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Investigation of the effect of stopper-rod misalignment on the fluid flow in the water model of continuous casting process

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Presented by Rajneesh Chaudhary

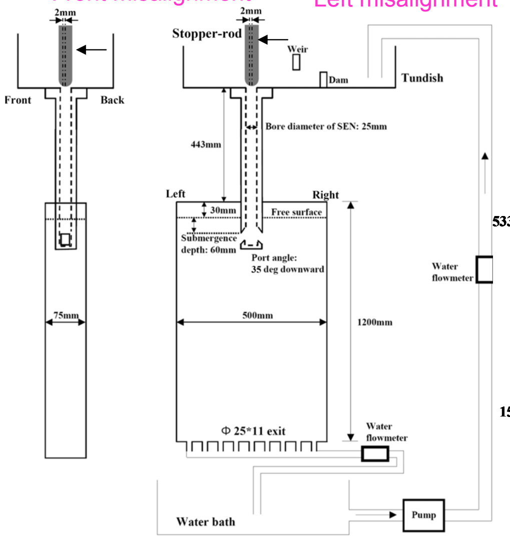
Project Overview

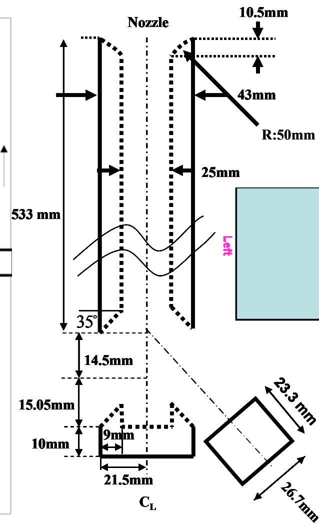
- Investigate effect of stopper rod misalignment on flow quality in the mold using:
  - 1/3rd scale water model experiments
    - using impeller velocity probe to measure surface velocity
    - Analysis to find time-average velocity, standard deviation and turbulent kinetic energy
  - Computational model
    - 3-D, steady, incompressible Navier-Stokes equations
    - with standard k-e model (RANS approach)
    - using FLUENT
- 3 cases:
  - aligned stopper rod,
  - misaligned (stopper moved to front)
  - misaligned (stopper moved to left).

1/3rd water model geometry with nozzle and stopper-rod positions

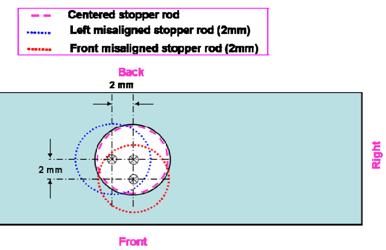
Front misalignment

Left misalignment





Top view



Top view of water model mold with various stopper rod positions

stopper rod is translated by:
2mm parallel to wide faces in left misalignment and
2mm parallel to narrow faces for front misalignment

Some process conditions:

Flow rate: 34.4 LPM

Casting Speed: 0.917 m/min

35 degree downward port

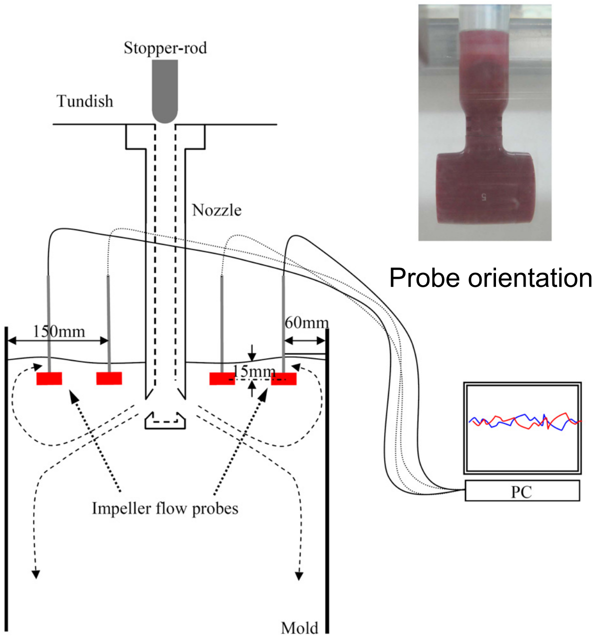
Stopper rod flow control

More details on process parameters are given on the next slide

Process parameters of 1/3rd water model used for stopper-rod misalignment studies

	1/3rd Water model
Casting speed	0.917 m/min
Water flow rate	34.4 LPM
Mold width	500 mm
Mold thickness	75 mm
Computational domain width	250/500 mm
Computational domain thickness	37.5/75 mm
Computational domain length	1200 mm
SEN depth	60 mm
Density	998.2 kg/m^3 (water)
Viscosity	0.001 kg/m-s (water)
Stopper-rod	Centered (i.e. aligned), front, and left misaligned (2mm)
Nozzle port angle	35 degree
Nozzle port area	23.3 mm (width) x 26.7mm (height)
Nozzle bore diameter (inner/outer)	25 mm/43 mm
Distance between tundish bottom and nozzle bottom	560 mm
Solidifying shell and gas injection	no
Domain bottom	no

