetic field (single-phase: Steel flow) ($V_{casting}$=1.64 m/min)

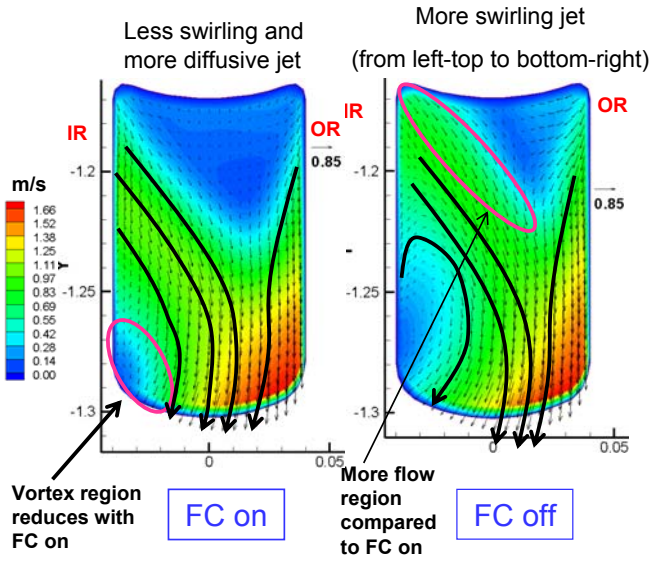
>>Magnetic field reduces swirl in the nozzle bottom thus lessens outward flow from the top left of port.

>>The suppression of swirl increases with magnetic field strength (upper ruler).



Comparison of port and SEN symmetry plane velocities in single-phase steel flow with FC on(U:300A, L:300A) and FC off conditions ($V_{casting}$=1.64 m/min)

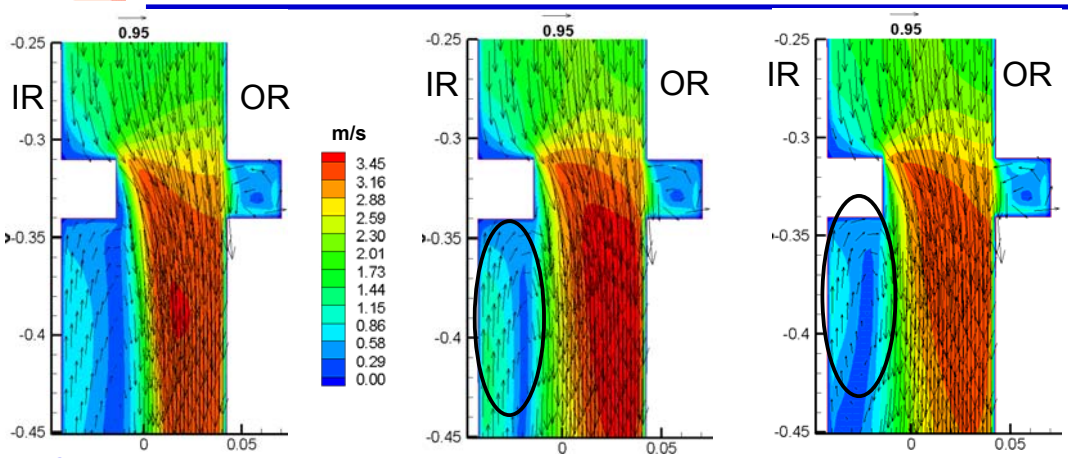




>>>More flow from left upward region in FC-off case thus causing nose to jet.

>>>FC off shows bigger swirl at symmetry plane at the well of the SEN

Single-phase steel and multiphase steel-argon flow comparison at the slide-gate region ($V_{casting}$=1.64 m/min)



Single-phase

Eulerian-Eulerian model (Two-fluid model) 30LPM:2.4 mm bubbles

Eulerian-mixture model (Slip velocity model) 30LPM:2.4 mm bubbles

>>Argon gas does not affect high speed flow close to slide-gate.
>>Eulerian-Eulerian and Eulerian-mixture models are found giving reasonably close results except showing minor differences in velocity behind slide-gate.

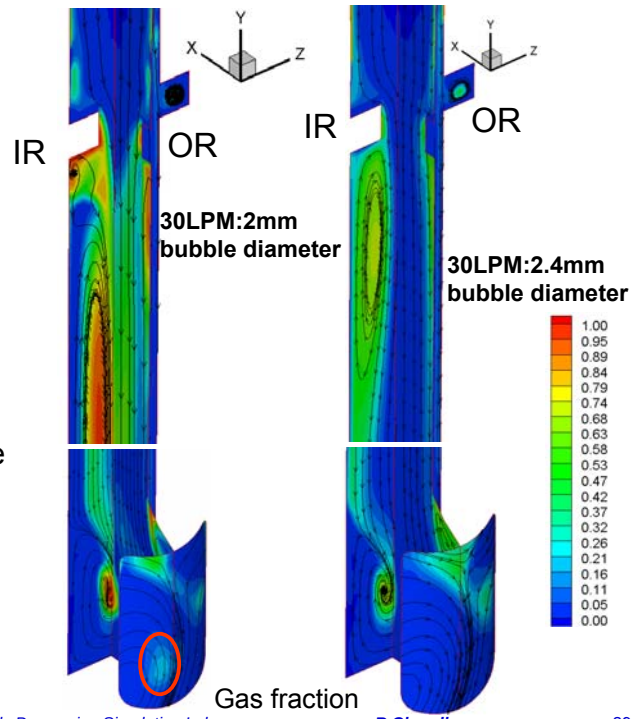
Effect of bubble size and b-b fluid interaction on gas collection in the nozzle (2mm and 2.4 mm bubble) (Eulerian-Eulerian model) ($V_{casting}$=1.64 m/min)

>> gas gets collected in recirculation zones.

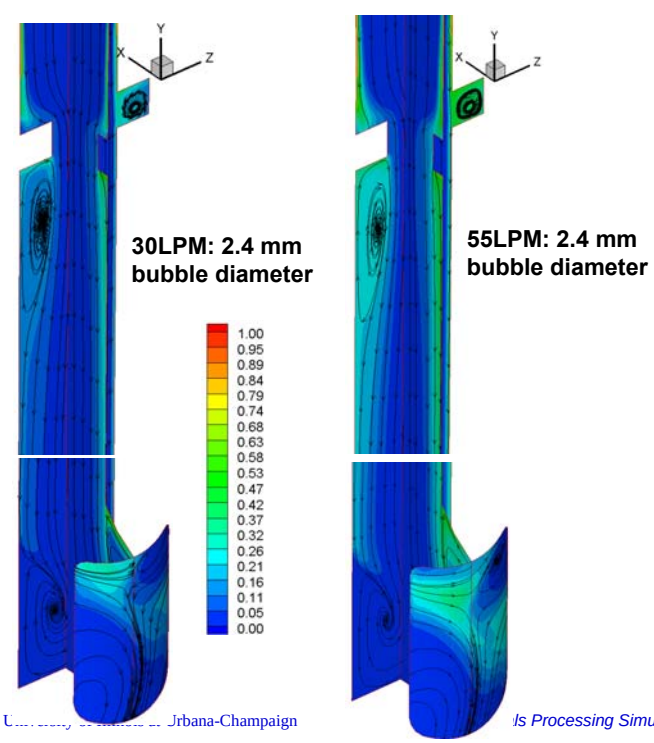
>> Smaller bubble size of 2mm & bb-fluid interaction correction shows higher gas fraction pockets with annular flow in the nozzle (matches plant observations – Burty et al, 1996, 1998, 2001).

>> with larger bubbles, gas stay attached to the nozzle wall

>> volume fraction distribution at port exit is around similar except smaller size showing a smaller region at bottom left and larger size shows more spread at the top of the port.



Effect of gas flow rate on gas fraction in nozzle for 29.39 and 54.8 LPM ($V_{casting}$=1.64 m/min)

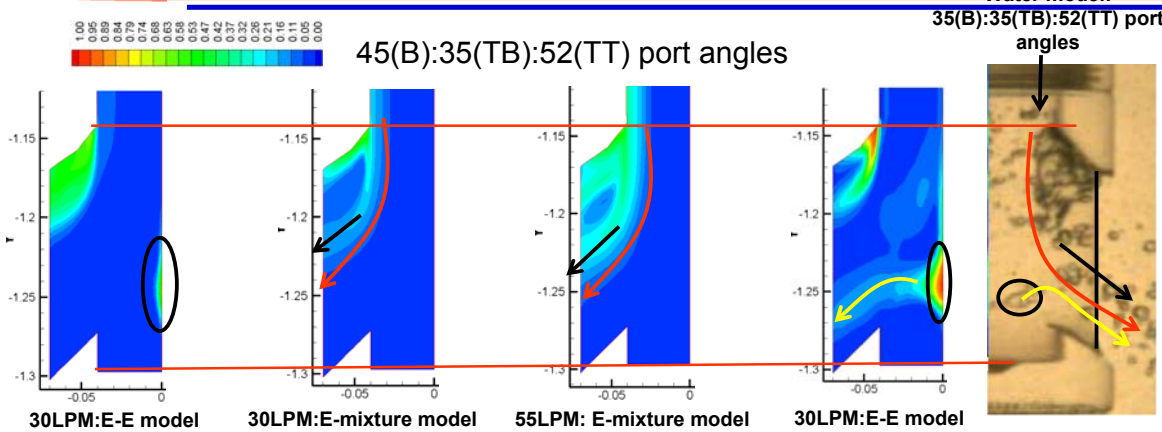


>> qualitatively look similar.

>>Higher gas injection clearly shows bigger gas pockets behind slide-gate and at the top of the port.

>>Gas with higher flow rate has more spread in left top and right middle region before exiting the port to the mold.

Qualitative comparison of argon gas volume fraction on the top of port with water model measurements ($V_{casting}$=1.64 m/min)



GG Lee's (2006) (measurements)

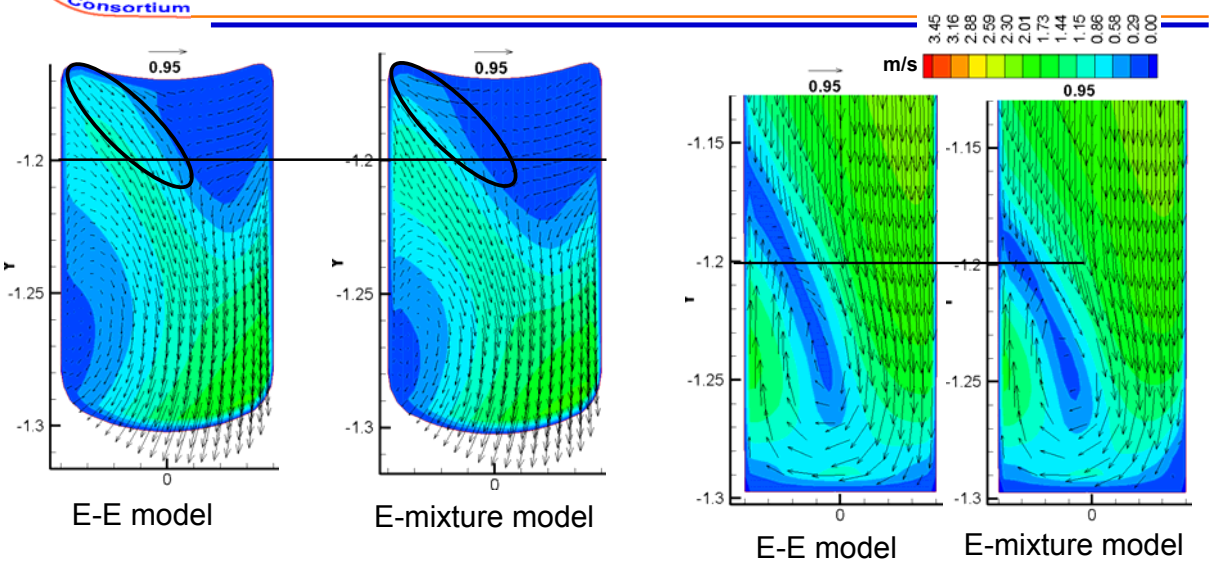
>>Gas collection at the top of the port is consistent in all cases.

>>E-E model always shows gas collected with the swirl at the bottom of the SEN.

>>E-mixture model suggest gas exiting from top and mid of the port and does not show significant collection of gas at bottom of SEN.

>>Gas behavior looks better captured by E-mixture model.

Port velocity in E-E and E-mixture models (Multiphase flow: steel-argon) ($V_{casting}$=1.64 m/min) (30LPM, 2.4 mm bubble)



>>E-E model shows stronger swirl at the bottom of the SEN.

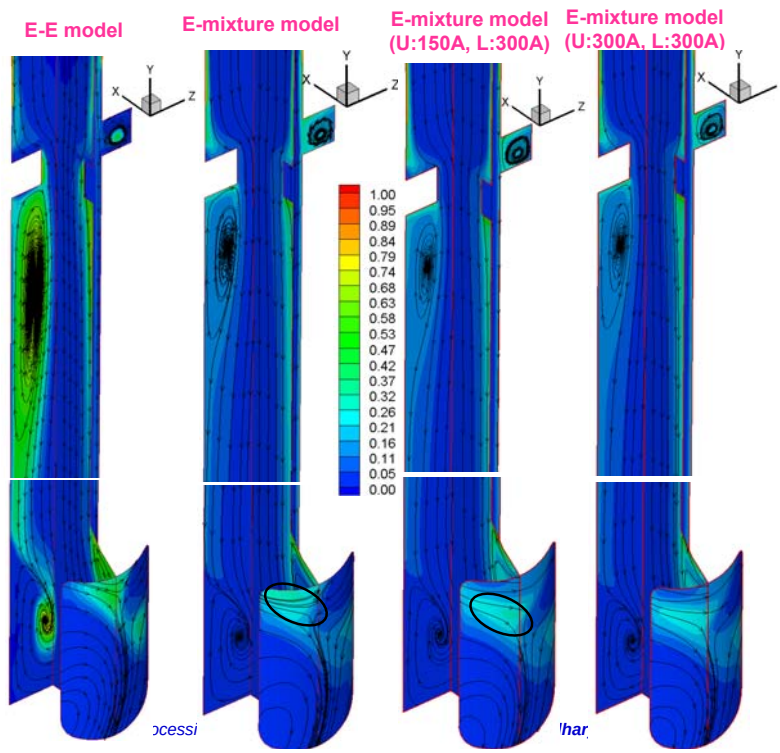
>> This swirl seems to be the main cause of bigger gas pocket in there.

Effect of gas and magnetic field on gas fraction in nozzle (30LPM gas, 2.4 mm bubble) ($V_{casting}$=1.64 m/min)

>> Qualitatively, E-E and E-mixture models predict around same argon gas distribution in the nozzle.

>> Magnetic field shifts gas exit slightly towards bottom.

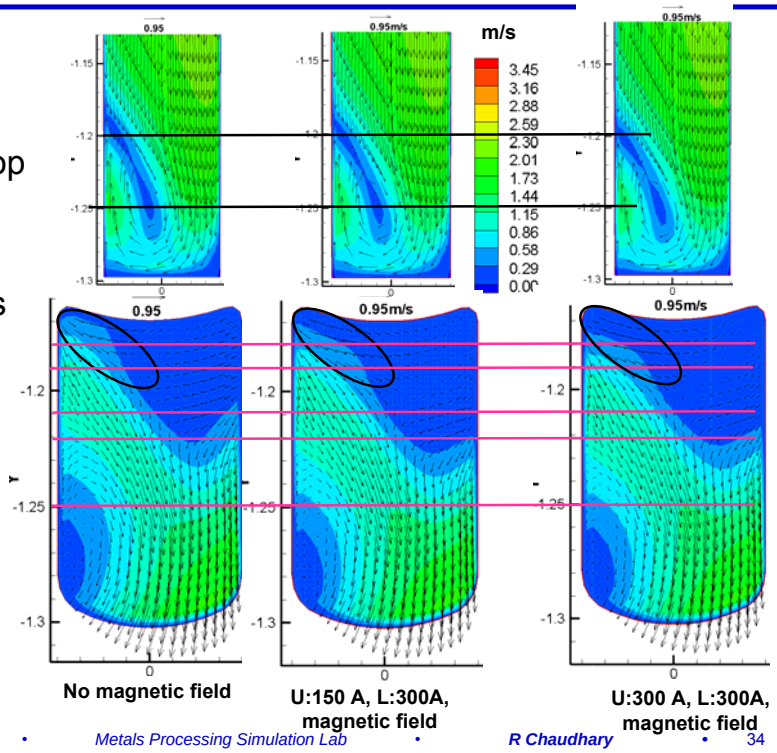
>>Change in magnetic field (from U:150A to U:300A) does not affect argon gas distribution much.



Effect of magnetic field on port velocity (Multiphase flow Steel-argon flow), (29.39LPM, 2.4 mm bubbles) ($V_{casting}$=1.64 m/min)

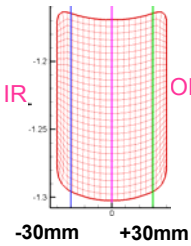
>> magnetic field slightly reduces the swirl and left top port velocity (which causes nose to jet).

