CCC Annual Report

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Applications of a Reduced-Order Model of CC Mold Heat Transfer

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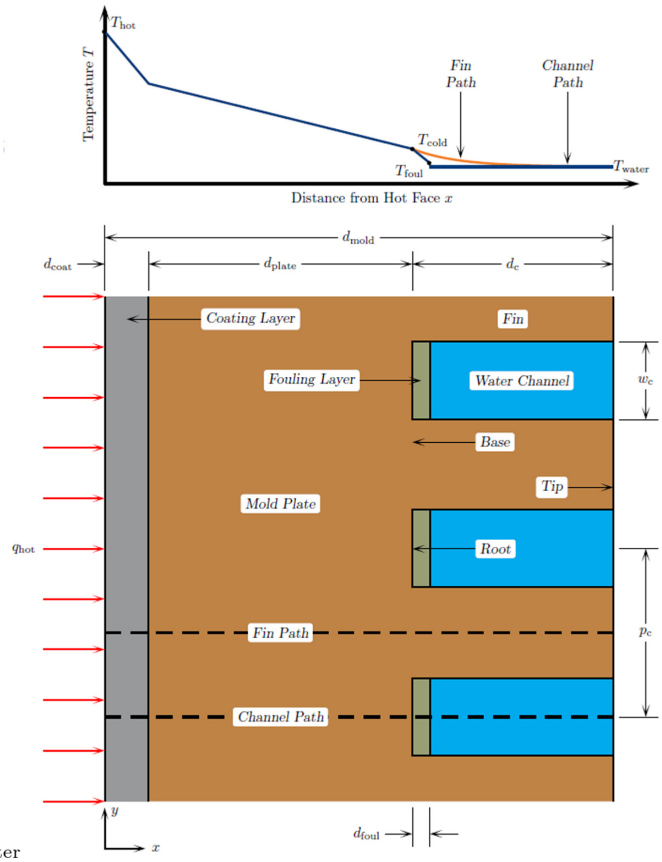
Introduction

- Need a simple model of the mold for shell solidification models coupled with:
  - Shell mechanical behavior
  - Mold distortion
  - Fluid flow
- "Reduced-order model" (ROM) options:
  - CON1D: 1D mold (2D at meniscus), interface, shell, *etc*.
  - Layer of finite elements: mold as a rectangle/brick
  - Boundary condition: mold as zero-D model

ROM Mold

13 Parameters

- Thicknesses
  - Coating layer d_{coat}
  - Mold plate d_{plate}
  - Fouling layer d_{foul}
  - Thermocouple position d_{TC}
- Channel geometry
  - Pitch p_{c}
  - Width w_{c}
  - Depth d_{c}
- Thermal conductivity
  - Coating layer k_{coat}
  - Mold plate k_{mold}
  - Fouling layer k_{foul}
- Boundary conditions
  - Uniform heat flux q_{hot}
  - Uniform convection condition $h_{\text{water}}, \bar{T}_{\text{water}}$



1D Temperature Solution

- Treat channels as fins, solve 1D steady conduction equation to give

$$T_{\text{1D}}(x) = \begin{cases} \bar{T}_{\text{water}} + q_{\text{hot}} \left(\dfrac{1}{h_{\text{cold}}} + \dfrac{d_{\text{plate}}}{k_{\text{mold}}} + \dfrac{d_{\text{coat}} - x}{k_{\text{coat}}} \right) & \text{if } 0 \le x \le d_{\text{coat}} \\ \bar{T}_{\text{water}} + q_{\text{hot}} \left(\dfrac{1}{h_{\text{cold}}} + \dfrac{d_{\text{plate}} + d_{\text{coat}} - x}{k_{\text{mold}}} \right) & \text{if } d_{\text{coat}} \le x \le d_{\text{coat}} + d_{\text{plate}} \end{cases}$$

