ANNUAL Meeting 2008

August 6, 2008

Transient mold fluid flow with well- and mountain-bottom nozzles in continuous casting of steel

Rajneesh Chaudhary [a], B. G. Thomas [a]

[a] Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, 1206 W. Green St., Urbana, IL, USA, 61801

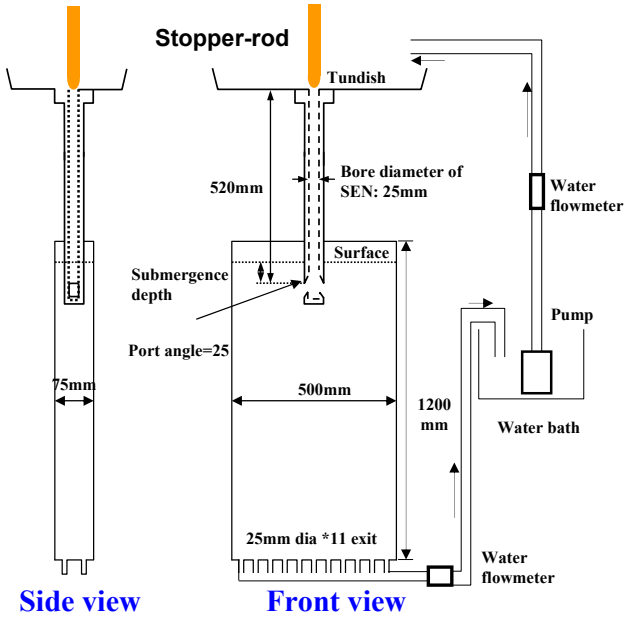
Go-Gi Lee [b], Seon-Hyo Kim [b]
[b] Department of Materials Science and Engineering, Pohang University of Science and Technology, Pohang, Kyungbuk 790-784, South Korea

Presented by Rajneesh Chaudhary

Project Overview

- Well- and mountain-bottom nozzles have been investigated experimentally as well as numerically.
- Experiments have been performed to measure velocity below SEN using PIV in the mold of well-bottom nozzle. Impeller velocity probe was used to measure jet and surface velocities in the molds of both nozzles.
- The time average velocities, turbulence kinetic energies, frequency distribution of fluctuations, and power spectrums have been analyzed for both nozzles.
- A computational model has been formulated to solve 3-D, steady, incompressible Navier-Stokes equations with standard k-e model (RANS approach) using FLUENT.
- Model predictions and measurements are compared and combined to draw conclusions on the flow quality in the mold of both nozzles. Furthermore, predictions from water model were compared with full scale steel caster simulations.

The geometry of 1/3rd water model with well-bottom nozzle



Pump along with two flow meters is used to control the flow rate corresponding to required casting speed.

Process conditions:

Flow rate: 38.2 LPM

Casting Speed: 1.02 m/min

25 degree downward port

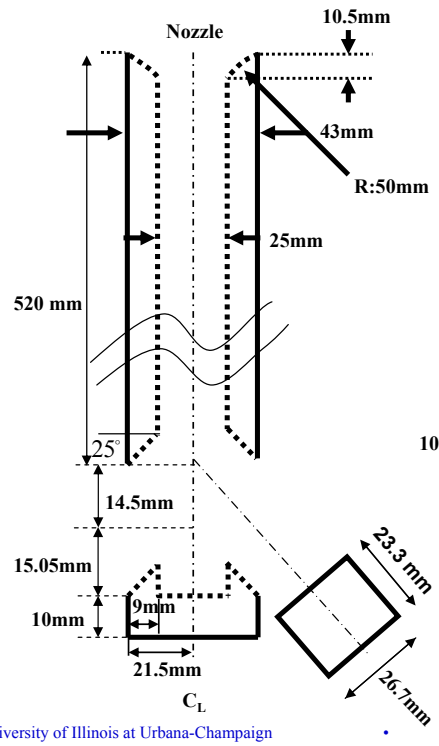
Stopper rod flow control

More details on process parameters are given on the next slide

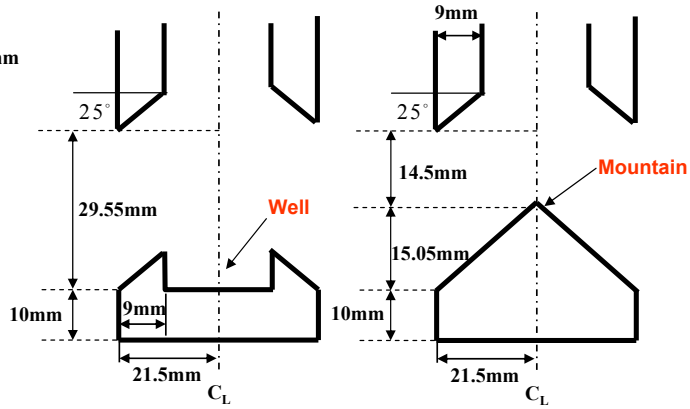
Process parameters of 1/3rd water model and corresponding full-scale steel caster

	Water model (1/3rd scale)	Steel caster (full-scale)
Nozzle port angle	25 deg down	25 deg down
Nozzle port area	23.3 mm (width) x 26.7mm (height)	69.9 mm (width) x 80.1 mm (height)
Nozzle bore diameter	25 mm	75 mm
Nozzle outer diameter	43 mm	129 mm
SEN Depth	60 mm	180 mm
Average port velocity	0.512 m/s	0.886 m/s
Fluid flow rate	38.2 LPM	595.4 LPM
Casting speed	1.02 m/min	1.76 m/min
Mold width	500 mm	1500 mm
Mold thickness	75 mm	225 mm
domain width	250 mm	750 mm
domain thickness	37.5 mm	112.5 mm (at the top)
domain length	1200 mm	3600 mm
Shell	no	Yes
Gas injection	no	no
ρ_{fluid}	998.2 kg/m^3 (water)	7020 kg/m^3 (steel)
μ_{fluid}	0.001003 kg/m-s (water)	0.006 kg/m-s (steel)
ρ_{slag}		3000 kg/m^3

Nozzle close-up, well and mountain shapes



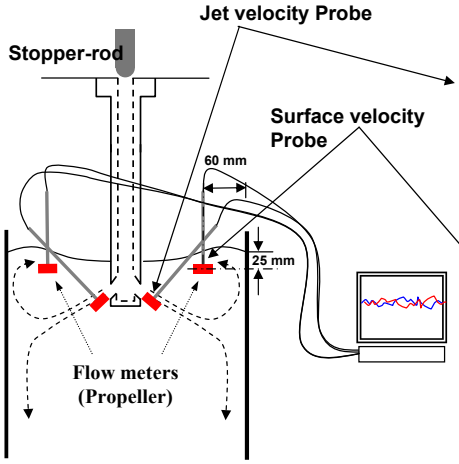
Difference is only of the bottom otherwise both nozzles have same geometry.