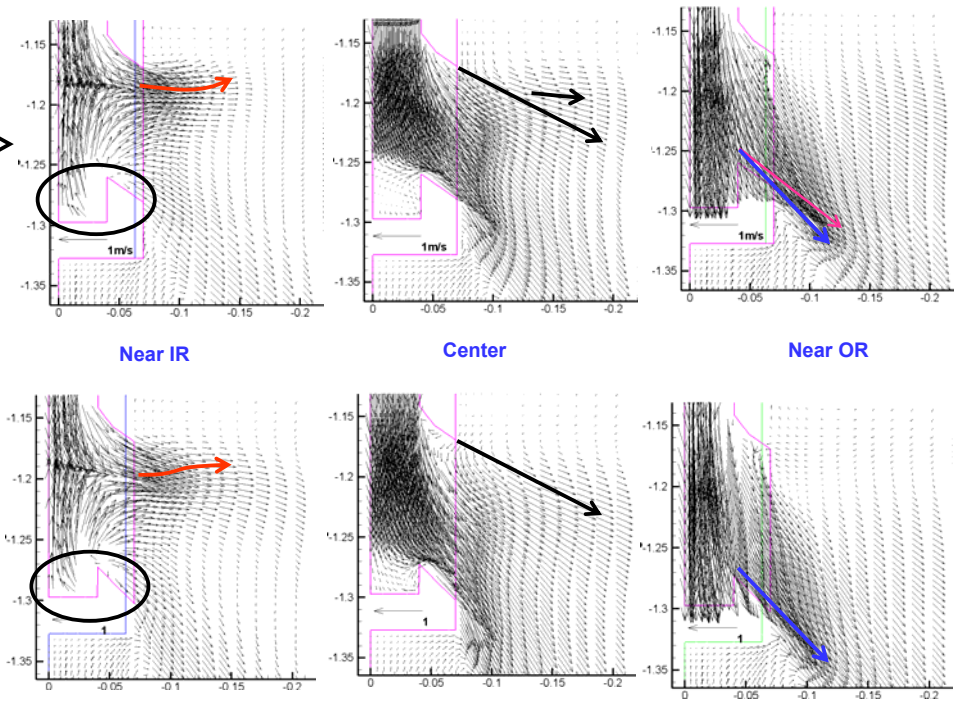
>>effect of magnetic field is small on turbulent steel-argon flow compared to single-phase steel flow.



Effect of port angle on steel flow: 35(B):35(TB):52(TT) vs 45(B):35(TB):52(TT) port angles ($V_{casting}$=1.64 m/min)

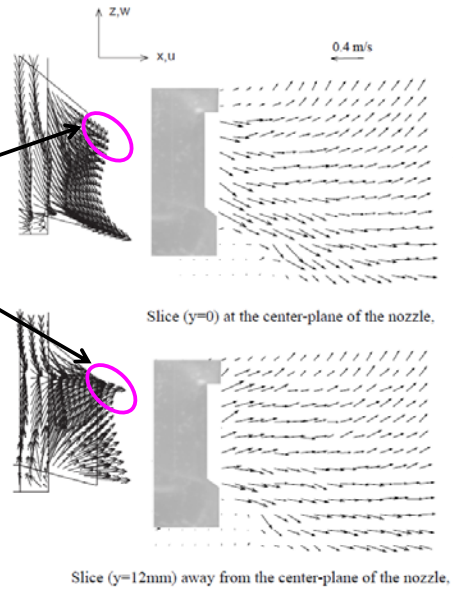
35(B):35(TB):52(TT) port angles





45(B):35(TB):52(TT) port angles

Current work is consistent with previous finding of jet nose



Nose at the top of jet: consistent with current work in slide-gate nozzle

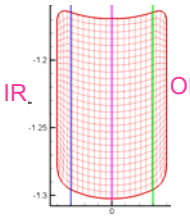
(caused by slide-gate front and back asymmetry, affected further by step-angle at the top of the port)

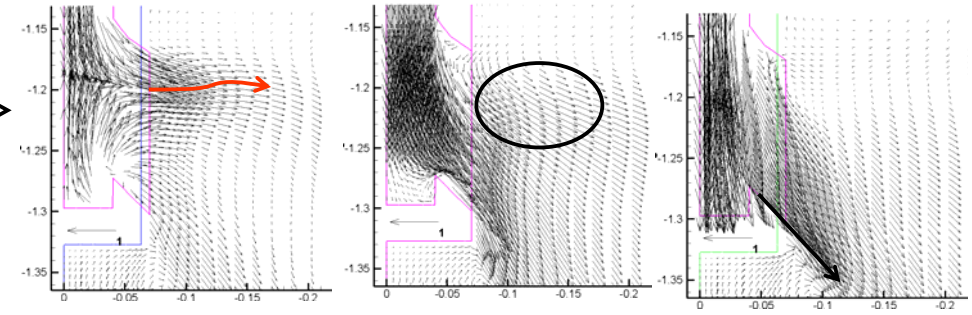
Thomas et al, 1999, **Detailed Simulation of Flow in Continuous Casting of Steel using K-ε, LES, and PIV** "International Symposium on Cutting Edge of Computer Simulation of Solidification and Processes", Osaka, Japan, Nov. 14-16, 1999, pp. 113-128.

CFX simulations PIV measurements

Effect of magnetic field on single-phase steel flow close to port ($V_{casting}$=1.64 m/min)

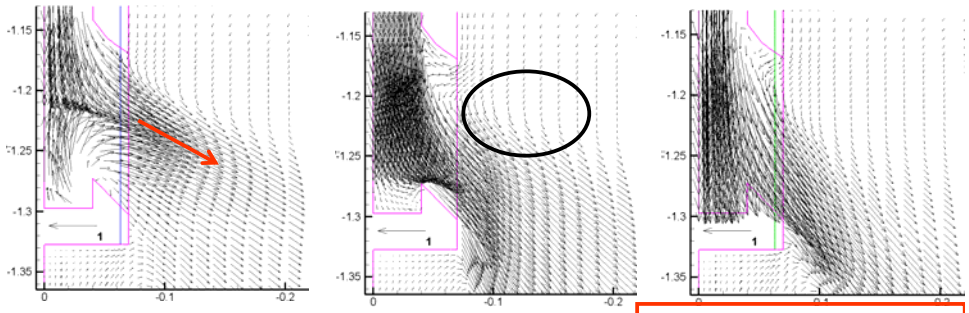
With FC-off





With FC-on

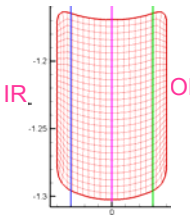
U:300A, L:300A

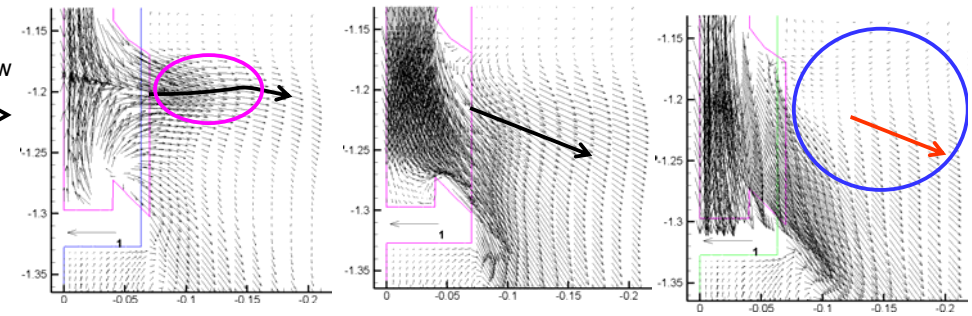


No significant effect (near OR)

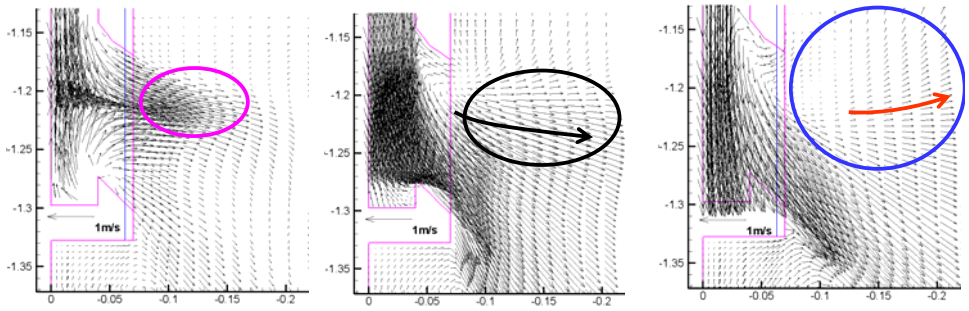
Effect of argon gas on steel flow close to port in mold and SEN ($V_{casting}$=1.64 m/min)

Single phase steel-flow

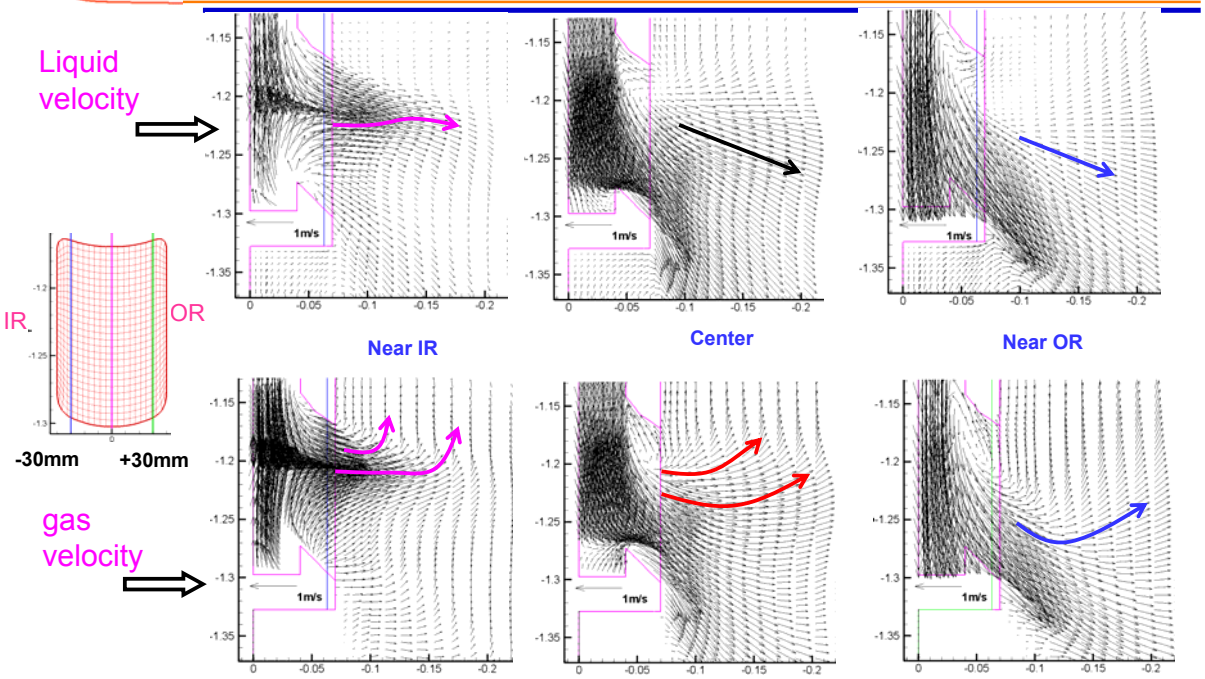




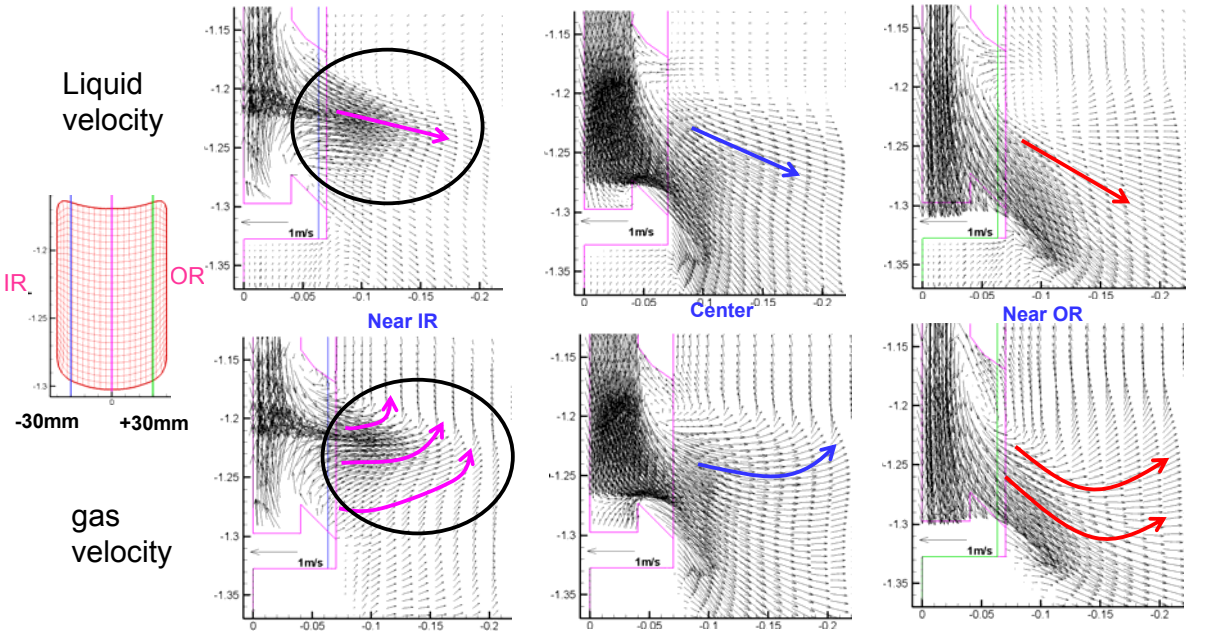
With 30LPM argon gas, 2.4 mm bubble



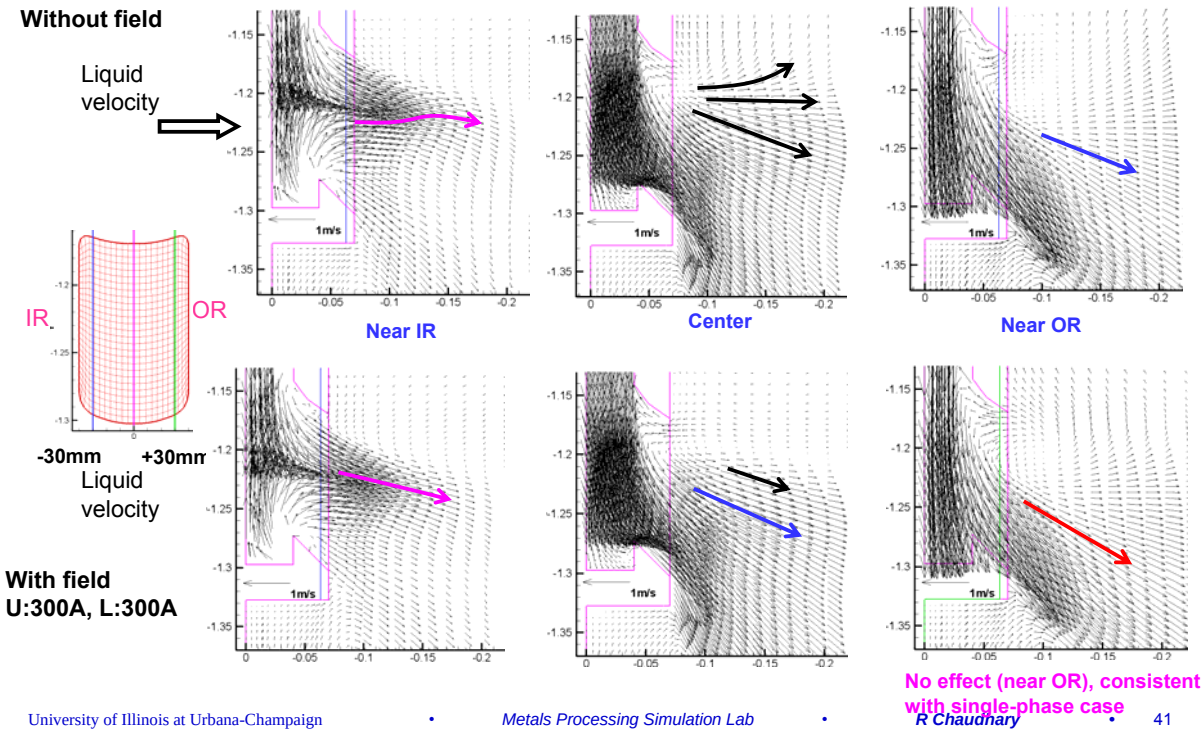
Steel and argon velocity close to port, FC-off ($V_{casting}$=1.64 m/min) (30LPM, 2.4 mm bubble)