- Cold face HTC: $h_{\text{cold}} = \left(\dfrac{w_{\text{c}}}{p_{\text{c}}} \right) h_{\text{roots}} + \left(1 - \dfrac{w_{\text{c}}}{p_{\text{c}}} \right) h_{\text{fins}}$

$$\frac{1}{h_{\text{roots}}} = \frac{1}{h_{\text{water}}} + \frac{d_{\text{foul}}}{k_{\text{foul}}}$$

$$h_{\text{fins}} = \frac{k_{\text{mold}}}{d_{\text{c}}} \beta \tanh(\beta)$$

$$\beta = \frac{h_{\text{water}}}{k_{\text{mold}}} d_{\text{c}} \Big/ \sqrt{\frac{h_{\text{water}}}{k_{\text{mold}}} \frac{p_{\text{c}} - w_{\text{c}}}{2}}$$

Water Channel HTC

- We recommend the Sleicher-Rouse model
  - Good fit (7% error) with measurements

$$h_{\mathrm{water}} = \mathrm{Nu}\frac{k_{\mathrm{water}}}{D_{\mathrm{h,c}}} \qquad \mathrm{Nu\ at\ } \bar{T}_{\mathrm{water}}$$

$$\mathrm{Nu} = 5 + 0.015\,\mathrm{Re}^{a_1}\mathrm{Pr}^{a_2}$$

$$a_1 = 0.88 - \frac{0.24}{4+\mathrm{Pr}} \qquad a_2 = \frac{1}{3} + 0.5\exp(-0.6\,\mathrm{Pr})$$

$$\mathrm{Re} = \frac{\rho_{\mathrm{water}}\bar{v}_{\mathrm{water}}D_{\mathrm{h,c}}}{\mu_{\mathrm{water}}}$$

$$\mathrm{Re\ at\ } T_{\mathrm{film}} = \tfrac{1}{2}\left(\bar{T}_{\mathrm{water}} + T_{\mathrm{c}}\right)$$

$$\mathrm{Pr} = \frac{\mu_{\mathrm{water}}c_{p,\mathrm{water}}}{k_{\mathrm{water}}}$$

$$\mathrm{Pr\ at\ } T_{\mathrm{c}}$$

Aside: Optimum Fin Geometry

- h_{cold} has the maximum value of 5/3 h_{water} with

$$p_{\mathrm{c}} = \frac{3}{4}\frac{k_{\mathrm{mold}}}{h_{\mathrm{water}}} \approx 9\,\mathrm{mm} \qquad w_{\mathrm{c}} = \frac{1}{4}\frac{k_{\mathrm{mold}}}{h_{\mathrm{water}}} \approx 3\,\mathrm{mm}$$

$$d_{\mathrm{c}} = \mathrm{atanh}(\chi)\,\frac{1}{2}\frac{k_{\mathrm{mold}}}{h_{\mathrm{water}}} \approx 21\,\mathrm{mm} \qquad 0.95 \le \chi < 1.0$$

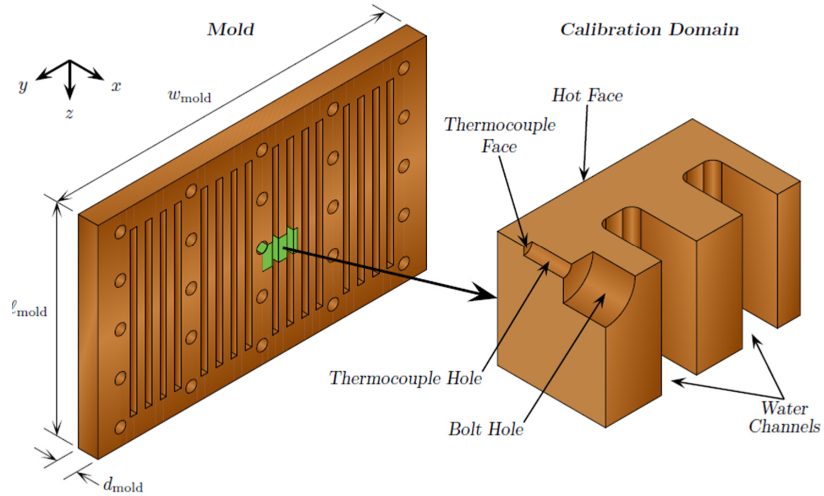
Values from solving the unconstrained optimization problem $\nabla h_{\mathrm{cold}}(p_{\mathrm{c}}, w_{\mathrm{c}}, d_{\mathrm{c}}) = 0$

assuming no fouling and constant h_{water}

- Fin assumption not valid at this configuration
- BUT, maximizing the heat extraction is one of many goals of mold/channel design

