ANNUAL Meeting 2009

August 5, 2009

Differences Between Water Models and Steel Casters: A Theoretical Evaluation

Rajneesh Chaudhary, B. T. Rietow, B. G. Thomas

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

Project Overview

- Non-optimal mold flow causes level fluctuations, excessive surface velocity, and inclusion particle transport, leading to defects in the cast product.
- Physical water model offers excellent visualization to study mold flow, and has similar kinematic viscosity to molten steel.
- What is the best way to construct and operate a water model and how accurately can it match flow-related behavior in the real caster?
- A validated computational model has been used to evaluate water modeling of both thick-slab steel caster and thin-slab funnel mold. Model formulation:
  - 3-D, steady, incompressible Navier-Stokes equations with mass conservation
  - Single phase with standard k-e model (RANS approach)
  - Mass and momentum sink to model shell solidification
  - using FLUENT
- The following differences between water models and steel casters are studied for effect on flow pattern, impingement point, surface velocity, and surface level fluctuations:
  - Effect of scaling (full and 1/3),
  - Top-surface layer treatment, (air, oil, or hollow beads)
  - Shell solidification (with sink terms)
  - Relative slab thickness (thick and thin caster).
- The results from different cases are compared to determine the accuracy of different types of water models, and to suggest guidelines for water model construction and operation.

Differences between water model and steel caster

- To capture flow features of a caster using water model, it is important to overcome the major differences between them:
  - Water and steel have greatly different properties, such as density, dynamic viscosity, surface tension, and multiphase contact angle.
  - Water models often are constructed at reduced scale, to lower cost.
  - Top surface is usually open to atmosphere while in steel casters it is covered with high viscosity slag (highly sensitive to temperature).
  - Water models lack shell solidification even though sometimes tapered walls on wide and narrow faces are manufactured to match solidification front.
  - Real casters have continuous solidification of steel with significant temperature variations, so buoyancy effects can be significant and are usually not modeled in water models.
  - Water model at the bottom usually delivers water to a tank to be pumped back into the tundish for recirculation. In casters, liquid steel domain tapers to end completely.
- Of these main differences, shell solidification and top free surface effects are most important especially in the upper region of the mold. Bottom effects can be addressed by making long-enough water model.

Water Model Construction and Operation Criteria: Single-phase

- To address these differences, scaling criteria have been developed:
  - Kinematic viscosity matches at ~27°C and is around 15% higher in water at ~20°C. Thus, for single-phase flow, water and steel behave very similarly. Their surface tensions and contact angles greatly differ.
  - To balance inertial and viscous forces, theoretically requires Reynolds similarity, meaning that the water model should have the same Reynolds number as the caster.
  - Because the free surface-flow is also important, the Froude number, which balances inertia and gravity, should be matched as well.
  - To match both Reynolds and Froude similarity simultaneously needs a full-scale water model, (assuming equal kinematic viscosities).
  - Once the flow is fully turbulent, the effect of Reynolds number is small, so the requirement of satisfying Reynolds similarity is often relaxed, and a small-scale model can often be used with only Froude satisfied.
  - In this case, the flow rate must be decreased in the water model by: $\lambda^{2.5}$. This means dropping casting speed by a factor of $\lambda^{0.5}$, or 0.6 for a 1/3 scale model (λ=1/3, geometric scaling factor), and scaling all velocities with $\lambda^{0.5}$

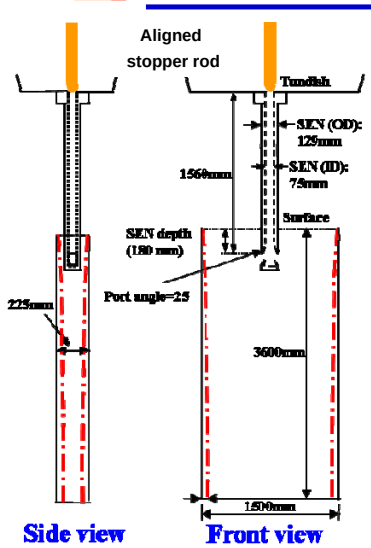
(Froude #) $Fr = V_{casting} / \sqrt{g h_{mold}}$ (Reynolds #) $\mathrm{Re} = D_h V_{casting} / \nu$

Water Model Construction and Operation Criteria: Multi-phase flow

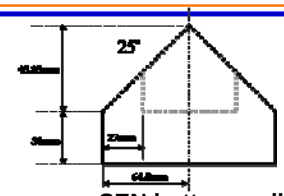
- To balance inertia and surface tension also requires satisfying Weber similarity.
- To satisfy Weber and Froude similarities together requires a 0.6-scale model.
- However, the phenomena involving surface tension are very complex, and usually involve slag-steel interaction, multiphase flow, and other important phenomena such as bubble size, slag/steel viscosities, slag and steel density, droplet emulsification which cannot properly incorporated with a simple water model.
- Thus, it is likely not helpful to match Weber number without matching many other phenomena as well, which is extremely difficult to achieve.

