CCC Annual Report

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Mold Heat Transfer and Distortion during Startup Transient

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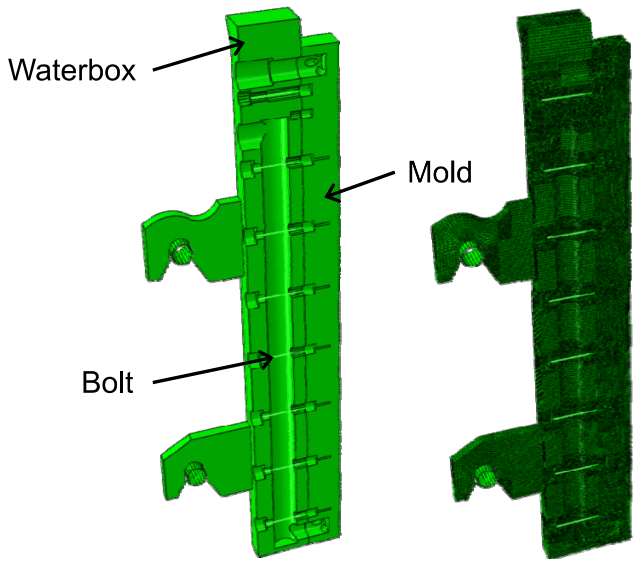
Introduction / Objectives

- Investigate the thermal and mechanical behavior of a thin-slab caster narrow-face mold
  - During startup and at steady-state casting
- Combine knowledge from mold-filling simulations and plant data to create a realistic model
- Compare distortion model predictions with plant measurements using inclinometer data. Validation already successful at steady-state.

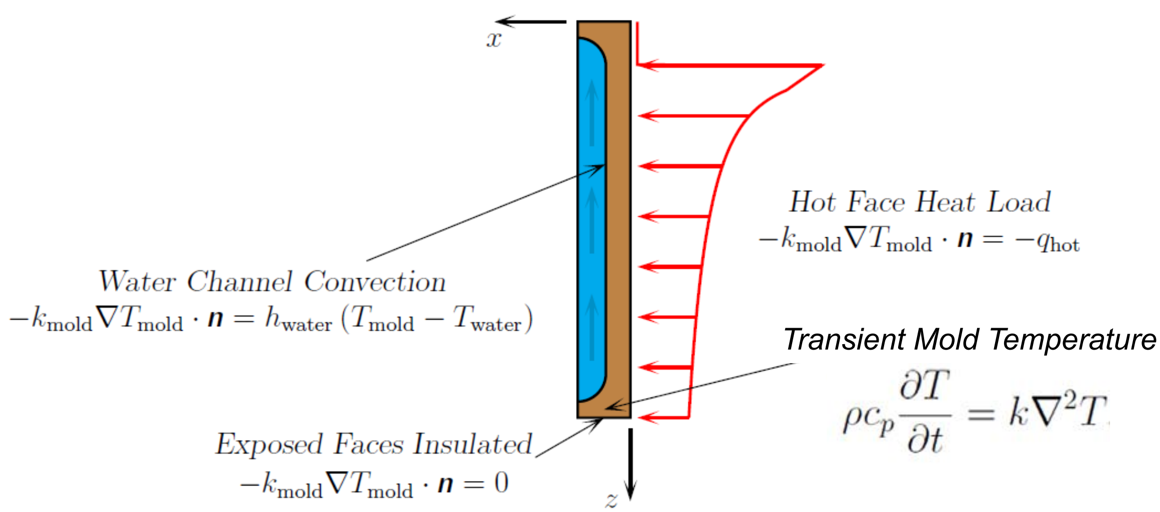
Detailed Model

- Symmetric half includes all geometric features
- Mold and waterbox = 317k nodes, 735k elements



- 64 cores on NCSA Blue Waters
- Thermal problem:
  - 234k DOF
  - 11 wall-clock seconds per iteration
  - 1 second per wall-clock hour
- Mechanical problem:
  - 1.04M DOF
  - 130 wall-clock seconds per iteration
  - 2.5 seconds per wall-clock hour

