MechSE

Continuous Casting Consortium

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Fluid Flow and Heat Transfer in the Beam Blank Mold

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Objectives

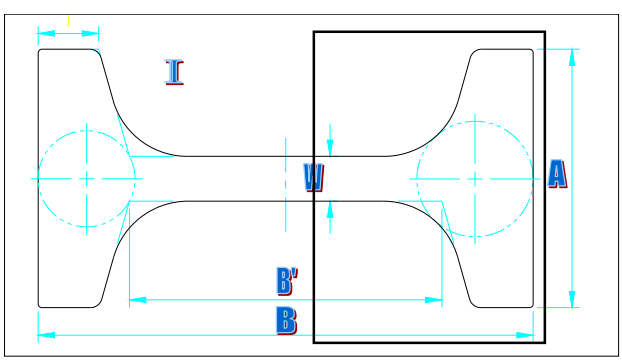
- Find out
  - the molten steel flow pattern in the Beam Blank mold taking into account the momentum and mass sinks at shell
  - heat transfer in the mold taking into account the heat sink at shell
  - the heat flux across the shell
- Perform thermal-mechanical analysis on the beam blank caster
- Find out how to incorporate the effects of heat transfer in the liquid pool into simulations of solidification in the mushy and solid regions

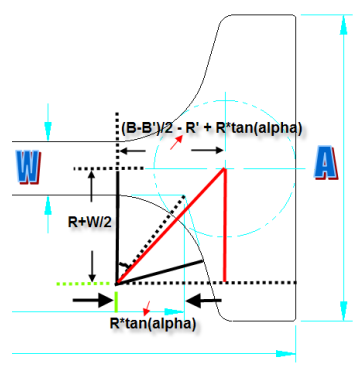
Model Assumptions

- Meniscus is flat and the no-slip wall boundary condition is applied
- No air is involved at the velocity inlet, and the velocity at the inlet keeps constant during the casting process
- The k-epsilon model is employed for turbulence
- No slag layer is involved in the computation
- The backflow at pressure outlet is carrying the liquidus temperature
- The fluid flow and heat transfer in this case are supposed to reach a final steady state

Mold Geometry

dimensions taken at mold top





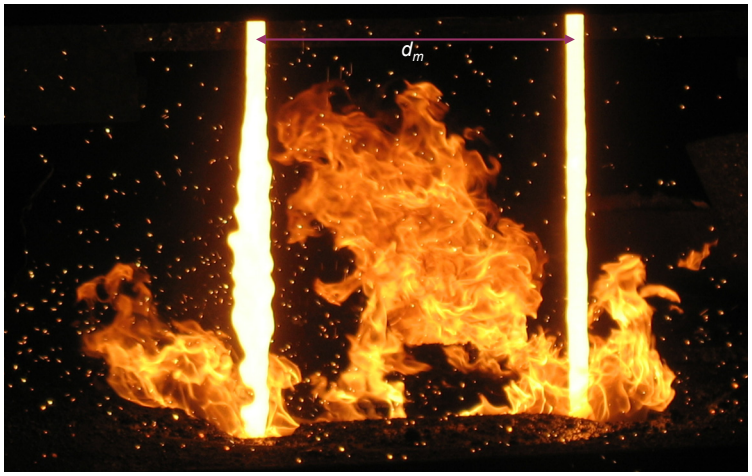
Mold Width (m)	*B*	0.576
Mold thickness (m)	*A*	0.436
Mold Web Thickness (m)	*W*	0.093
Inside width (m)	*B'*	0.323
Mold Length (m)	*H*	0.667

$$\left(\frac{(B-B')}{2} - R' + R\cdot\tan(\alpha)\right)^2 + \left(R+\frac{W}{2}\right)^2 = (R+R')^2$$

$$R' = \left[\frac{\left(R+\frac{W}{2}\right)^2}{R(1+\tan\alpha)+\frac{(B-B')}{2}}\right] + \frac{(B-B')}{2} + R(\tan\alpha - 1)$$

$$= 68.2mm$$

Scaling of inlet Diameter/Area



$$d_m / d_e = dia_m / dia_e$$
$$d_m = 82mm$$
$$d_e = B - 2R' = 418.6mm$$
$$dia_m = 5mm$$
$$dia_e = dia_m d_e / d_m = 25.5mm$$

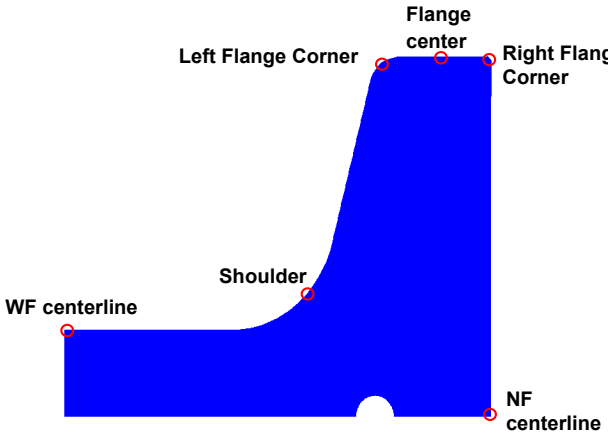
***d_m*: the measured distance between the two stream centers**