(Weber #) $We = \rho V_{casting}^2 d_b / \sigma$

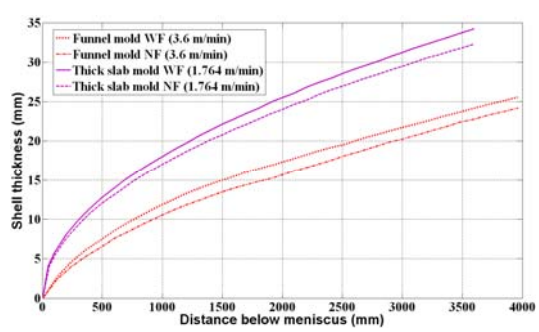
Full-scale water model of a thick-slab caster with shell thickness



Water model (no-shell) & caster (shell)



SEN bottom well

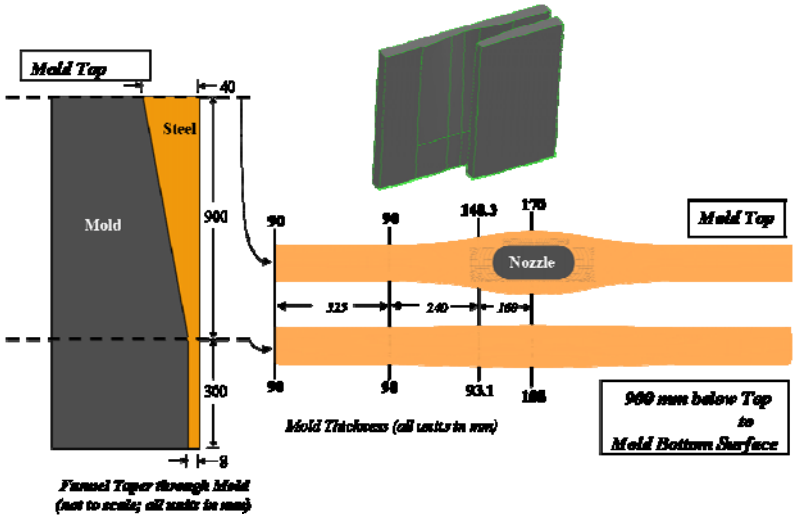


Solidifying shell for thick slab caster and thin slab funnel mold (using CON1D)

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

>>For 1/3rd water model, all linear dimensions are scaled down by 3, keeping port angles same

Dimensional details on thin-slab funnel mold model and its full scale water model



Solidifying shell profile for thin-slab funnel mold is given on previous slide.

Process parameters of various models

Parameter/property	Thick slab			Thin-slab funnel mold	
	Caster	Full-scale water model (@27°C)	1/3rd water model (@ 20 °C)	Funnel mold	Full-scale water model (@ 20 °C)
Casting speed (m/min)	1.764	1.764, 5.44	1.0186,3.145	3.6	3.6
Mold width (mm)	1500	1500	500	1450	1450
Mold thickness (mm)	225	225	75	90/170	90/170
Mold length (mm)	3600	3600	1200	1200	1200
SEN depth (mm)	180	180	60	265	265
Nozzle port (mm) (H,W,T)	80.1, 69.9	80.1, 69.9	26.7, 23.3	141,127, 28	141, 127, 28
Nozzle port angle (deg)	25	25	25	9.8(vertical)	9.8(vertical)
Nozzle bore ID/OD (mm)	75/129	75/129	25/43	80	80
Density (kg/m^3)	7020	1.0	998.2	7020	998.2
Dynamic viscosity (Ns/m^2)	0.006	0.00085	0.001	0.006	0.001
Kinematic viscosity (m^2/s)	0.85×10^{-06}	0.85×10^{-06}@27 °C	1.0×10^{-06} @ 20 °C	0.85×10^{-06}	1.0×10^{-06}@20 °C
Fluid above top surface (density, kg/m^3))	Slag(ρ=3000)	Beads(ρ=426), oil (ρ=890)	Air(ρ=1.18),beads(ρ=426),oil(ρ=890)	Slag (ρ=3000)	Beads (ρ=426)
Mass/momentum sink with shell solidification	Yes	No	No	Yes	No
Domain modeled (nozzle & mold)	¼	¼	¼	½	½
Top surface condition	No-slip	No-slip	Free- and no-slip	No-slip	No-slip
Vertical downward motion of wide and narrow faces with casting speed	Yes	No	No	Yes	Yes