ROM Calibration

- Use a small 3D FEM model of the mold that captures all the details of mold heat transfer
  - Called "snapshot" model in ROM literature



ROM Calibration Summary

- Examine blueprints, calculate channel geometry $p_{\mathrm{c}}\ w_{\mathrm{c}}\ d_{\mathrm{c}}$

$$w_{\mathrm{c}}, d_{\mathrm{c}} = \frac{A_{\mathrm{physical}}}{D_{\mathrm{h,physical}}}\left(1 \pm \sqrt{1 - \frac{D^2_{\mathrm{h,physical}}}{A_{\mathrm{physical}}}}\right) \qquad \frac{A_{\mathrm{c}}}{p_{\mathrm{c}}} = \frac{A_{\mathrm{c,total}}}{w_{\mathrm{mold}}}$$

Maintain 1) cross-sectional area 2) hydraulic diameter and 3) water area per unit width

- Build 3D calibration model, calculate average hot face, average channel, max channel, average TC temperatures

$$d_{\mathrm{plate}} = \frac{k^\diamond_{\mathrm{mold}}}{q^\diamond_{\mathrm{hot}}}\left(T_{\mathrm{3D,hot}} - \bar{T}^\diamond_{\mathrm{water}}\right) - k^\diamond_{\mathrm{mold}}\left(\frac{1}{h^\diamond_{\mathrm{cold}}} + \frac{d^\diamond_{\mathrm{coat}}}{k^\diamond_{\mathrm{coat}}}\right)$$

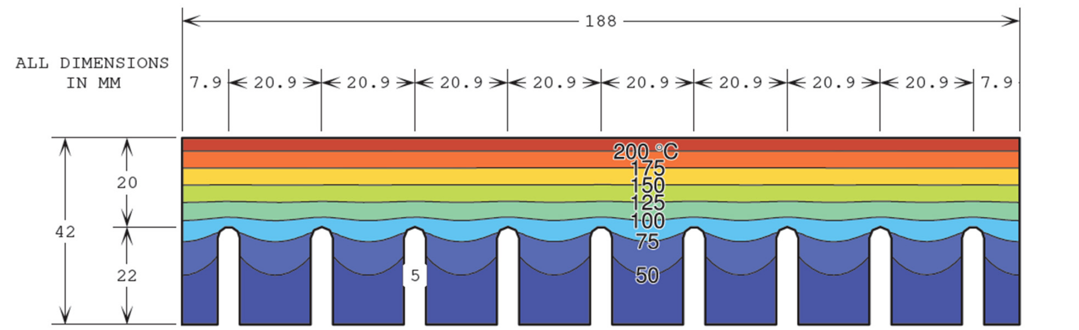
$$d_{\mathrm{roots}} = \frac{k^\diamond_{\mathrm{mold}}}{q^\diamond_{\mathrm{hot}}}\left(T_{\mathrm{3D,hot}} - T_{\mathrm{3D,roots}}\right) + d^\diamond_{\mathrm{coat}}\left(1 - \frac{k^\diamond_{\mathrm{mold}}}{k^\diamond_{\mathrm{coat}}}\right)$$

$$d_{\mathrm{channels}} = \frac{k^\diamond_{\mathrm{mold}}}{q^\diamond_{\mathrm{hot}}}\left(T_{\mathrm{3D,hot}} - T_{\mathrm{3D,c}}\right) + d^\diamond_{\mathrm{coat}}\left(1 - \frac{k^\diamond_{\mathrm{mold}}}{k^\diamond_{\mathrm{coat}}}\right)$$

$$d_{\mathrm{TC}} = \frac{k^\diamond_{\mathrm{mold}}}{q^\diamond_{\mathrm{hot}}}\left(T_{\mathrm{3D,hot}} - T_{\mathrm{3D,TC}}\right) + d^\diamond_{\mathrm{coat}}\left(1 - \frac{k^\diamond_{\mathrm{mold}}}{k^\diamond_{\mathrm{coat}}}\right)$$