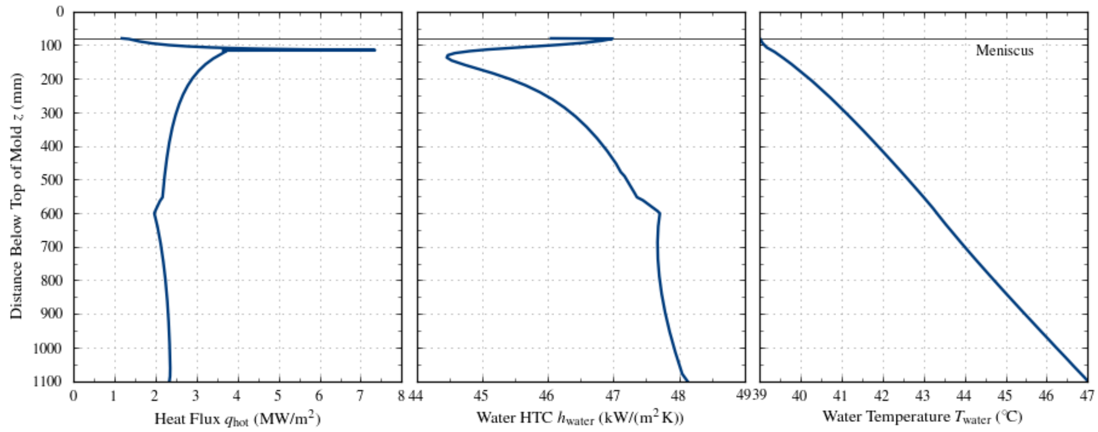
Thermal Problem



- Waterbox assumed thermally inert and not included
- Both detailed and reduced-order mold models used here

Thermal Boundary Conditions

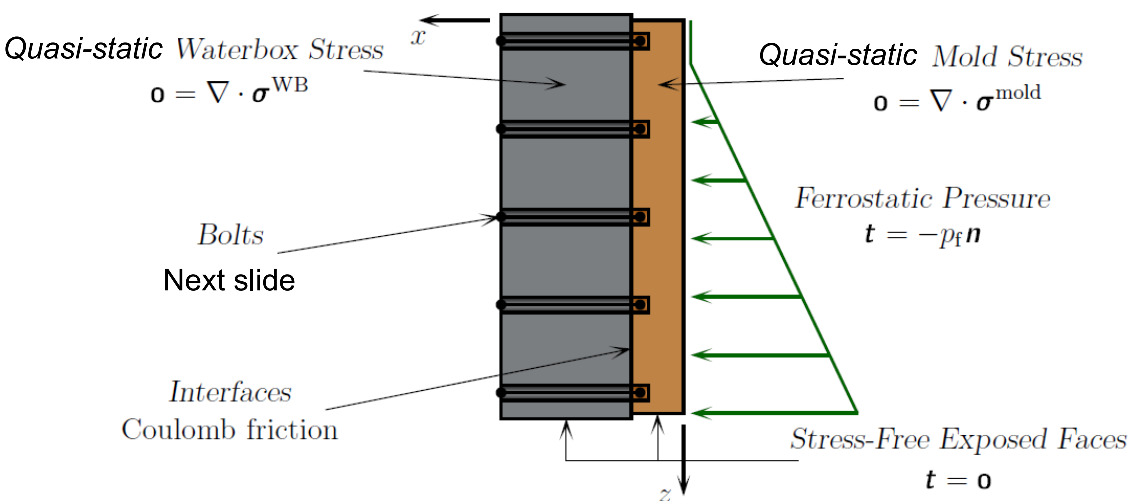
Heat Flux Water HTC Water Temperature



Steady-state boundary conditions, calibrated from plant data

Santillana *et al.*, *ISIJ Int.* 2008

Mechanical Problem



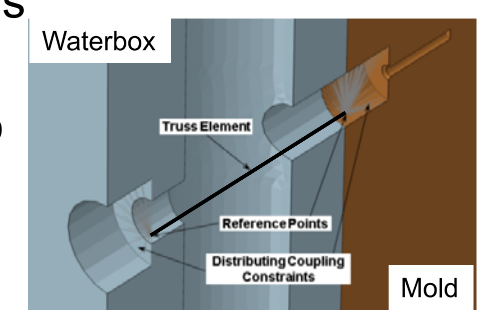
- Mold temperatures calculated from thermal model drive the thermal strain (one-way coupled)
- Ferrostatic pressure applied on “active” hot face