Various cases studied to evaluate water modeling

Thick-slab mold					
Case no	Type of model	Top surface condition	Froude no (Fr)	Reynolds no (Re)	Casting speed (m/min)
Case:1	Steel caster	No-slip (slag)	0.0050	--	1.764
Case:2	Full-scale water model at 27 ºC	No-slip (beads & oil)	0.0050	13462	1.764
Case:3	Full-scale water model at 27 ºC	No-slip (beads & oil)	0.0152	41519	5.440
Case:4	1/3rd water model at 20 ºC	No-slip (beads & oil)	0.0152	6817	3.141
Case:5	1/3rd water model at 20 ºC	Free-slip (air)	0.0152	6817	3.141
Case:6	1/3rd water model at 20 ºC	No-slip (beads & oil)	0.0050	2203	1.0186
Case:7	1/3rd water model at 20 ºC	Free-slip (air)	0.0050	2203	1.0186
Thin-slab funnel mold					
Case:8	Steel caster	No-slip (slag)	--	--	3.6
Case:9	Full-scale water model at 20 ºC	No-slip (beads)	--	--	3.6

Two Froude numbers: Fr=0.0050 & Fr=0.0152

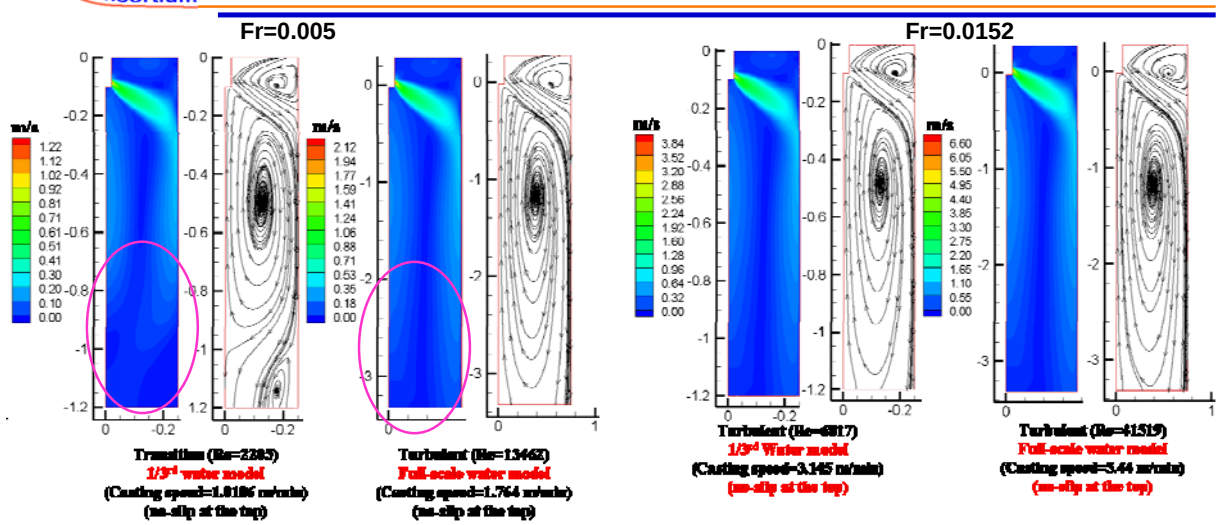
Thick-slab mold: 1/3rd and full scale water model

Thin-slab funnel mold: Full-scale water model

Top surface treatment: Beads & oil (no-slip), air (free-slip)

$\rho_{beads} / \rho_{water} = \rho_{slag} / \rho_{steel}$ Hollow beads to achieve same density ratio as slag in steel

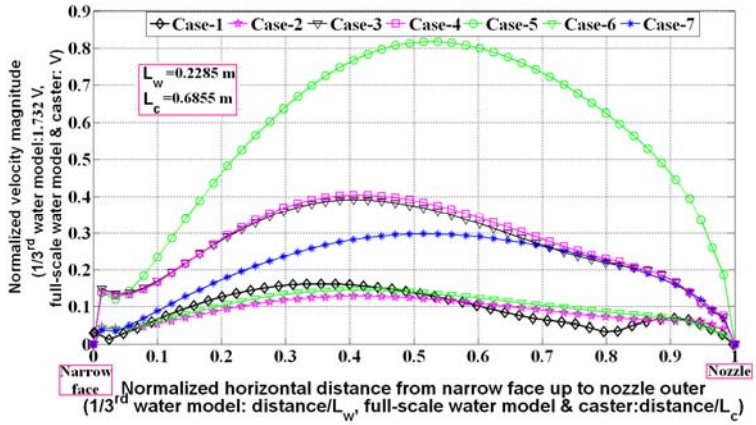
Effect of scaling (full vs 1/3rd): comparison of mold-mid plane velocity contours and streamlines



>>Since only Froude similarity is satisfied and full-scale is 3 times in all linear dimensions, maximum velocity in full-scale is sqrt(3) times that in 1/3rd water model.
>>Flow patterns do not match in lower region at Fr=0.0050, because of flow becoming laminar in the lower region of 1/3rd scale water model.
>>At Fr=0.0152, flow patterns matches closely in the whole domain (and with the high-velocity Fr=0.0050).
>>Although such high casting speed (5.44 m/min, at Fr=0.0152) is practically difficult to achieve, but importance of flow regime is clearly shown through this study.