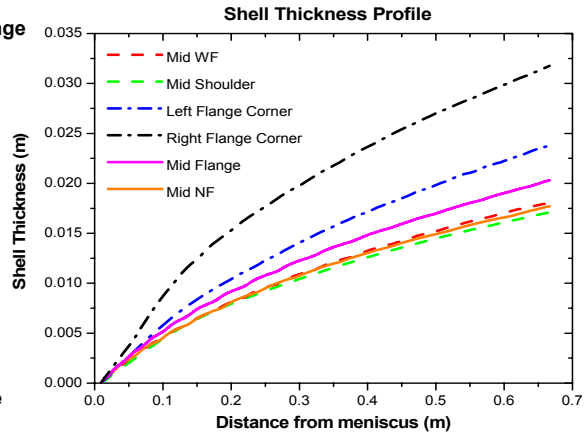
***dia_m*: measured stream diameter**

***dia_e* and *d_e* represents the exact lengths of the above parameters**

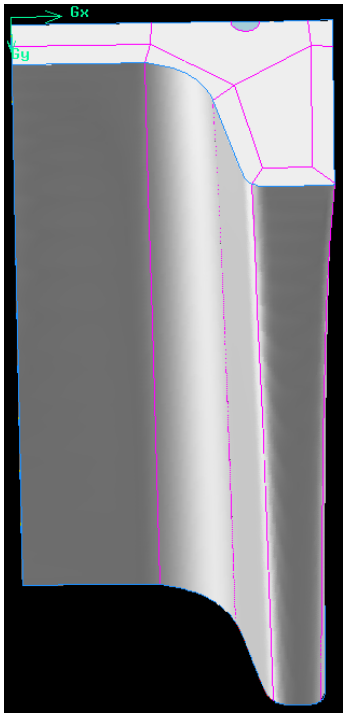
Critical locations along shell perimeter

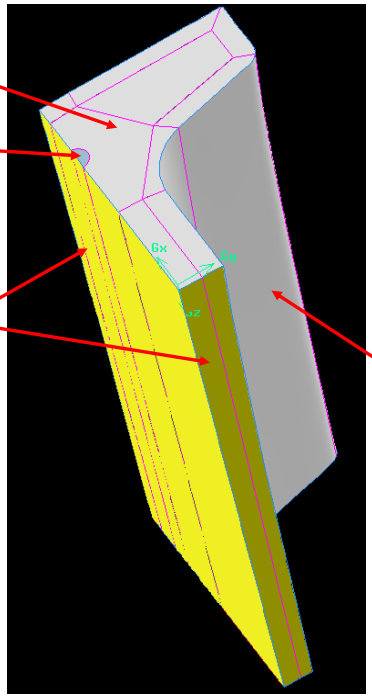
Six points are chosen along the shell perimeter



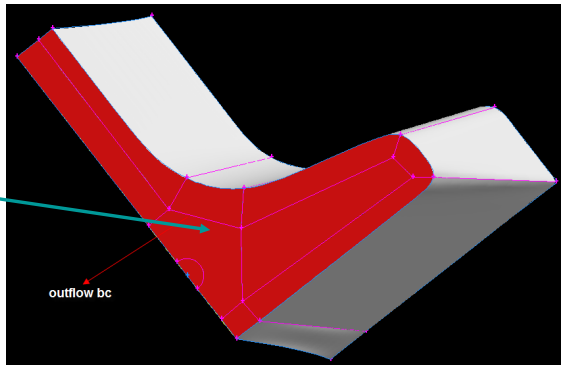


Computational Domain



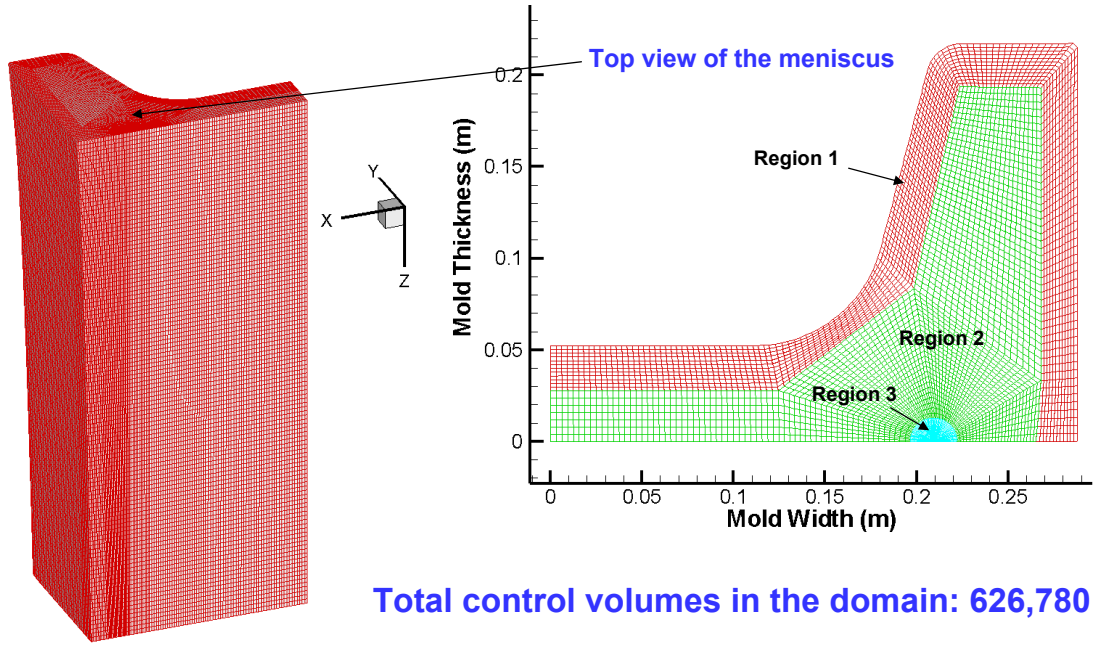


Boundary Conditions



Boundary Name	Boundary condition
shell interface	moving wall
outlet	Pressure outlet
inlet	Velocity inlet
meniscus	No-slip wall
Sym. Plane	Symmetry plane