Use same values of k_{mold}, q_{hot}, h_{water}, and coating and fouling layers as used in 3D model

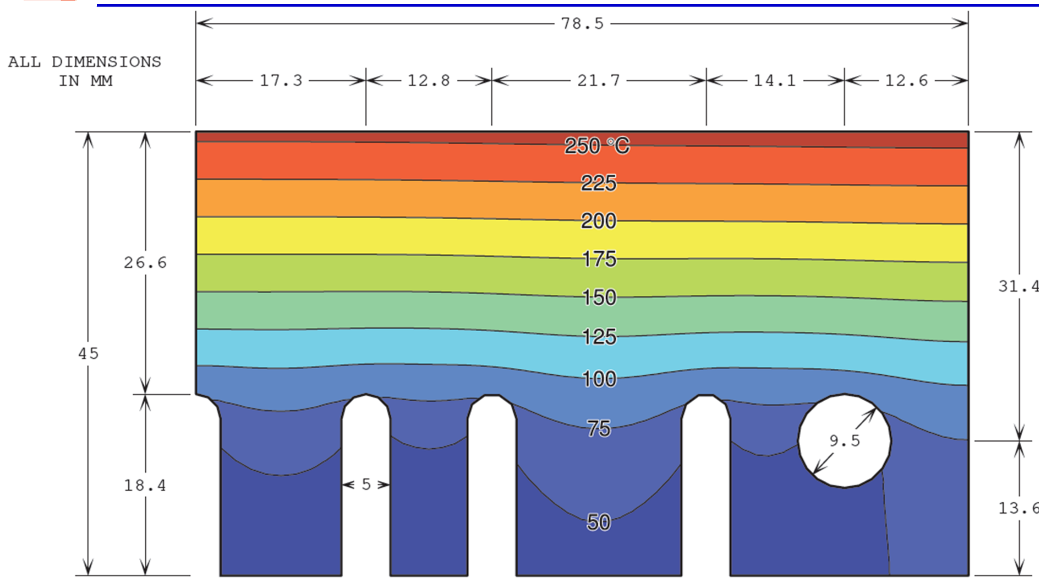
Example Slab Caster
Wide Face



Channel	1	2	3	4	5	6	7	8	9	ROM
A_c, mm^2	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3	107.3
$D_{h,c}$, mm	8.278	8.278	8.278	8.278	8.278	8.278	8.278	8.278	8.278	8.278
T_{roots}, °C	85.68	83.19	83.29	83.16	84.44	84.48	83.13	83.18	85.63	85.68
T_c, °C	47.66	47.30	47.65	47.14	47.86	47.88	47.17	47.24	47.61	47.50
h_{water}, kW/(m$^2\cdot$K)	27.68	27.68	27.68	27.68	27.68	27.68	27.68	27.68	27.68	27.68

WF and NF: q_{hot} = 1.31 MW/m², k_{mold} = 200 W/m·K, T_{water} = 27.5 ºC

Example Slab Caster
Narrow Face



Channel	1	2	3	4	5	ROM
A_c, mm^2	89.27	89.27	89.27	89.27	71.26	85.26
$D_{h,c}$, mm	8.000	8.000	8.000	8.000	9.525	8.339
T_{roots}, °C	79.71	78.54	81.14	82.36	83.07	83.07
T_c, °C	47.34	45.09	47.16	48.71	59.03	49.70
h_{water}, kW/(m$^2\cdot$K)	27.09	27.08	27.09	27.09	26.37	26.93

Example Slab Caster
ROM Mold Geometry

Mold	d_{plate}	d_{roots}	$d_{channels}$	p_c	w_c	d_c	d_{TC}
WF	21.86	20.48	26.31	20.89	5.170	20.76	12.17
NF	28.43	26.90	31.99	17.44	5.834	14.62	--