Effect of scaling (full vs 1/3rd): Comparison of surface velocity

	Fr=0.0152	Fr=0.0050
Beads (full water)	Case 3	Case 2
Beads (1/3 water)	Case 4	Case 6

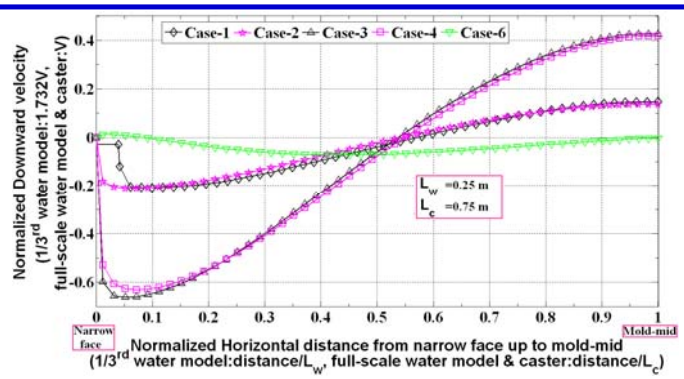


>>Scaled surface velocity (5 mm below surface in 1/3rd and 15 mm in full scale) matches well at both Froude numbers.
Compare case-2 &case-6 (Fr=0.0050) and case-3 & case-4 (Fr=0.0152).

>> This study shows a quantitative match in upper recirculation zone between 1/3rd and full scale water models at both Froude numbers.
This match is also achieved with other scaling criteria (such as Re number similarity, or linear scaling)

Effect of scaling (full vs 1/3rd): comparison of downward velocity

	Fr=0.0152	Fr=0.0050
Beads (full water)	Case 3	Case 2
Beads (1/3 water)	Case 4	Case 6



Compare downward velocity
(1 m below surface in 1/3rd scale and 3 m below surface in full scale)

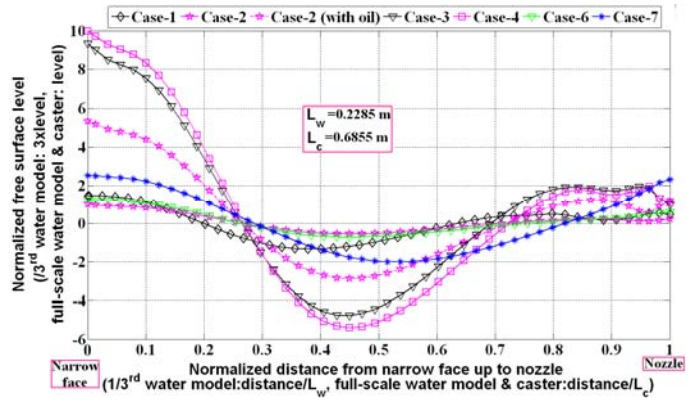
>>For low-velocity Fr=0.0050, (cases 2 and 6), flow patterns are quite different in 1/3rd and full-scale water models in lower region (below ~0.8m) because slower jet detaches from narrow face in laminar 1/3rd water model. The full-scale jet has enough momentum to stay attached so velocity is different.

>>Root cause of difference is: Reynolds number in 1/3rd water model is in transition regime while full-scale model is fully turbulent for this Fr=0.0050.

>>For high-velocity Fr=0.0152, scaled downward velocity in both cases (3 &4) match because both are fully turbulent.

Effect of scaling (full vs 1/3rd): comparison of free surface profile

	Fr=0.0152	Fr=0.0050
Beads (full water)	Case 3	Case 2
Beads (1/3 water)	Case 4	Case 6

