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Coupled Heat Transfer Optimization Calculation of ABAQUS and DOT for Beam Blank Mold

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Objective

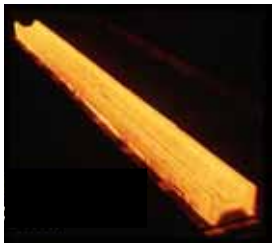
- Use Abaqus to get the approximate uniform heat flux to match the experimental temperature results of thermocouples
- Compare experimental temperature data and numerical data under uniform heat flux and discuss the possible distribution of heat flux along the section perimeter in order to match measured temperature closely
- Coupled linear heat flux optimization calculation of Abaqus and for six sections along the casting direction
- Use interpolation to get the whole heat flux file for the mold, and compare the total heat loss with the experimental data
- Explain the difference of calculated and experimental total heat loss and possible way to handle the problem

Beam Blank Mold

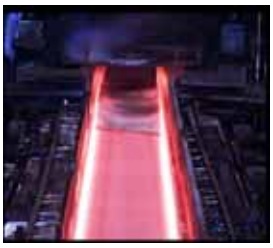
Beam Blank Mold

Casting

Semi-Finished



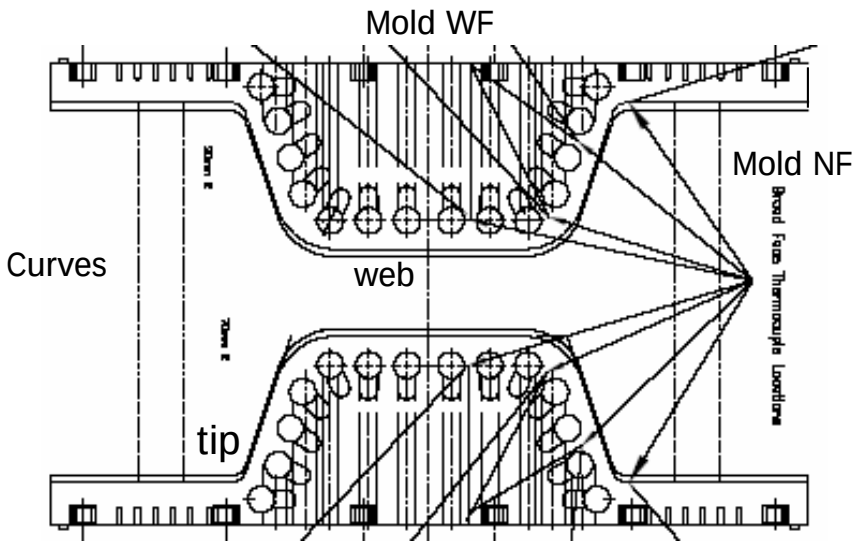
Reheating



Rolling

Final Product

Beam Blank Mold Design (BB2)



Experimental Measurement using Mold Thermocouples

Conducted by SDI and Accumold

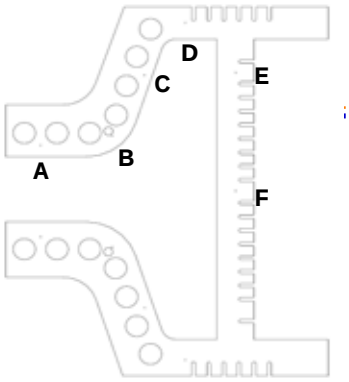
3 columns of 6 in “cove”, 1 Column of 3 on flange tip: 21 TCs per broad face