All dimensions in mm

- Calibrated geometry perturbed <10% from closest nominal blueprint geometry
- Use this geometry in CON1D to get results as accurate as 3D model

Sensitivity to BCs

- If the calibrated plate thickness in the 1D solution were sensitive to the heat load, then the derivatives involve extra terms, *e.g.*,

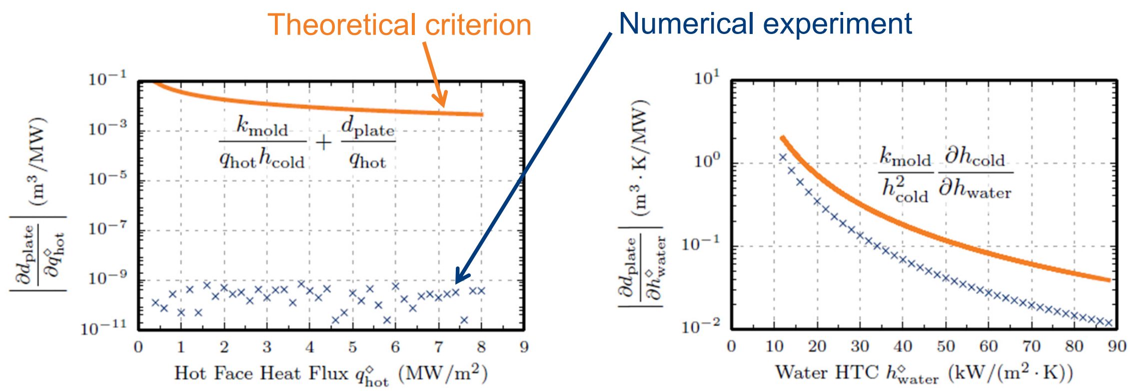
$$\frac{\partial T_{\mathrm{1D}}}{\partial q_{\mathrm{hot}}} = \left(\frac{1}{h_{\mathrm{cold}}} + \frac{d_{\mathrm{plate}}}{k_{\mathrm{mold}}}\right) + \underline{\left(\frac{q_{\mathrm{hot}}}{k_{\mathrm{mold}}}\frac{\partial d_{\mathrm{plate}}}{\partial q_{\mathrm{hot}}}\right)}$$

- If the second term is small relative to the first,

$$\left|\frac{\partial d_{\mathrm{plate}}}{\partial q_{\mathrm{hot}}}\right| \ll \frac{k_{\mathrm{mold}}}{q_{\mathrm{hot}} h_{\mathrm{cold}}} + \frac{d_{\mathrm{plate}}}{q_{\mathrm{hot}}}.$$

then we can say the calibration procedure is independent of the particular choice of q_{hot}