Surface velocity measurement locations and probe details

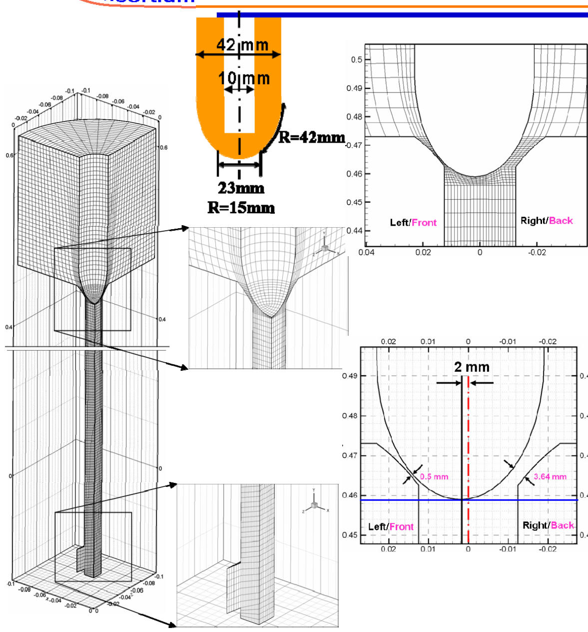


Probe orientation

Measurement locations:
- 2 places on both sides of mold:
- 60 mm and 150 mm from narrow faces,
- 15 mm below free surface

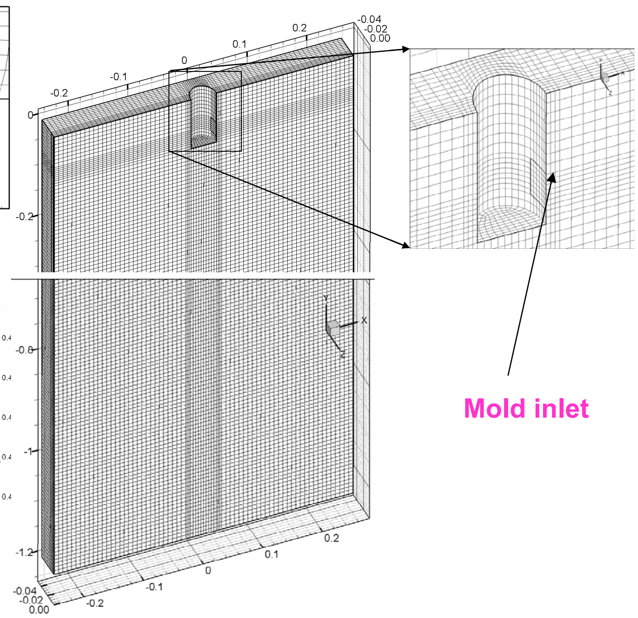
Probe details:
- -35mm long tube,
- -22/28 mm inner/outer dia
- -Propeller rotates in proportion to flow speed.
- -Total response time is ~10 s
  - - electronic (~0.4 s to reach 63%)
  - - mechanical response time (~8s)

Nozzle and mold mesh and dimensional details of stopper head and annular flow region with misalignment



Quarter nozzle

(~0.1 Million (changes little bit in different misalignments) hexa cells in full nozzle)



Half mold

(0.36 Million hexa cells in full mold)

Model Validation: Comparison of average surface velocity between measurements and predictions

	(unit: m/s)	60mm from left NF	150mm from left NF		150mm from right NF	60mm from right NF
Center	**Measurements**	**0.093**	**0.098**		**0.103**	**0.094**
	Standard deviation	**0.018**	**0.018**		**0.019**	**0.022**
	Predictions	0.102	0.120		0.120	0.102
Front	**Measurements**	**0.094**	**0.105**	**Nozzle**	**0.096**	**0.096**
	Standard deviation	**0.018**	**0.019**		**0.018**	**0.021**
	Predictions	0.097	0.122		0.122	0.097
Left	**Measurements**	**0.096**	**0.084**		**0.111**	**0.105**
	Standard deviation	**0.023**	**0.016**		**0.018**	**0.017**
	Predictions	0.084	0.060		0.1041	0.095

Discussion of model validation (Average surface velocity)

- At 60mm from narrow face, predictions match well with experiments:
  - maximum error of 14% in left misaligned case on left side,
  - otherwise less than 9%.
- At 150 mm from narrow face, model slightly over-predicts experiments:
  - maximum error is ~25%
  - (except in left side of left misaligned case where error is ~40%).
- Reason for maximum error in left side of left-misaligned case might be the complex vortexing flow pattern at this location.
- Higher surface velocity is expected at 150mm from narrow face because it is closer to midway between SEN and NF than 60mm.
  - Simulations predict this.
  - Surprisingly, experiments give similar velocities at 60 and 150 mm in aligned and front misaligned cases.