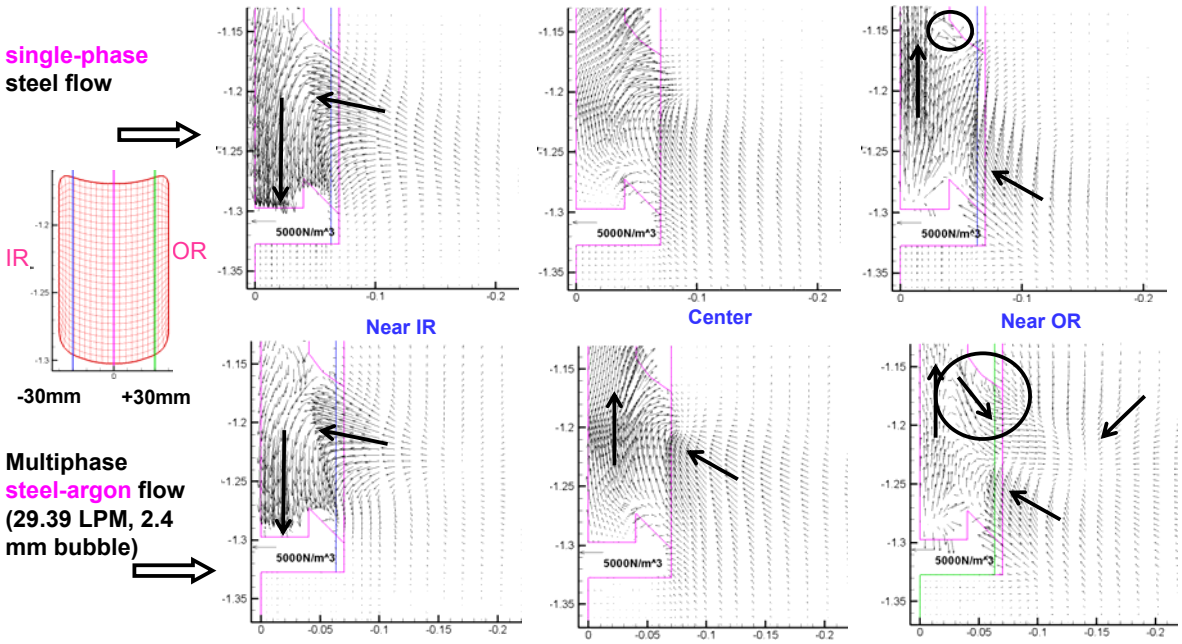
Steel and argon flow close to port, FC-on (U:300A, L:300A) (30LPM, 2.4 mm bubble) ($V_{casting}$=1.64 m/min)



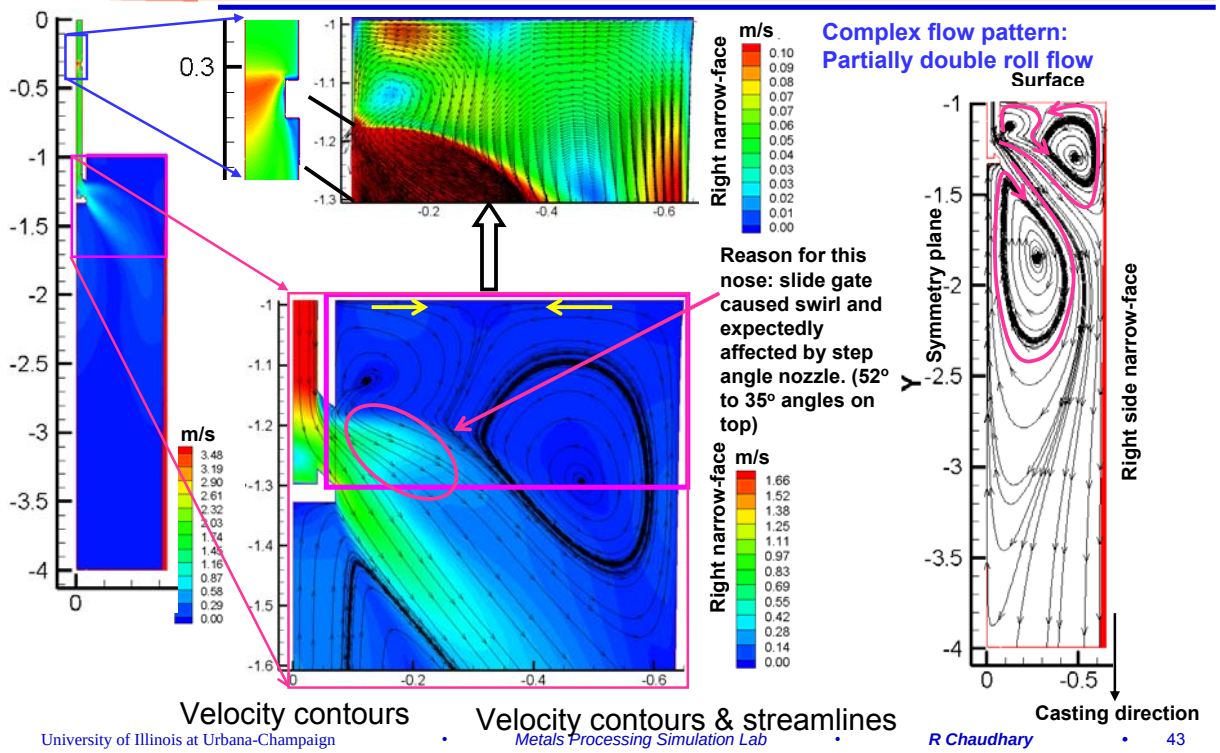
Effect of magnetic field on multiphase steel-argon flow (30LPM, 2.4mm bubble) ($V_{casting}$=1.64 m/min)



Lorentz force with and without gas ($V_{casting}$=1.64 m/min) (U:300A, L:300A)

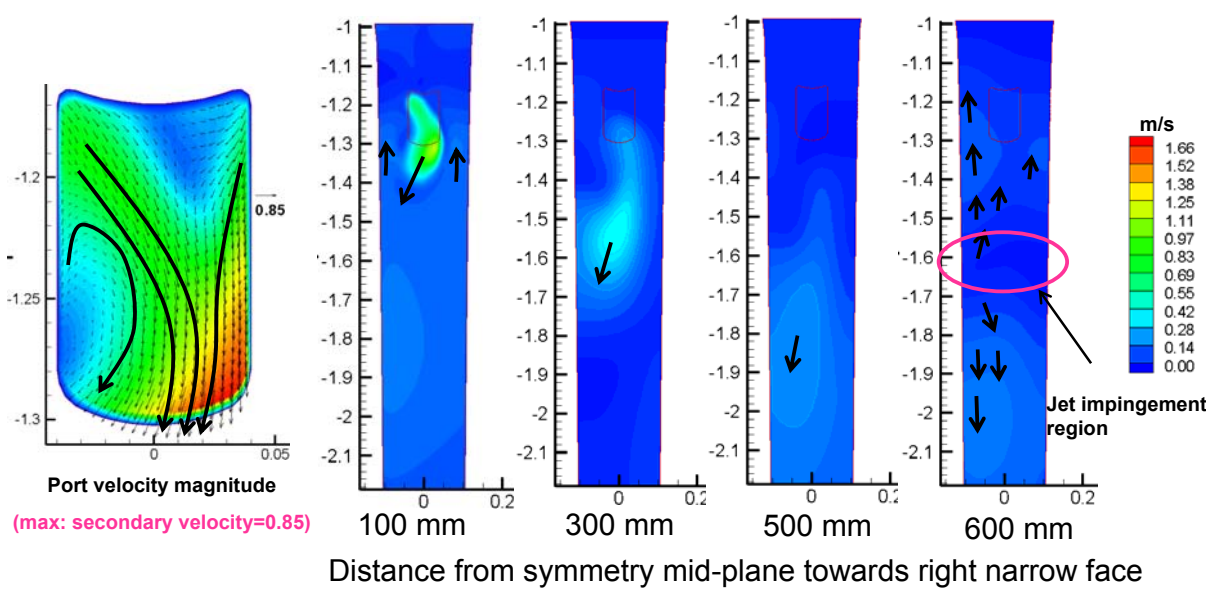


Single-phase steel flow in the mold ($V_{casting}$=1.64 m/min)

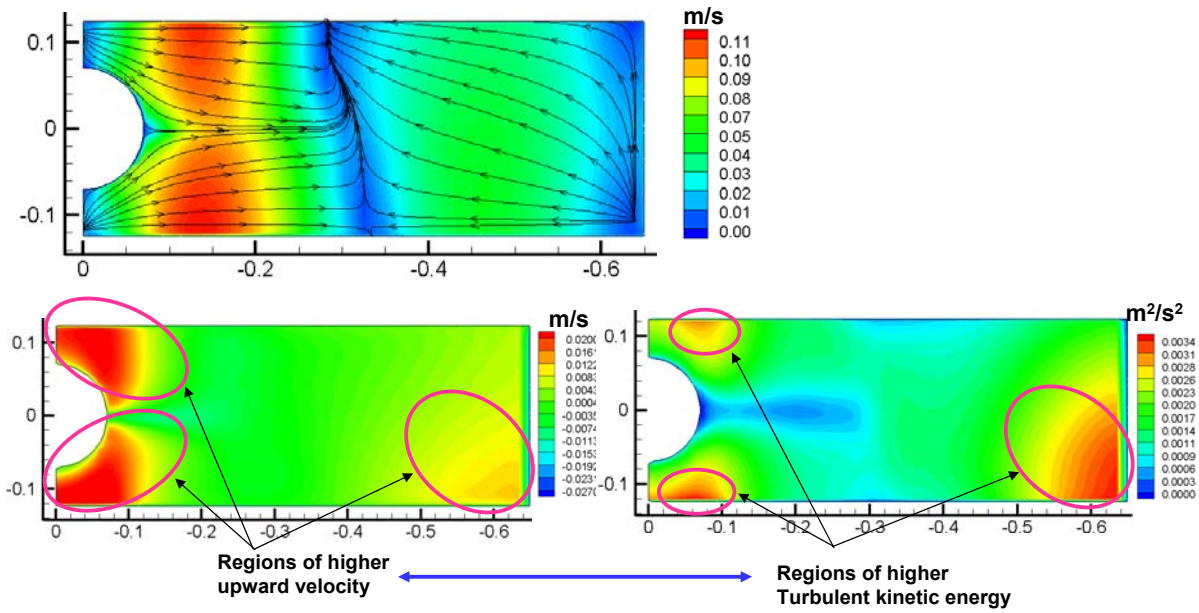


Steel velocity vectors and contours while looking from right narrow face (single-phase steel flow)

View from right narrow face with location of port shown in inset



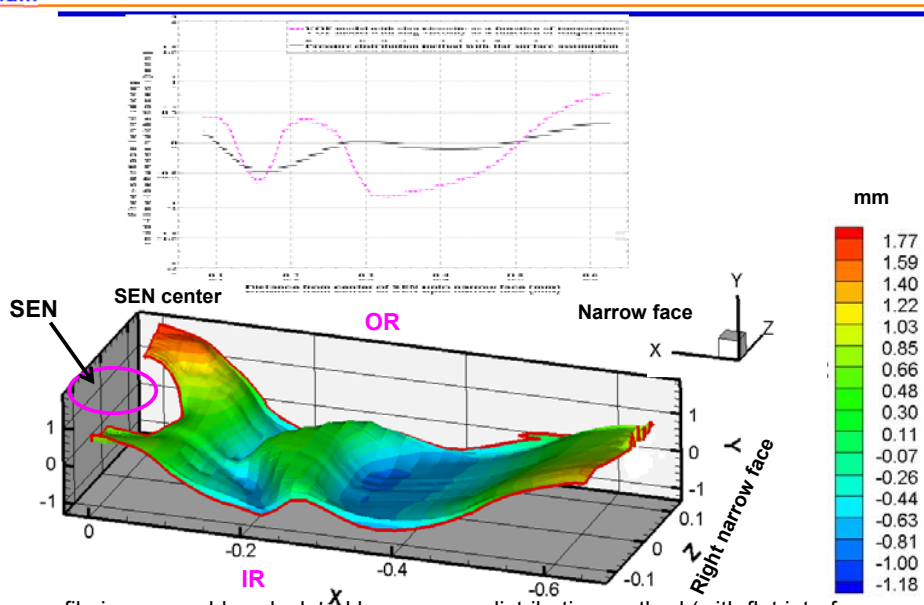
Velocity and kinetic energy contours with streamlines at 15 mm below surface (single-phase steel flow)



Upward velocity contours

Turbulent kinetic energy

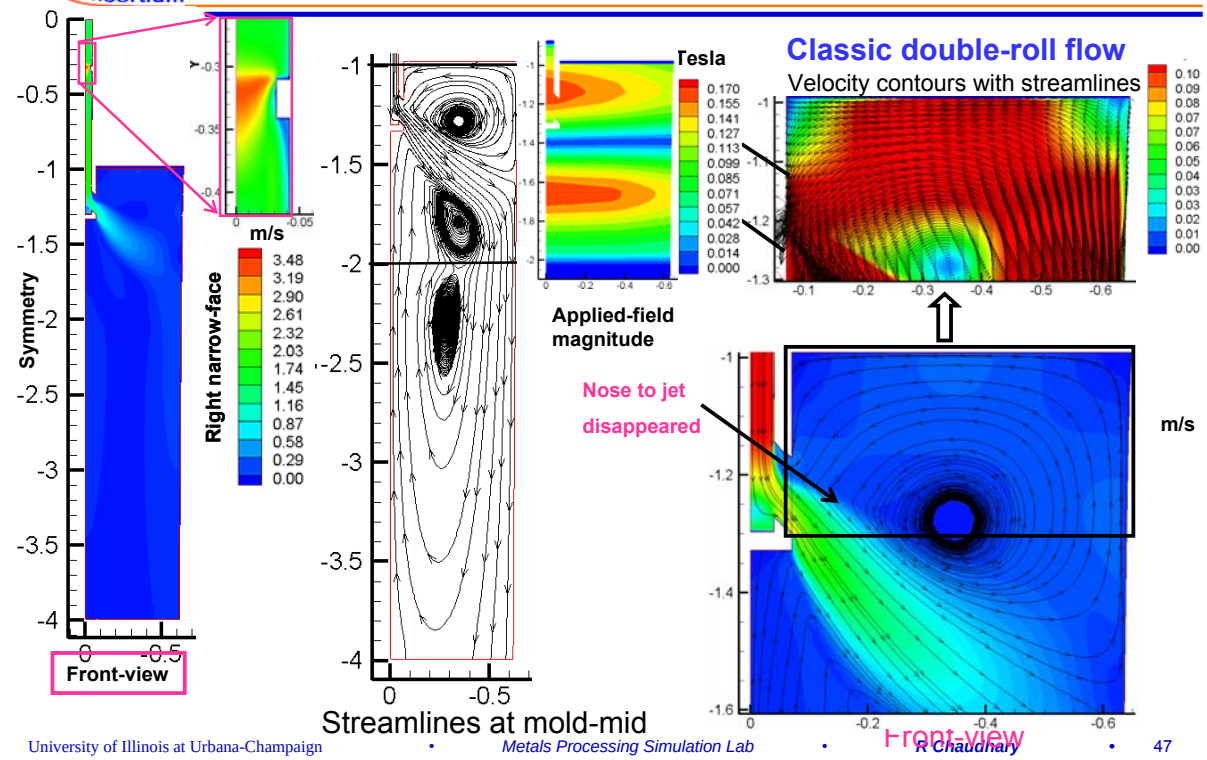
Free surface level comparison between VOF model and pressure distribution method assuming flat no-slip top surface ($V_{casting}$=1.64 m/min)



>> Free surface profile is reasonably calculated by pressure distribution method (with flat interface assumption) considering the computational difficulties involved with VOF method (especially in multiphase and multiphase MHD flows)

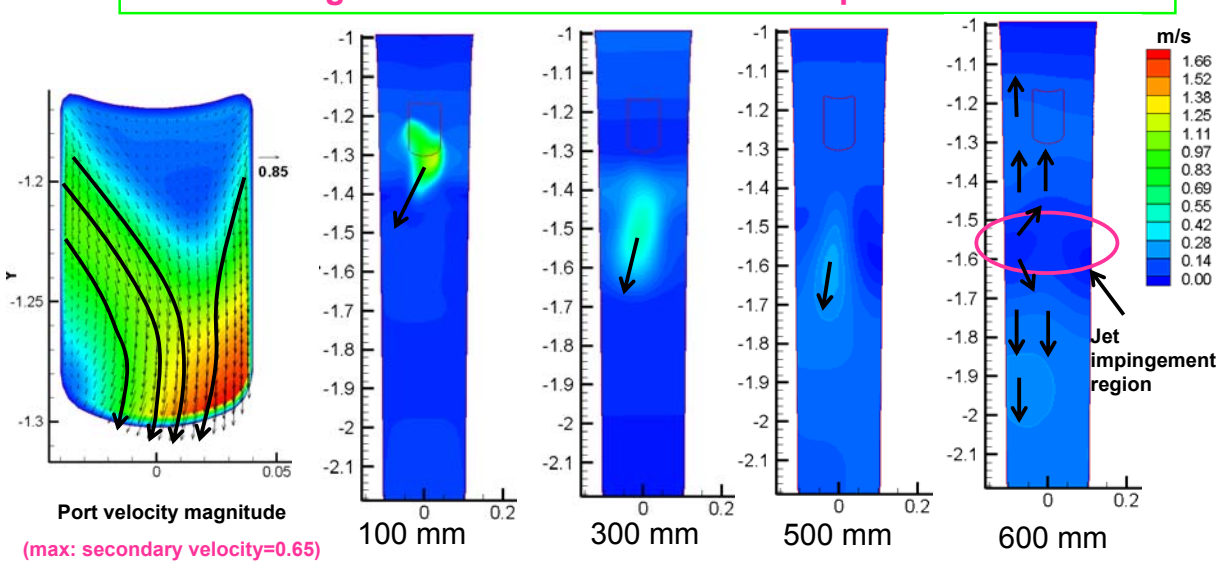
Effect of magnetic field on single-phase steel flow (velocity contours and streamlines at mold-mid plane)

(single-phase flow, U:300A, L:300A)



Velocity contours looking from right narrow-face towards symmetry (single-phase flow, U:300A, L:300A)