Domain Mesh



Total control volumes in the domain: 626,780

structured mesh, with hexahedral elements

Input parameters

Density	(kg/m^3)	ρ	6800
Kinetic Viscosity	(m^2/s)	v	0.006
Inlet Velocity	(m/s)	v_{in}	1.854
Turbulence intensity at inlet	(%)	I	200
Inlet kinetic energy	(kg*m^2/s^2)	k	0.464
Inlet dissipation rate	(m^2/s^3)	ε	2.077
Area of inlet flow	(m^2)	A_{in}	2.56×10^{-4}
Area of outflow	(m^2)	A_l	0.0215
Area of top surface	(m^2)	A_m	0.032
Liquidus temperature	(K)	$T_{liquidus}$	1770
Pouring temperature	(K)	T_{in}	1800
Specific heat of steel	(J/(kg*K))	C_p	687
Casting Speed	(m/s)	v_C	0.0148

Validation of Mass Sink at Shell

Mass balance from simulation

Mass Flow Rate	(kg/s)
Outflow	-2.1660
Inlet	3.2228
Net	1.0568

Mass absorbed rate by the shell

(mass sink)

Mass balance from hand calculation

Area of meniscus (m^2)	A_m	0.032
Area of outflow (m^2) (for liquid steel)	A_l	0.0215
Casting speed (m/s)	v_c	0.0148

The area of solid steel at mold exit, A_s

$$A_s = A_m - A_l = 0.0105 m^2$$

The mass flow rate of solid steel at mold exit is

$$\rho \cdot V_C \cdot A_s = 1.0572 kg/s$$

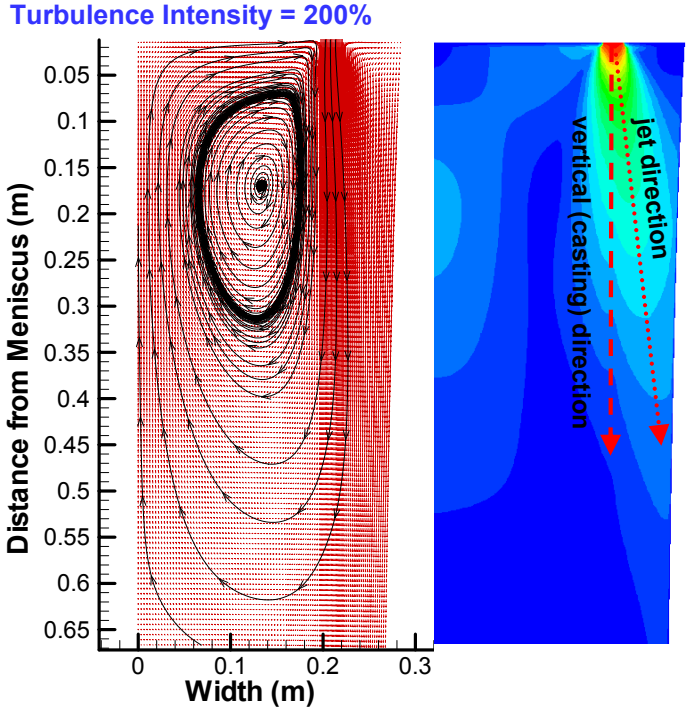
Difference between the hand calculation and simulation: 0.038 %

Conclusion:

numerical errors are reasonably small, so model is converged.

Flow Pattern in the Mold

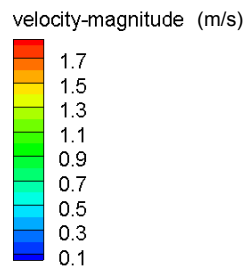
Turbulence Intensity = 200%



Jet leaning against the shell

(with an angle ~ 20 deg)

Single, strong recirculation zone formed



AT SYMMETRY PLANE

Heat Transfer – heat sink

The heat sink term is evaluated with the mass flow rate and temperature difference between the liquidus and the reference temperature

$$\dot{Q} = \dot{m} C_P \left(T_{liq} - T_{ref} \right) \qquad \dot{m} = v_{cast} \cdot \rho \cdot A_z$$

T_{ref}: Reference temperature, 298.15 K fixed by FLUENT

A_z : Control volume face area projection on the casting direction.

In order to validate the heat sink added in the model, two cases are needed:

- Computation using superheat temperatures

Let the liquidus temperature adopt the value of T_{ref}, so the heat sink term becomes 0. Superheat temperature is computed in the simulation.

- Computation using real temperatures

Let the liquidus temperature be the real liquidus temperature. The heat sink term is NOT 0.

Validation — using superheat

The heat transfer B.C.

Boundaries	BC Prescribed
Velocity Inlet	Fixed temperature, at 328.15 K
Shell Interface	Liquidus temperature, at 298.15 K
Pressure Outlet	Fixed backflow temperature, at 298.15 K
Symmetry Planes	Heat flux = 0.
Meniscus	Heat flux = 0.

Superheat temperature at velocity inlet: 30 K

Heat balance calculation from simulation

Heat Flow-in (kW)		Heat Flow-out (kW)	
Inlet	75.9	Outlet	19.5
		shell	56.3

(Heat Flow-in) – (Heat Flow-out) : 0.1 kW

Heat extracted by shell in mold: 56.3/75.9 = 74.2%

Total heat transfer is balanced in this model with the error of 0.1%.

Validation — using real temperature

The heat transfer B.C.

Boundaries	BC Prescribed
Velocity Inlet	Fixed temperature, at 1800 K
Shell Interface	Liquidus temperature, at 1770 K
Pressure Outlet	Fixed backflow temperature, at 1770 K
Symmetry Planes	Heat flux = 0.
Meniscus	Heat flux = 0.

Superheat temperature at velocity inlet: 30 K

Heat balance calculation from simulation

Heat Flow-in (kW)		Heat Flow-out (kW)	
Inlet	3335.2	Outlet	2209.6
		shell	56.2

(Heat Flow-in) – (Heat Flow-out):

1068.5 kW

Heat taken away by the sink (read from the UDF results):

1084.3 kW

Total heat transfer is balanced in this model with the error of 0.4%.