Mold Bolts

- Bolts modeled as truss elements
- Distributed constraint equations tie bolts to mold and waterbox
- Tightening torque converted to axial force

$$F_{\mathrm{bolt}} = \frac{T}{D_{\mathrm{bolt}}/2}\left(\frac{\pi D_{\mathrm{bolt}} - \eta_{\mathrm{bolt}} p_{\mathrm{t}}}{p_{\mathrm{t}} + \eta_{\mathrm{bolt}} \pi D_{\mathrm{bolt}}}\right)$$

  – 100 N·m torque = 30 kN force
  – η_{bolt} = 0.25 coefficient of friction for greased bolts



More detail: Hibbeler *et al.*, *MTB* 2012 and Thomas *et al.*, *I&SM* 1998

Mechanical Behavior

- Mold and waterbox modeled as elastic

$$\boldsymbol{\sigma} = \mathbb{C} : \left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{\mathrm{th}}\right)$$

$$\boldsymbol{\varepsilon} = \frac{1}{2}\left(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^{\top}\right) \qquad \boldsymbol{\varepsilon}^{\mathrm{th}} = \alpha\left(T - T_{\mathrm{ref}}\right)\boldsymbol{I}$$

$$\mathbb{C}_{ijk\ell} = \frac{E}{2(1+\nu)}\left(\delta_{ik}\delta_{jl} + \delta_{i\ell}\delta_{kj}\right) + \frac{\nu E}{(1+\nu)(1-2\nu)}\delta_{ij}\delta_{k\ell}$$

- Elastic models can match measurements of waterbox distortion (Thomas *et al.*, *I&SM* 1998), but inelastic behavior necessary to predict cracks (O'Connor and Dantzig, MMTB 1994)

Material Properties

Quantity	Symbol	Value	Unit
Mold - CuCrZr alloy			
Thermal conductivity	k_{mold}	350	$\text{W m}^{-1}\,\text{K}^{-1}$
Mass density	ρ_{mold}	8900	kg m^{-3}
Specific heat capacity	$c_{p,\text{mold}}$	385	$\text{J kg}^{-1}\,\text{K}^{-1}$
Young's modulus	E_{mold}	117	GPa
Poisson's ratio	ν_{mold}	0.181	–
Coefficient of thermal expansion	α_{mold}	18	(µm/m)/K
Waterbox - AISI 316Ti			
Young's modulus	E_{waterbox}	200	GPa
Poisson's ratio	ν_{waterbox}	0.299	–
Mold-waterbox coefficient of friction	μ	0.5	–
Liquid steel mass density	ρ_{steel}	7400	kg m^{-3}
Acceleration due to gravity	g	9.807	m s^{-2}

Startup Model – During Filling

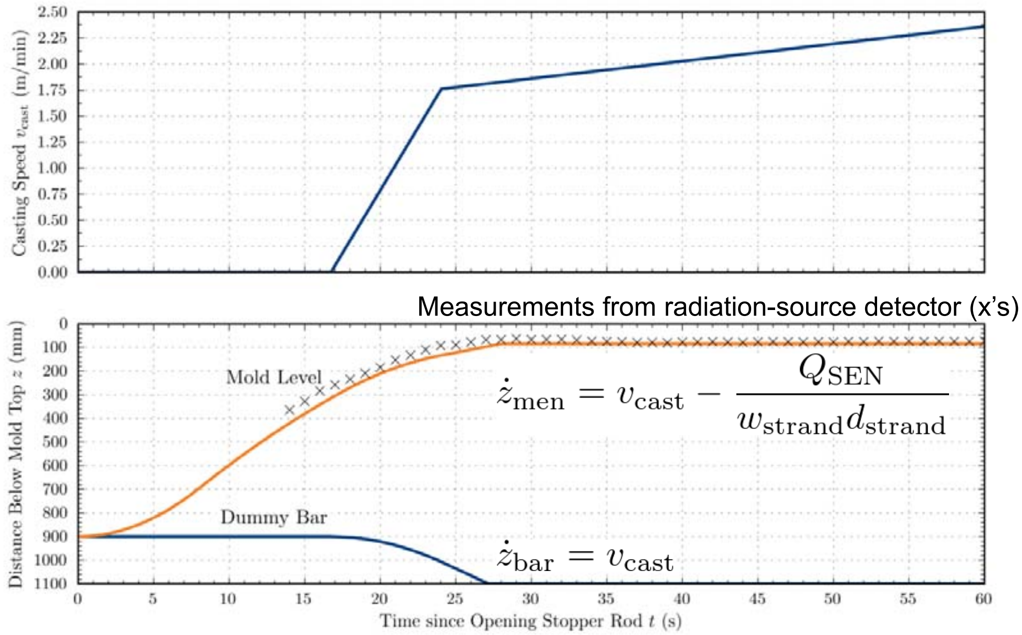
- Average mold level based on assumption of rising flat surface during filling is reasonable (Wang and Zhang, *ISIJ Int.* 2010), and Hai Hao (previous talk)
- Apply a transient BC from the steady-state profiles, *e.g.*, $q_{\text{hot}}(z,t) = q_{\text{hot}}^{\text{SS}}(t - t_0)$