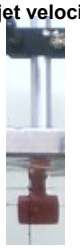
Well-bottom shape **Mountain-bottom shape**

Oversized ports with port-to-bore area ratio=2.8

Impeller velocity probe locations and orientations



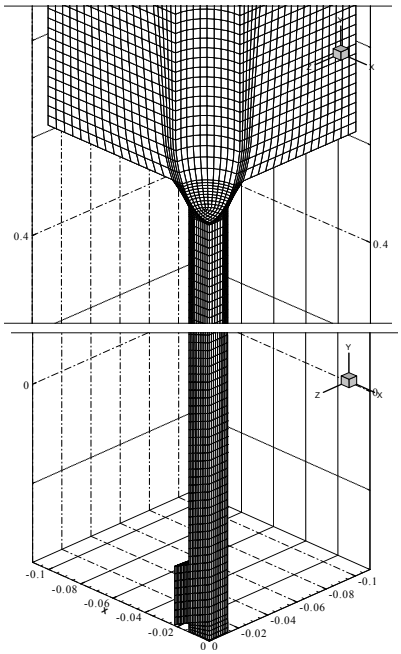
Probe orientation for jet velocity



Probe orientation for surface velocity

1) Probe: 35mm long tube, 22/28 mm inner/outer dia
2) Propeller rotating in proportion to flow speed.
3) Total response time of probe is ~10 sec, (electronic (~0.4 s to reach 63%) and mechanical response time)
4) To measure jet velocity, probe is aligned with port angle (25 degree downward) at the bottom of the port.

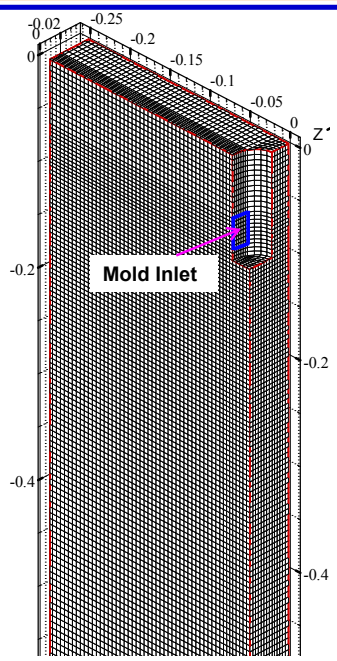
Isometric view of well-bottom nozzle and strand meshes



1)Quarter nozzle and mold mesh were used to save computational time owing to 2-fold symmetry

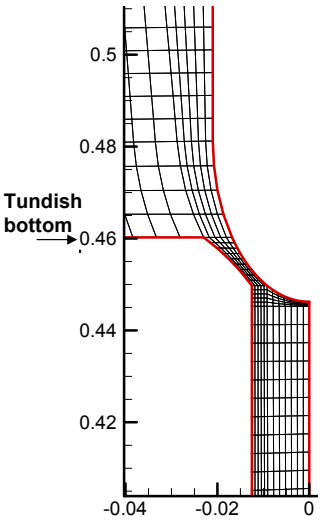
2) A cylindrical portion of the tundish bottom (with 200 mm diameter and 150 mm height), is created around the top of the SEN.

3)Average velocity on the circumference and top annular region of this cylinder were fixed to match casting conditions.

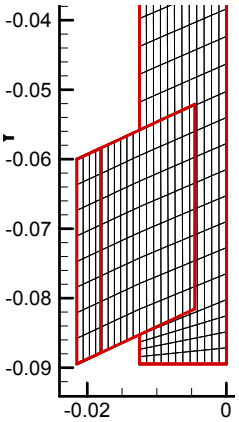


(a) Nozzle mesh (19,000 hexa-cells) **(b) Mold mesh (0.136 Million hexa-cells)**

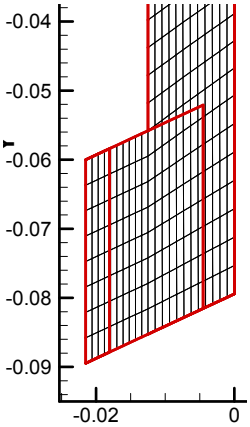
Mesh close-up at stopper rod head, and nozzle bottom regions



(a) Stopper rod head region

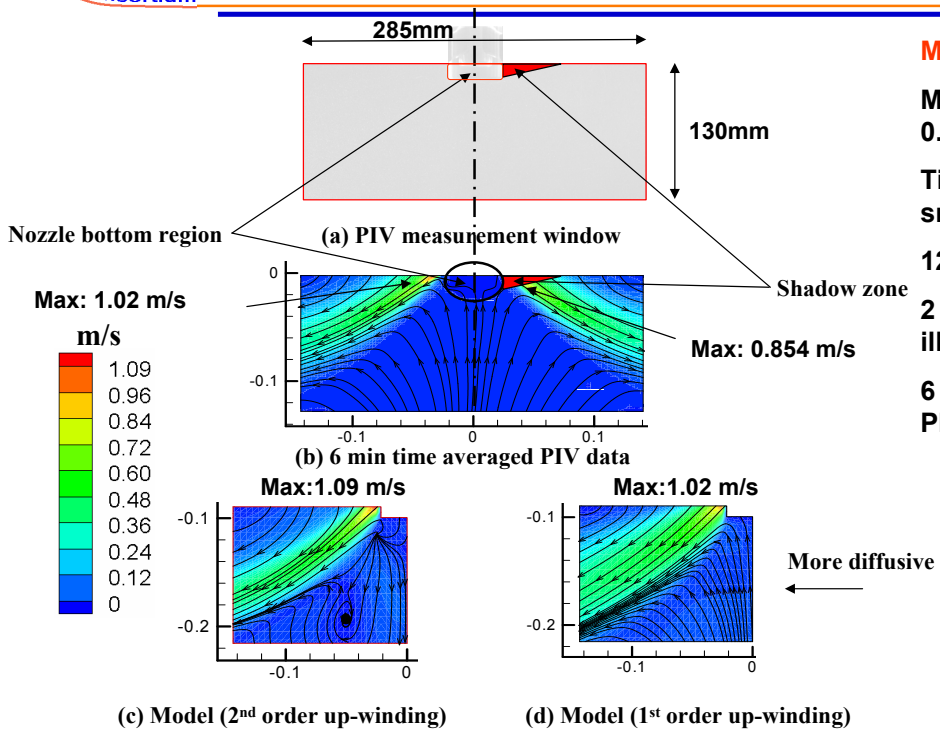


(b) Well-bottom nozzle



(c) Mountain-bottom nozzle

PIV measurement below SEN with well-bottom nozzle and comparison with simulations



Measurement details:

Measurement interval: 0.14 s

Time between two snap shots: 0.6 ms

125x56 grid points

2 mm thick plane illuminated

6 min time averaged PIV data

Discussion on PIV measurements and simulations

- Shadow spoils PIV measurements on the right side below SEN
- 1st order upwind convection scheme gives jet thickness and profile matching closely with PIV measurements
- 2nd order upwind convection scheme is more consistent with flow patterns and streamlines
- However, 2nd order scheme has stability issues with thinner jet (especially for jet coming from mountain-bottom nozzle)
- Therefore, 1st order upwind-scheme was used in further simulations.