Validation — case comparison

Compare the results from computations using both superheat and real temperatures, the difference should be

$$\Delta\dot{Q} = \dot{m}C_P\left(T_{liquidus} - T_{reference}\right)$$

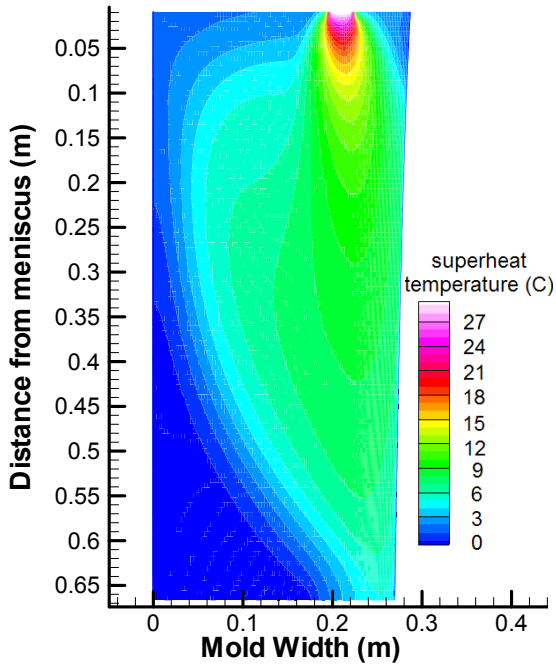
Boundary	$Q_{superheat}$	dQ (kW)	dQ + $Q_{superheat}$ (kW)	$Q_{real\_temperature}$ (kW)
inlet	75.9	3259.0	3334.9	3335.2
Outlet	19.5	2190.1	2209.6	2209.6
shell	56.3	0.0	56.3	56.2

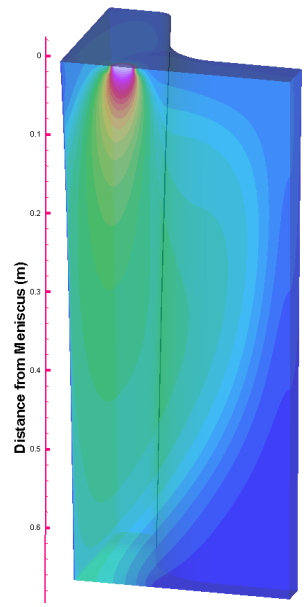
($Q_{superheat}$ + dQ) matches the value of $Q_{real\_temerature}$

So the heat sink term added in the real temperature computation is validated.