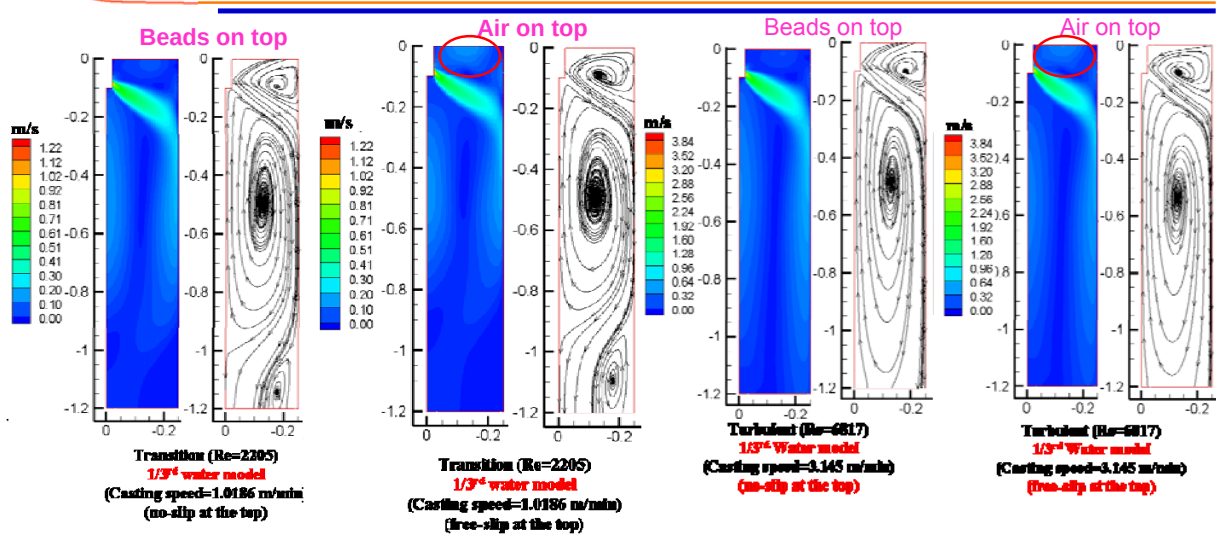


Compare surface level along mid-line between wide-faces

>>Higher surface level close to narrow face.

>>Surface level variation matches in between 1/3rd and full-scale water models at both Froude numbers (case-2 & case-6(Fr=0.005) and case-3 & case-4 (Fr=0.0152)).

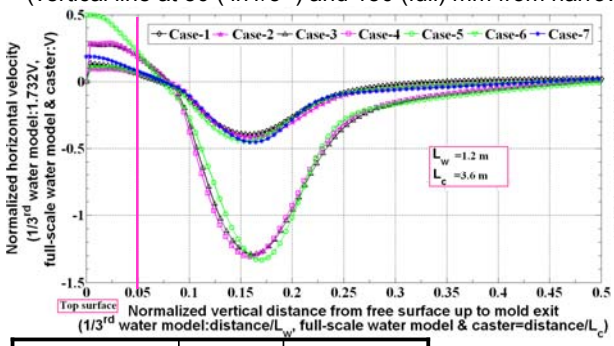
Effect of Slag: Comparison of flow patterns in 1/3rd water models



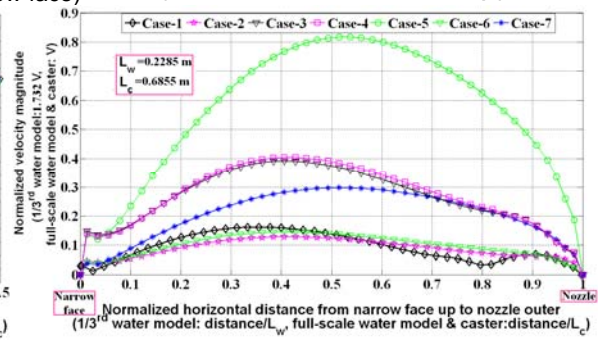
>>Flow patterns at both Froude numbers (=0.005 & 0.0152) matches closely in between beads and air cases except close to top surface where assuming air on the top gives much higher surface velocity.

Effect of slag: horizontal velocity

Horizontal velocity down caster
(vertical line at 50 (in1/3rd) and 150 (full) mm from narrow face)



Surface velocity along top
(at 5 and 15 mm from top)



	Fr=0.0152	Fr=0.0050
Beads (1/3 water)	Case 4	Case 6
Air(1/3 water)	Case 5	Case 7

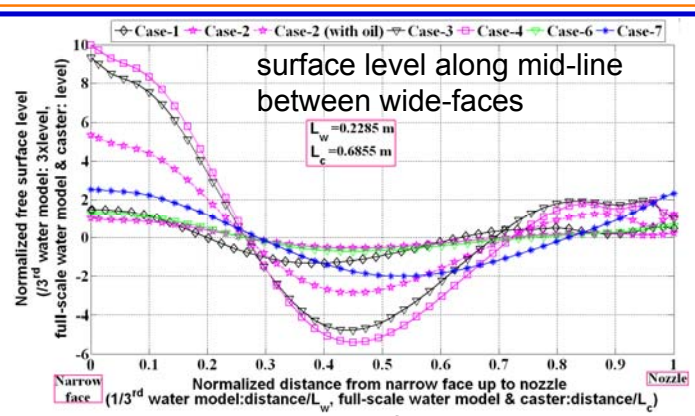
>> Surface velocity magnitude with air on the top (free-slip) is ~2 times higher than with Beads (no-slip) at both Froude numbers. (case-6 & 7 (Fr=0.0050) and case-4 & 5(Fr=0.0152))

>>Top surface boundary affects velocity in upper zone up to 0.05 units normalized vertical distance afterwards close to jet and in lower region this effect disappears.