View from right narrow face with location of port shown in inset

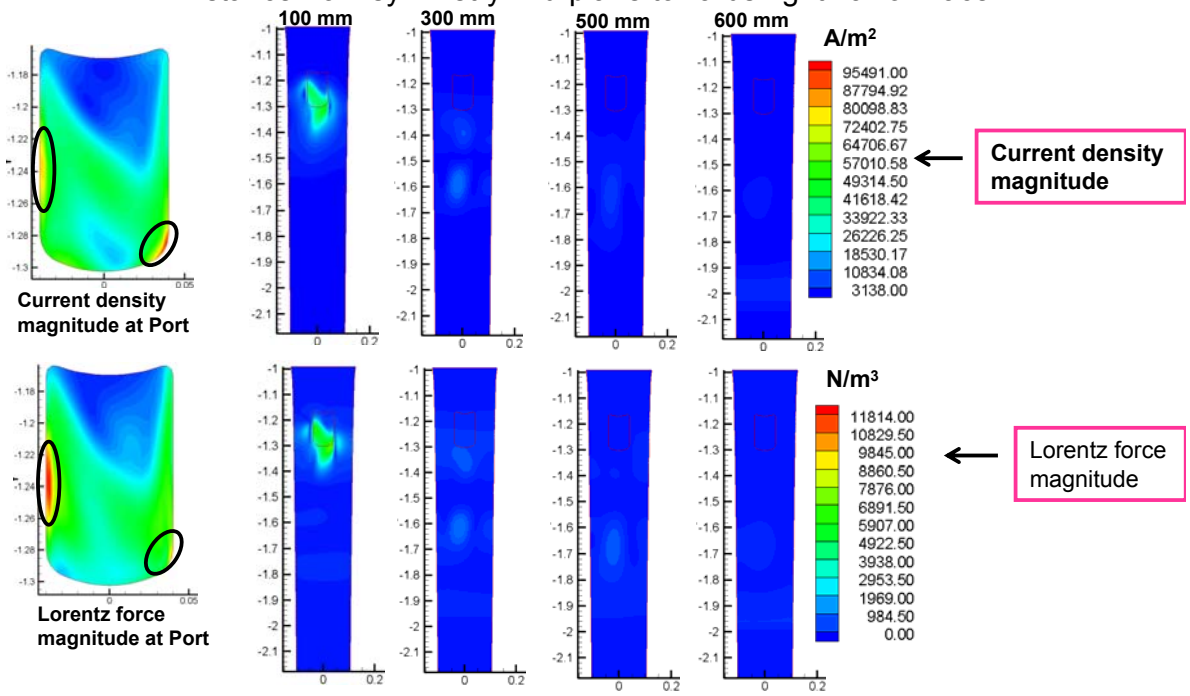


Distance from symmetry mid-plane towards right narrow face

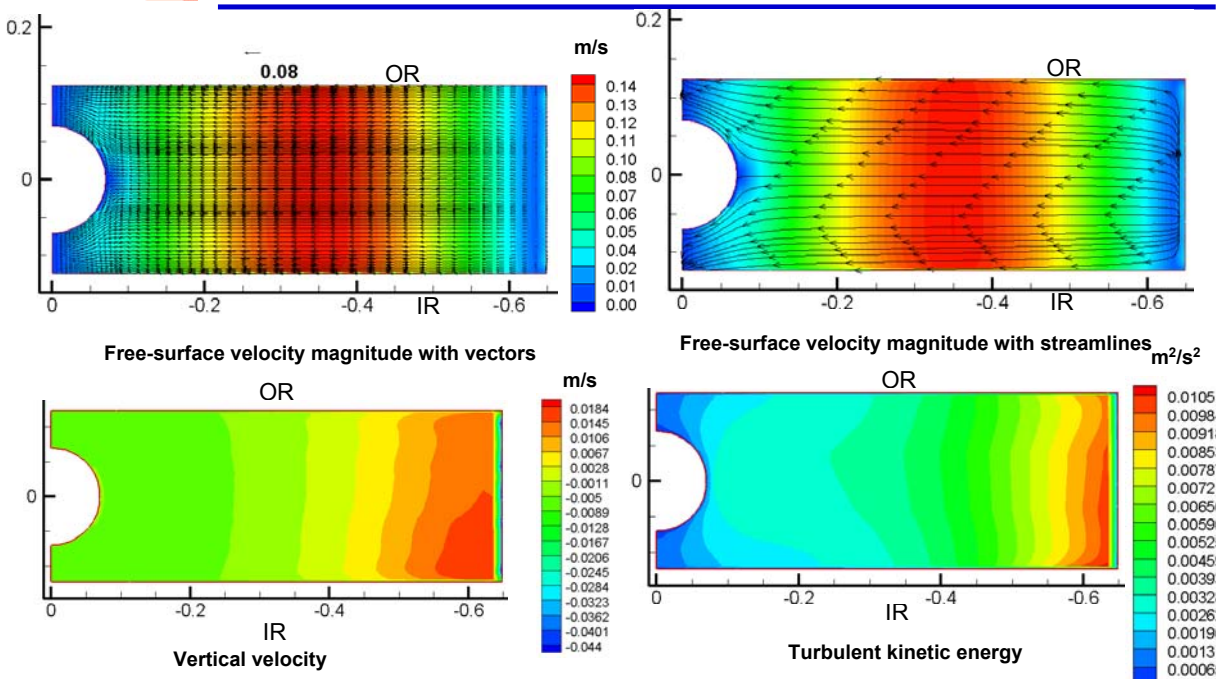
Jet has more horizontal but less vertical spread compared to non-magnetic field case.

Induced current density and Lorentz force (single-phase flow, U:300A, L:300A)

Distance from symmetry mid-plane towards right narrow face

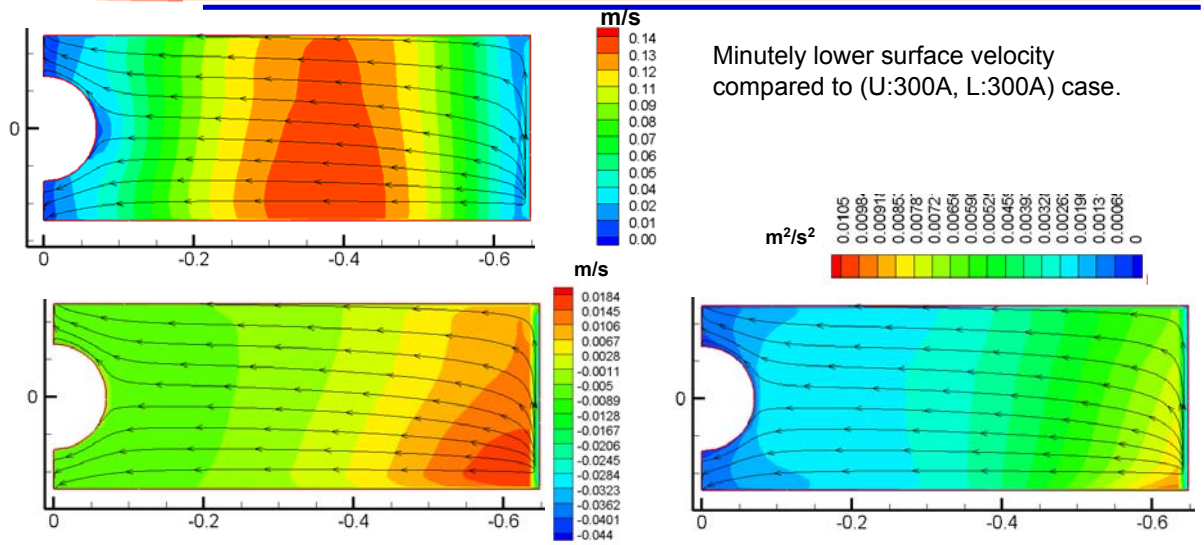


Velocity and streamlines at 15 mm below surface (single-phase flow, U:300A, L:300A)



>>Classic double-roll flow, i.e. steel rising up after striking narrow face and flowing in reverse direction towards SEN in plug like flow.

Velocity and streamlines at 15 mm below surface
(single-phase flow, U:150A, L:300A)

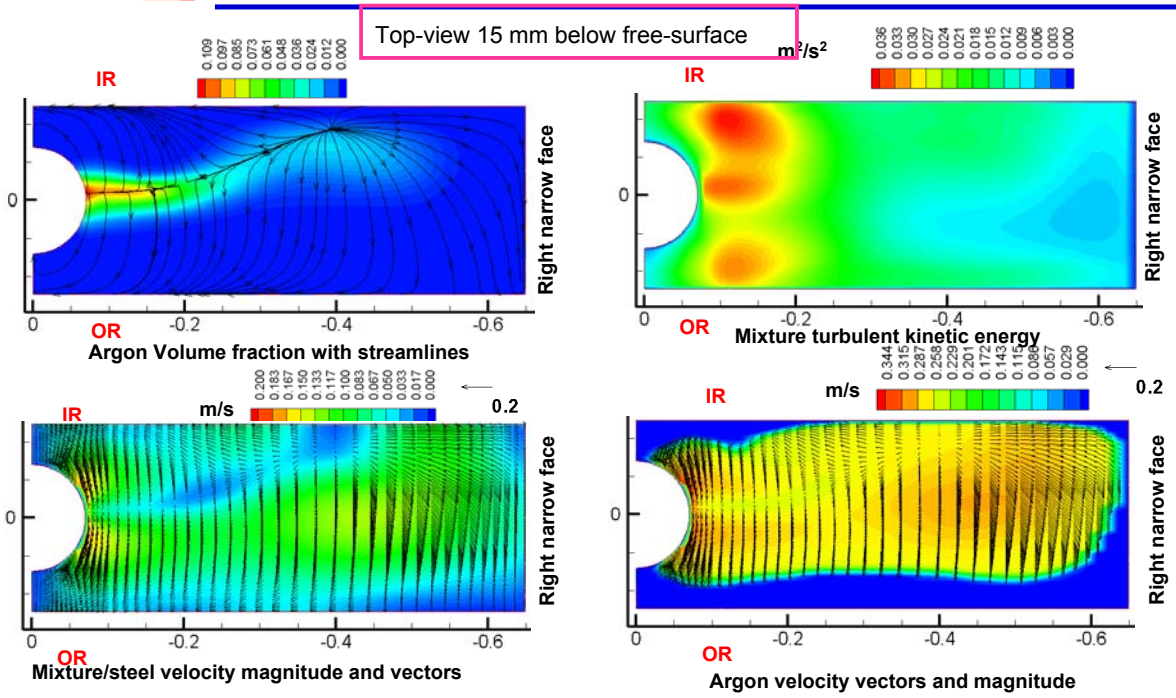


Minutely lower surface velocity compared to (U:300A, L:300A) case.

>>Since, upper ruler is not exactly at port and moreover has weak strength close to narrow face, it does not have much effect on surface velocity.
>> field strength of lower ruler in jet region has more effect on surface velocity.

Eulerian-Mixture model with terminal velocity formulation (30LPM, 2.4 mm bubble size)

Top-view 15 mm below free-surface



Argon Volume fraction with streamlines

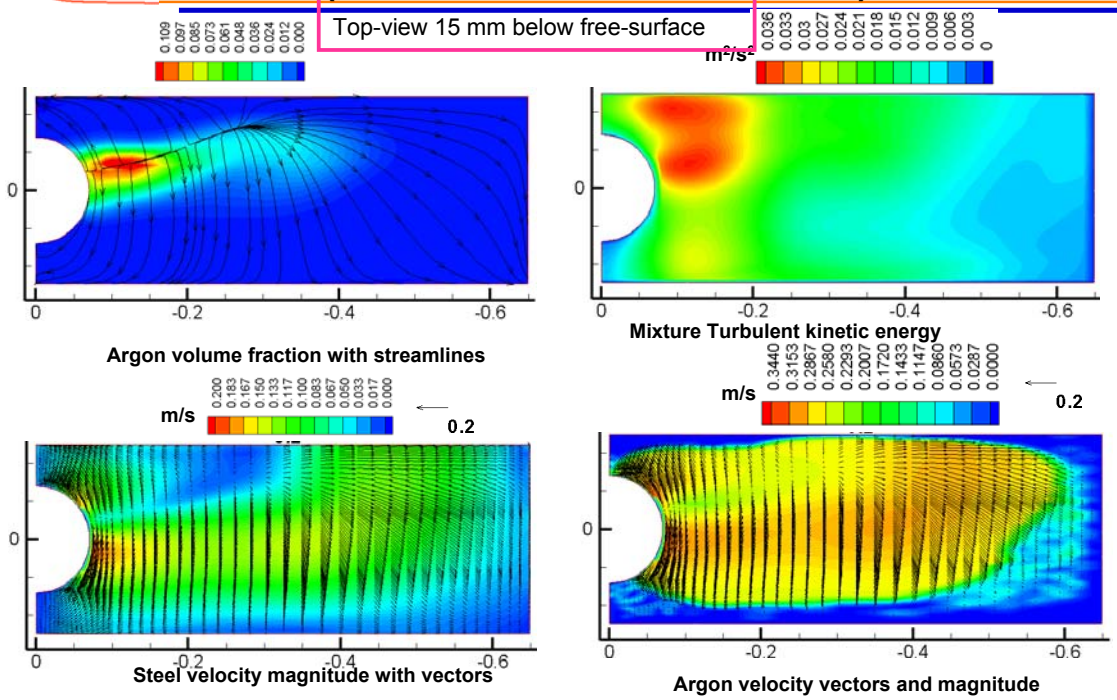
Mixture turbulent kinetic energy

Mixture/steel velocity magnitude and vectors

Argon velocity vectors and magnitude

Two-Fluid model
(i.e. Eulerian-Eulerian model)
(30LPM, 2.4 mm bubble size)

Top-view 15 mm below free-surface



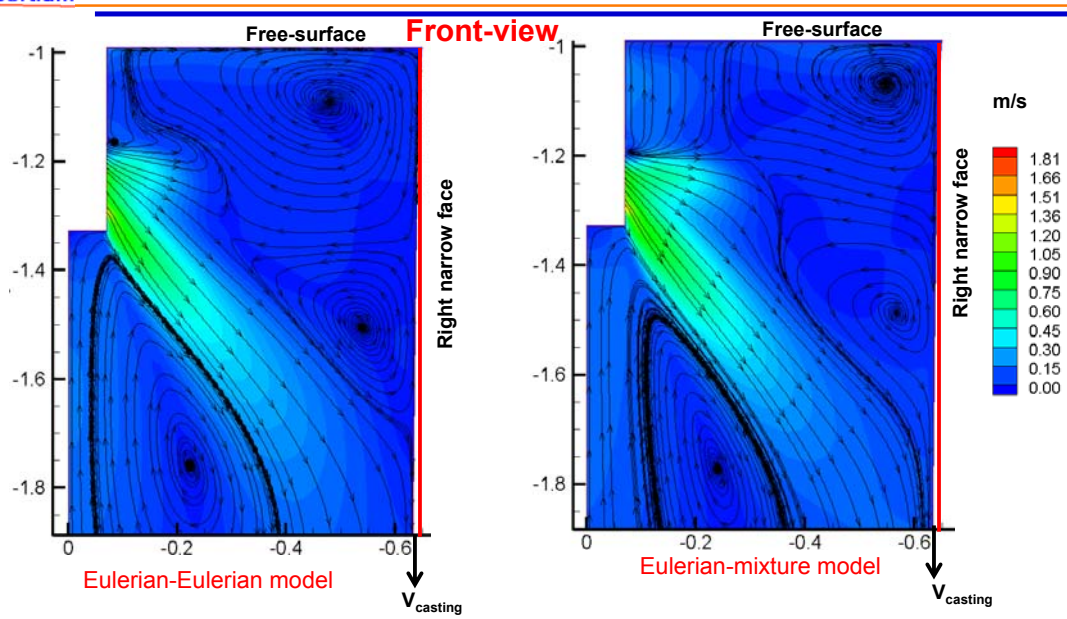
Argon volume fraction with streamlines

Mixture Turbulent kinetic energy

Steel velocity magnitude with vectors

Argon velocity vectors and magnitude

Comparison of mold-mid plane velocity contours and streamlines (E-E and E-M models)
(30LPM, 2.4 mm bubble size)



Velocity contours & streamlines

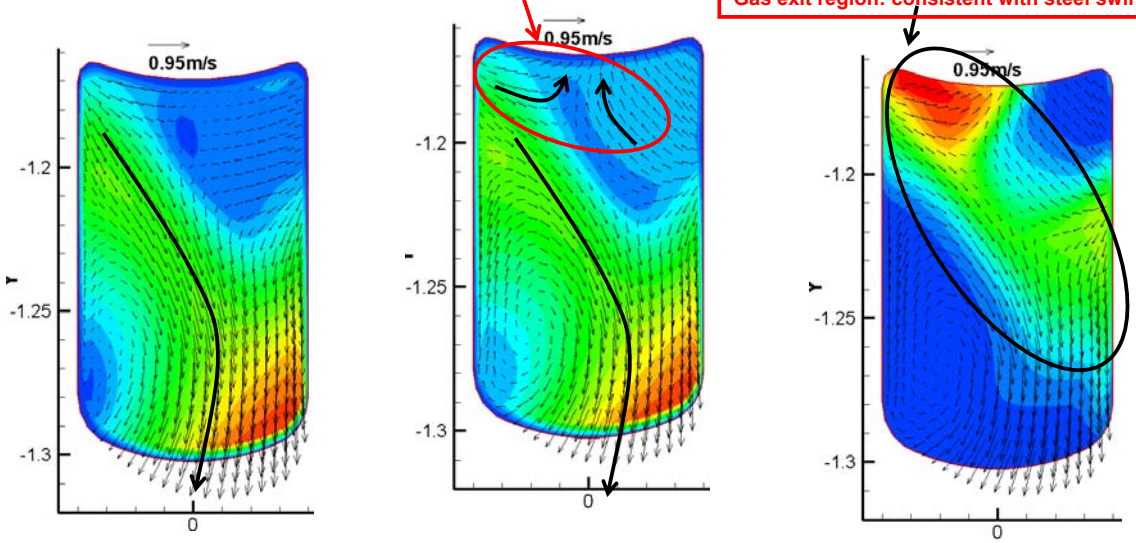
Discussions on comparison of Eulerian-Eulerian and Eulerian-mixture model

- Eulerian-Eulerian model (Two-Fluid model) is the most accurate and versatile multiphase model. Model is stable and applicable over whole range (0-1) of gas volume fraction.
- Unfortunately, FLUENT does not have MHD model implemented in Eulerian-Eulerian model and has it only with Eulerian-mixture model therefore we are bound to use Eulerian-mixture model.
- Eulerian-mixture model becomes less and less applicable at higher volume fractions and therefore as gas volume fraction increases in stagnation regions (like behind slide-gate, on the top of port etc) conventional slip velocity formulation (algebraic slip or terminal velocity) blows up and solution never converges. Reason for this is constant high gas velocity with slip formulation and mixture continuity equation becoming more dependent on gas mass.
- In order to avoid stability problems, three-way coupling correction (Richardson-Zaki power equation, bubble-bubble fluid dynamic interaction) has been implemented in drag formulation of Eulerian-Eulerian and slip velocity formulation of Eulerian-mixture models.
- After the implementation of this correction, Eulerian-mixture model behaved nicely and the results of the two models matched closely. Minute changes in the results of Eulerian-Eulerian model are seen with the implementation of this correction.
- Argon gas is found to be following steel closely in Eulerian-mixture model as per expectations.