Discussion of model validation
(Average surface velocity) (Cont…)

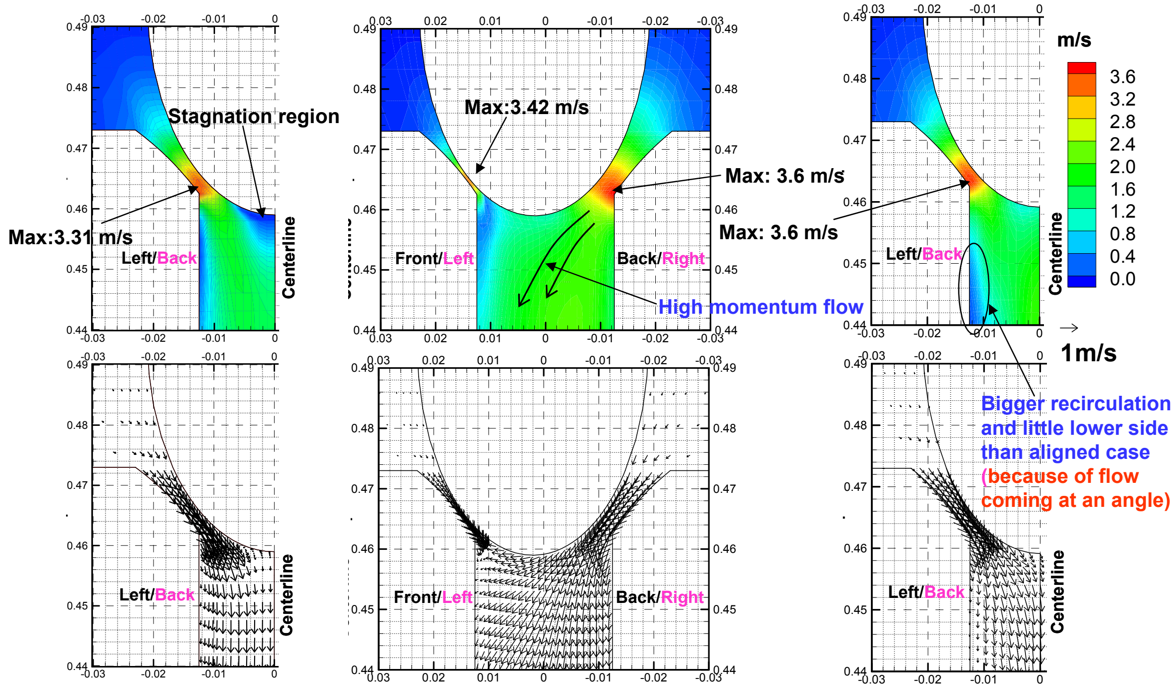
- Simulations and experiments agree within standard deviation ~0.02 m/s in all cases.
- Aligned and front misalignment cases have right-left symmetry in both simulations and experiments (well within standard deviation).
- Left misaligned stopper rod causes real right-left asymmetry:
  - right side has higher surface velocity
  - Difference greatly exceeds standard deviation.
  - Same trend is seen in experiments and simulations.

Model validation: Comparison of predicted turbulent kinetic energy with measurements

	(unit: m^2/s^2)	60mm from left NF	150mm from left NF		150mm from right NF	60mm from right NF
Center	**Measurements**	**4.6e-04**	**3.15e-04**	Nozzle	**3.53e-04**	**3.23e-04**
	Predictions	6.9e-04	3.75e-04		3.75e-04	6.9e-04
Front	**Measurements**	**4.24e-04**	**3.68e-04**		**3.38e-04**	**3.19e-04**
	Predictions	7.24e-04	5.33e-04		5.33e-04	7.24e-04
Left	**Measurements**	**5.47e-04**	**2.69e-04**		**3.25e-04**	**2.83e-04**
	Predictions	3.57e-04	1.4e-04		3.0e-04	5.02e-04

1) **Turbulent kinetic energy matches quite well (same order) in all cases with simulations.**
2) **Turbulent kinetic energy also has right-left symmetry in aligned and front misaligned cases, although asymmetry is seen in left misaligned case. Trend is reverse in simulations at 60 mm from narrow face.**
3) **Turbulence always matches better at surface than at jet. (also observed in well and mountain bottom comparison studies).**
4) **Observed differences of ~50% are expected due to anisotropy of real turbulence, total measurement time, sampling frequency and numerical errors (truncation and round off).**