2 Columns on narrow face, 3 on outside column, 2 in center column: 5 TCs on narrow face

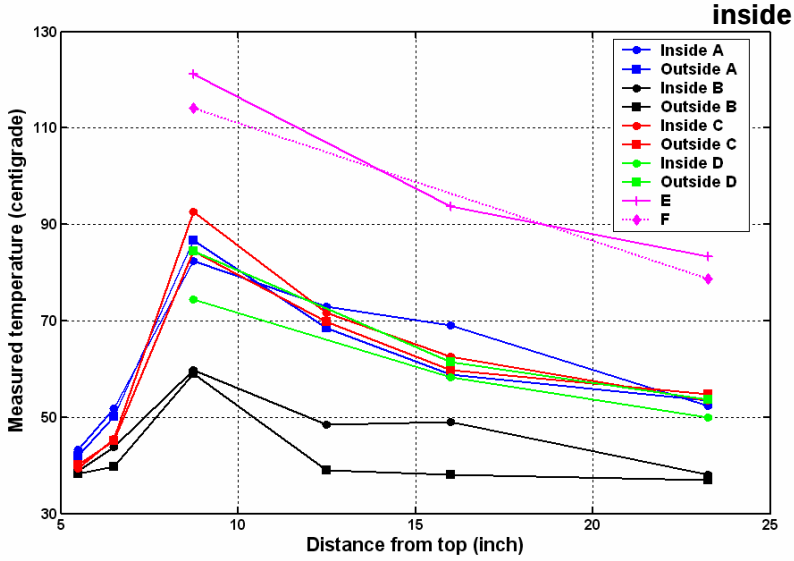
47 total thermocouples

TCs drilled between water slots to 1/10” past tangent line through water slot closest to hot face (centered between slots)
1/8” diameter Cr-Al (K-type) TCs
close contact fit (no thermal paste)

Experimental Results

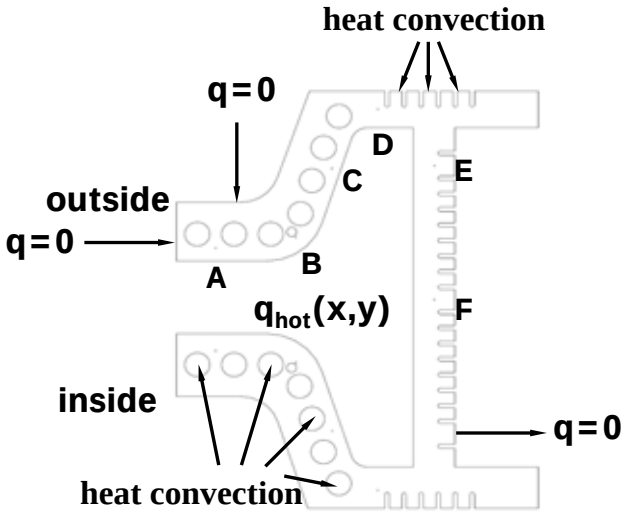


Averaged temperatures over 30 min of steady casting
Cast at 0.92 m/min; 32” mold; 26” working length



2-D Finite-Element Model of Horizontal Section through Mold

Steady-state heat conduction using Abaqus



Governing Equation

$$\nabla\bullet(k\nabla T)+Q=0$$

Boundary condition

Heat flux $-k\frac{\partial T}{\partial \hat{n}}=q$

Convection $-k\frac{\partial T}{\partial \hat{n}}=h(T-T_{\infty})$

Total: 10 thermocouples

Material Properties & Water Heat Balance Measurements

A 992 structural steel: 0.071%C, 1.31Mn, 0.012Ph, 0.026S, 0.17%Si, 0.36Cu, 0.06%V, 0.02Nb, 0.0116%N, 0.0017%Al