Comparison of simulations with measurements (average velocity and turbulent kinetic energy)

Jet velocity

	Jet Velocity (m/s)			Turbulent kinetic energy(m^2/s^2) (x 10^{-3})		
	Water model		Fluent	Water model		Fluent
	Left side	Right side		Left side	Right side	
Well bottom	**0.687**	**0.685**	**0.69**	**0.0611**	**0.0898**	**22.3**
Mountain bottom	**0.957**	**0.944**	**0.92**	**0.0216**	**0.0087**	**20.1**

Surface velocity

	Horizontal Surface Velocity (m/s)			Turbulent kinetic energy(m^2/s^2) (x 10^{-3})		
	Water model		Fluent	Water model		Fluent
	Left side	Right side		Left side	Right side	
Well bottom	**0.103**	**0.115**	**0.11**	**0.31**	**0.38**	**1.4**
Mountain bottom	**0.148**	**0.166**	**0.18**	**2.23**	**3.14**	**2.4**

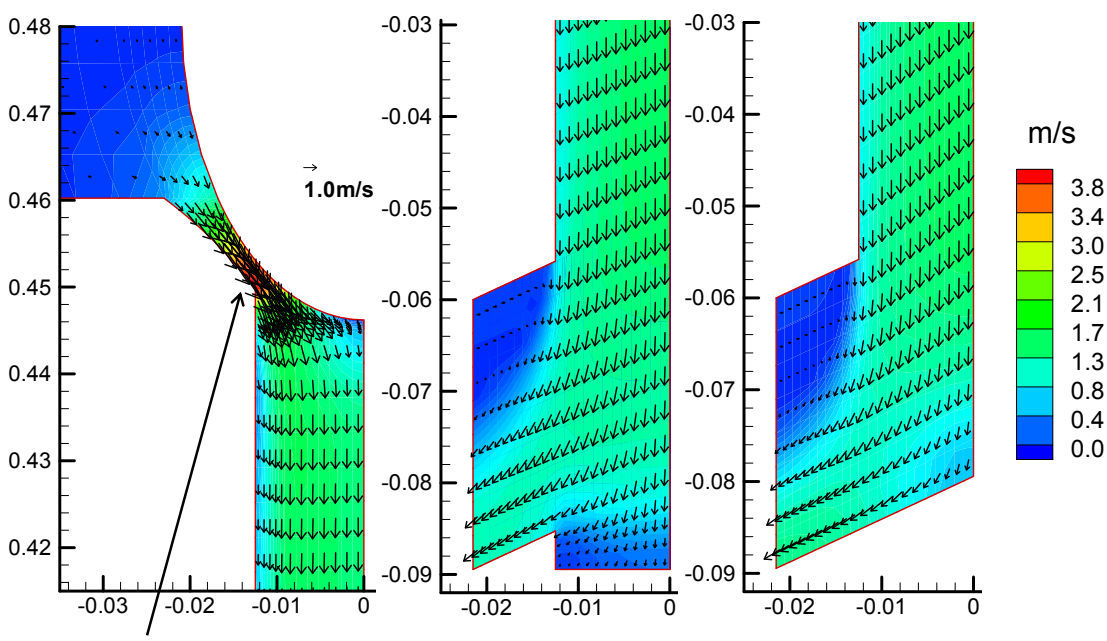
Compare simulations with measurements (average velocity)

- Well-bottom nozzle velocity measurements show little variation between sides, and agree with the predictions within 1%.
- Mountain-bottom nozzle exhibits significant asymmetry between left and right, indicating short time averaging.
- Predictions agree within these variations. For example, surface velocity averaged over the last 500s (0.180m/s) matches exactly with the prediction.

Compare simulation with experiments (turbulent kinetic energy)

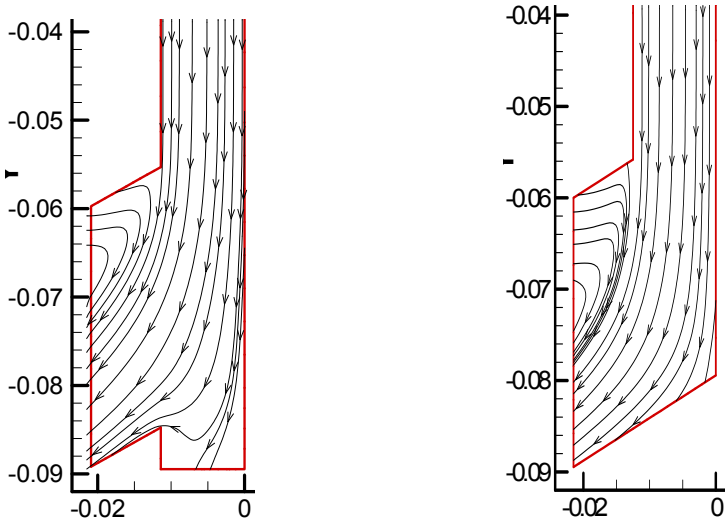
- Agreement with the turbulent kinetic energy measurements is not quite as good except at the surface.
- Impeller probe is unable to respond to the high-frequency jet turbulence fluctuations due to the inertia of the impeller. Moreover, fixed probe orientation misses non-axial fluctuations.
- Measurements and predictions agree reasonably at the surface for the mountain-bottom nozzle. (being low frequency)

Comparison of velocity at stopper head region, bottom regions of well- and mountain-bottom nozzles



Maximum velocity is 3.8 m/s and found in the thinnest part of the annular region between stopper rod and tundish bottom.