Velocity contours and vectors in stopper-rod head region

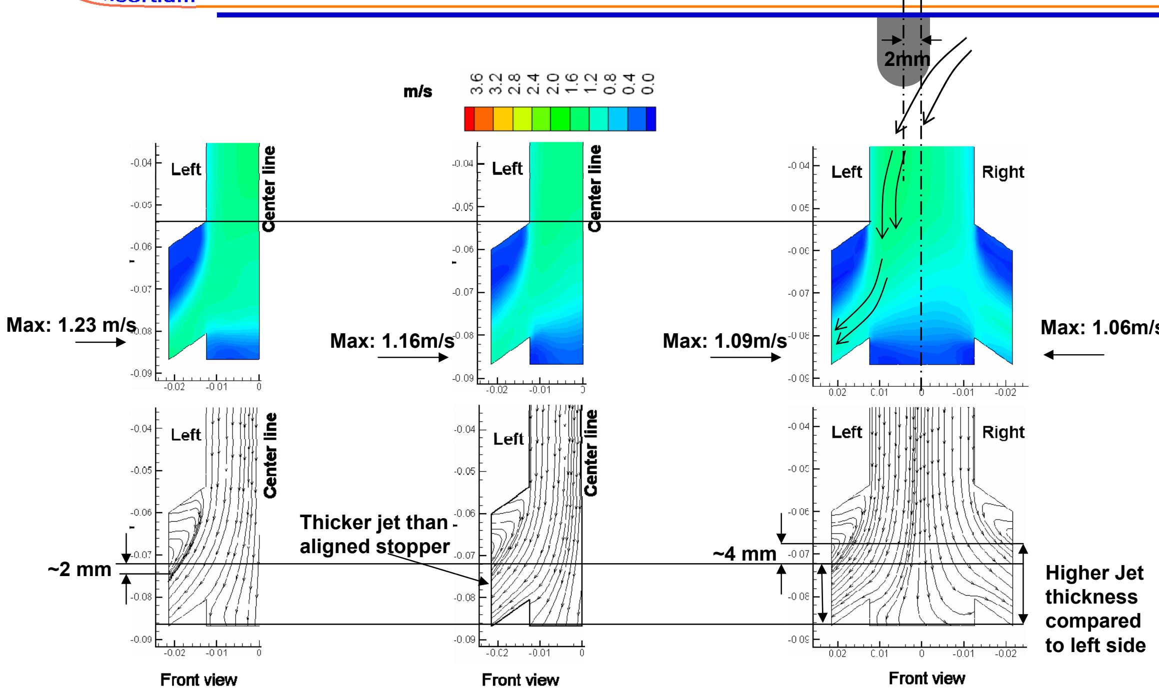


Aligned

2 mm front/left misaligned

2 mm front/left misaligned

Velocity contours and streamlines in nozzle bottom region

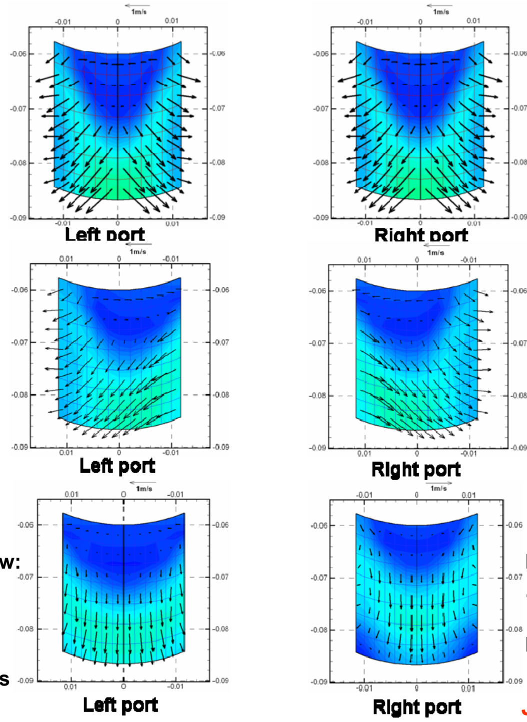


Aligned

2 mm front misaligned

2 mm left misaligned

Velocity contours and vectors at port outlets



Max: 1.23 m/s

Back flow:19% Aligned stopper rod (symmetric flow)

Max: 1.16 m/s

Back flow:19% Front misaligned stopper rod (Front and back asymmetry within a port)

Back flow: 28%

Max: 1.09 m/s

Back flow: 12%

Max: 1.06 m/s

Left misaligned stopper rod (Right and left asymmetry)

Jet characteristics are summarized on the next slide.

Jet characteristics in aligned, front misaligned and left misaligned cases

	Centered		Front misaligned stopper-rod		Left misaligned stopper-rod	
	Left	Right	Left	Right	Left	Right
Weighted average nozzle port velocity in x-direction (outward) (m/s)	0.66	0.66	0.68	0.68	0.73	0.69
Weighted average nozzle port velocity in y-direction (downward) (m/s)	0.53	0.53	0.51	0.51	0.53	0.35
Weighted average nozzle port velocity in z-direction (horizontal) (m/s)	0.058	0.058	0.022	0.022	0.055	0.021
Weighted average nozzle port turbulent kinetic energy (m^2/s^2)	0.060	0.060	0.026	0.026	0.020	0.028
Weighted average nozzle port turbulent kinetic energy dissipation rate (m^2/s^3)	3.24	3.24	1.15	1.15	0.83	1.29
Vertical jet angle (degree)	39	39	37	37	36	27
Horizontal jet angle (degree)	0	0	1.9	1.9	0	0
Horizontal spread (half) angle (degree)	5.08	5.08	-	-	4.33	1.76
Average jet speed (m/s)	0.85	0.85	0.85	0.85	0.91	0.78
Back-flow zone (%)	19	19	19	19	28	12
Flow rate (%)	50	50	50	50	46	54
Maximum velocity magnitude (m/s)	1.23	1.23	1.16	1.16	1.09	1.06