q_{hot} in 3D model at given position *z* and time since start *t*

Steady state (CON1D) q_{hot} time below meniscus computed from time since start *t* and the time of initial solidification $t_0(z,t)$ for the 3D model point at position *z*

Mold Filling

Mold level and dummy bar movement calculated based on casting speed and SEN flow rate



Time Since Initial Solidification

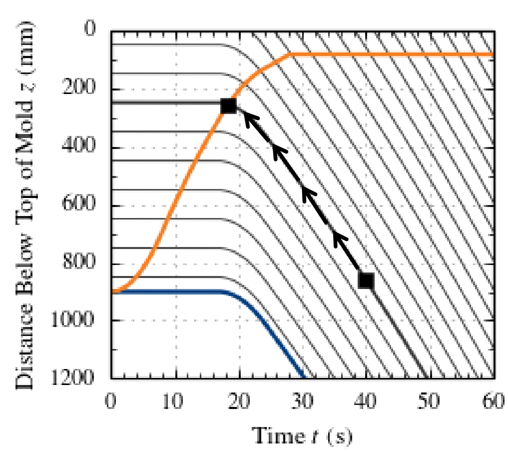
- The initial solidification time of the point at z is found by integrating the casting speed backwards in time to the meniscus (similar to Iwasaki and Thomas, TMS 2012)

Find t_0 such that:

$$z_{\text{men}}(t_0) = z - \int_{t_0}^{t} v_{\text{cast}}(\tau)\ \mathrm{d}\tau$$

At steady state,

$$t_0(z) = t - \frac{z - z_{\text{men}}}{v_{\text{cast}}}$$

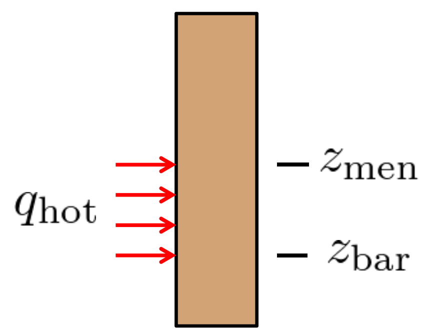


Startup Heat Flux – Filling

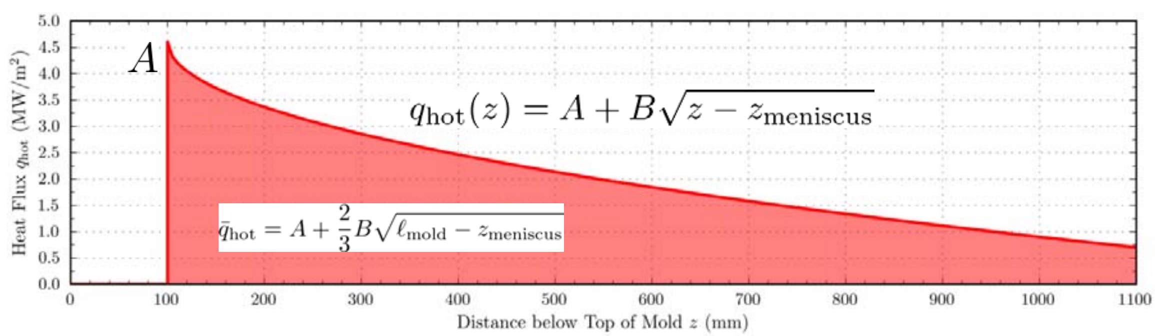
- Based on the work of Hai Hao, the heat flux during startup can be taken as uniform
- Apply this uniform value as the measured heat flux, scaled to the effective mold length

$$q_{\text{hot}} = \frac{\ell_{\text{mold}} - z_{\text{men,SS}}}{z_{\text{bar}} - z_{\text{men}}} \bar{q}_{\text{hot}}$$