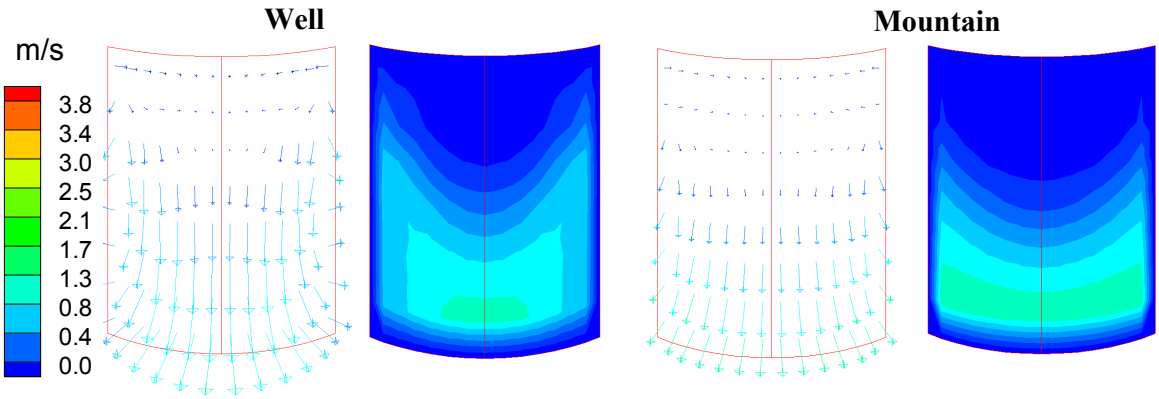
Comparison of streamlines and port velocities in both nozzles



(a) Well-bottom nozzle (b) Mountain-bottom nozzle

Mountain-bottom nozzle has higher back-flow zone at the port.

Port velocities with both nozzles



0.3175 kg/s (50%) 0.3175 kg/s (50%)

Secondary flow is weak in mountain-bottom nozzle and flow is directed more towards narrow face.

Calculated jet characteristics in both nozzles

Weighted Average Parameter	Well bottom nozzle	Mountain type nozzle
Port x-velocity (outward) (m/s)	0.75	0.92
Port y-velocity (downward) (m/s)	0.48	0.52
Port z-velocity (horizontal) (m/s)	0.065	0.076
Port turbulent kinetic energy (m^2/s^2)	0.040	0.018
Port turbulent dissipation rate (m^2/s^3)	2.11	0.64
Vertical jet downward angle (deg)	32.8	29.3
Horizontal jet angle (deg)	0	0
Horizontal spread (half) angle (deg)	5.0	4.7
Average jet speed (m/s)	0.89	1.06
Back-flow zone	27%	30%

Table- Jet characteristics in both nozzles

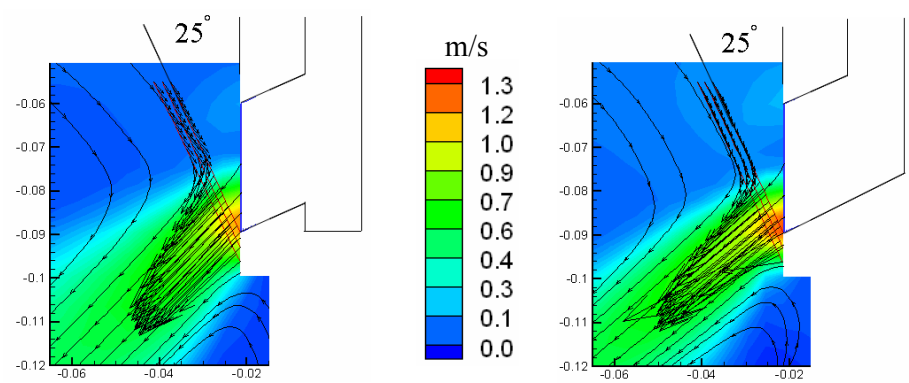
Equations from

H. Bai and B.G. Thomas, *Turbulent Flow of Liquid Steel and Argon Bubbles in Slide-Gate Tundish Nozzles: Part I. Model Development and Validation.* Metallurgical and Materials Transactions B, 2001. 32(2): p. 253-267.

Jet velocity vectors and speed contours below nozzle at mold centre plane

Well bottom nozzle

Mountain bottom nozzle



Steeper jet and lower velocity

(Diffused jet)

Shallower jet and higher velocity

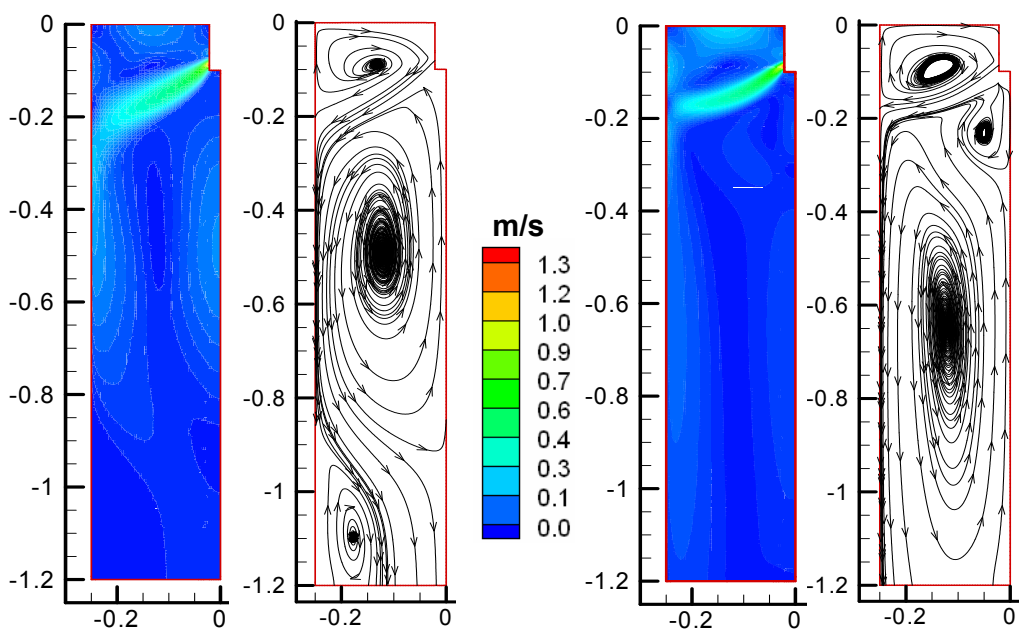
(Focused jet)

The maximum velocity is close to the port bottom in both ports with a steeper, thicker jet (also seen in Jet characteristics and streamline plot) from the well-bottom nozzle.