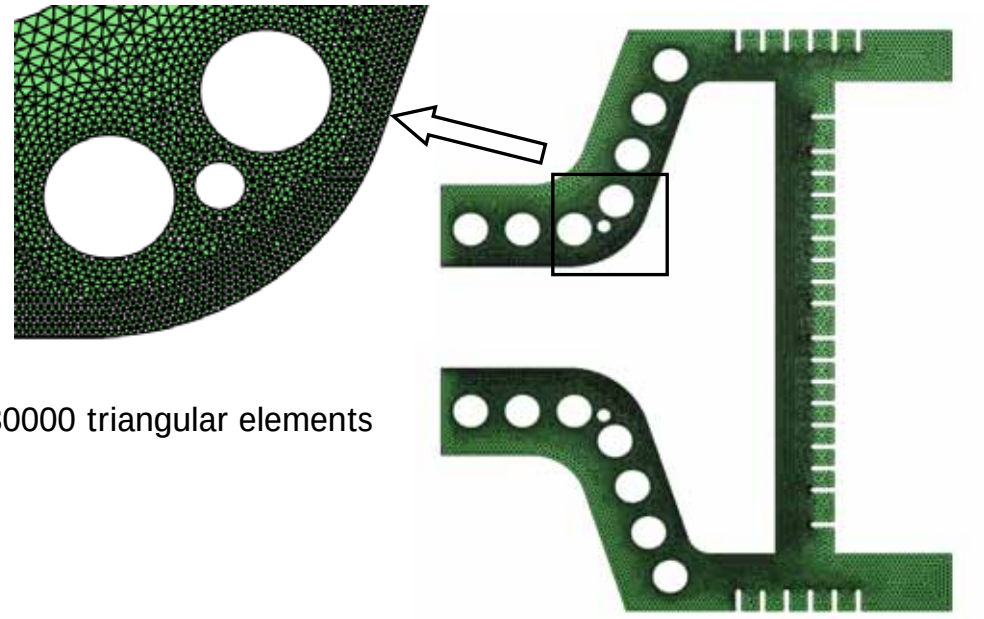
Copper thermal conductivity 350W/mK

	Water Flow (kg/s)	Inlet temp (°C)	Outlet temp (°C)	Flow velocity (m/s)	Heat loss (10^3W)
Front	43.34	31.87	34.91	9.73	551.3
Back	46.04	31.87	34.78	10.34	561.1
Left	14.77	31.87	37.23	7.79	331.8
Right	15.00	31.87	36.96	7.91	319.6
Total	119.16				**1763.8**

Wide face: $T_{ref}=33.35^{o}C$, $h=45\text{kW/m}^2\text{K}$

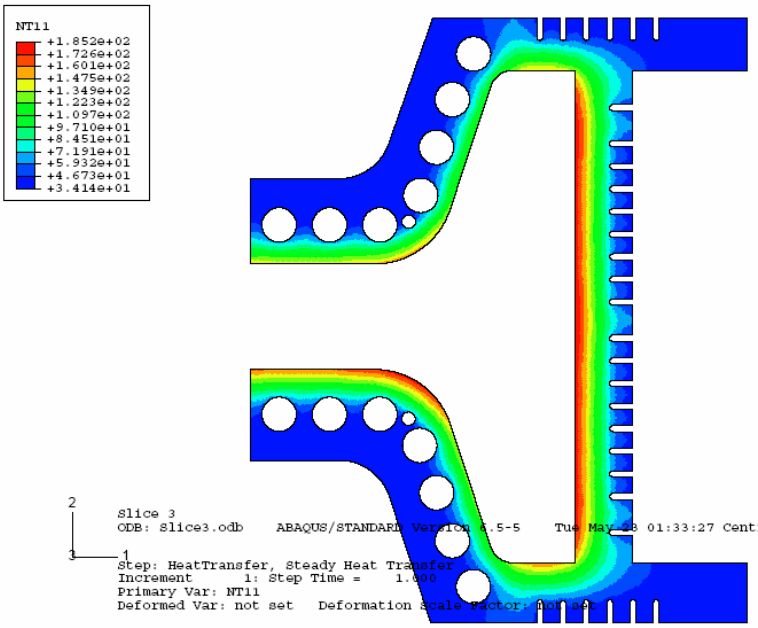
Narrow face: $T_{ref}=34.48^{o}C$, $h=34\text{kW/m}^2\text{K}$

Mesh



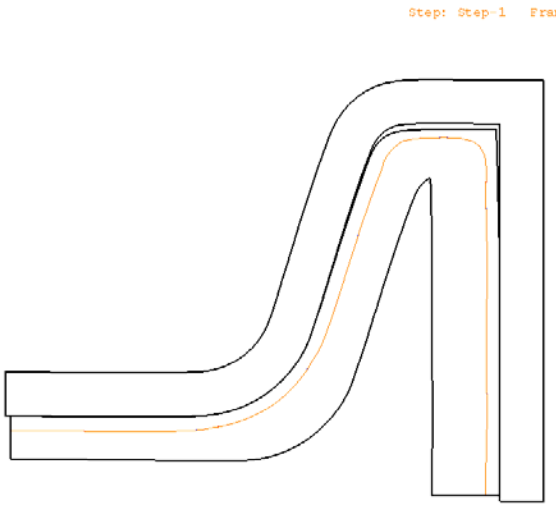
Total ~30000 triangular elements

Uniform Flux 1250kW/m^2 (8.75 inch below top)



	Experiment	Simulation
Inside A	82.41°C	86.00°C
Outside A	86.69°C	85.71°C
Inside B	59.75°C	85.54°C
Outside B	59.01°C	83.60°C
Inside C	92.60°C	86.41°C
Outside C	84.42°C	86.06°C
Inside D	74.43°C	73.52°C
Outside D	84.37°C	77.91°C
E	121.21°C	98.00°C
F	114.22°C	98.94°C