and zero outside of the "active" hot face



Startup Heat Flux – After Filling

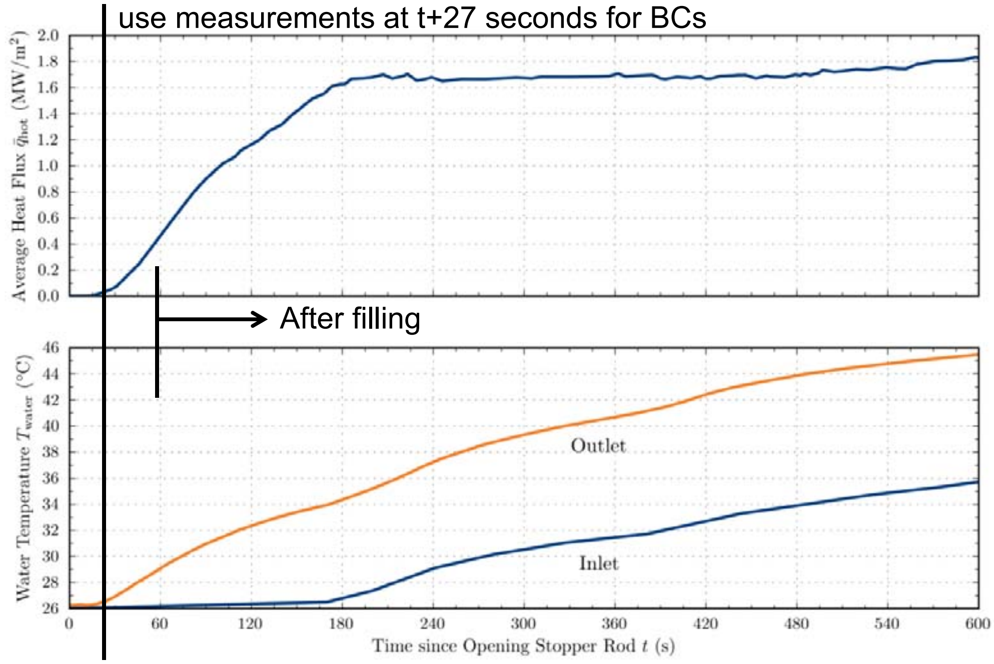


- Used by Savage—Pritchard (1954)
- Choose max as $\chi = 2.3$ times measured $\bar{q}_{\text{hot}}$
- Coefficients

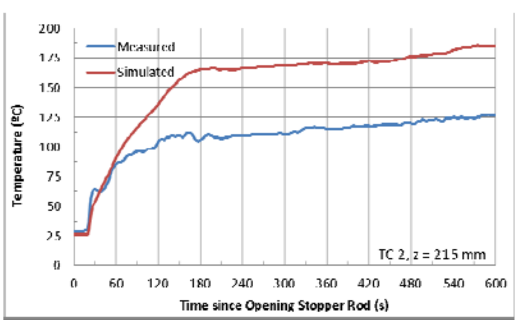
$$A = \chi \bar{q}_{\text{hot}} \qquad B = \frac{3}{2} \frac{(1-\chi)\,\bar{q}_{\text{hot}}}{\sqrt{\ell_{\text{mold}} - z_{\text{meniscus}}}}$$

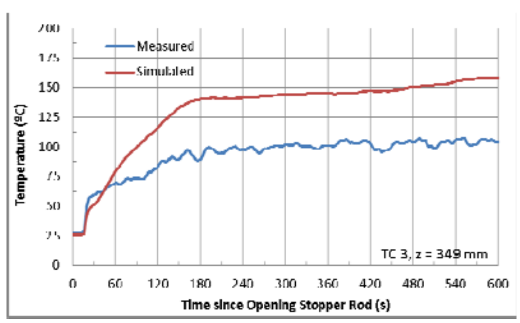
Heat Flux & Water ΔT Measured during Startup

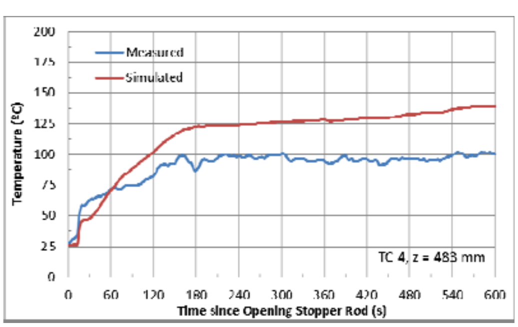
27 s lag between stopper rod opening and water outlet thermocouple; use measurements at t+27 seconds for BCs