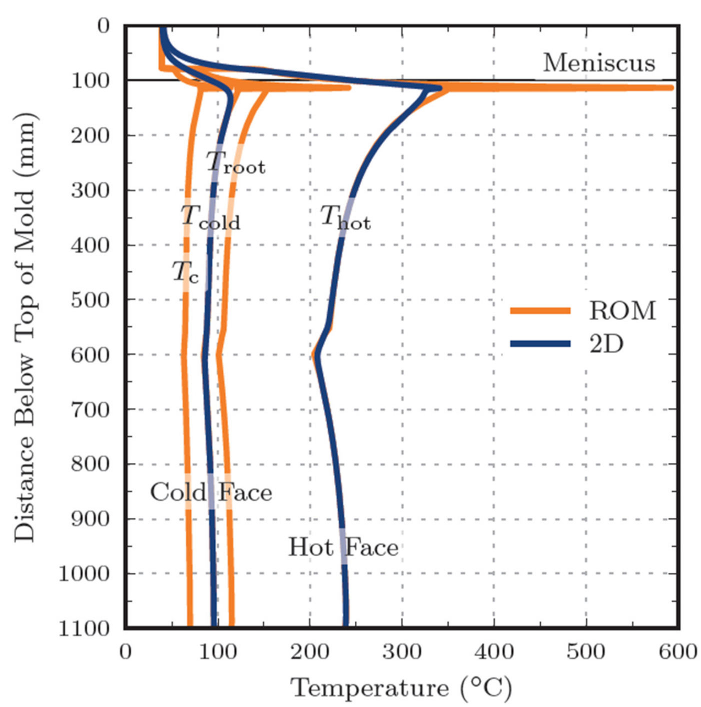
Sensitivity to BCs



- Calibration is **independent** of heat load, weakly sensitive to conductivity, and somewhat sensitive to water HTC
- Calibrating with h_{water} = 40 kW/m²·K and using the ROM with h_{water} = 50 kW/m²·K causes about 0.6 mm error in d_{plate}, which causes about 4 ºC error in mold temperatures

ROM vs 2D FDM Model

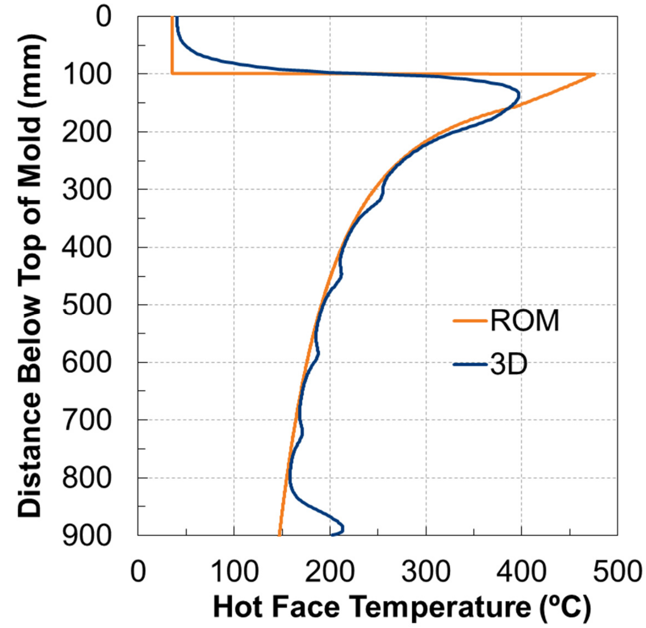
- Away from meniscus the ROM matches well with a 2D FDM model with same BCs
- This example uses a q_{hot} profile with a sharp peak



Thanks to K. Swartz for 2D calculations

ROM vs 3D FEM Model

- Away from meniscus and mold exit the ROM matches well with a 3D FEM model with same BCs
  - Bumps are bolt holes
- This example uses a "typical" q_{hot} profile



Thanks to G. Hamilton
for 3D calculations

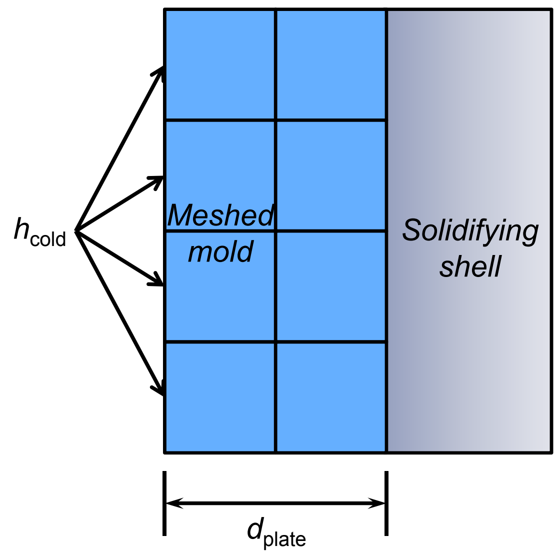
Using the ROM

1. Standalone CON1D is fast and accurate
   – Includes 2D correction near meniscus
2. In 2D and 3D models of shell heat transfer (with deformation, fluid flow, *etc*.),
   a) model the mold as a rectangular plate of calibrated thickness d_{plate} with h_{cold} and T_{water} convection on the back
   b) use a "zero-D" model of the mold with

$$\frac{1}{h_{\mathrm{mold}}} = \frac{1}{h_{\mathrm{cold}}} + \frac{d_{\mathrm{plate}}}{k_{\mathrm{mold}}} + \frac{d_{\mathrm{coat}}}{k_{\mathrm{coat}}}$$