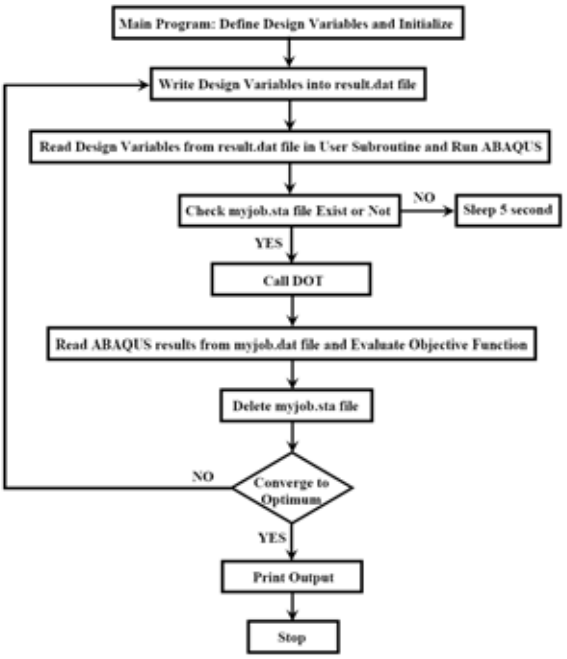
Solidification and Deformation of Casting in Mold



During solidification, there will form a gap between the casting and mold. Thermal resistance of the gap could cause the slow solidification during corner