Temperature distribution

superheat temperature distribution at symmetry plane

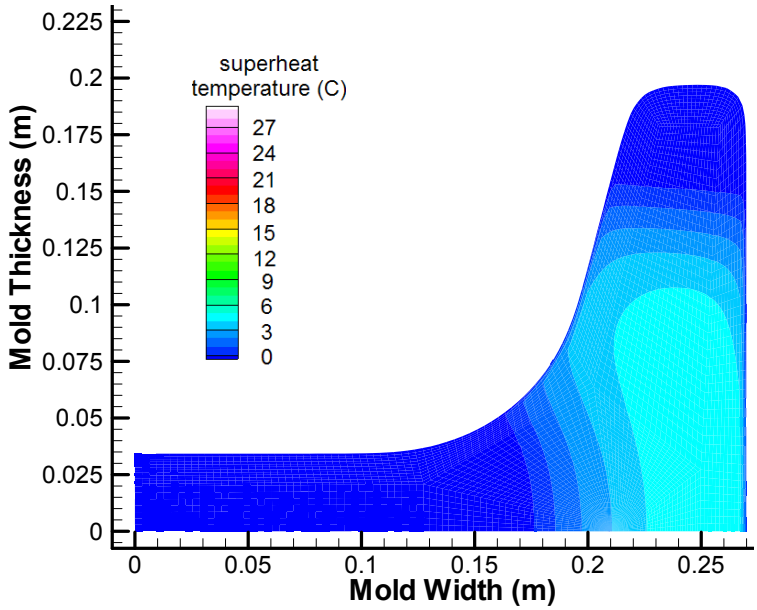




Symmetry Plane

Temperature distribution

superheat temperature distribution at outflow, z = 0.667 *m* below meniscus

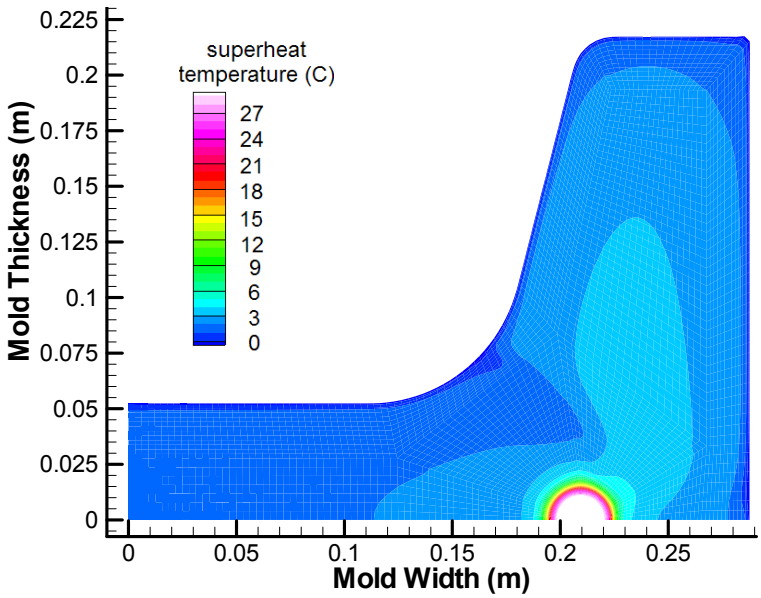


--outflow region

667 *mm* below meniscus

Temperature distribution

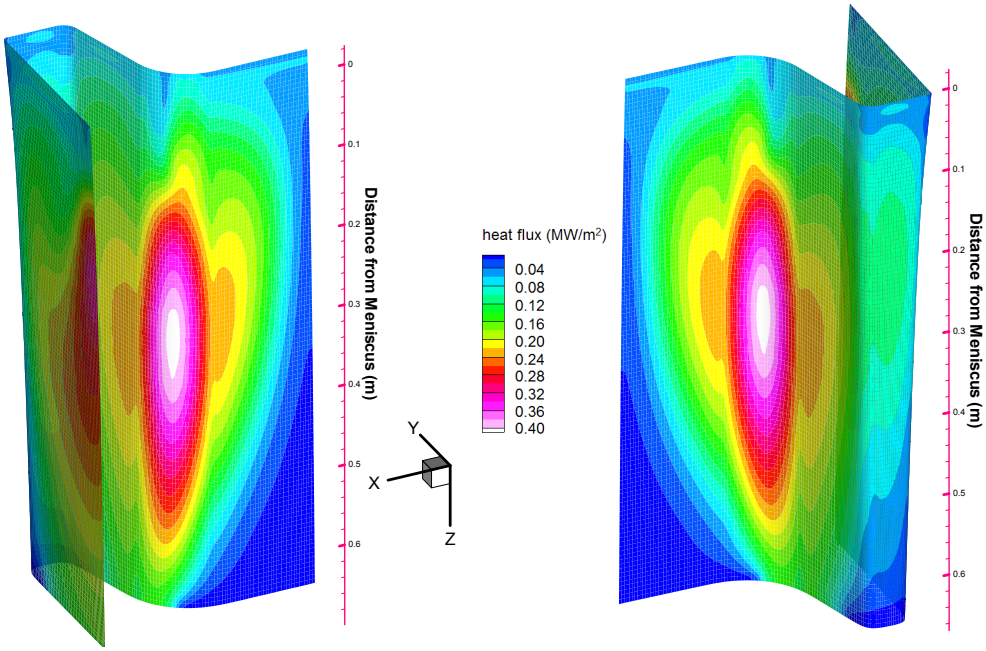
superheat distribution at z = 0.009 *m* below meniscus