Discussion on jet and port flow qualities with both nozzles

- The jet in the well-bottom nozzle is more diffusive and thicker with a smaller back flow zone (27% vs. 30% in mountain bottom).
- In the mountain-bottom nozzle, flow goes straight along the side of the mountain with high velocity, producing a thinner and less diffusive jet with smaller horizontal spread- and vertical jet- angles.
- Secondary flows from the mountain bottom nozzle are weaker, as flow is directed more towards the narrow face.
- Higher outward, downward and horizontal weighted-average jet velocities exiting the mountain bottom nozzle are observed in both the experiments and computations.
- Turbulent kinetic energy is much higher in the well-bottom nozzle, with higher frequency fluctuations causing a more dissipative jet.

Velocity contours and streamlines at the mold mid-plane in both nozzles



(a) Well bottom

(b) Mountain bottom

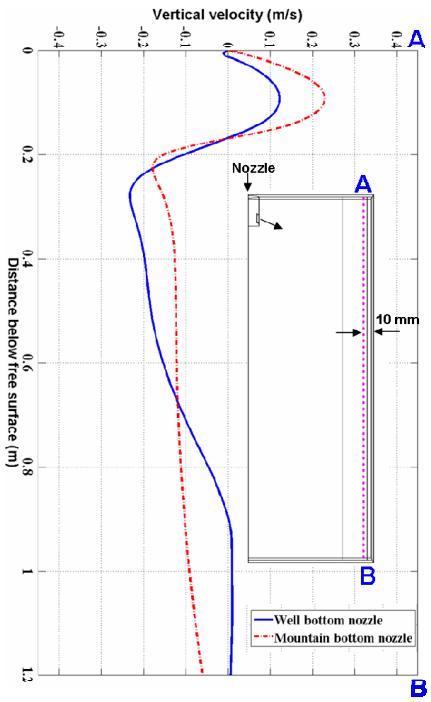
Discussion on mold flow with well-bottom nozzle

- The higher dissipation rate leaving the port of the well-bottom nozzle causes the jet turbulent kinetic energy to decrease more as it moves through the mold.
- This thicker and more diffusive jet thus loses its momentum faster as it splits into upper and lower recirculation zones with weaker flow along the narrow face.
- Maximum velocity is found near the bottom of port exit, and is 1.23 m/s with the well-bottom nozzle.

Discussion on mold flow with mountain-bottom nozzle

- With the mountain-bottom nozzle, the jet is faster (1.31 m/s) which leads to higher surface velocity.
- The latter jet also bends upwards more as it crosses the mold, further contributing towards the higher surface velocity.
- Also, the lower recirculation zone is predicted to break up into more complex flow structures.

Vertical velocity 10 mm from narrow face in both nozzles

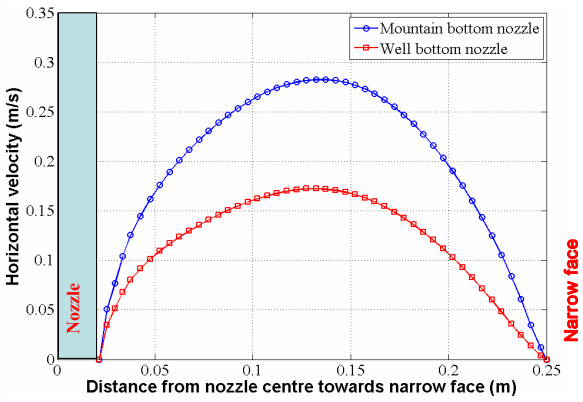


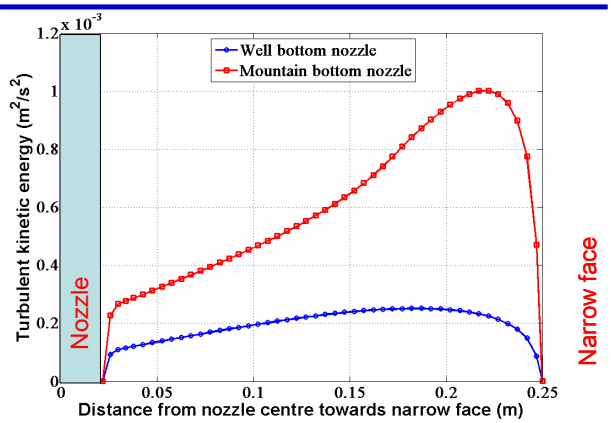
1)The mountain-bottom nozzle has faster flow in the upper recirculation zone.

2) The jet impinges the narrow face at 180 mm below the top free surface with both nozzles.

3) Well-bottom nozzle has weak reverse flow at the bottom of the strand. However, strong downward flow is seen in mountain-bottom nozzle.

Horizontal free surface velocity and turbulent kinetic energy at mid-plane





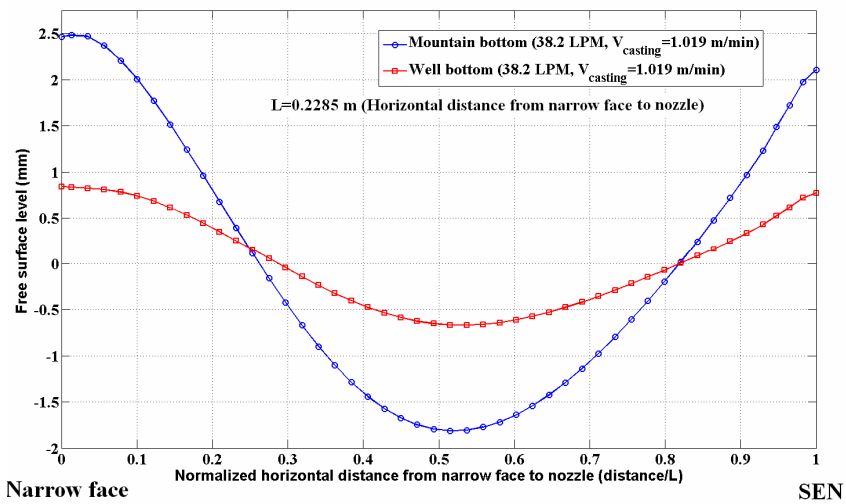
Centerline meniscus velocity towards SEN

1) Mountain bottom nozzle gives ~1.5 times higher horizontal surface velocity. This higher surface velocity agrees with measurements.

2) The mountain-bottom nozzle gives ~5 times higher turbulent kinetic energy compared to the well-bottom.

3) This is due to the low frequency and high magnitude fluctuations in the surface velocity for this nozzle.