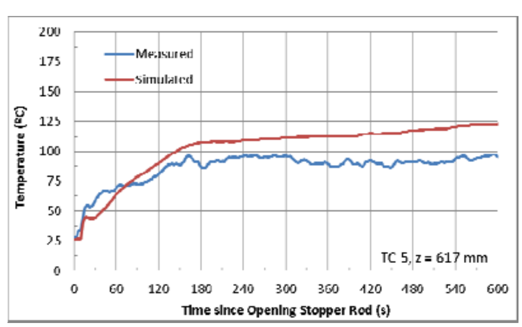


Thermocouple Temperatures during Startup – Top Half

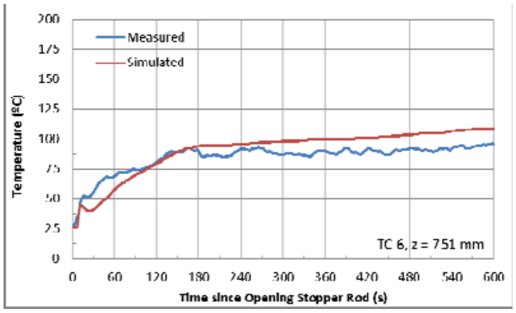


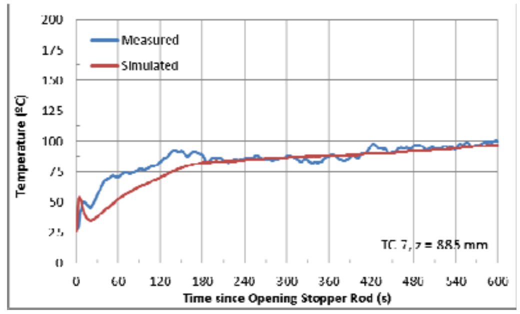


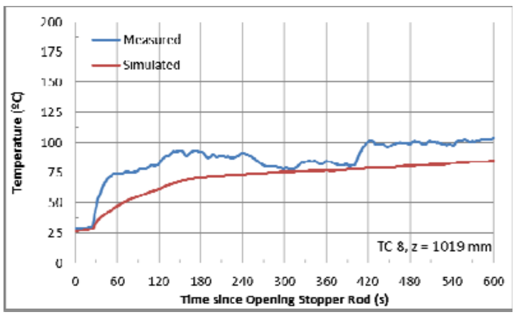




Thermocouple Temperatures during Startup – Bottom Half







All thermocouples matched reasonably well during first 60 seconds

Mismatch afterwards at TCs higher in mold, suggests χ = 2.3 too large

Trends and timing of TCs correct

Timing

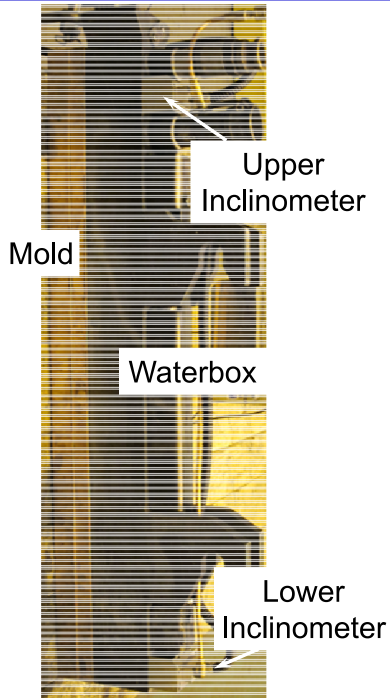
Heat Transfer

Machine	Cores	Sim Time after 24 h	Speedup
Desktop	2	1.3 s	1
Blue Waters	16	3.2 s	2.5
Blue Waters	32	7.9 s	6.1
Blue Waters	64	21.2 s	16.3

Using temperature-difference-controlled time-stepping,
$\Delta t < 0.002$ until 30 s,
then $\Delta t < 0.05$ until 150 s,
then $\Delta t < 2$ s out to 600 s (limited by output requests)