ROM Mold as Plate

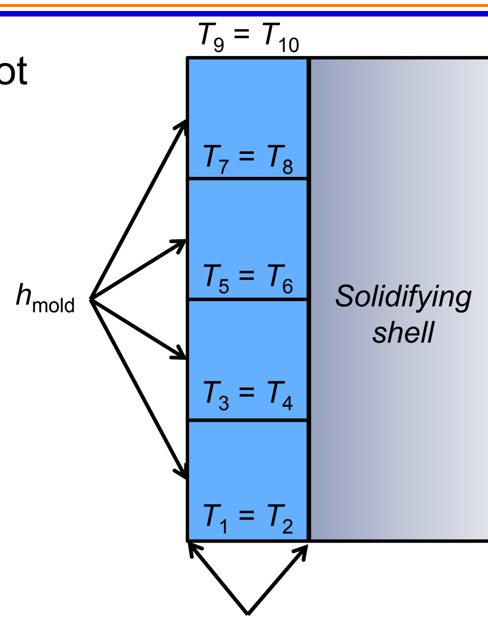
- Mold as rectangle or brick of thickness d_{plate}, with h_{cold} and T_{water} for cold-face convection
- Allows for heat conduction in other directions
  - Axial near meniscus
  - Transverse near slab corners
- Several layers of elements for transient behavior



Mold	d_{plate} mm	h_{water} kW/m²·K	h_{cold} kW/m²·K
WF	21.86	26.4	31.5
NF	28.43	26.4	33.6

ROM Mold as BC

- Mold a single row of elements at hot face temperature (use constraint equations) with h_{mold} on cold side
- ABAQUS subroutine `FILM` gives T_{hot} as input and wants h_{mold} and dh_{mold}/dT_{hot} as output



Constrain temperatures to be the same for all pairs of nodes

Mold	h_{water} kW/m²·K	h_{mold} kW/m²·K
WF	26.4	6.76
NF	26.4	5.64

ROM as BC – Implementation

- Within `FILM` subroutine, solve two equations

$$T_{\text{hot}} = \bar{T}_{\text{water}} + q_{\text{hot}} \left(\frac{1}{h_{\text{cold}}(T_{\text{c}})} + \frac{d_{\text{plate}}}{k_{\text{mold}}} + \frac{d_{\text{coat}}}{k_{\text{coat}}} \right)$$

$$T_{\text{c}} = \bar{T}_{\text{water}} + q_{\text{hot}} \left(\frac{1}{h_{\text{cold}}(T_{\text{c}})} + \frac{d_{\text{plate}} + d_{\text{coat}} - d_{\text{channels}}}{k_{\text{mold}}} \right)$$

  simultaneously for q_{hot} and T_{c} (coupled with $h_{\text{water}}(T_{\text{c}})$)
- Mold HTC is then

$$h_{\text{mold}} = \frac{q_{\text{hot}}}{T_{\text{hot}} - \bar{T}_{\text{water}}} \qquad \frac{\partial h_{\text{mold}}}{\partial T_{\text{hot}}} = \frac{h_{\text{mold}}}{T_{\text{hot}} - \bar{T}_{\text{water}}}$$

- Demonstrated in later talk

Conclusions

- Physics of 1D temperature solution used to construct a ROM of mold heat transfer
- Heat transfer characteristics consistent with the physical mold, by construction
- Key temperatures as accurate as a 3D FEM model, by construction, in fraction of the time
  - Hot face
  - Channel root and average
  - Thermocouple

References

- For model details and complete discussion of assumptions,

  L. C. Hibbeler, M. M. Langeneckert, J. Iwasaki, K. E. Swartz, R. J. O'Malley, and B. G. Thomas, "A Reduced-Order Model of Mold Heat Transfer in the Continuous Casting of Steel." To appear, 2014.

Acknowledgments

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- M. Langeneckert, J. Iwasaki, I. Hwang, K. Swartz, R. O'Malley