Steel and argon velocity contours & vectors with Argon gas volume fraction, (30LPM, 2.4 mm bubble) (E-M model)

Gas rising from port top, Upward flow

Gas exit region: consistent with steel swirl flow



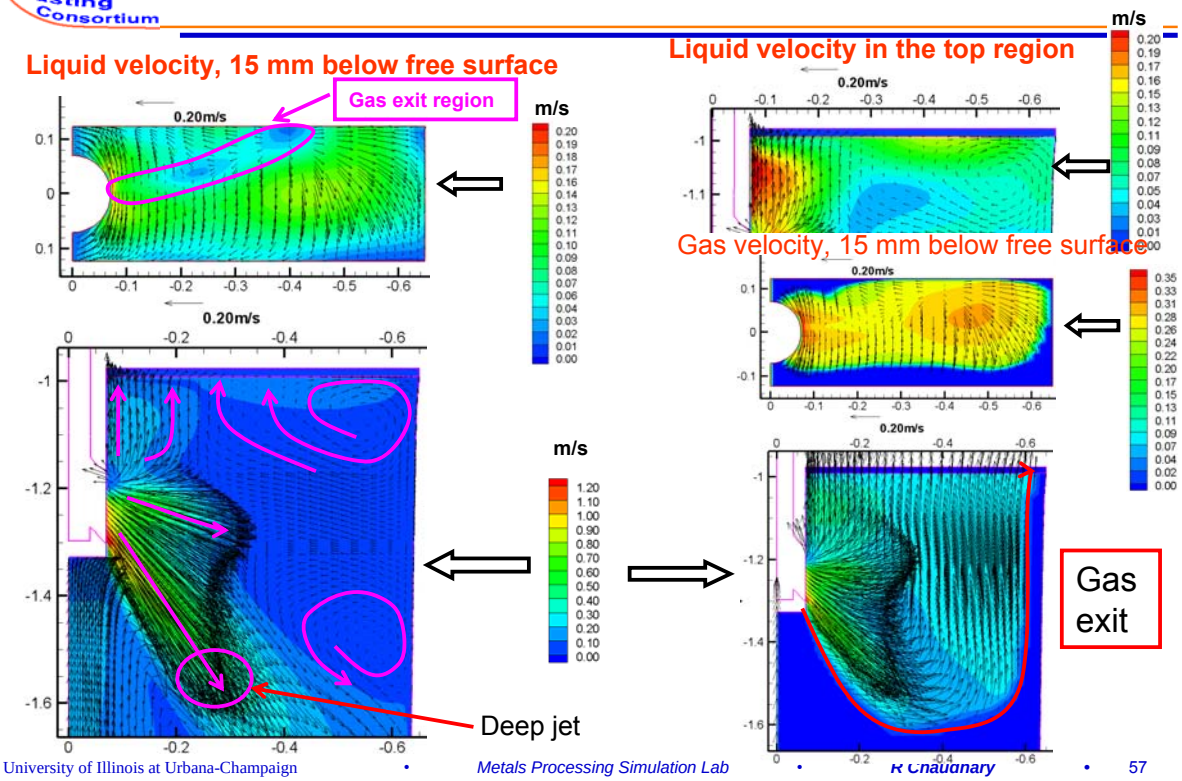
Mixture/steel velocity magnitude with secondary flow vectors

Argon gas velocity magnitude with secondary gas flow vectors

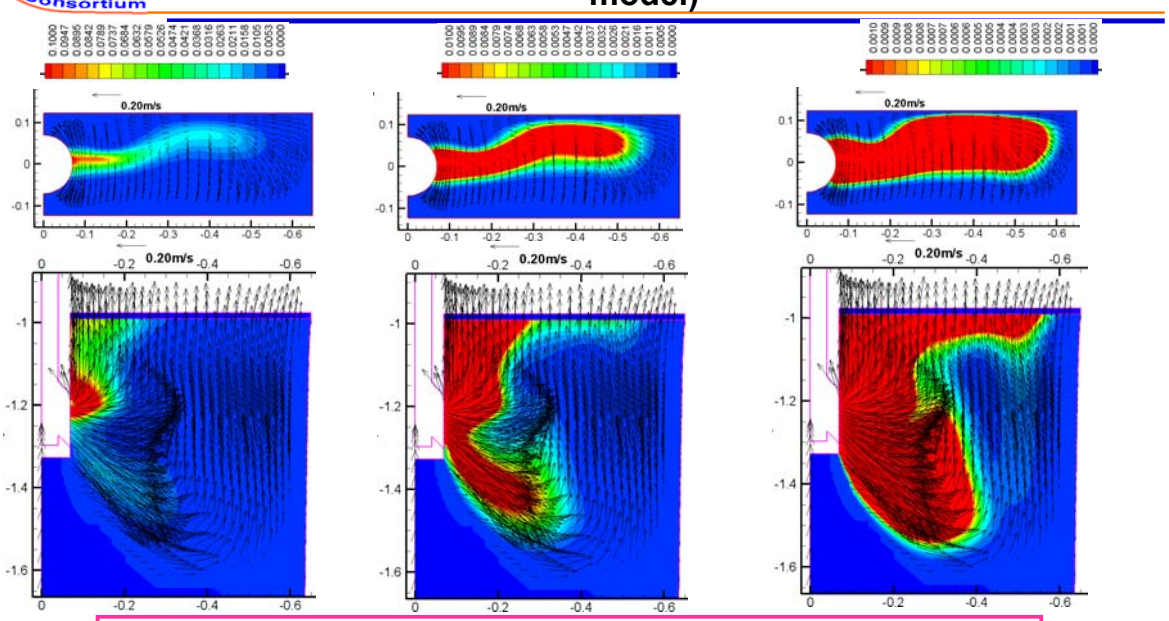
Argon gas volume fraction with secondary gas flow vectors

View from right narrow-face

Steel and argon gas velocity vectors & contours (30 LPM, 2.4 mm bubble) (E-M model)



Argon volume fraction contours with argon velocity vectors (30LPM, 2.4 mm bubble) (E-M model)

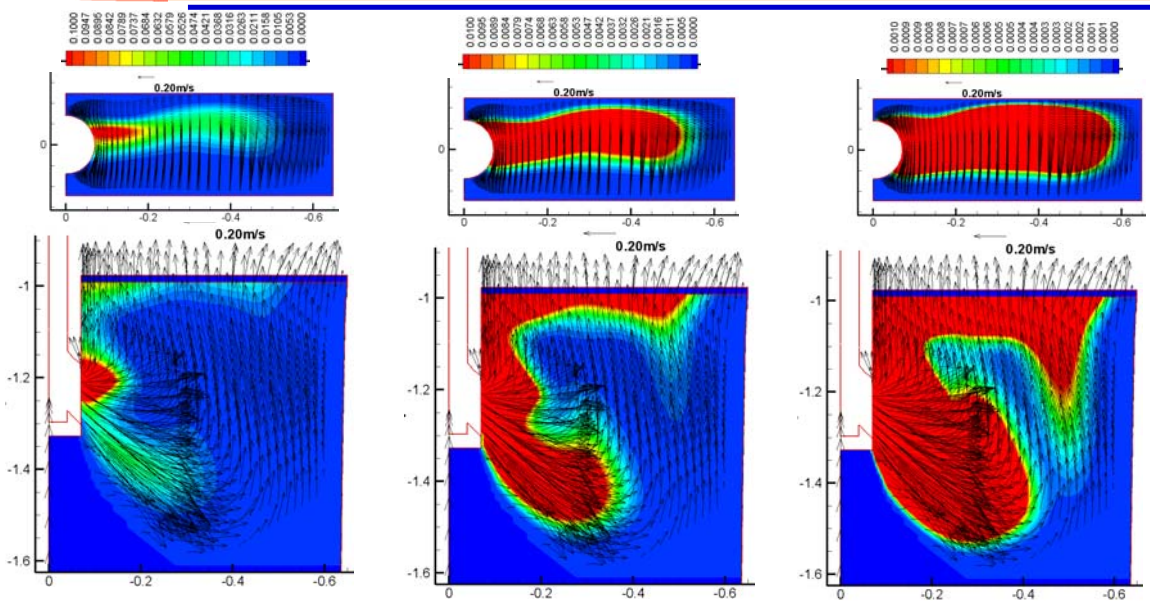


NOTE: three figures have the difference of contour color bar range

Contours of argon gas volume fraction with velocity vectors at mold mid-plane

Front-view

Argon volume fraction contours with argon velocity vectors (55LPM, 2.4 mm bubble) (E-M model)

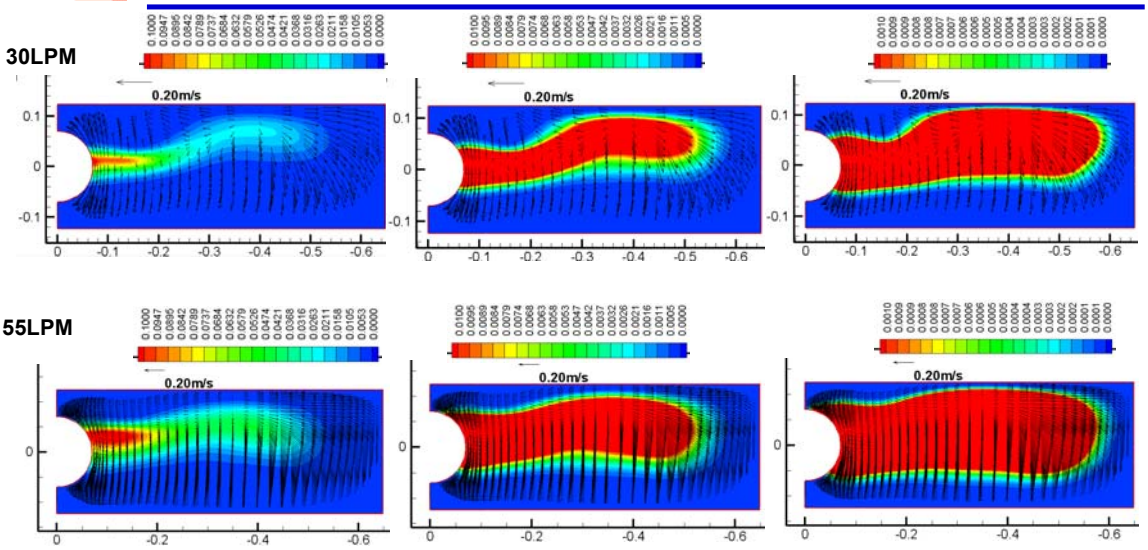


Higher gas flow rate, 54.8 LPM

comparison of argon gas volume fraction at 15 mm below free surface in 30LPM and 55LPM gas flow rates (2.4 mm bubble) (E-M model)

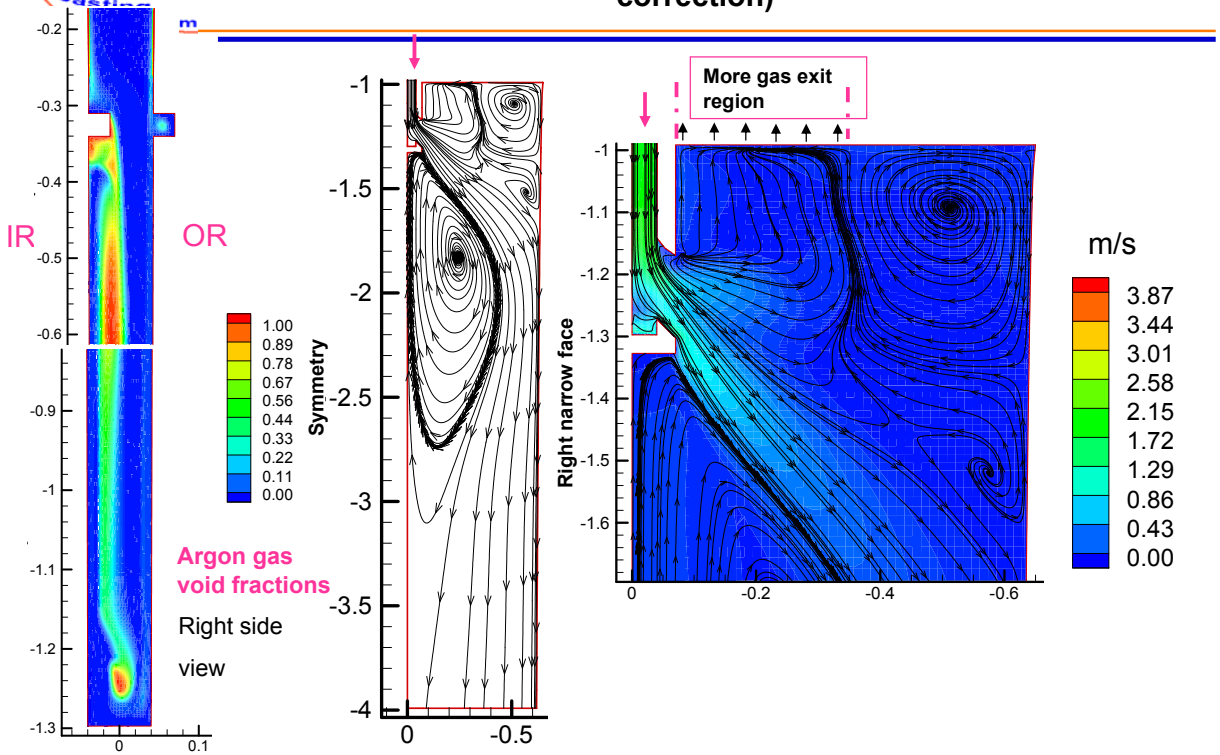
Gas: 30LPM

Gas: 55LPM

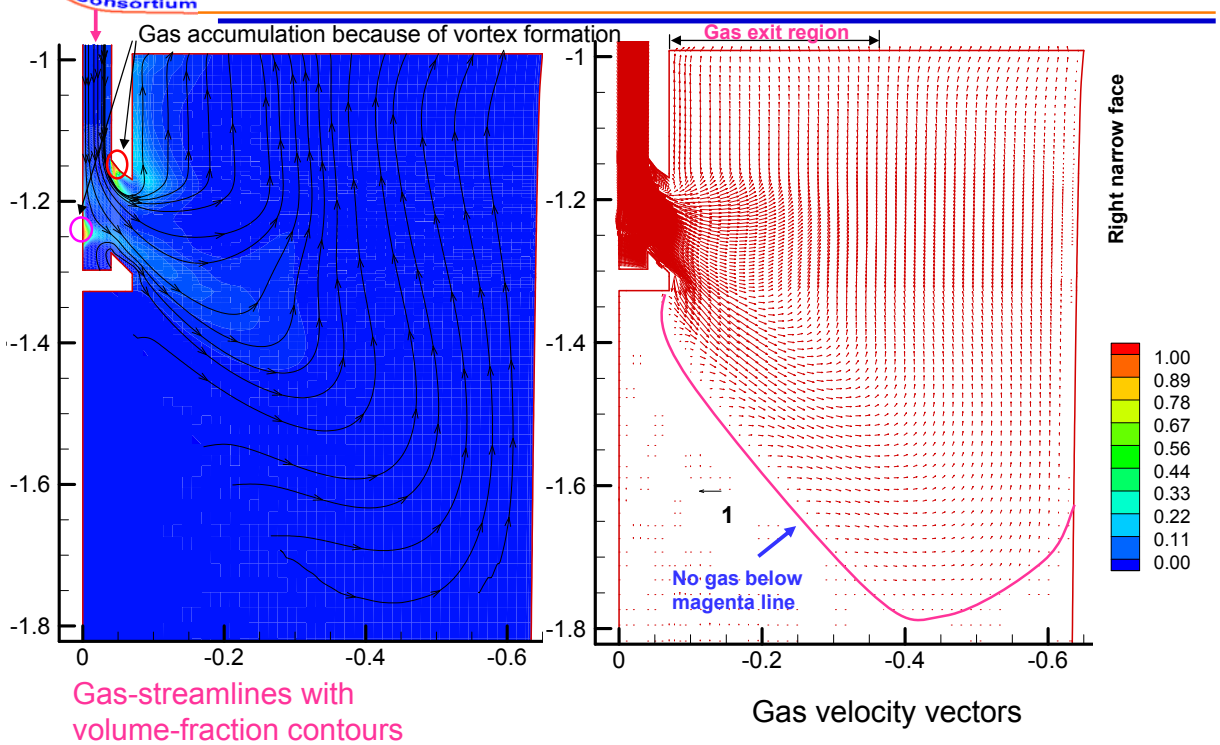


Higher gas flow rates shows more spread of gas on the top surface with lower fraction following steel velocity wave closely and thus causing more asymmetry in gas fraction.