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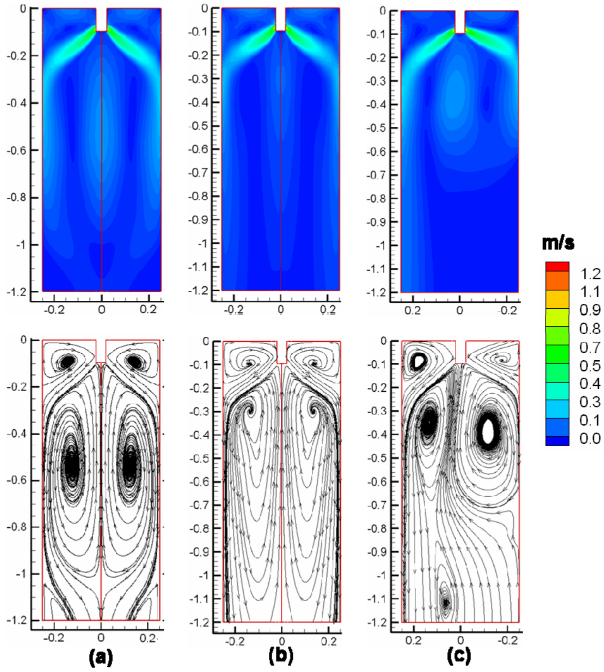
Velocity contours and streamlines at center plane between wide faces



Aligned Front misaligned Left misaligned

Aligned:

-conventional double roll flow pattern

Front misaligned:

- More Flow from the front side of the ports but jet is bent towards back (can be seen in port velocity vectors)
- This flow hits narrow face at back side (OR) close to the corner between wide and narrow faces.
- After hitting narrow face, flow comes towards the front side and causing higher surface velocity region shifted towards front side.
- Upper and lower recirculation zones are slanted and can be seen chopped in mid-plane streamlines.
- Because of flow being slanted, lower velocity is seen at the mold center compared to aligned case.

Left misaligned:

-Right port has higher mass flow rate and lower velocity compared to left side (biased flow).

-This imbalance in momentum encourages the vortex formation at the free surface on the left side close to SEN.

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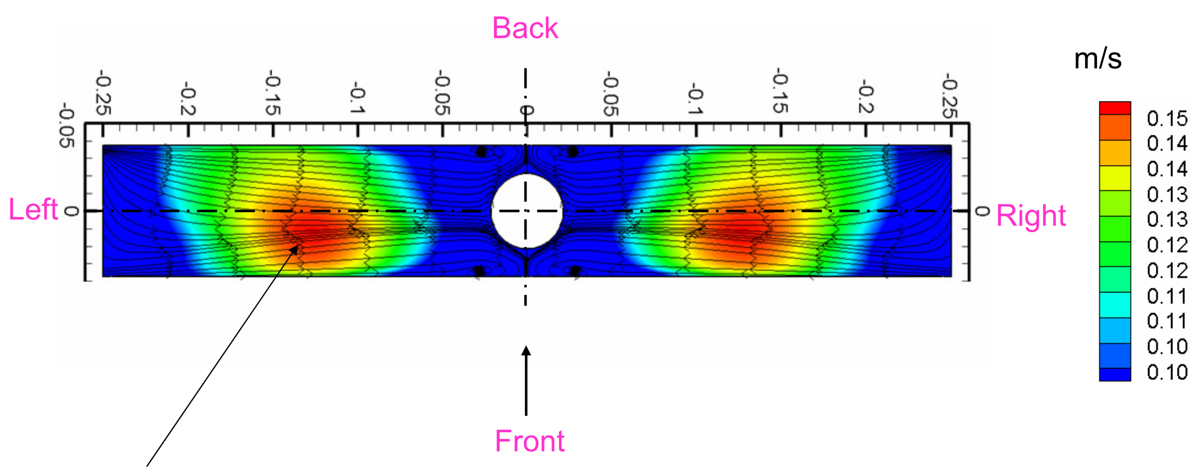
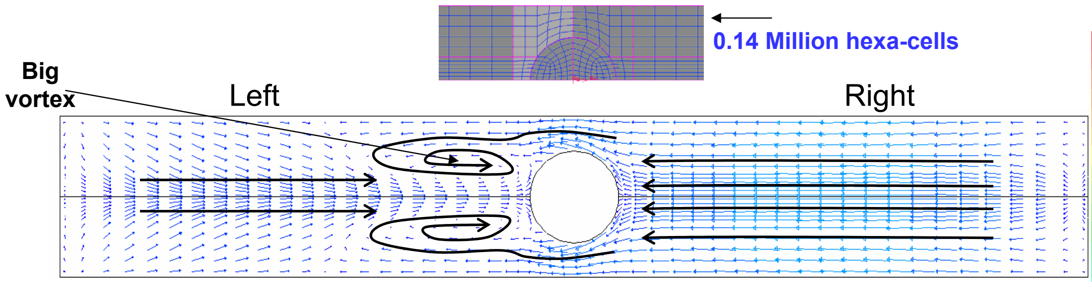
Velocity contours and streamlines at top free surface in front misaligned case