>> Beads imitate high viscosity slag to give proper surface velocity, air on the top of water model gives unreasonable high velocity.

Effect of slag: free surface level profiles

	Fr=0.0152	Fr=0.0050
Beads (1/3 water)	Case 4	Case 6
Air (1/3 water)	Case 5	Case 7
Slag (Steel)		Case 1
Oil (full water)		Case 2 with oil



>>Higher Fr number gives ~9X higher waves (due to square of ~3X higher velocity)

>>Beads on top, chosen to match the slag-steel density ratio, can give reasonable surface level profiles matching caster, in 1/3-scale water model (case 1 vs. case 6).

>> Air on top gives much higher (~2 times) surface wave (case 7 vs. case 1) at both Froude Numbers (at Fr=0.0152, case 5 gives wave height 20mm which is off the chart!)

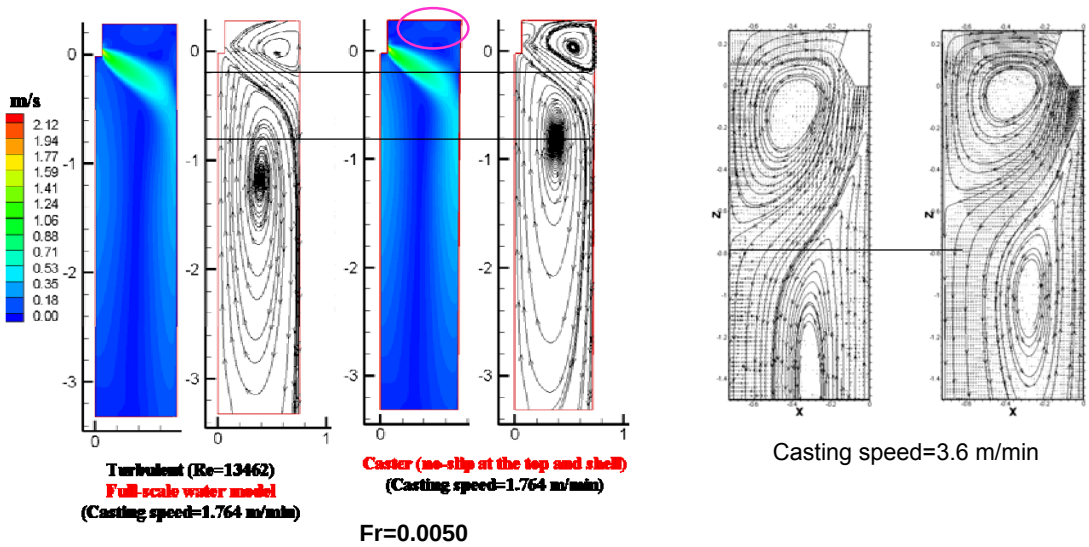
>>Oil on top is heavier than beads or air (density: 890 vs 426 and 1 kg/m3), has even higher amplitude surface waves than with air (case 2 with oil vs. case 7).

Effect of shell and mold thickness: Flow patterns

thick-slab and thin-slab casters and their full-scale water models

thick-slab | **thin-slab**

Full-scale water model | **Caster** | **full-scale water model** | **funnel-mold**