From S. Koric simulation, 2006

Complete Procedure of Optimization Calculation

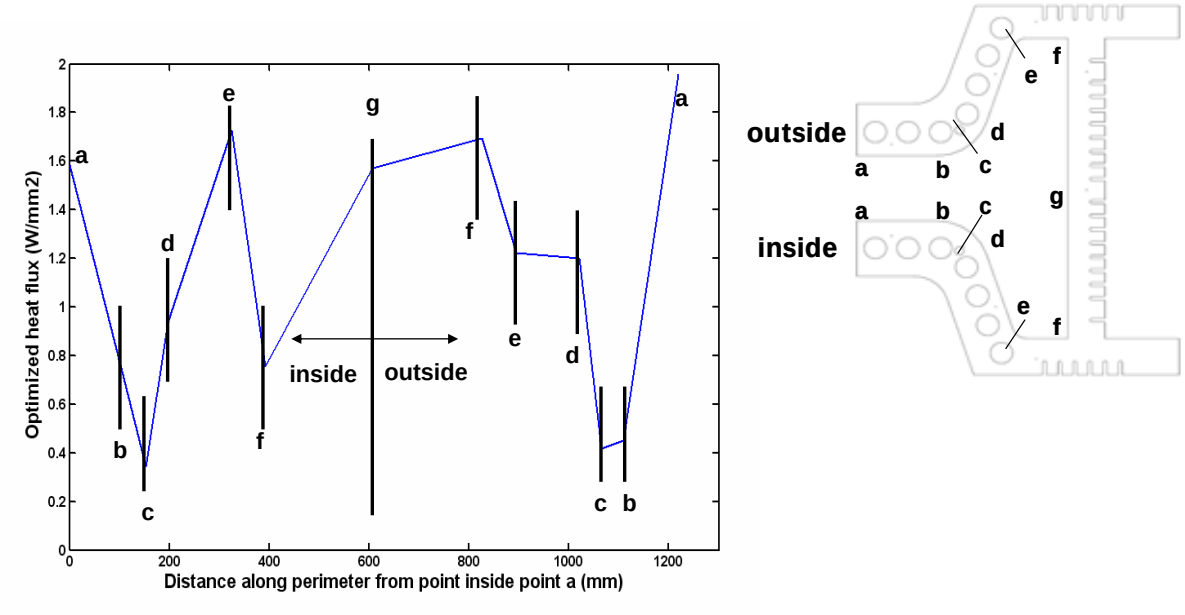


Objective function

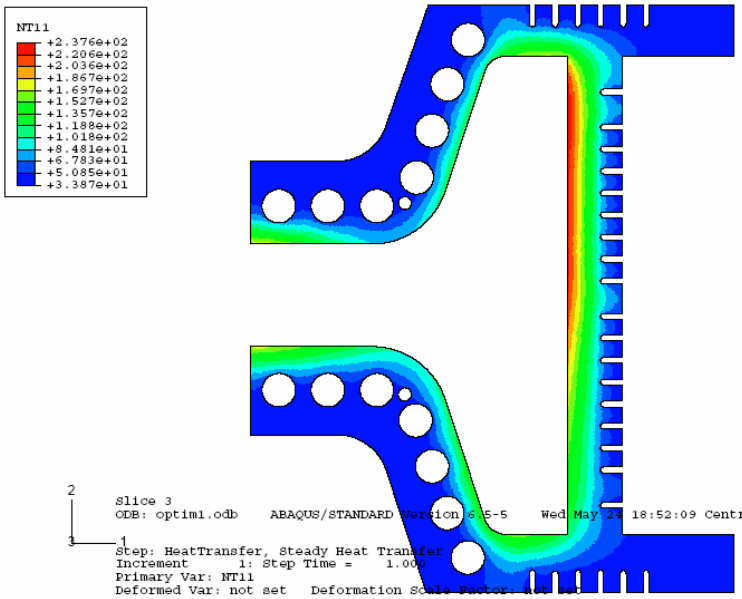
$$F = \sqrt{\sum_{i=1}^{10} (T_i^{num} - T_i^{\exp})^2}$$

Design Optimization Tool (J. Dantzig)

Optimized Heat Flux (8.75 inch below top)



Result for Optimized Heat Flux (8.75 inch below top)

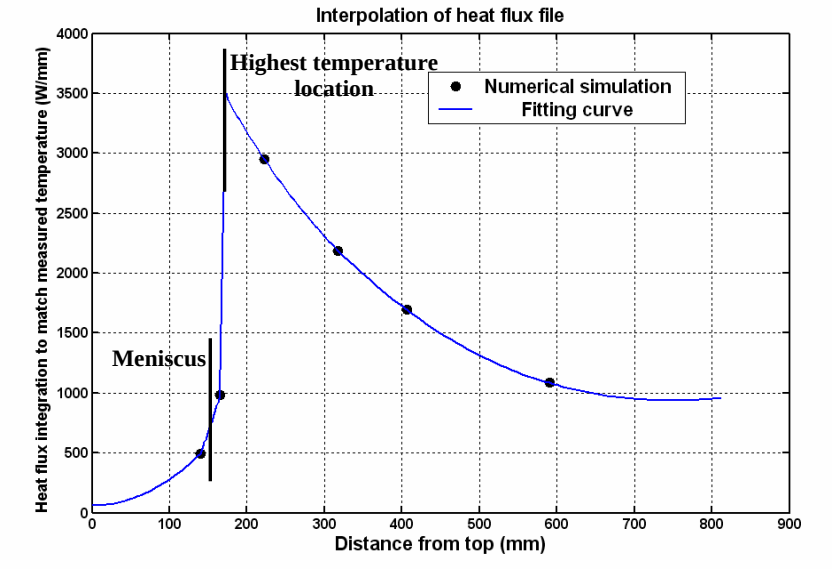


	Experiment	Simulation
Inside A	82.41 °C	82.45 °C
Outside A	86.69 °C	86.71 °C
Inside B	59.75 °C	59.66 °C
Outside B	59.01 °C	58.95 °C
Inside C	92.60 °C	92.53 °C
Outside C	84.42 °C	84.41 °C
Inside D	74.43 °C	74.43 °C
Outside D	84.37 °C	84.45 °C
E	121.21 °C	121.15 °C
F	114.22 °C	114.06 °C