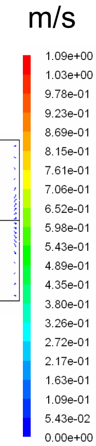


Maximum surface velocity is towards front side (front-back asymmetry)

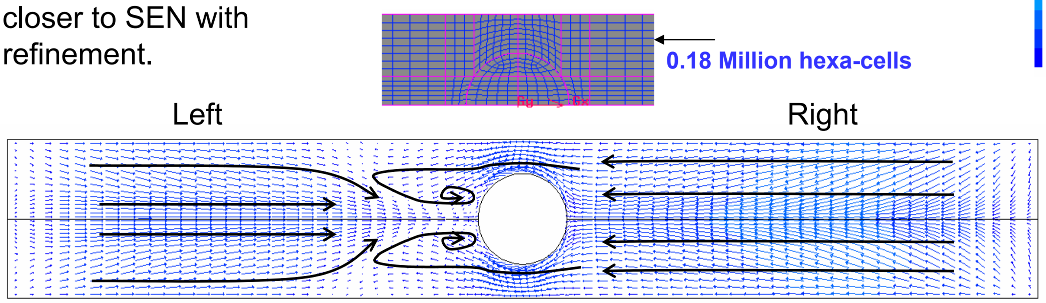
Left misalignment causes vortex formation (which is sensitive to mesh)

Top view close to SEN



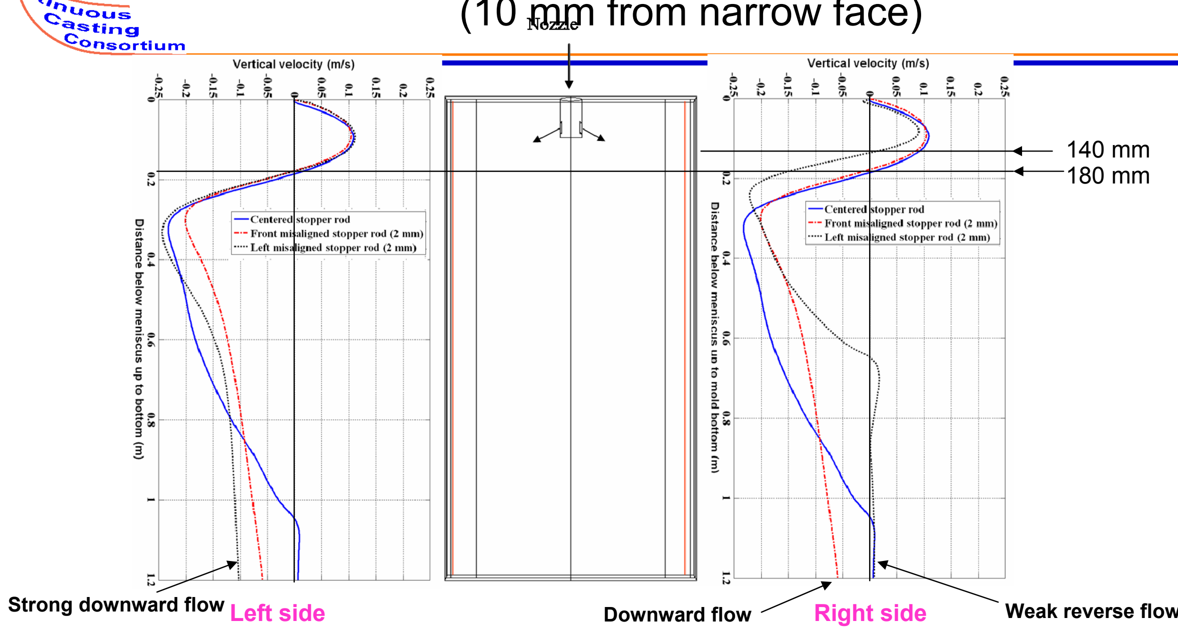


Vortices shrink and move closer to SEN with mesh refinement.



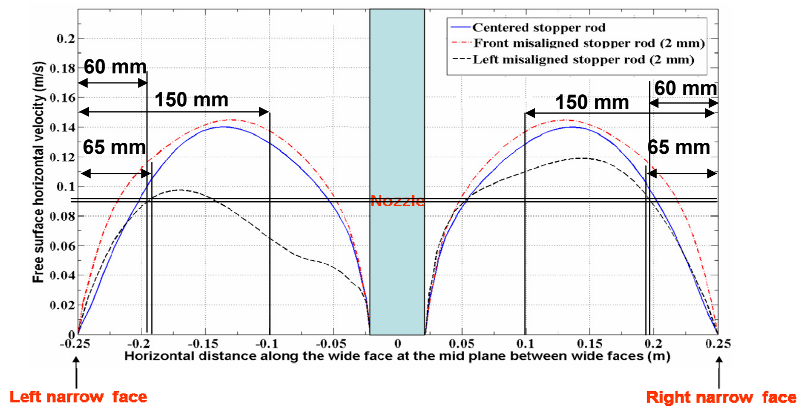
Vertical velocities in all 3 cases

(10 mm from narrow face)