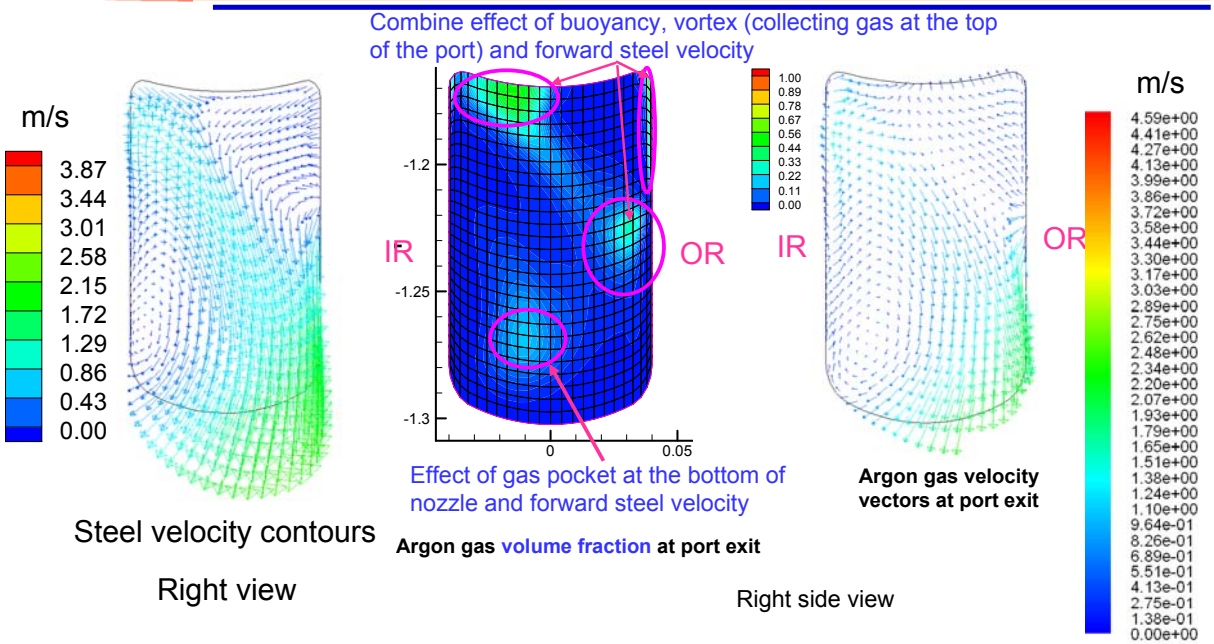
Streamlines and velocity contours of steel flow at mold mid-plane (30LPM, 2.0 mm bubble) (E-E model without bb interaction correction)



Gas trajectories, gas volume fraction contours and velocity vectors at the mid-plane in the mold (30LPM, 2.0 mm bubble) (E-E model without bb interaction correction)



Steel and argon gas velocity vectors and volume fraction contours at the right port exit (30LPM, 2.0 mm bubble) (E-E model without bb interaction correction)

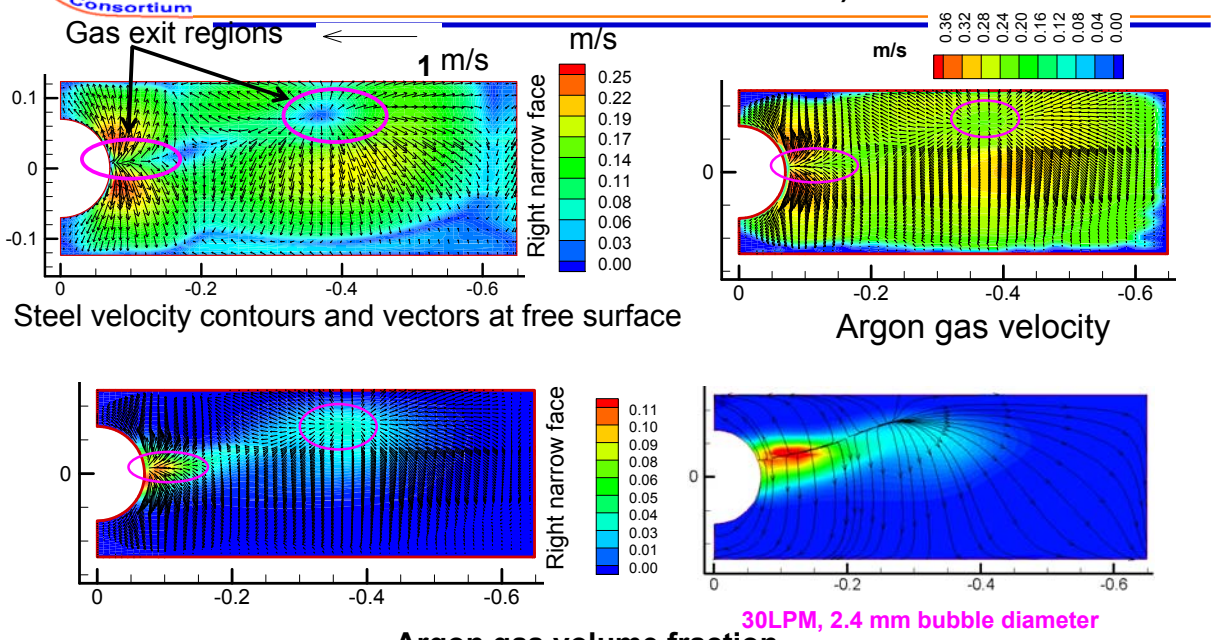


Steel velocity contours

Right view

Right side view

Steel velocity, argon velocity and fraction at 15 mm below surface (30LPM, 2.0 mm bubble) (E-E model without bb interaction correction)



Steel velocity contours and vectors at free surface

Argon gas velocity

Argon gas volume fraction

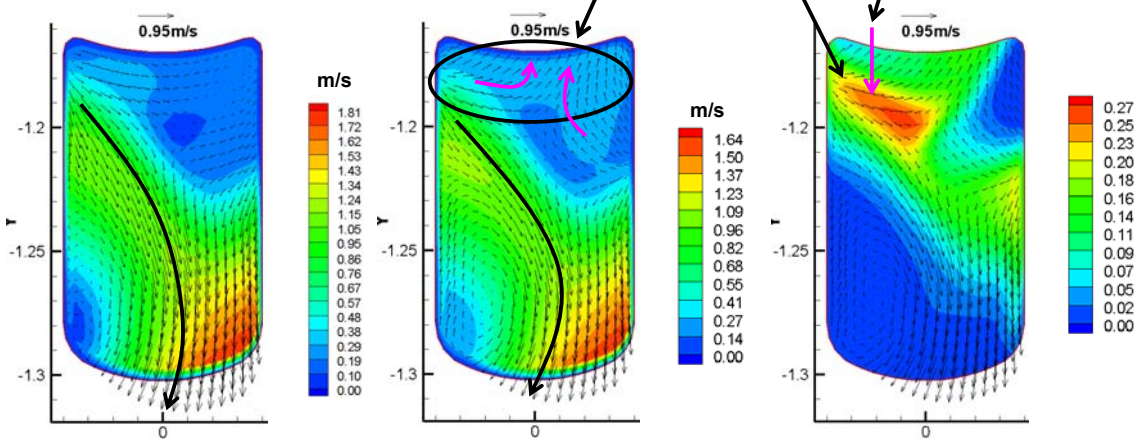
>> Argon gas spread more on the top surface in case of smaller diameter.

Strong Mag Field: Steel and argon velocity contours & vectors with Argon gas volume fraction (30LPM, 2.4 mm bubble size, E-M) (U:300A, L:300A)

Gas exit region: consistent with steel swirl flow

Gas rising from top of port

Gas exit region shifted downwarc



Mixture/steel velocity magnitude with secondary flow vectors

Argon gas velocity magnitude with secondary gas flow vectors

Argon gas volume fraction with secondary gas flow vectors

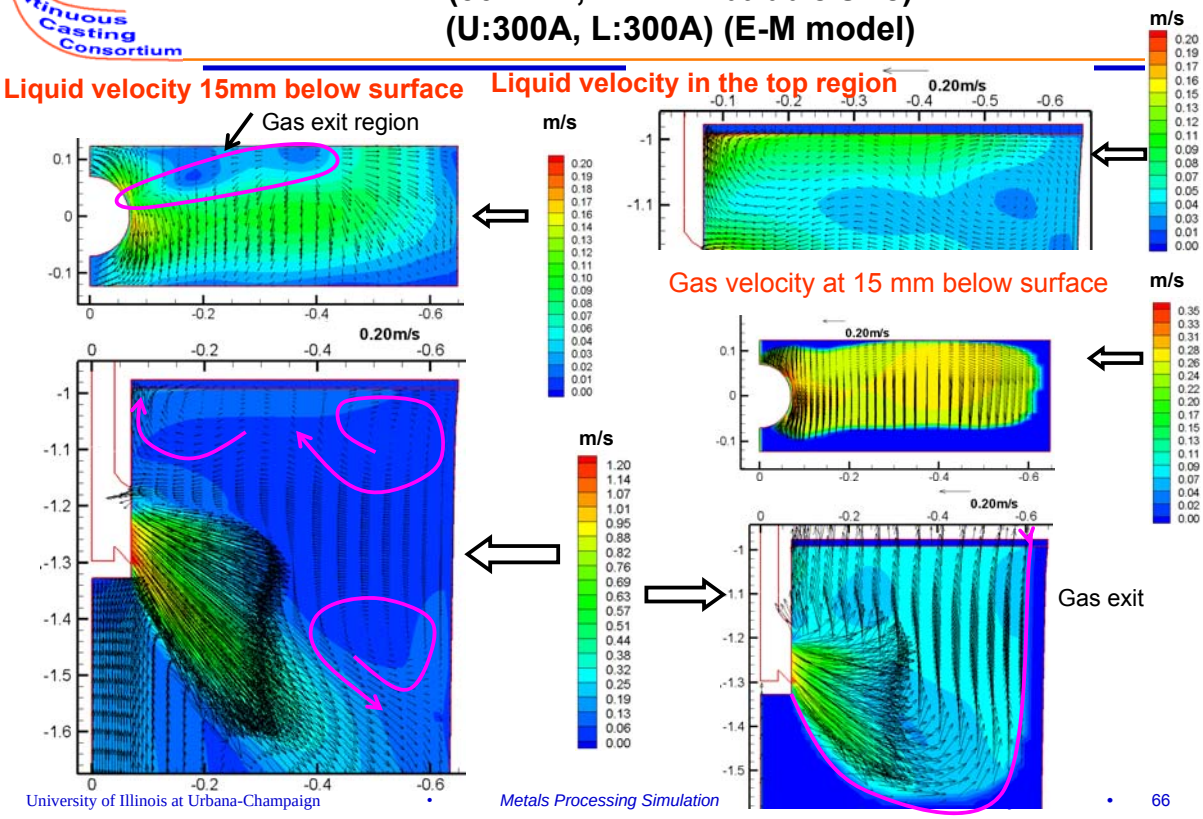
View from right narrow-face

Steel-argon multiphase flow (30 LPM, 2.4 mm bubble size) (U:300A, L:300A) (E-M model)

Liquid velocity 15mm below surface

Liquid velocity in the top region

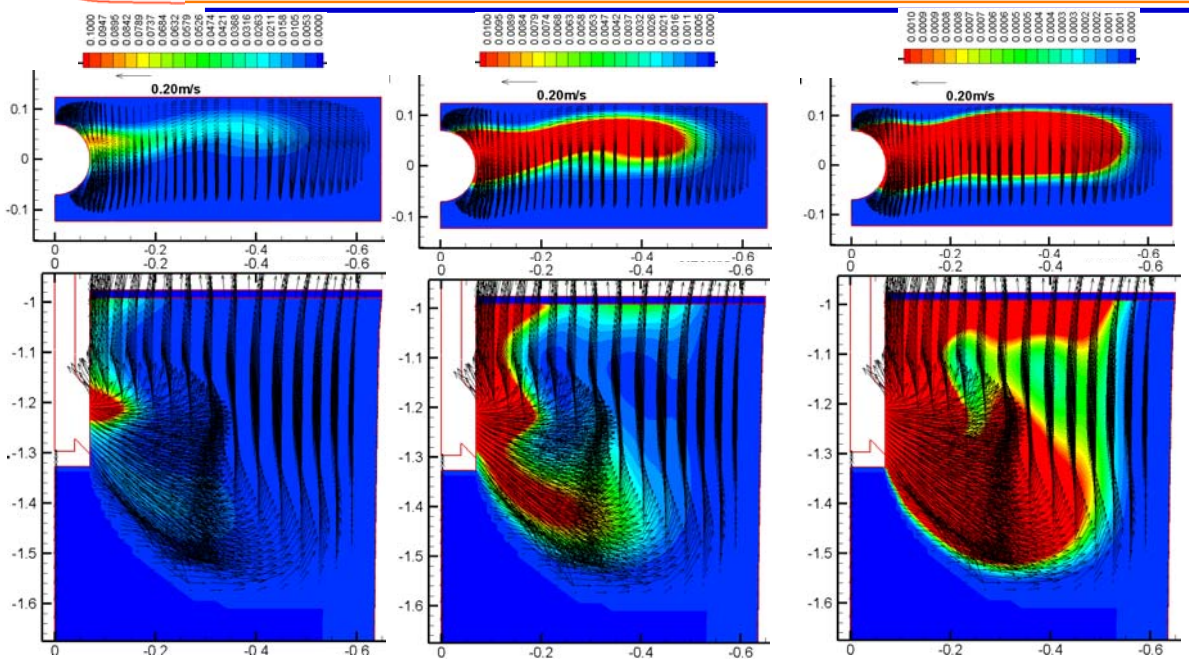
Gas exit region



Gas velocity at 15 mm below surface

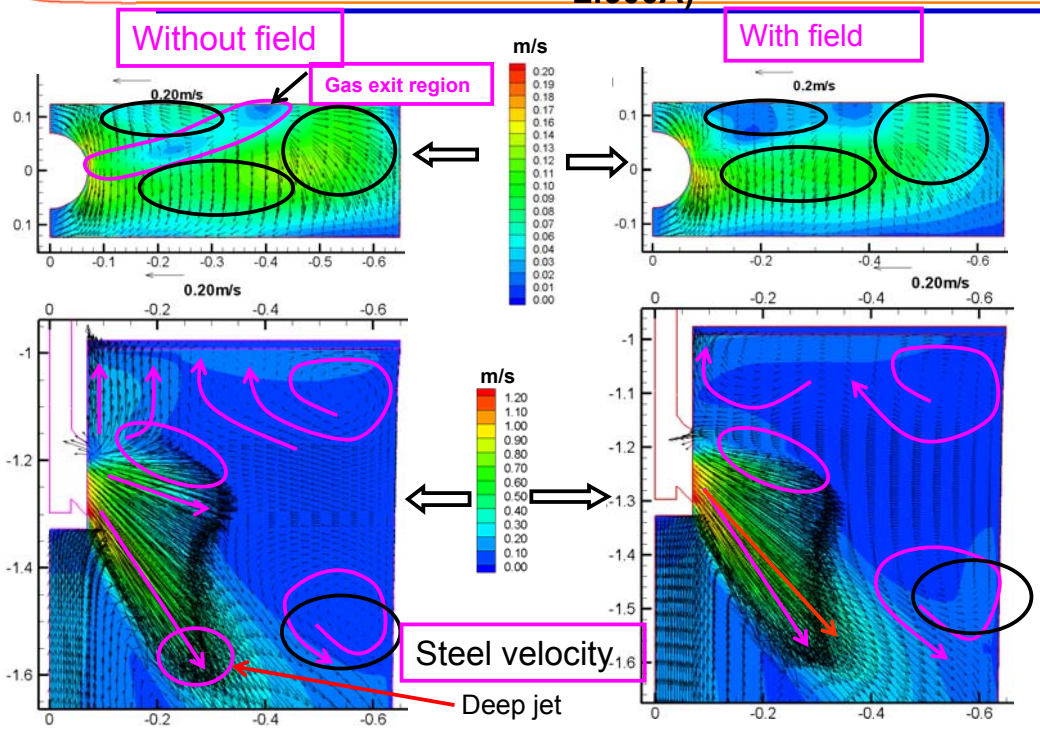
Gas exit

Gas velocity vectors and volume fraction contours (30LPM, 2.4 mm bubble size) (U:300A, L:300A) (E-M model)