Initial OBJ=33.2

Optimized OBJ=0.3

Interpolation of heat flux file



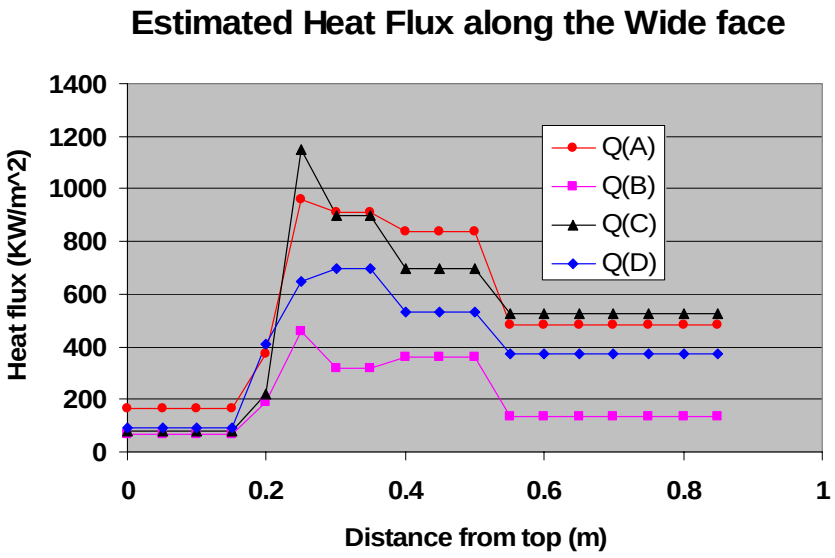
Integrate the area under fitting curve

Total heat loss 1100KW

Experimental value ~1763.8KW

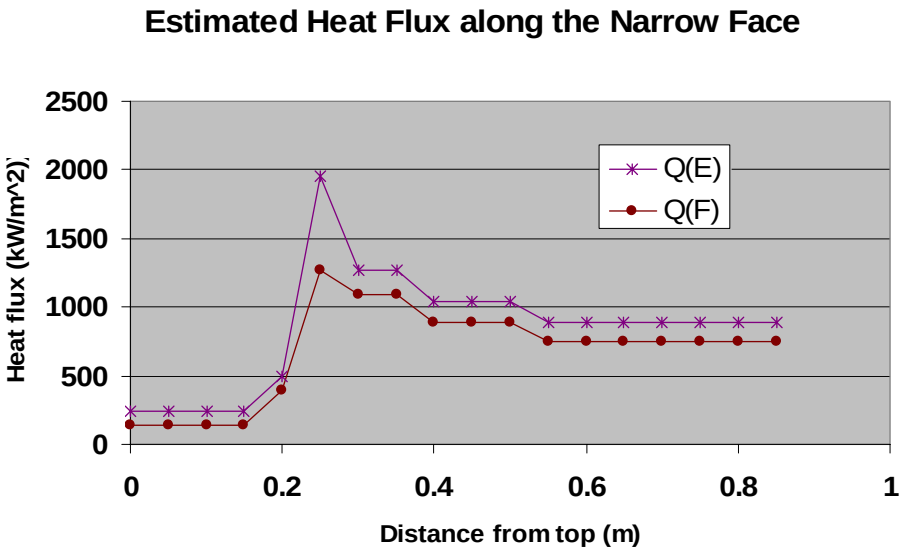
Error ~37.6%

Heat Flux Variation along mold (WF)

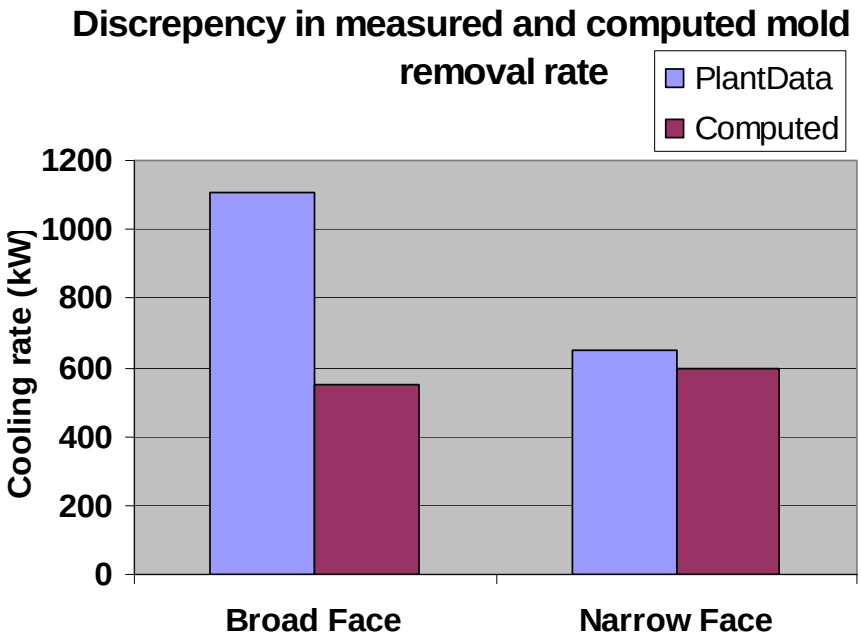


TmmFe (T.S.P. Kumar)