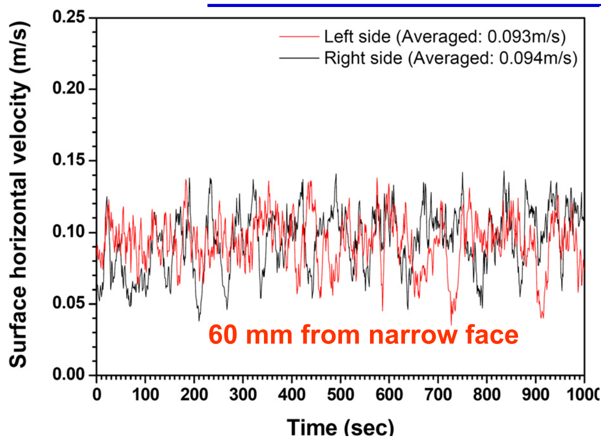
1) Jet hits almost at the same location (180mm) on the left side with three misalignments, on the right side, in left misalignment case jet impinges slightly above (140mm) the other two

Horizontal velocity at the free surface (mid-plane between wide faces)

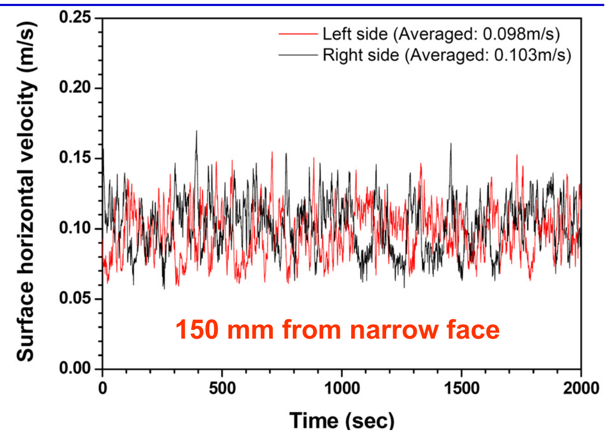


1) Up to ~65 mm from narrow face velocities at mid-plane are almost right-left symmetric in all cases.
2) In left misalignment case, right-left asymmetry in surface velocity is seen from 65 mm from narrow face up to very close to SEN.
3) In front misaligned and aligned stopper rod case surface velocities at mid-plane are close to each other with right-left symmetry but are higher than any sides of left misalignment.

Surface velocity, 15 mm below free surface in aligned case



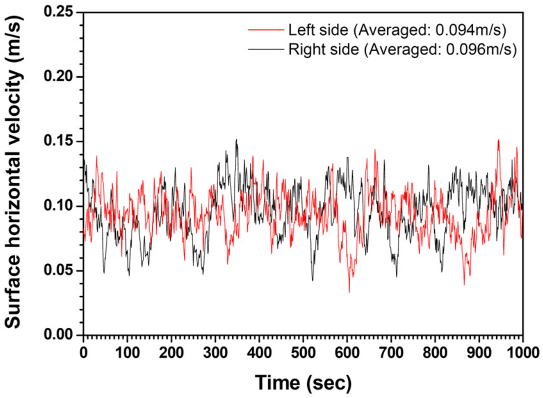
Average: 0.0935 m/s, right side is ~1% higher than left.

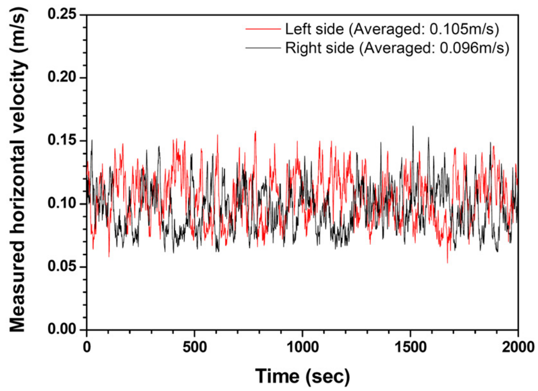


Average: 0.1005 m/s, right side is ~5% higher than left.

1) **Flow has right-left symmetry (within standard deviation) at both locations (i.e. 60mm and 150 mm), as expected in aligned stopper case.**
2) **Asymmetry is worse at 150 mm location (than at 60mm) due to intermittent vortexing and flow near SEN.**

Surface velocity, 15 mm below free surface in front-misaligned case





60 mm from narrow face

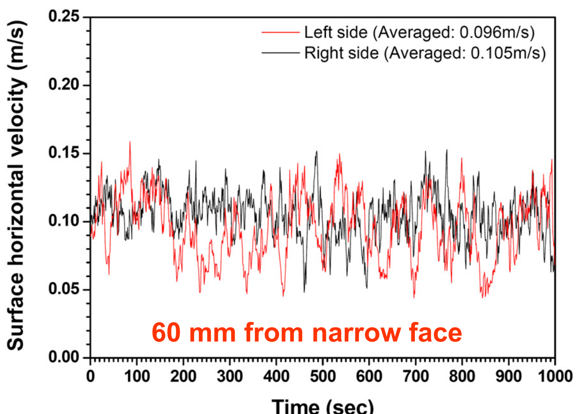
Average: 0.095 m/s, right side is ~2% higher than left.