9 *mm* below meniscus

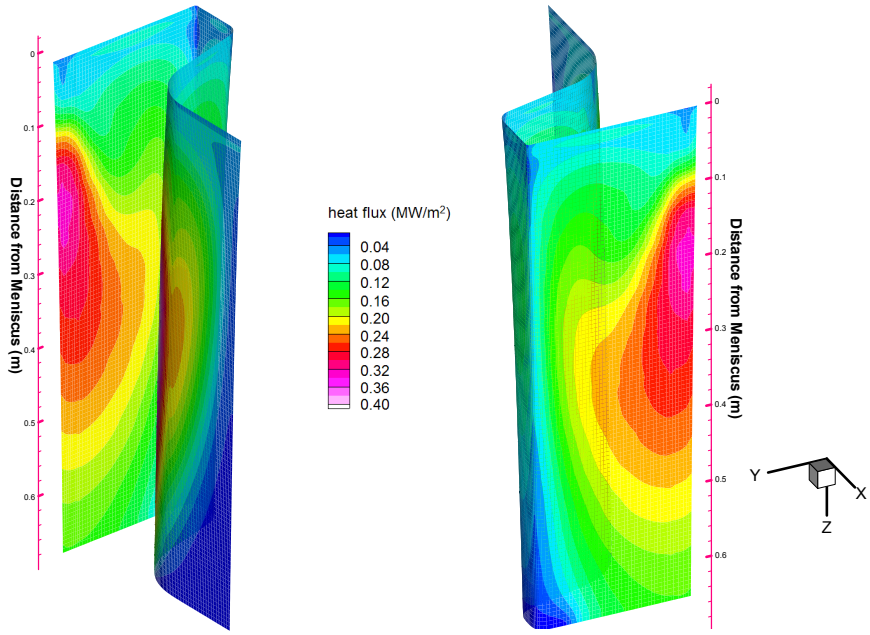
Heat flux distribution at Shell

Heat flux distribution on the shell interface – 3D view



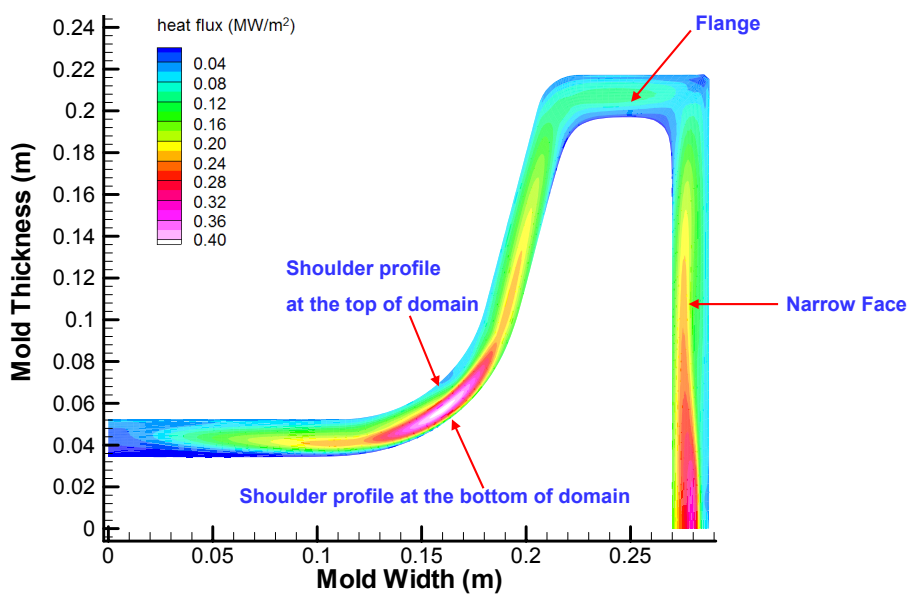
Heat flux distribution at Shell

Heat flux distribution on the shell interface – 3D view



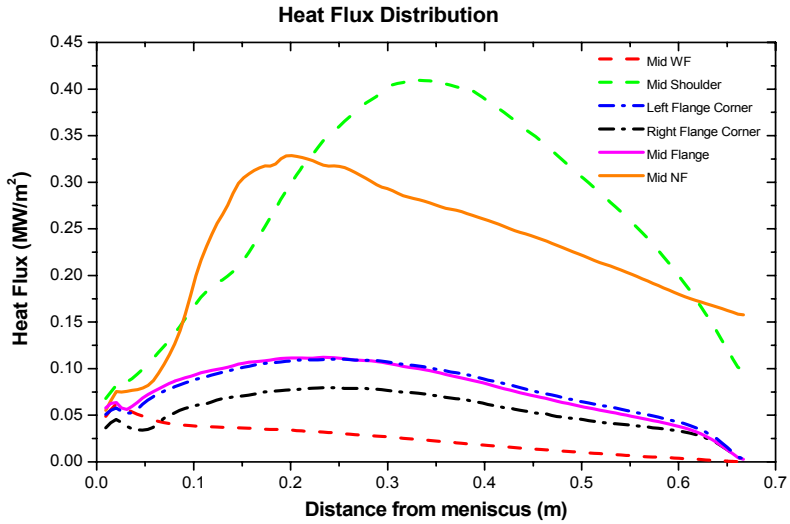
Heat flux at Shell – top view

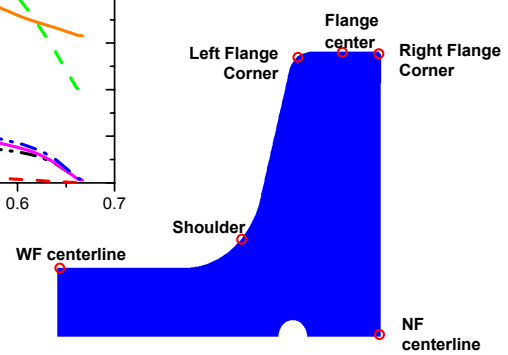
Heat flux distribution on the shell interface –-- top view



Heat flux along casting direction

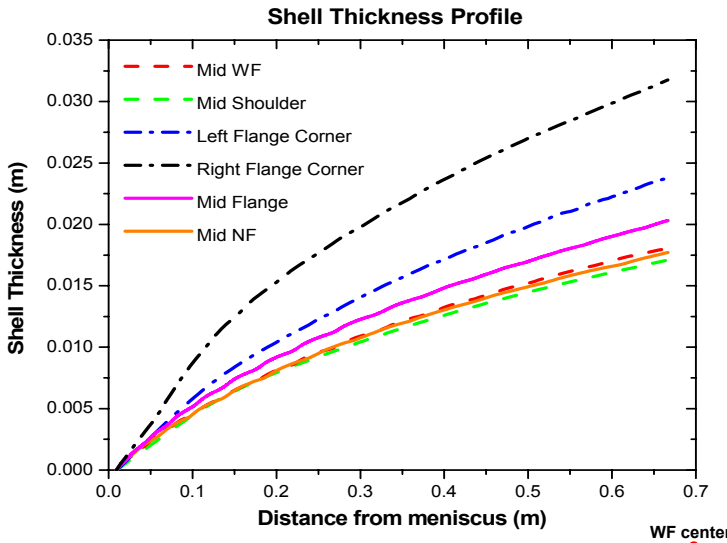
Heat flux distribution on the shell interface along the longitude direction

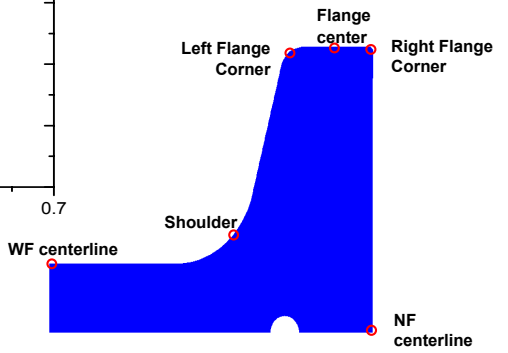




Shell Thickness profile

Shell thickness profile for the six points along the shell perimeter





Thermal-mechanical analysis

Equations to solve:

Energy:

$$\rho\left(\frac{\partial H(T)}{\partial T}\right)\left(\frac{\partial T}{\partial t}\right)=\frac{\partial}{\partial x}\left(k(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)$$

Equilibrium: $\nabla\cdot\boldsymbol{\sigma}(\mathbf{x})+\mathbf{b_o}=\rho\ddot{\mathbf{u}}$

Strain Decomposition: $\dot{\boldsymbol{\varepsilon}}=\dot{\boldsymbol{\varepsilon}}_{el}+\dot{\boldsymbol{\varepsilon}}_{ie}+\dot{\boldsymbol{\varepsilon}}_{th}$

Two-way thermal-mechanical coupling:

Mechanical Solution depends on temperature filed through thermal strains

$$\{\varepsilon_{th}\}=\left(\alpha(T)\left(T-T_{ref}\right)-\alpha(T_i)\left(T_i-T_{ref}\right)\right)[111000]^T$$