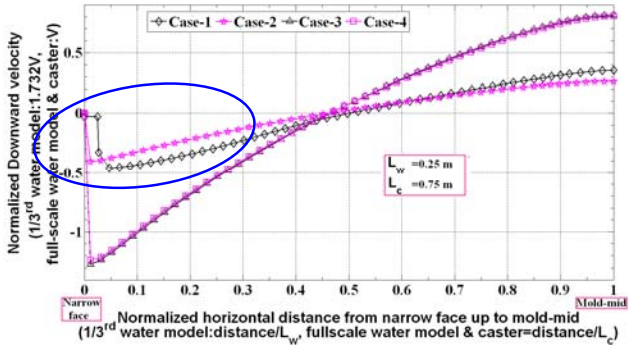


Effect of shell and mold thickness: Discussion of flow patterns

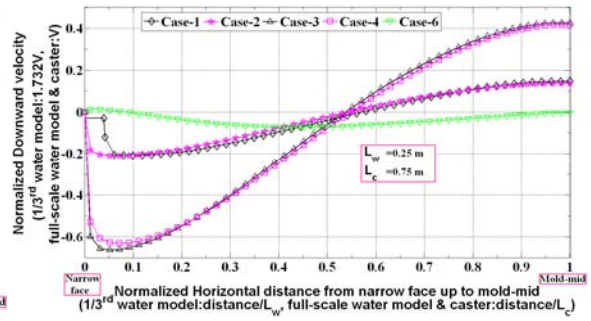
- Flow pattern is classic double-roll in both thick-slab mold and thin-slab funnel mold and their water models.
- Water model differs from steel caster, in spite of length assumed very long (so that outlet does not interfere).
- Thick-slab mold:
  - Qualitatively, flow pattern in caster matches its full-scale water model in upper region. The lower roll is extended slightly downward
  - Caster gives higher surface velocity than water model (same port inlet velocity)
- Thin slab funnel mold:
  - water model has straighter jet trajectory than steel caster, yielding a lower jet impingement location and elongated rolls (in the *z*-direction).
  - Both recirculation zones are extended downwards in the water model, especially the lower roll.
- Thin slab mold shows greater differences than thick-slab mold.

Effect of shell and mold thickness: Downward velocity profiles

At 0.4 m in 1/3rd and 1.2 m in full-scale/caster



At 1 m in 1/3rd and 3 m in full-scale/caster



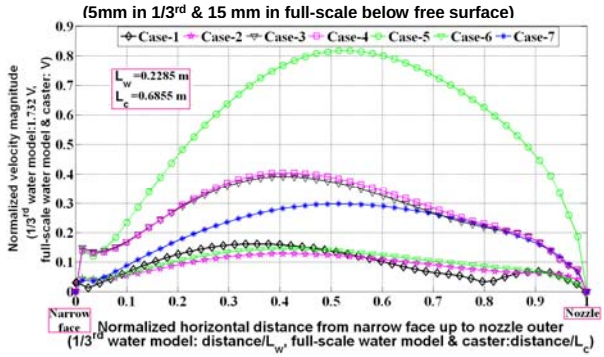
	Fr=0.0050
Slag (Steel)	Case 1
Beads (full water)	Case 2

>> Below jet (at 0.4 & 1.2 m), caster shows higher downward flow from mid-half to shell to adjust for less mass going through shell compared to no-shell. (case 1 & 2)

>>Effect of shell solidification is small at the mold center compared to near narrow face.

Effect of shell and mold thickness: Free surface velocity

Thick-slab mold (5mm in 1/3rd & 15 mm in full-scale below free surface)



Thin-slab funnel mold (10mm below free surface)

	Fr=0.0050	
Slag (Steel)	Case-1	
Beads (full water)	Case-2	
Beads (1/3rd water)	case 6	
Beads (Full scale water model of funnel mold)		Case-8
Slag (thin-slab funnel mold)		Case-9

>>At Fr=0.0050, thick slab caster gives slightly higher surface velocity close to narrow face and lower close to nozzle compared to both 1/3rd and full-scale water models (case 1, 6 & 2). This finding is consistent with the previous work of Creech.

>>In thin-slab funnel mold, while both predict a maximum velocity at about 0.38 m from the center of the SEN, the fluid speed at this location is greatly underestimated by the water model (approximately 32% lower than the steel case, 0.324 m/s versus 0.478 m/s).

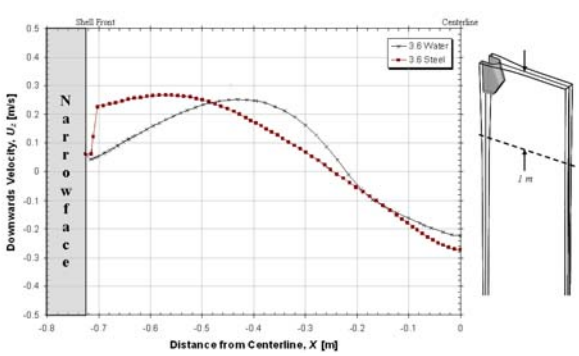
>>Effect of shell solidification is much more prominent at free surface in thin slab funnel mold because of shell occupying higher fraction of mold cross-section. (Case 8 &9)

Effect of shell and mold thickness: Thick-slab vs Thin-slab

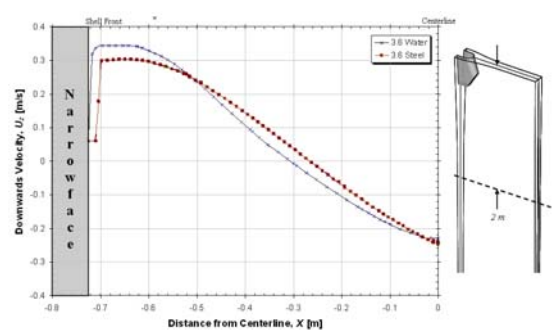
- The tapering of the shell and subsequent reduction in fluid cross-sectional area provides resistance for fluid leaving the domain.
- The higher resistance to downward flow in the steel case facilitates more fluid being "pushed" into the upper recirculation zone, yielding higher velocities at the top surface.
- As per expectations, the effect of shell at free surface velocity is more pronounced in thin-slab funnel mold compared to thick-slab mold.