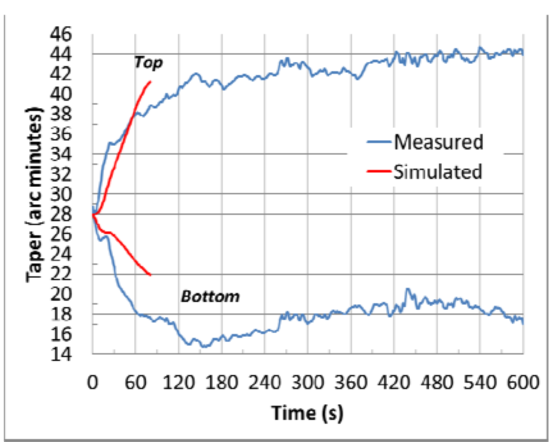
Inclinometer Measurements

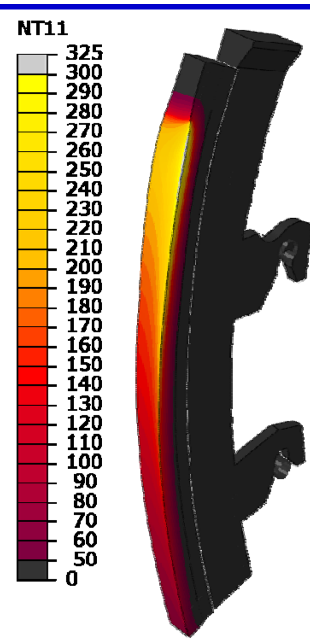
- Slope of waterbox measured online with inclinometers
  - 94 mm below top of mold
  - 31 mm above bottom of mold
- ±10 V signal mapped to ±6°
- First-order low-pass filter to remove noise from oscillation



Mechanical Behavior – Startup

- Mold distorts into parabolic arc but ***transient*** slope not matched by current model
  - Upper half too hot?
  - Need inelastic effects?

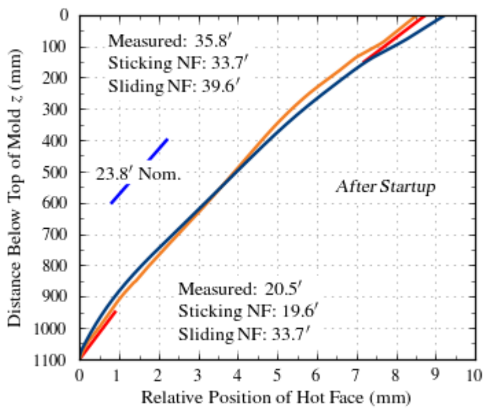




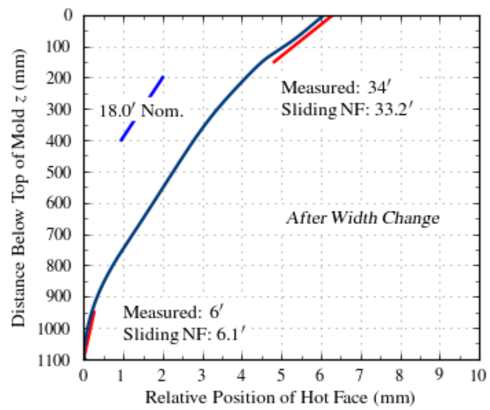
Distortion and temperatures at 80 s after start of mold filling

Mechanical Behavior – SS

v_{cast} = 3.5 m/min, before width change



v_{cast} = 4.0 m/min, after width change



Sliding NF is "free" distortion of NF mold and waterbox
Sticking NF accounts for effect of WF movement on NF (Hibbeler MTB 2012)

- Model predictions in both cases match measurements **within about 1'**
- Middle-mold taper matches applied value, significantly different at ends

Conclusions

- Computational model and plant measurements used to investigate thermo-mechanical behavior of NF mold during startup and at steady state
- Taper at top and bottom of mold markedly different than in the middle
- WF-NF friction / clamping effects constrain behavior of NF before a width change
- Mold distortion must be accounted for when designing taper practices

Further Reading

- L. C. Hibbeler, B. G. Thomas, R. C. Schimmel, and H. H. Visser, "Simulation and Online Measurement of Narrow Face Mold Distortion in Thin-Slab Casting." *Proceedings of the 8th European Continuous Casting Conference*, 2014.

Acknowledgments

- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp., Nucor Steel, Postech/ Posco, Severstal, SSAB, Tata Steel, ANSYS/ Fluent)

- National Center for Supercomputing Applications, Blue Waters cluster

- R. C. Schimmel, H. H. Visser, and A. Chown of Tata Steel IJmuiden