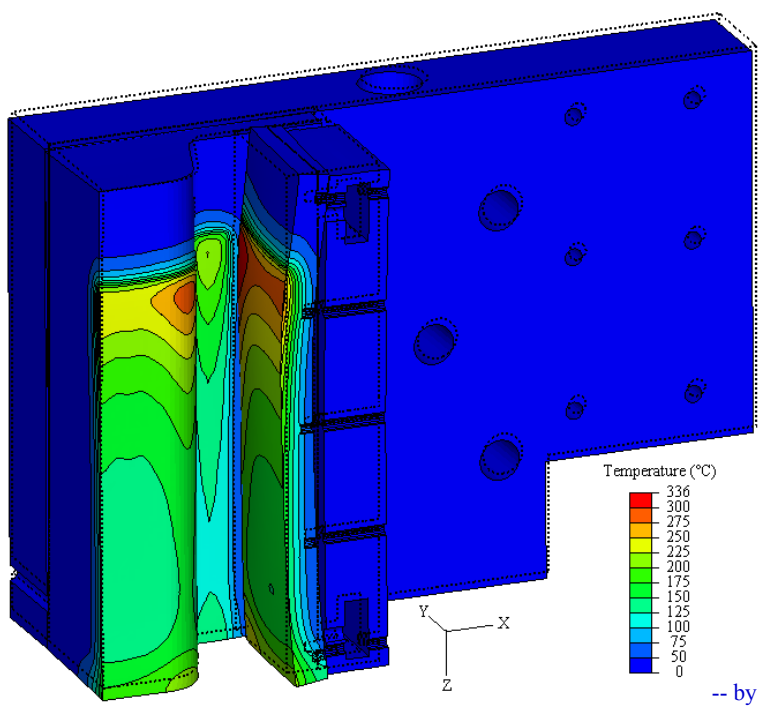
The gap heat coefficient h_g depends on the gap distance d calculated from mechanical solution

$$h_g=h_o \qquad d\le d_0$$

$$h_g=\frac{1}{\frac{d}{k_{air}}+R_c}+h_{rad} \qquad d_0<d$$

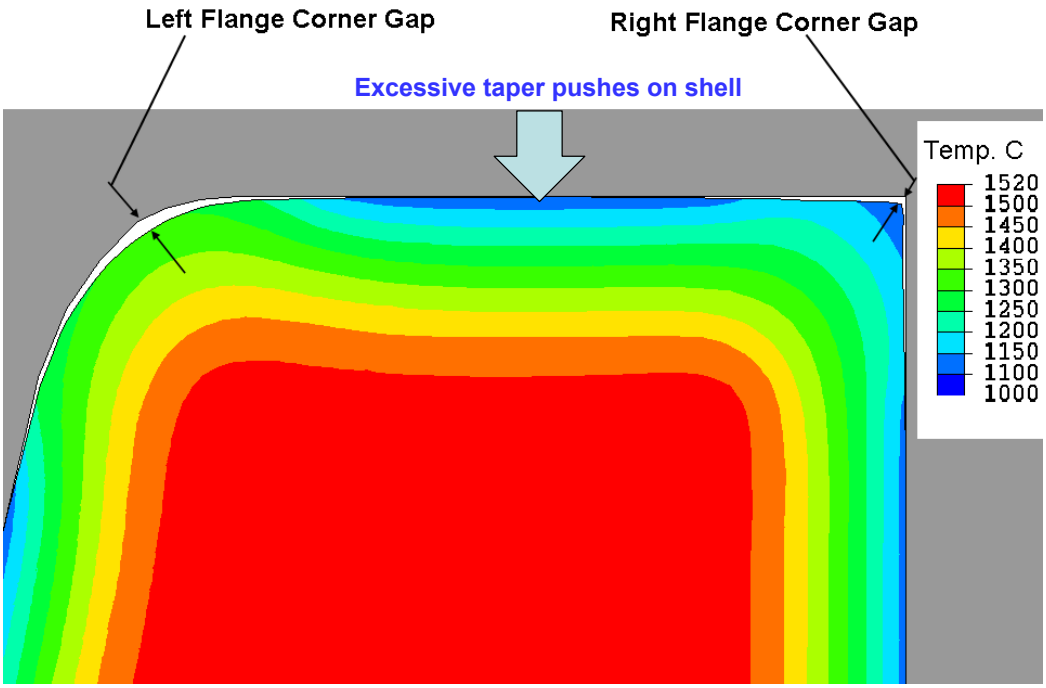
Ref:
S. Koric and B.G. Thomas. International Journal for Num. Methods in Eng. Vol. 66 1955-1989, 2006