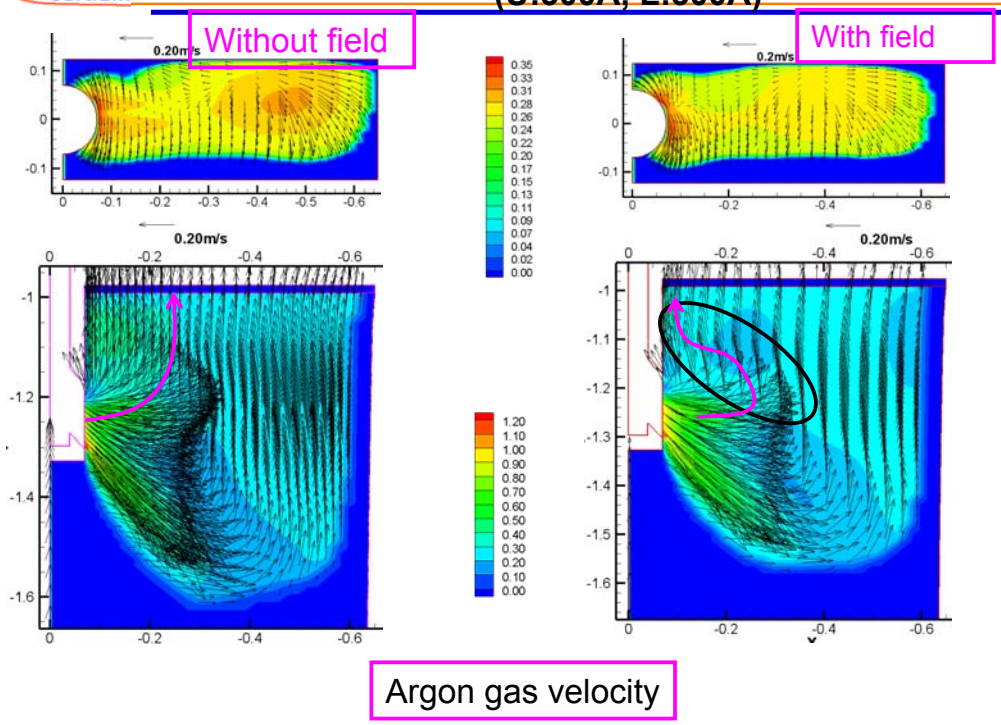
Effect of Magnetic Field:

(compare steel velocity at mold mid plane and at 15 mm from top surface) (30 LPM, 2.4 mm bubble) (E-M model) (U:300A, L:300A)



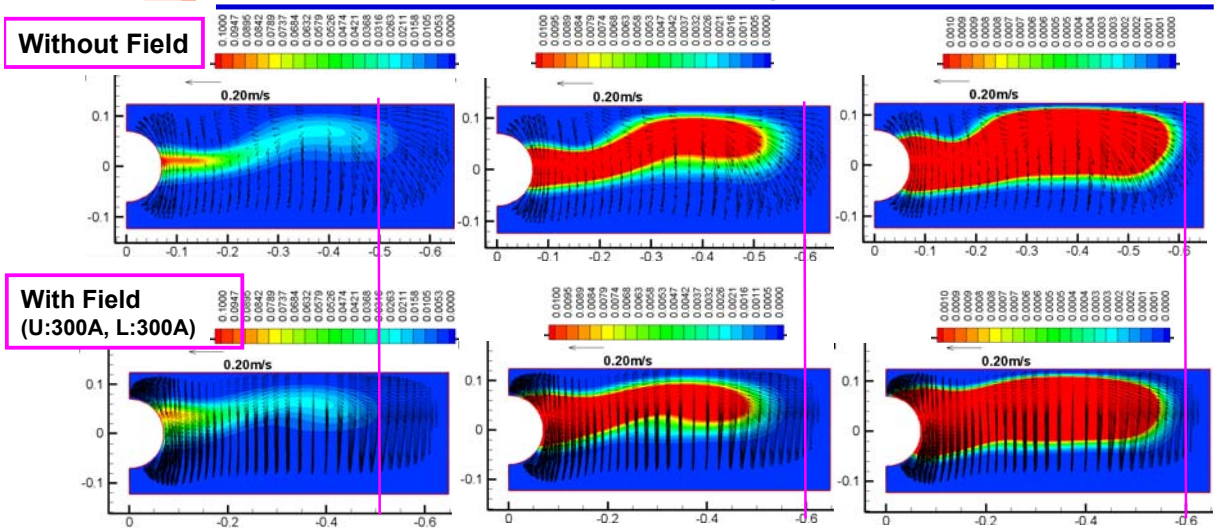
Effect of Magnetic Field:

(compare argon gas velocity at mold mid plane and at 15 mm from top surface) (30 LPM, 2.4 mm bubble) (E-M model) (U:300A, L:300A)



Effect of Magnetic Field:

(compare gas fractions 15 mm from top surface) (30 LPM, 2.4 mm bubble) (E-M model)

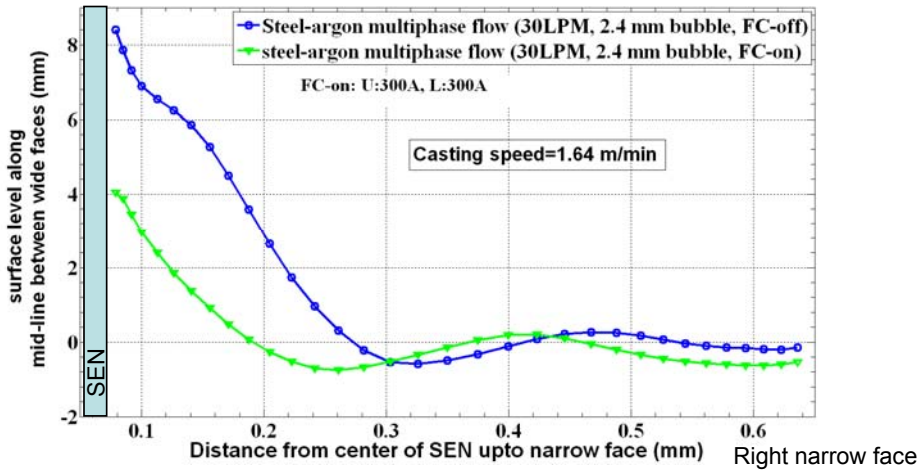


>>FC on reduces gas spread towards narrow face.

>> FC on shifts gas exit regions towards OR close to SEN.

Gas: 29.39 LPM

Effect of magnetic field on surface level along the mid-line between wide faces

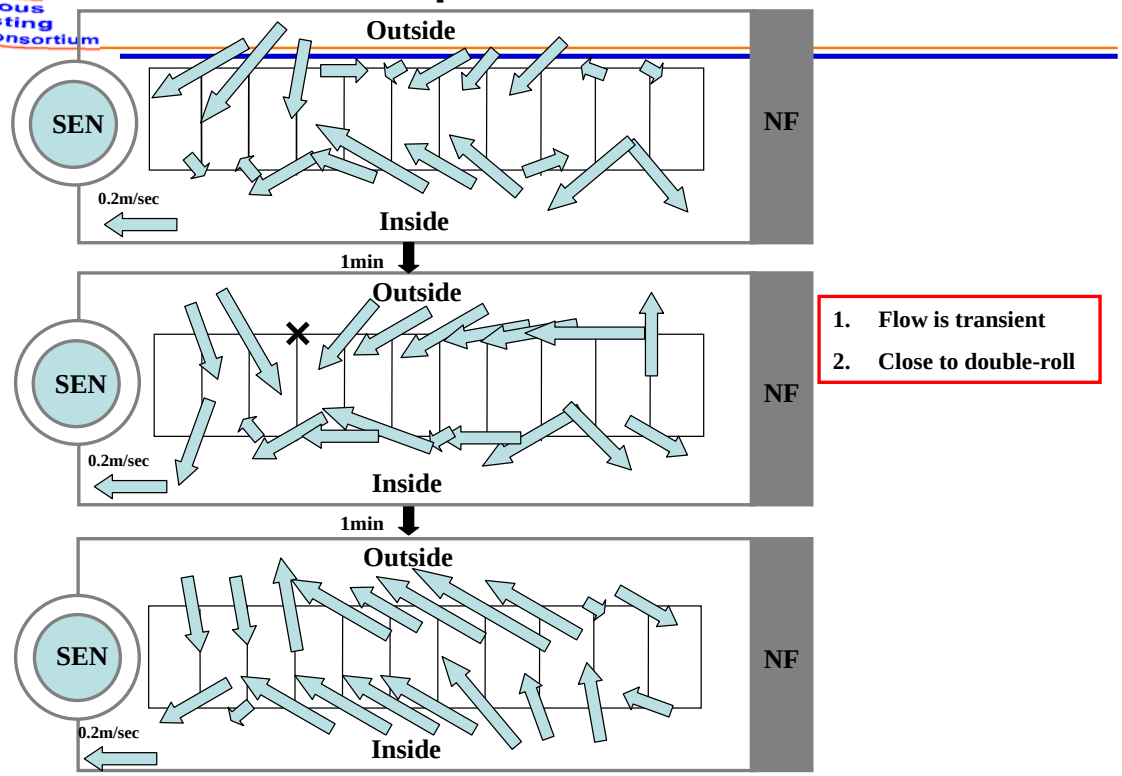


>>Close to SEN, gas gives higher surface wave.
>>Magnetic field suppresses the rising velocity of gas close to SEN and therefore indirectly reducing the surface level.

Discussion on effect of magnetic field on steel-argon multiphase flow

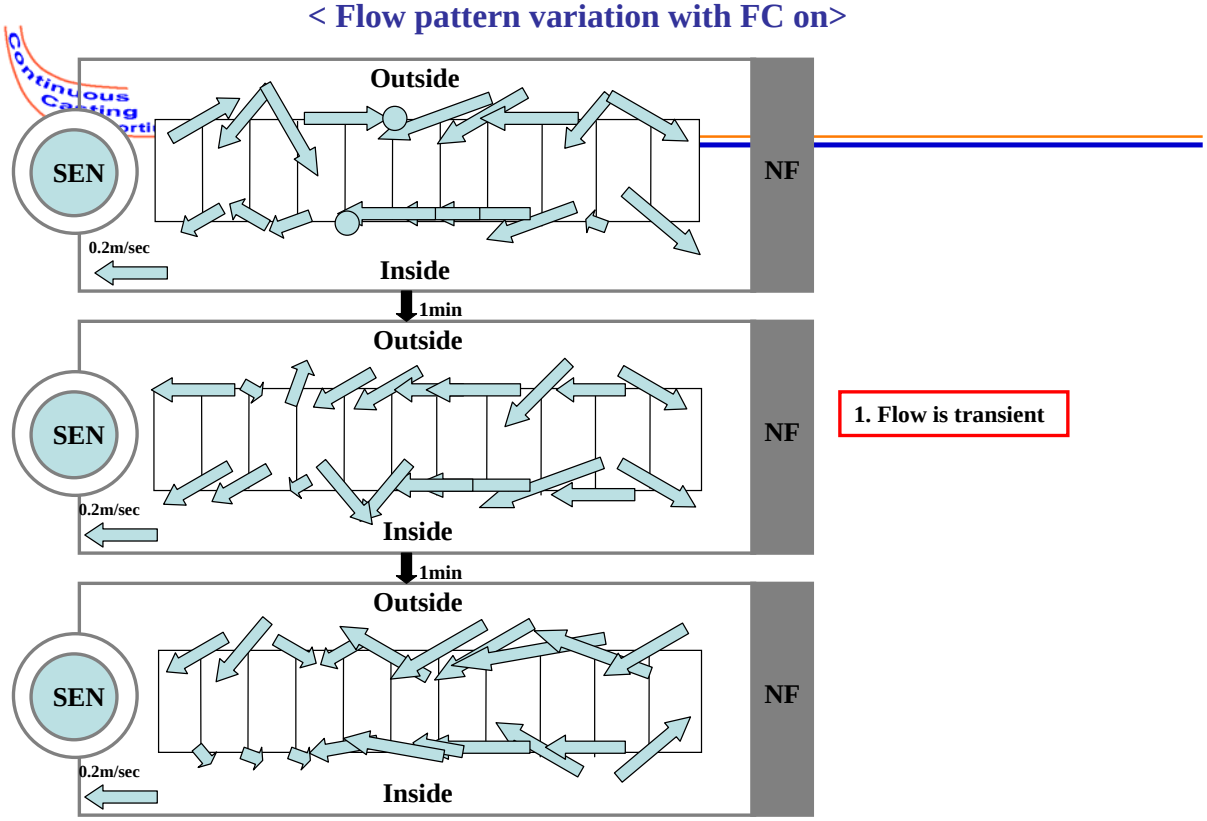
- Steel and argon flow on the surface perpendicular (horizontal & vertical) to magnetic field is reduced in FC on case.
- Magnetic field suppresses nose to the jet. (consistent with single-phase steel flow)
- Magnetic field has no effect on velocity parallel to field.
- Magnetic field reduces vertical gas velocity.
- Lower field ruler bends jet slightly upward causing higher upward velocity in FC on compared to FC off.
- Upper ruler pushes this upward flow towards SEN horizontally and thus forcing this to move towards SEN along with gas.
- Gas exits from OR side close to SEN.

Flow patterns with FC-off



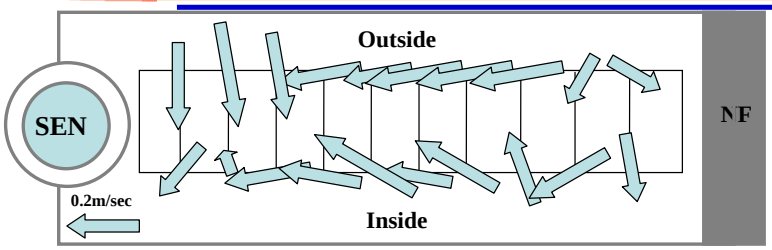
1. Flow is transient
2. Close to double-roll

< Flow pattern variation with FC on>



1. Flow is transient

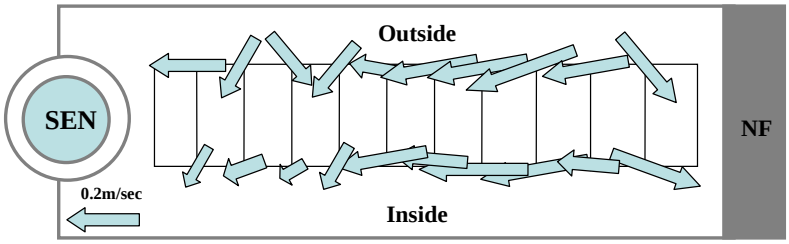
< Dominant flow pattern considering horizontal velocity >



< FC off >

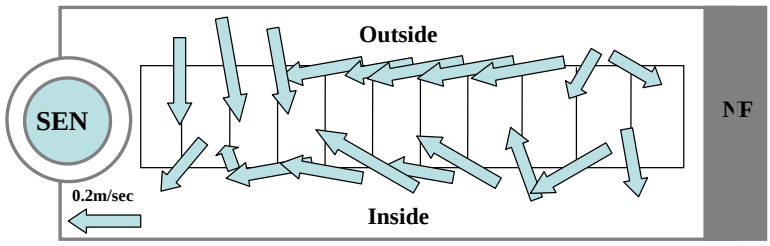
Flow is more uniform toward SEN with FC on

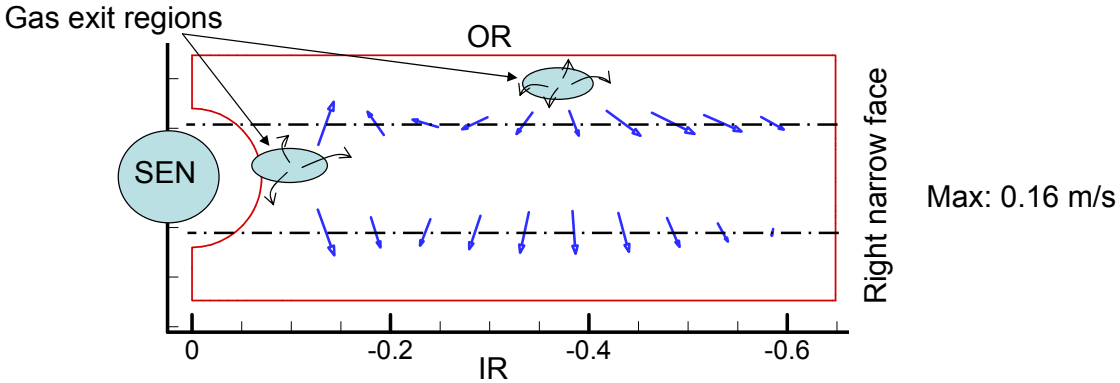
Less cross-flow from outside to inside with FC on



< FC on>

Comparison of surface-velocity predictions with nail board measurements (FC-off)

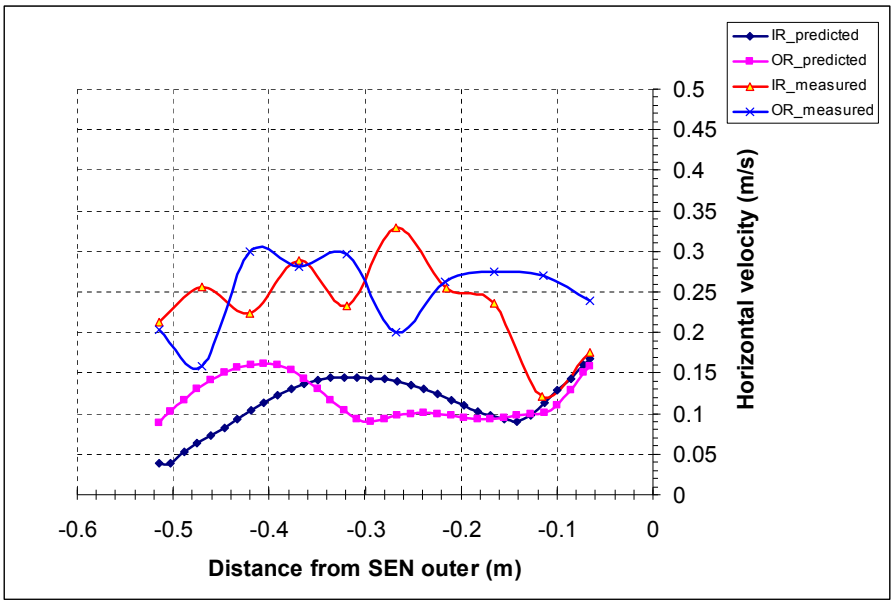




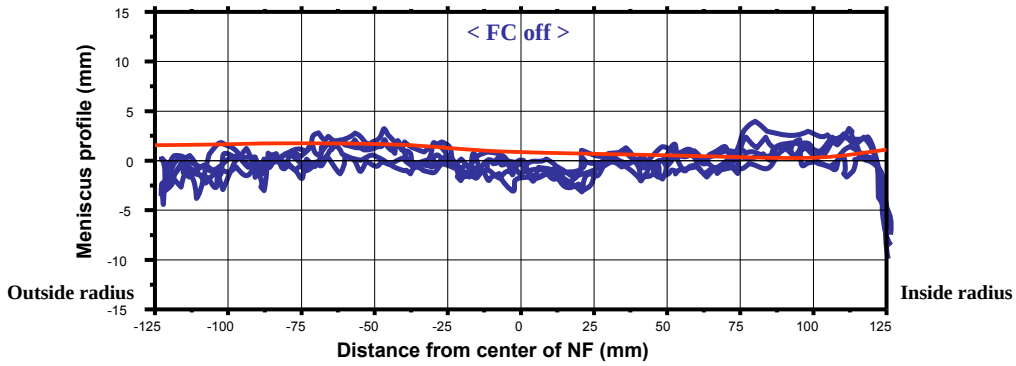
Note: Vectors are anchored at the center position.