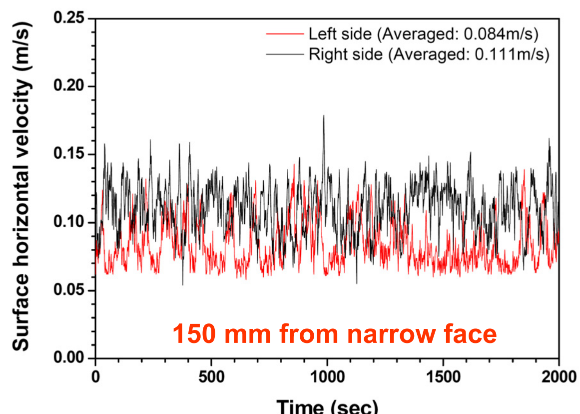
150 mm from narrow face

Average: 0.1005 m/s, right side is ~9% higher than left.

1) Right - left symmetry (within standard deviation) is observed at both locations, as expected.
2) Right-left asymmetry bigger at 150mm than at 60 mm.

Surface velocity, 15 mm below free surface in left-misaligned case





Right side is ~9% higher than left.

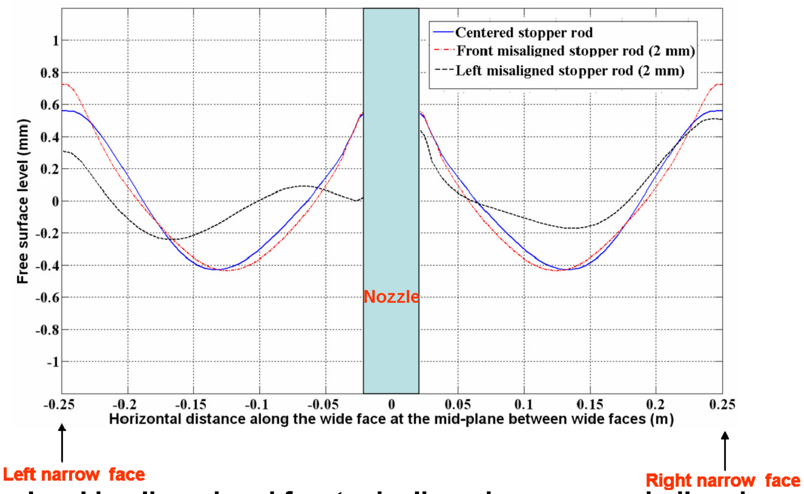
(insignificant asymmetry)

Right side is ~32% higher than left.

(significant asymmetry)

1) **Flow is symmetric at ~60 mm from narrow face, (within standard deviation).**
2) **Asymmetry is significant at 150mm from narrow face (i.e. close to SEN).**
3) **Right side surface velocity is higher than left side, because of lower vertical jet angle and higher mass flow rate from right port. Same result from model predictions.**

Predicted free surface level



1) **Surface level in aligned and front misaligned cases are similar shape and typical (higher close to narrow faces and SEN) as common in double roll pattern flow.**
2) **In left misalignment, surface is generally flatter due to lower surface velocity.**
3) **Level is lower on left side and also drops close to SEN where vortex forms.**

Summary

- Effect of stopper rod misalignment has been studied for 3 cases: (aligned, 2mm front misaligned, 2 mm left misaligned).
- Model is validated with measured surface velocities and turbulent kinetic energies at two locations (60mm and 150mm).
- No significant right-left asymmetry predicted near narrow face for all cases. Experiments agree at 60 mm from narrow face.
  Right-left asymmetry predicted from 65 mm to SEN in left misaligned simulations. Experiments agree at 150mm from NF.
- In front misalignment, flow from UTN region higher momentum hits the bottom of nozzle towards front side and exits the front of ports but is directed towards back side of mold (WF).
- Asymmetry is higher near SEN than near NF.
- In left misalignment, right port has higher mass flow rate (54%) but lower velocity, and shallower jet.
- Vortices are found on the left side in left misalignment case.
  The cause of vortex formation is one surface stream having higher flow momentum towards the SEN than the other, which generates rotational flow.
- Vortices are believed to have significant contribution to mold powder entrapment and entrapped flux may be carried down deeply into the mold leading to sliver defects.
- Stopper rod misalignment has significant effect on fluid flow:
  Left misalignment causes left-right asymmetry
  Front misalignment gives front-back asymmetry (as in 90 degree slide-gate).

Acknowledgments

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