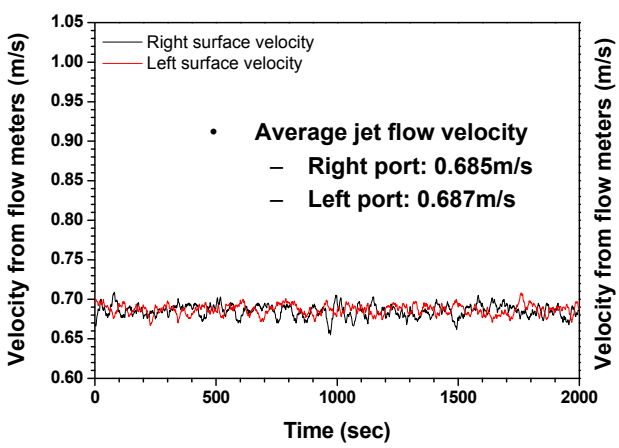
Free surface level in the mold with both nozzles

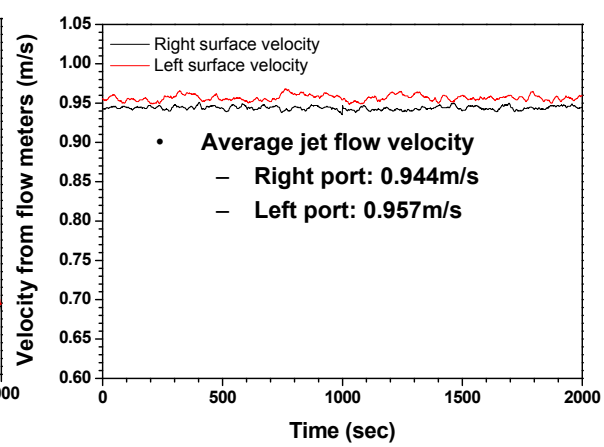


1) The surface is raised near the narrow face and SEN, as common with a double-roll flow pattern.
2) The mountain-bottom nozzle gives around ~2.5 times higher surface waves, owing to its ~1.5 times higher horizontal surface velocity.

Jet velocities measured using impeller probe aligned with port angles

Jet velocity





*) Stopper-rod: No misalignment
*) Location of flow meters:
At Ports with port angle at the mid-plane between wide faces
*) Measuring time: 2000sec

(a) Well bottom

(a) Mountain bottom

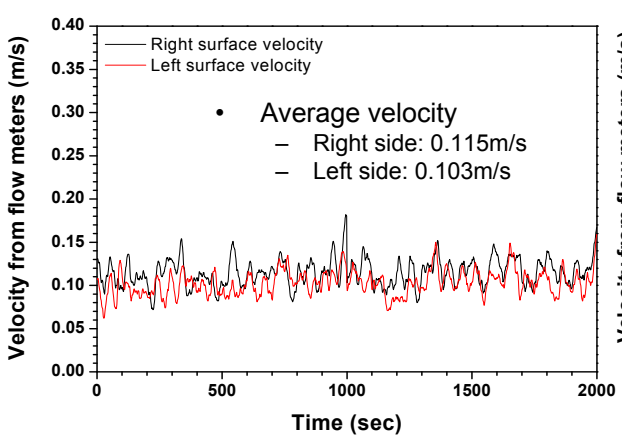
Discussion on measured jet velocity

- Time-averaged jet velocities with the well-bottom nozzle are ~0.686 m/s and are quite symmetric, with the left and right sides matching within ~0.3% over 2000s.
- In the mountain bottom nozzle, the corresponding jet velocities average ~0.950 m/s, which is significantly higher.
- They are also less symmetric with ~1.4% higher velocity on the left side, which indicates stronger, lower-frequency variations.

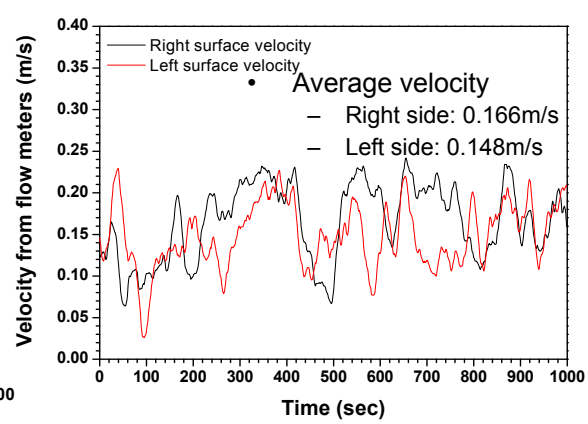
Measured surface velocity using impeller probe

Surface velocity

(at 60 mm from narrow face and 25 mm from free surface)



(a) Well-bottom



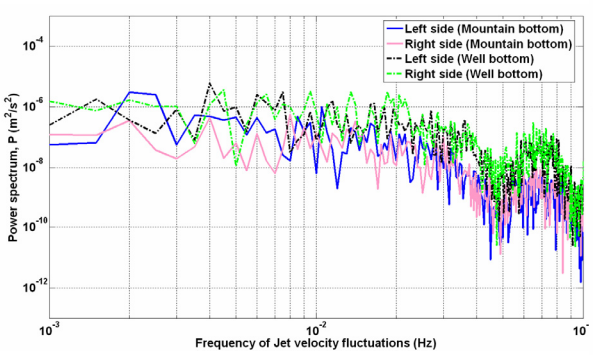
(b) Mountain bottom

Discussion on measured surface velocity

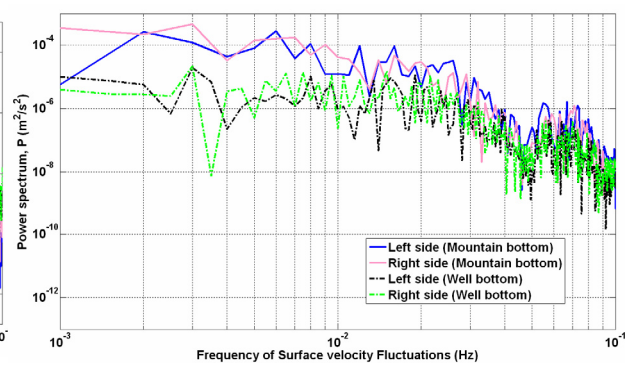
- For the well bottom nozzle, time-averaged horizontal surface velocities are ~0.109 m/s, with the right side 11.6% higher than the left.
- The mountain-bottom nozzle has more than 50% higher average surface velocities, 0.157 m/s, due to the higher jet velocity.
- Its asymmetry is also higher, with 12.1% higher velocity on the right side.
- Relative to the jet, these surface flow results show that asymmetry increases as the flow travels through the mold.
- Furthermore, the mountain-bottom nozzle is more susceptible to asymmetric flow.