Effect of shell and mold thickness: Downward velocity

Thin-slab funnel mold and full-scale water model:1 m below free surface



Thin-slab funnel mold and full-scale water model:2 m below free surface



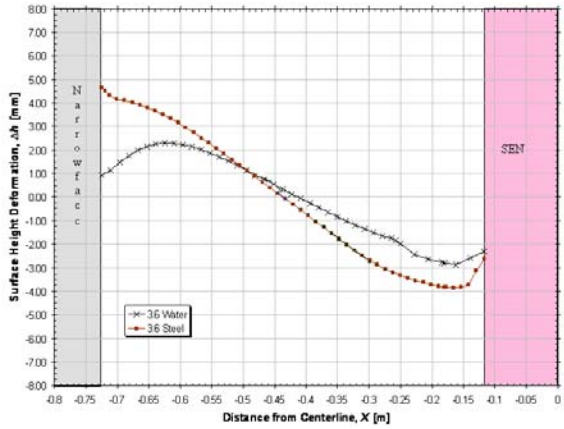
Beads (Full scale water model of funnel mold)	Case-8
Slag (thin-slab funnel mold)	Case-9

>>Downward velocity at distances down the mold with and without shell behaves the same way as in thick slab caster. (case 8 & 9)
>>At both locations, shell has minor effect at the mold center.

Effect of shell and mold thickness: Free surface profile

Thin-slab funnel mold and corresponding full-scale water model

Beads (Full scale water model of funnel mold)	Case-8
Slag (thin-slab funnel mold)	Case-9



>>In caster slag and in water model beads were used at the top for surface level calculations.

>>The steel caster shows ~5 times higher surface wave close to narrow face, level difference is not significant close to nozzle therefore signifying reducing importance of shell there.

Implications for Water Model Construction and Operation

- Qualitatively flow patterns are always okay in the top of the mold.
- Be careful to interpret flow in lower recirculation zones since inaccuracies are caused by the bottom of water model, shell and perhaps even from thermal buoyancy.
- Full-scale water model is best, smaller scale is always ok in the top of the mold, but can deviate lower in strand if flow becomes laminar.
- Water models of thinner slabs under-estimate velocities, owing to the increased importance of shell solidification

Matching surface velocity and level

- Must have Froude similarity for a reduced scale water model to work, since gravitational forces are dominating.
- At the top surface, beads with density of ~400 kg/m3 would be best (to match density ratio of slag to steel to capture free surface waves).
  Oil over-estimates level profile variations, but is otherwise ok.
- Shell presence increases surface velocity (unavoidable).
  - Water model surface velocity is too low.
  - Problem gets worse with decreasing slab thickness and decreasing casting speed).
- Putting the shell into water model makes the surface velocity too high (plastic does not move at casting speed). This error is even worse, so should not be done.
- Recognize that actual defect simulation (slag entrainment, etc.) will never match the steel caster:
  - Must infer behavior by studying the surface velocity and level fluctuations.
  - Look for keeping the time-average velocities in good ranges (windows of acceptable operation) and to avoid occasional bad transients, jumps, glitching in flow.

Summary & Conclusions

- **Effects of the water model scaling, (1/3rd and full-scale), free-surface condition (beads, air, oil) have been analyzed and compared with the real steel caster (with slag and shell) for both thick- and thin-slabs.**
- **Scaling:**
  - **For single-phase steel flow, Reynolds-Froude similarity requires full scale water model.**
  - **Downscaled water model with Froude similarity matches flow patterns and surface waves with caster as long as flow regime is maintained same in both (i.e. fully turbulent).**
- **Surface effects:**
  - **Water models open to air show unreasonable high surface velocity and level profile variations.**
  - **Beads, oil, and slag on the top all have high-enough viscosity (relative to liquid) so have a no-slip surface boundary condition.**
  - **Beads with same density ratio to water as slag/steel matches slag-steel interface behavior.**
- **Effect of shell:**
  - **Greatly increases velocity in steel thin-slab molds, including top surface.**
  - **Effect of shell is similar but less important in thick-slab caster, owing to less cross-section area covered.**

Acknowledgments

- Continuous Casting Consortium Members (ABB, Arcelor-Mittal, Baosteel, Corus, Delavan/Goodrich, LWB Refractories, Nucor, Nippon Steel, Postech, Steel Dynamics, ANSYS-Fluent)
- POSCO, South Korea
- Seong-Yeon Kim, Lance Hibbeler and other graduate students at Metal Processing Simulation Laboratory, UIUC.