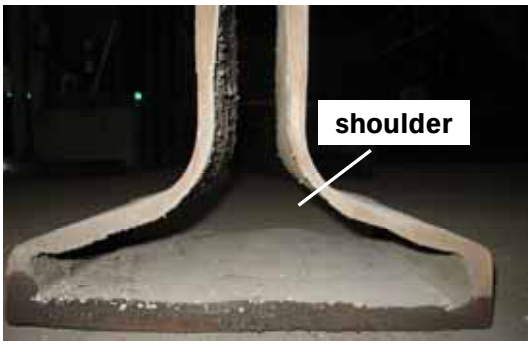
Heat Flux Variation along mold (NF)



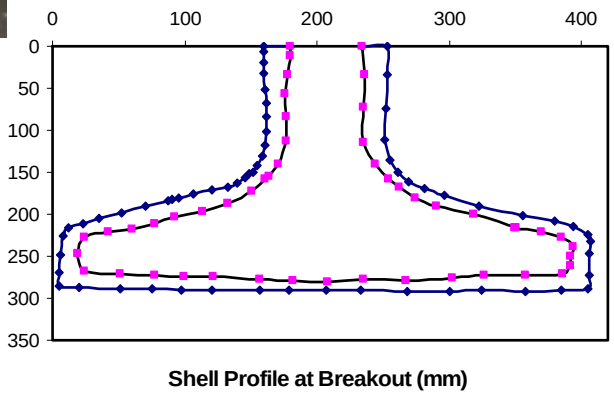
Heat balance calculation



Breakout Shell Measurements: Slow solidification near shoulder

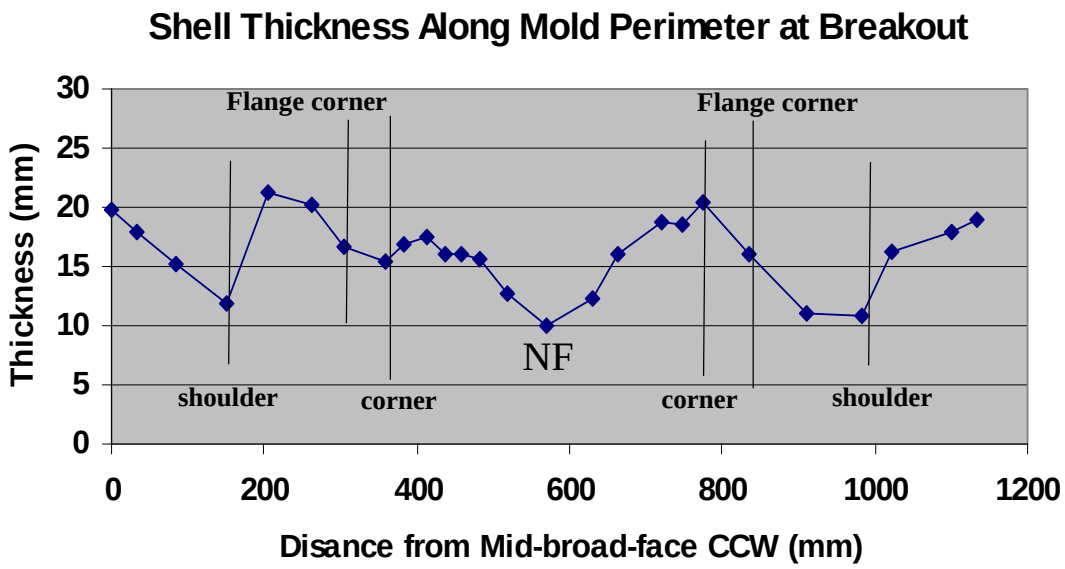


Thickness near the shoulder is smaller – air gap – low heat flux and temperature

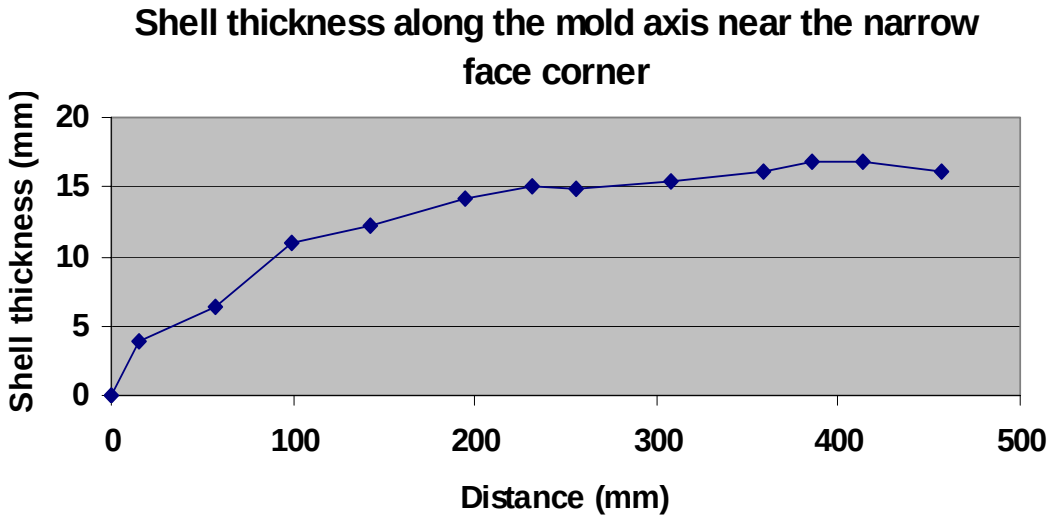


Shell Profile at Breakout (mm)

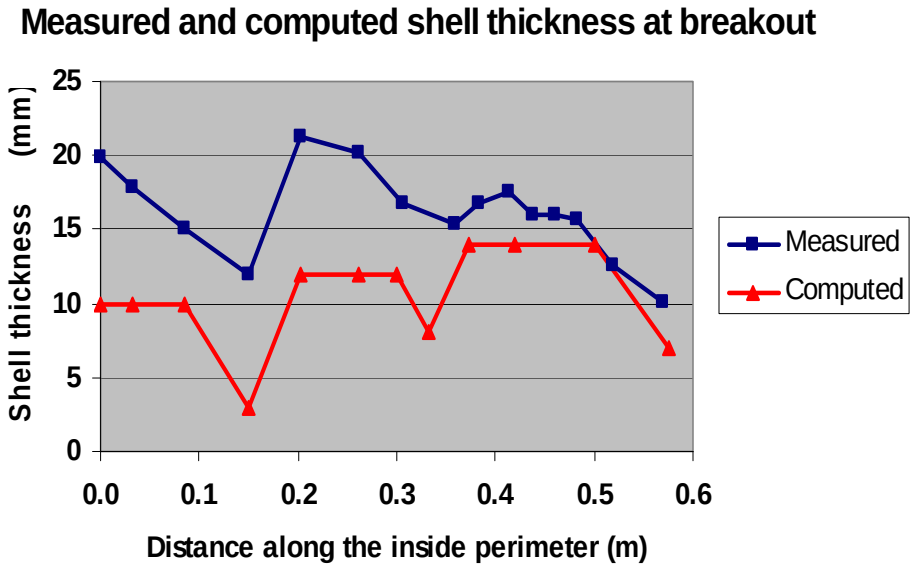
Shell thickness measurement across mold



Shell thickness measurement down mold



Shell thickness calculation



Note: mismatch on WF due to underprediction of heat flux there

How to explain the difference between experimental and numerical value of total heat loss?

1. The accuracy of measure temperature is 0.5 F. Compared with the total water temperature rise 5F (wide face) and 9F (narrow face), the measured error of water temperature can be 5~10%.
2. After the mold heat ups, thermal expansion likely creates a small air gap between the mold and the thermocouples. This can cause a thermal resistance and a lower temperature at the thermocouple, relative to the adjacent copper wall that is being modeled. It appears that ~10^{o}C temperature drop would explain the mismatch with the total heat loss.
3. For thermocouple near B, extra heat is likely lost by transmission of water around the TC which passes through the small hole. Thus, this TC is likely to experience a larger temperature drop than the others.

Conclusions

- Coupled heat flux optimization calculation of ABAQUS / DOT or TmmFe can obtain the heat flux distribution to match measured mold temperatures
- Integration of heat flux curves are currently less than the total heat loss from the cooling water heat balance (37.6% error)
- Trends in heat flux, shell thickness and model calculations all agree: lower heat flux and shell thinning at: the shoulder region, flange off-corner and narrow face center
- The thermal resistance from the air gap between the thermocouple and mold needs to be considered in next modeling to match the total heat loss more closely
- It is recommended that future mold TC measurements use thermal paste to minimize the resistances

Acknowledgements

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J. Dantzig, Design Optimization Tool

Continuous Casting Consortium

Thank you for attendance!