Power spectrum of jet and surface velocity

Jet velocity



Surface velocity



1) Due to ~10s response time of the impeller probe, only energies for frequencies up to 0.1 Hz are plotted.
2) In all cases, most of the energy is found in low frequencies.
3) The general drop in energy observed with increasing frequency matches previous work. An exception is the small peak found at ~0.07 Hz (~14s).

Discussions on turbulent velocity fluctuations

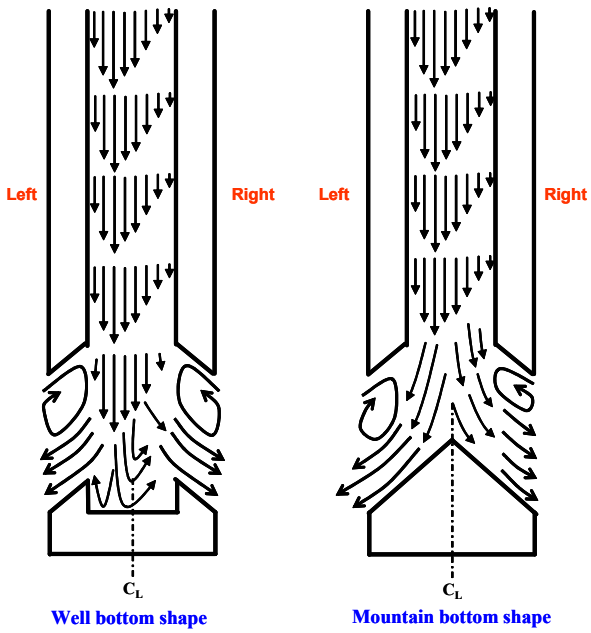
- The same frequencies dominate in the jet and surface for both nozzles.
- Energy in the jet is higher in the well-bottom nozzle, especially at frequencies above 0.01 Hz. This is due to strong recirculation observed in the bottom of the nozzle.
- The mountain nozzle deflects the jet smoothly towards the ports, slicing through the flow like a knife-edge. This allows the jets to retain more of their momentum, but with less turbulence. This causes the trend in energy spectrum at the surface to reverse.
- The mountain-bottom nozzle experiences much greater surface velocity fluctuations. The increase to be more than an order of magnitude at frequencies ranging from 0.002 – 0.035 Hz, which corresponds with time periods of 33-500 s.
- The well bottom nozzle has energy distributed over a wider frequency range in both jet and surface velocities.

Qualitative description of flow characteristics with well- and mountain-bottom nozzles

	Jet velocity		Surface velocity		Asymmetry (Due to flow transients)
	Average velocity	Fluctuations	Average velocity	Fluctuations	
Well bottom	Low (Thick jet)	High (High frequency)	Low	Low (High frequency)	Low
Mountain bottom	High (Thin jet)	Low (Low frequency)	High	High (Low frequency)	High

Qualitative description of the surface and jet velocities based upon simulations as well as experiments

Mechanism of asymmetric flow in well- and mountain-bottom nozzles

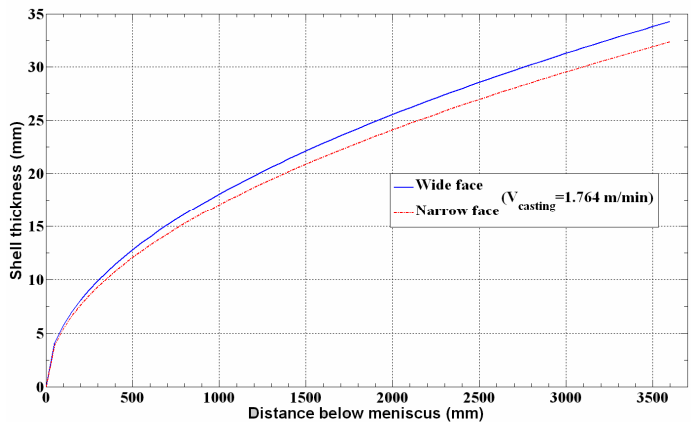


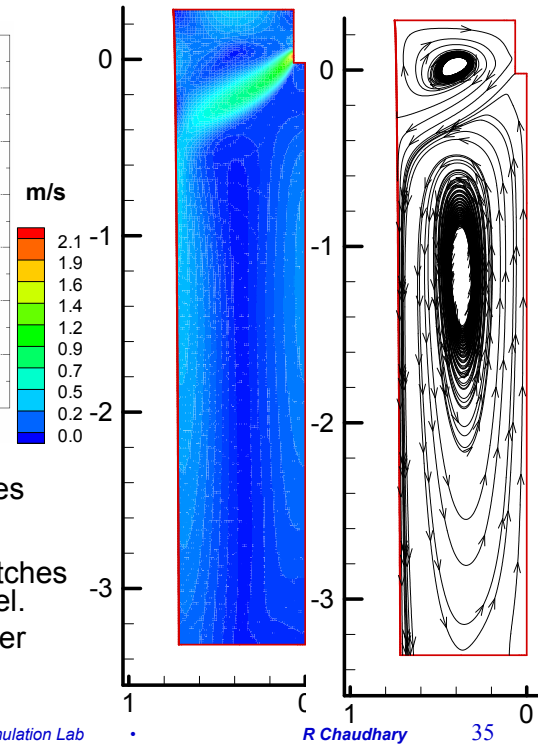
- Transient variations in nozzle flow may send higher velocity down one side of the nozzle.
- The mountain bottom slices the flow, sending this higher velocity flow directly out the adjacent port.
- The well bottom, on the other hand, mixes the flow so the jets exiting the ports are less sensitive to asymmetries.
- Mountain-bottom nozzle is more sensitive to asymmetry

Differences between laboratory water model and steel caster

- Geometric scaling of all linear dimensions to 1/3rd
- No solidifying shell and stationary walls
- A domain bottom with water exiting through circular holes in a horizontal plate instead of a very long, gradually-tapering flow domain
- Air above the free surface instead of powder, sintered and liquid slag layers.