Thermal distortion of Mold



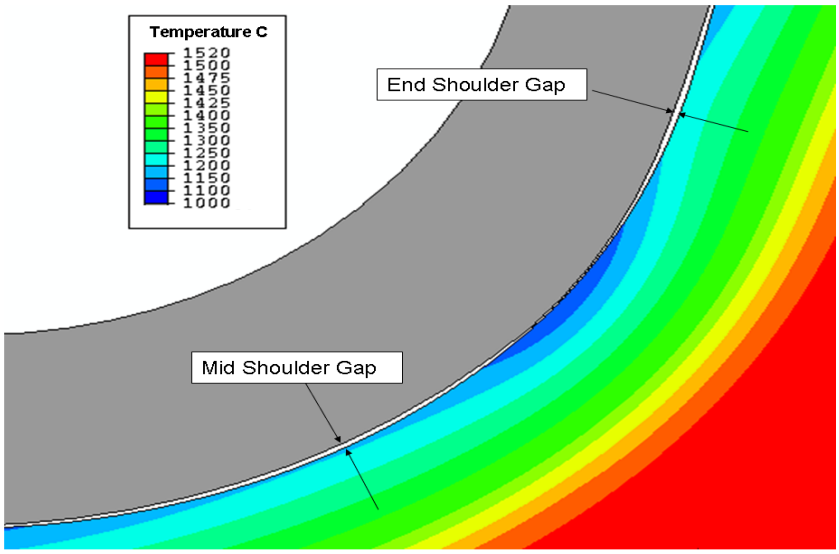
-- by L. Hibbeler, 2008

Shell Solidification and Shrinkage

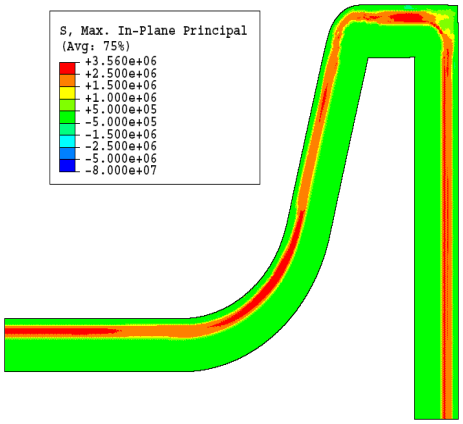


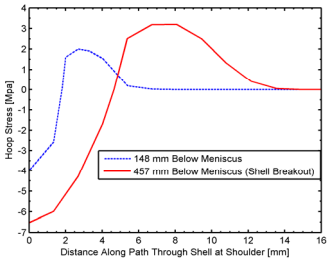
Shoulder Shell Temperature Contour 457 mm down the mold

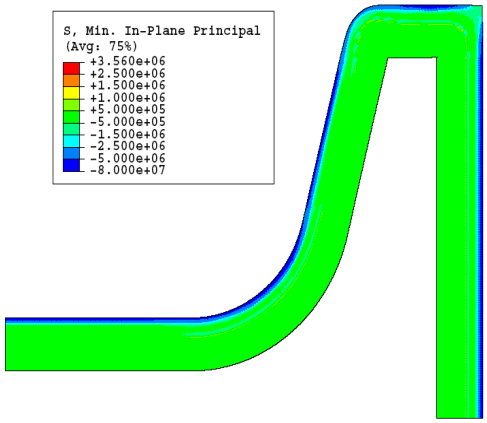
Hot shell pushed down by mid flange is bending and opening gaps at the shoulder region



Principal Stresses 457 mm Below Meniscus

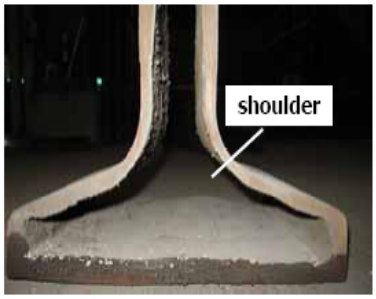


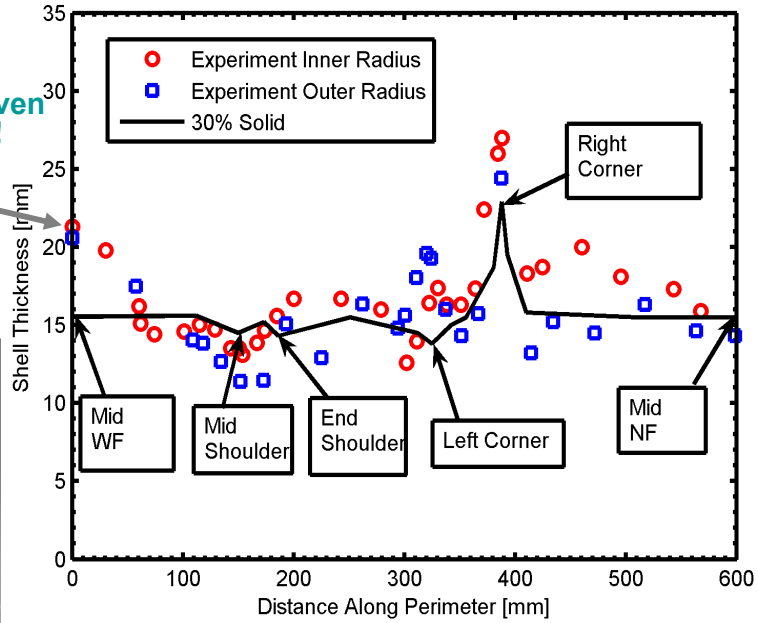




Breakout Shell Thickness Comparison Between Model and Plant Data

Mismatch here due to uneven superheat distribution !





Enhanced Latent Heat method

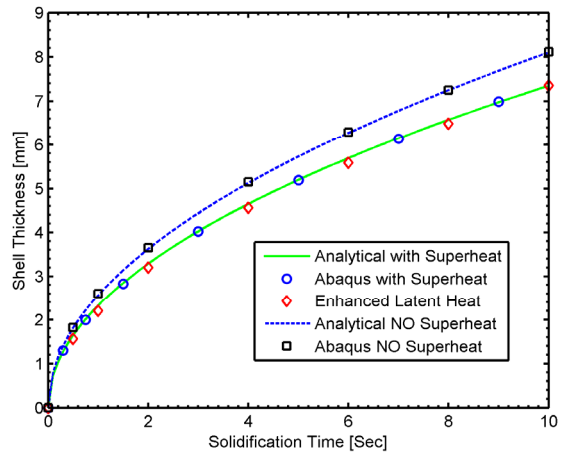
Apply additional latent heat to account for superheat flux delivered from liquid pool calculated

$$\Delta H_f = \frac{q''_{\text{super}}}{\rho_s \, v}$$

instantaneous velocity *v*, estimated from analytical or numerical solutions

Validation Case:

Shell thickness history



Conclusions

- **The stream of liquid metal entering the Beam Blank mold forms a single jet in the liquid bulk, and the jet generates a single recirculation zone in this half-mold**
- **The superheat decreases along the jet, and dissipates quickly with the jet penetrating the fluid surrounded**
- **The shell extracts around 74% of the total heat flowing in the mold**
- **The maximum heat flux occurs at the shoulder, around 0.3 *m* below meniscus**

Conclusions

- A new enhanced latent heat algorithm for treatment of superheat fluxes on moving solidification interface is developed and verified
- The focus of future work is to include superheat distribution from fluid flow/heat transfer computation into the coupled thermo-mechanical models for the Beam Blank mold

Acknowledgments

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- National Center for Supercomputing Applications
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