1 m/s

Comparison of surface velocity (magnitude) predictions with nail-board measurements

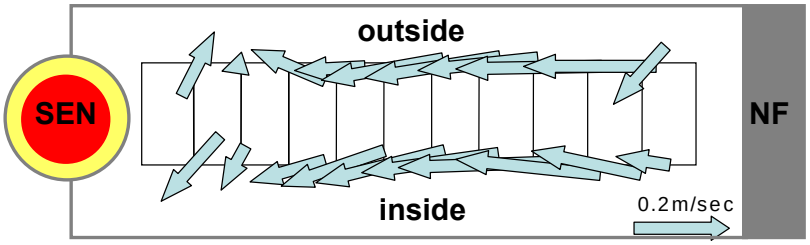


Meniscus level profile (at left narrow face)



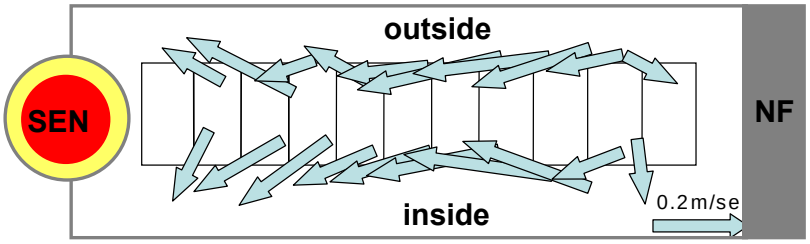
Test3(most recent): Influence of FC on Surface Flow Pattern

FC OFF



FC ON

Total 6 cases: means are shown here



Measurements suggest double-roll flow.

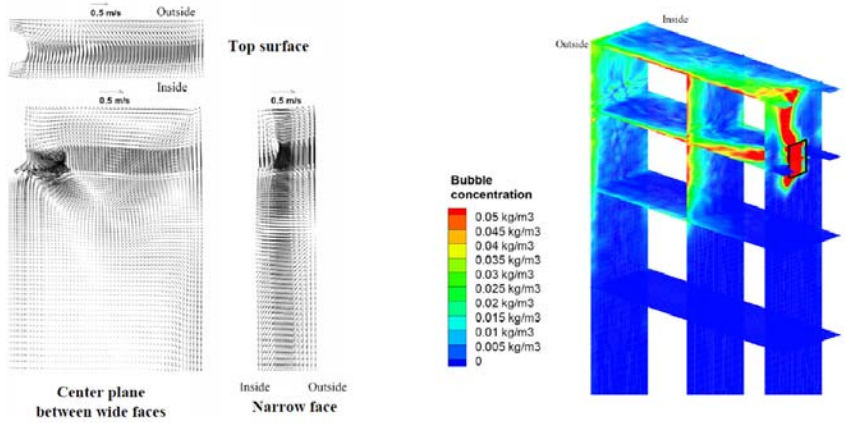
Differences between current work (Chaudhary R, Cho S-M and Lee Go-Gi (2008-2009)) and Lee et al's(2006) previous work

Parameters	Previous work (Go Gi, 2006)	Current work (simulations) (Cho S-M & Lee Go Gi, measured, 2008& 2009)
Casting speed	1.46 m/min	1.64 m/min
Slab width	1570 mm	1300 mm
Slab thickness	230 mm	250 mm
Gas injection	9.6 SLPM	9.2 SLPM
Mean bubble diameter	2.3 mm (simulation)	(2.0/2.4 mm in current simulations)
Port angles (step angle)	52, 35 degree (top) 35 degree (bottom)	52, 35 degree (top) 45 degree (bottom)
Nozzle details	90 degree slide-gate, bifurcated type	90 degree slide-gate, bifurcated type
Nozzle port height x width	98mm x 70mm	85mm x 80mm
Nozzle bore diameter	75 mm (constant)	91mm(top)-80mm (bottom)
SEN depth	180mm	178mm
Shell	No shell in the model.	Shell incorporated in the model.

Practically, current work is quite similar to GG Lee et al's (2006) work except minor differences mentioned above.

I expect these two works should match qualitatively????

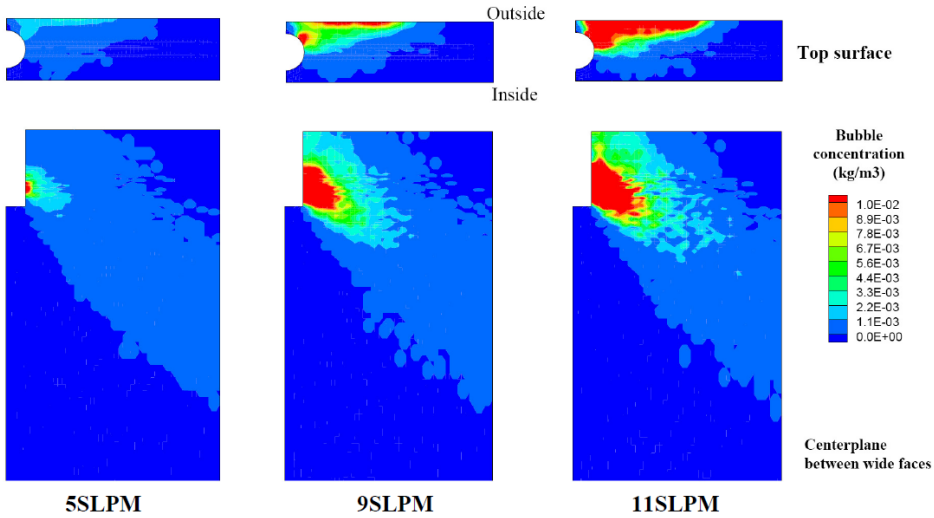
Lee et al (2006) simulation work (results after 30 secs)



- Generally double-roll flow pattern, impinging on NF;
- Some flow up outside wide face, across top surface, and down inside wide face
- results match plant measurements

Is this really double roll flow????? I think not!!

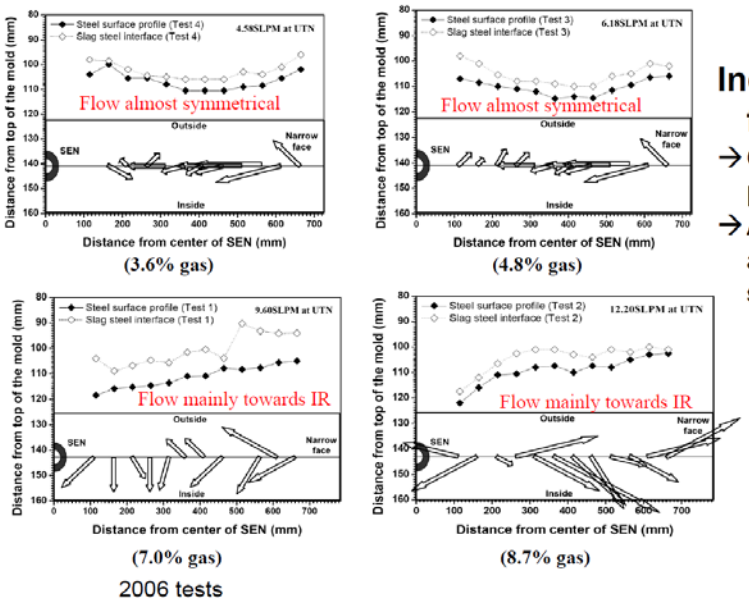
Lagrangian gas bubble simulations for 4 secs (Lee et al(2006))



>>>4 sec not enough for steady state

>>> gas exits from OR side of the free surface (consistent with current simulation findings)

GG Lee et al (2006) free surface level and nailboard velocity measurements



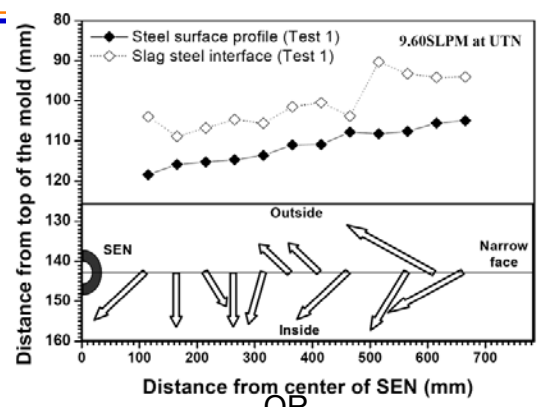
2006 tests

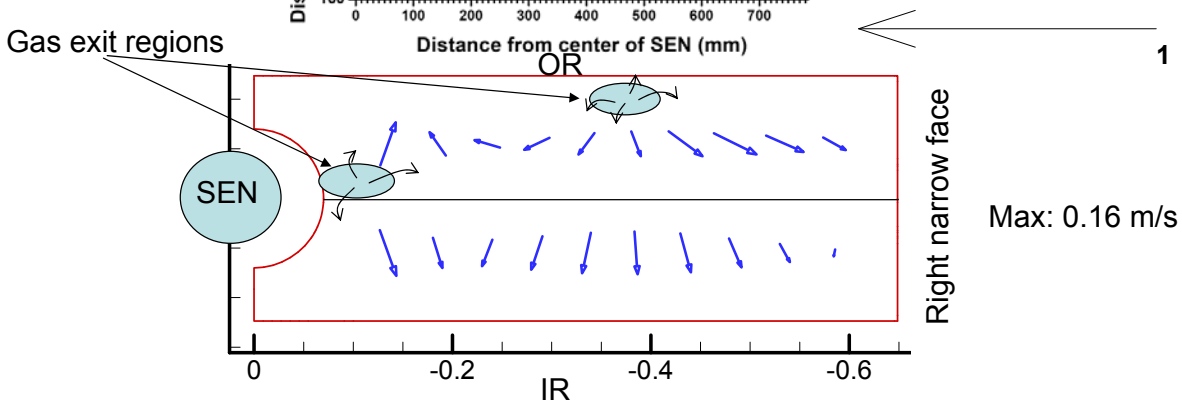
Increasing gas flow rate

→ Changes flow pattern

→ Asymmetric flo across the top surface

Comparison of current simulations with GG Lee (2006) measurements

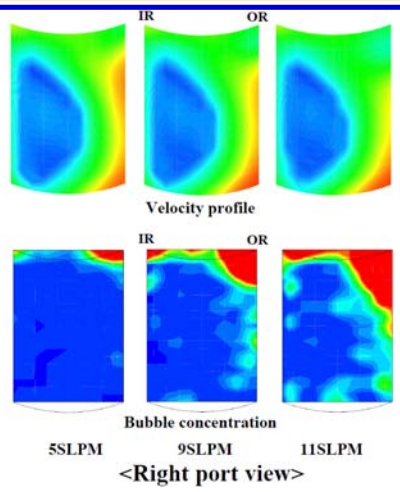




1

Max: 0.16 m/s

Simulated port velocities and gas bubble concentration (Lee et al(2006)



- Stronger steel flow from bottom right (of right nozzle port)
- More gas exits top right
- Higher gas flow rate causes stronger asymmetric recirculation flow at nozzle outlet port

I do not agree with this claim, asymmetric recirculation flow is mainly caused by slide-gate and gas is found to have very small effect on it. Moreover, it is difficult to claim this based upon 30 sec real time simulations. As I found gas follows the nozzle swirl and exits port from left top then right top as claimed by Go Gi.

>>>Port velocities showing swirling flow are consistent with current work.

Summary

- 3-D, steady, steel single-phase and steel-argon multiphase MHD flow simulations were performed on a slide gate type flow control nozzle and mold.
- In all flow simulations, mold was modified based up on solidified shell profile and sink terms were added to model the effect of shell solidification.
- In multiphase steel-argon flows, argon gas was injected based upon calculated gas velocity profile above UTN.
- This injected gas was removed by creating sink elements just below free surface.
- Constant mean bubble diameter calculated based upon GG Lee and Bai et al's work (=2.4 mm) was considered in modeling.
- Eulerian-Eulerian and Eulerian-mixture model are found matching nicely with the three-way coupling effects (bubble-bubble fluid dynamic effects). Based upon this outcome, Eulerian-mixture model augmented with bubble-bubble fluid dynamic interaction correction is used for multiphase simulations (i.e. with and without magnetic field).

Conclusions on single-phase steel flow

- Slide gate causes swirl in the nozzle bottom and therefore jet gives higher velocity at the bottom right of the port directed towards inner radius. With stopper rod type SEN, flow shows front and back symmetry with more flow coming out from nozzle bottom.
- Slide gate also causes nose to the jet with the swirl. With the nose and steeper jet, flow is directed downward and jet looses momentum faster and thus giving weak upward reverse surface flow towards SEN after hitting narrow face. Reporting of nose in the jet is consistent with the findings of Thomas et al (1999) in 90 degree slide-gate nozzle.
- This weak upward flow in the upper roll from narrow face to SEN fights upward flow from around jet close to SEN and ends up causing two rolls in the upper region. (partially double-roll flow)
- Port with 35(B):35(TB):52(TT) angles showed stronger swirling flow with more stagnation region at the bottom of the SEN well and smaller reverse flow zone at the top of the port.
- With magnetic field, upper magnetic ruler kills nose and lower ruler bends the jet towards upward and thus promoting classic double roll flow.

Conclusions on Multiphase flow (steel-argon flow)

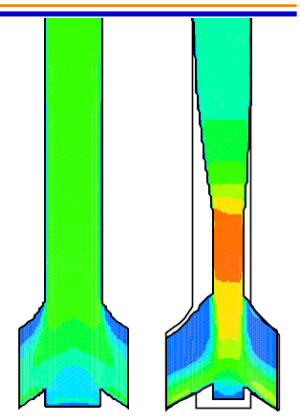
- Argon gas collects in stagnation regions behind slide-gate, and on the top of port. More gas exits from the top of the port thus buoyancy effect are evident.
- Argon gas has minor effects on high speed steel flow in the nozzle. E-E and E-M models match nicely except behind the slide-gate where gas collects.
- In mold, maximum gas comes out from OR side close to SEN. As expected, buoyancy force is high in steel-argon system which forces gas to leave mold domain through the shortest path. Remaining gas flows with steel momentum because of drag force towards OR and exit mold mid-way the SEN and narrow face towards OR. On the top surface, mixture/steel flow is directed away from the gas exit regions (mostly from OR side towards IR). This finding is consistent with Go Gi's (2006) measurements and simulations on step-angle slide gate nozzle.

Conclusions on effect of magnetic field on multiphase steel-argon flow

- With magnetic field, more gas exits closer to SEN towards OR due to decelerating effects of Lorentz force on the jet.

Discussion on experimental validation

- Since, GG Lee et al's (2006) work on steel-argon flow is quite similar to the current multiphase work and as per expectations, these two are qualitatively matching.
- Possible reasons of non-matching with current measurements:
  - Multiphase flow model trouble (need more than 1 bubble diameter)
  - K-ε turbulence modeling limitations/transient flow
  - Leaking gas (injected 9.2 SLM, in steel ??)
  - Clogging (focused jet: better penetration, different velocities right and left)
  - Flow misalignment
- Suggestions???



Acknowledgements

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Corus, Delavan/Goodrich, LWB Refractories, Nucor, Nippon Steel, Postech, Steel Dynamics, ANSYS-Fluent)
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