Shell thickness and velocity in full scale steel caster corresponding to 1/3rd water model

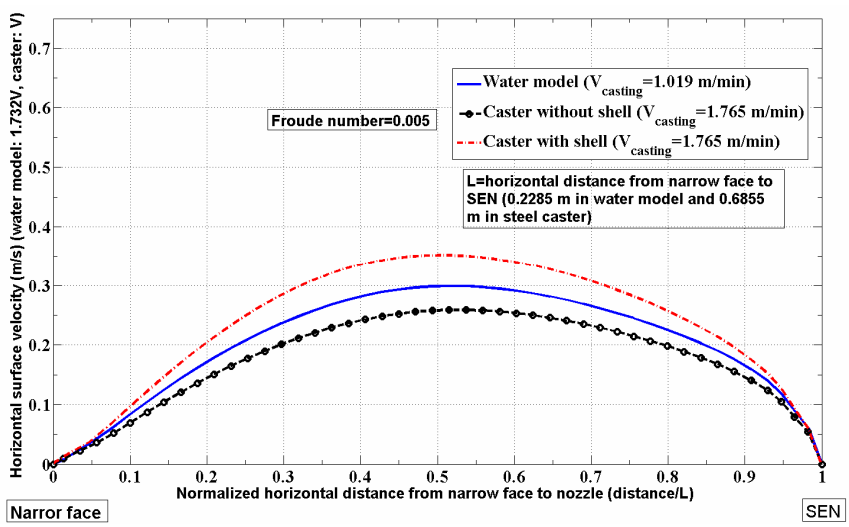




Shell thickness down the wide and narrow faces (CON1D)

- The casting speed for the full-scale caster matches the Froude number of 0.005 of the water model.
- The flow pattern is generally similar to the water model.

Free surface velocity comparison between 1/3rd water model and full scale steel caster



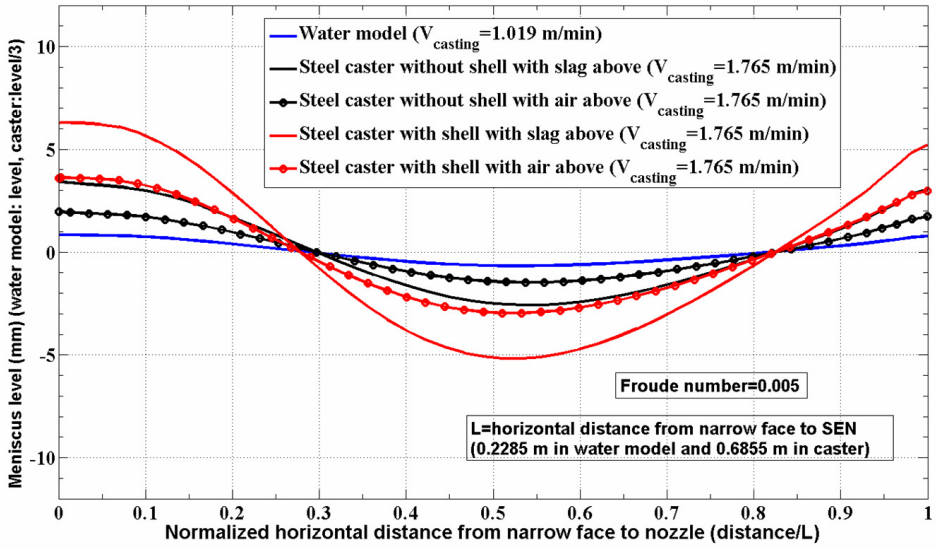
Discussions on surface velocity in full scale caster

- The horizontal velocity in the water model falls in between the caster velocities with and without the solidifying shell.
- Note that flow in the water model is in the transition regime (Re=2200 based on strand hydraulic diameter) while the steel caster is fully turbulent (Re=13500). The water model velocities would match the caster without the shell if it was fully turbulent..
- The maximum surface velocity predicted in the real full-scale steel caster with the well-bottom nozzle is ~0.3 m/s, which is in the safe operating window of 0.2-0.4 m/s (Kubota).
- Maximum surface velocity with the mountain-bottom nozzle is predicted to be ~0.5 m/s (based upon scaling from water model), which is above the upper limit suggested by Kubota to avoid flow problems such as slag entrainment.

Discussions on surface velocity in full scale caster (Cont…)

- Thus, the well-bottom nozzle is preferred over the mountain-bottom nozzle for this steel caster and conditions.
- If casting conditions produced very small surface velocities, then the mountain-bottom nozzle might appear to be better. However, the results of this work suggest that changing the flow pattern in some other way and using the well-bottom nozzle is the best solution.

Free surface level in 1/3rd water model and corresponding steel caster



Discussions on free surface level

- The free surface level without shell and air above matches most closely with water model, as expected, although the water model underpredicts by a factor of 2.3.
- Introducing the shell and adding slag both increase the profile variations.
- Thus, the water model underpredicts surface level variations in the caster using Froude scaling.

Summary

- This work investigates well-bottom and mountain-bottom type nozzles both experimentally and numerically.
- The computational model agrees very well with measured velocities in all cases, but overpredicts turbulent kinetic energy in the jet and surface of the well bottom nozzle perhaps due to time resolution (~0.1 Hz) of the impeller probe and fluctuations being higher frequency.
- The measured surface turbulence in mountain bottom nozzle matches well with the simulations.

Summary (Cont…)

1) The jet from the well-bottom nozzle is thicker, steeper-downward and more diffusive, with higher turbulent kinetic energy and dissipation rate, relative to the mountain bottom nozzle jet.
2) The mountain-bottom nozzle produces a thinner jet with stronger, lower-frequency fluctuations, making it more asymmetrical in short-term time averages.
3) Velocity fluctuations decrease in frequency from the jet leaving the ports to the surface in both nozzles.
4) The mountain-bottom nozzle produces ~50% higher surface velocity in the mold.

Summary (Cont…)

5) The mountain-bottom nozzle causes surface velocity fluctuations with almost 96% of total measured energy at lower frequencies (33-500s time periods).
6) The higher velocity and turbulence at the surface causes higher variation in surface level profile, more level fluctuations, and easier slag entrainment with the mountain-bottom nozzle.
7) Full scale steel casters have proportionally higher speed, including higher surface velocities, and level fluctuations, which are reasonably characterized by Froude similarity. The above water-model findings are predicted to hold in the steel caster as well.
8) With less surface fluctuations, the well-bottom nozzle is recommended over the mountain-bottom shape for steel quality.

Acknowledgments

- Young-Jin Jeon and Prof. Hyung-Jin Sung, Dept. of Mechanical Eng., KAIST, South Korea, and Seong-Mook Cho, POSTECH, South Korea for help with the PIV measurements.
- Oh-Duck Kwon, Shin-Eon Kang, POSCO Technical Research Laboratories, South Korea.
- Continuous Casting Consortium, University of Illinois at Urbana-Champaign, POSTECH, and POSCO, South Korea
- Seong-Yeon Kim and Graduate students at Metal Processing Simulation Laboratory, UIUC.
- Fluent and ANSYS Inc.