Investigation of ideal taper in billet molds to avoid in-mold and sub-mold cracks using 2D FEM thermal stress model

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Objective

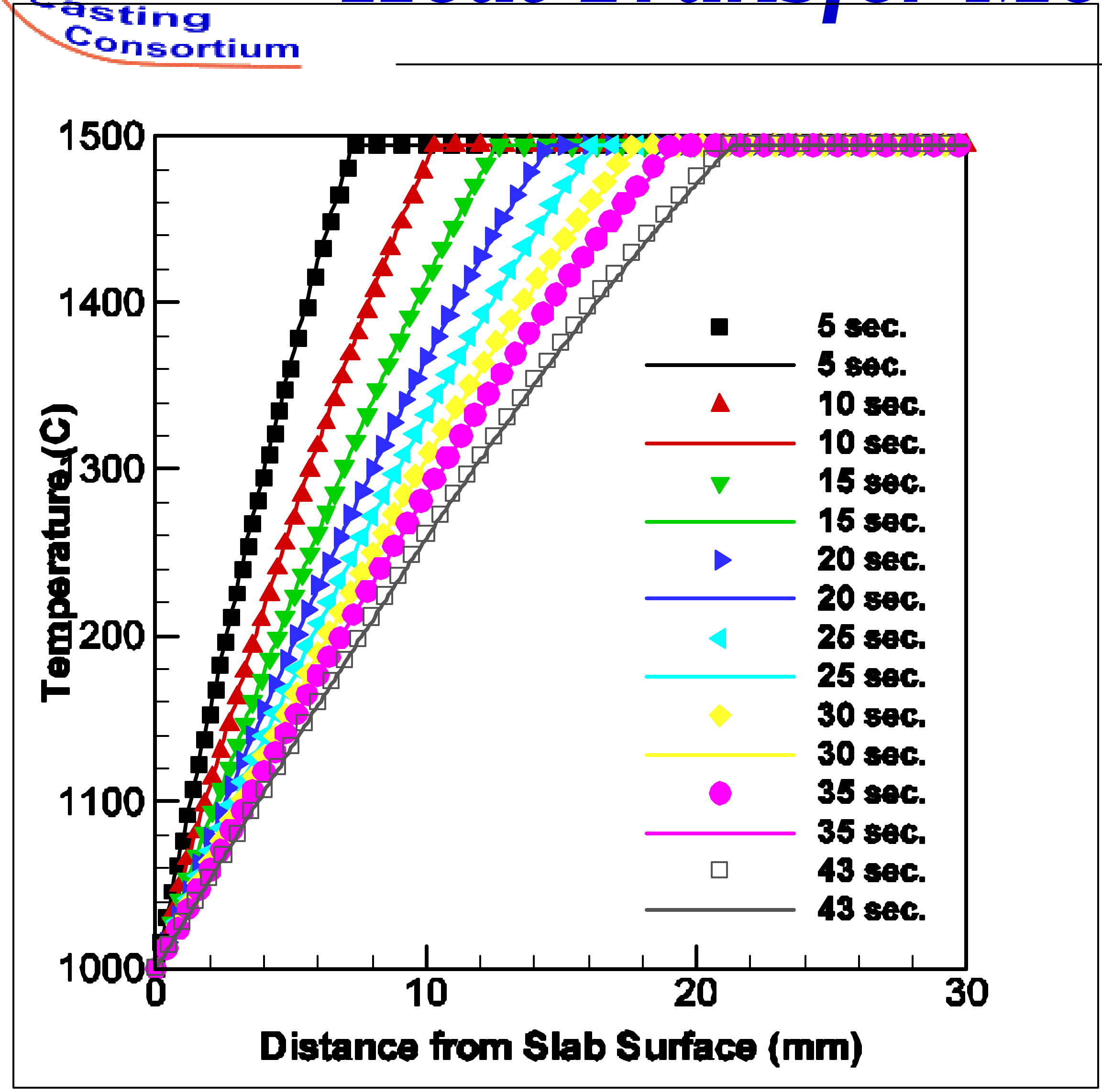
- *Investigate the optimal mold wall profile to avoid in-mold or sub-mold cracks for billet casters without sub-mold support.*
- *Predict the ideal taper profiles for billet casters as a function of casting speed, heat flux, mold distortion, and mold length using slice domain simulation.*
- *Study the corner effects to the ideal taper profiles predicted by slice domain simulation.*

Model Descriptions

- *Finite element thermal stress model*
- *Phase fractions from non-equilibrium Fe-C phase diagram for plain carbon steel*
- *Recalescence and kinetics neglected*
- *Efficient contact algorithm to simulate the interaction between mold wall and shell surface.*
- *Fully coupled thermal-stress simulation to capture the thermal and mechanical behavior of the interfacial layer in reality.*
- *2-D generalized plane strain*

$$\dot{e}_{total} = \dot{e}_{elastic} + \dot{e}_{plastic/creep} + \dot{e}_{thermal} + \dot{e}_{flow}$$

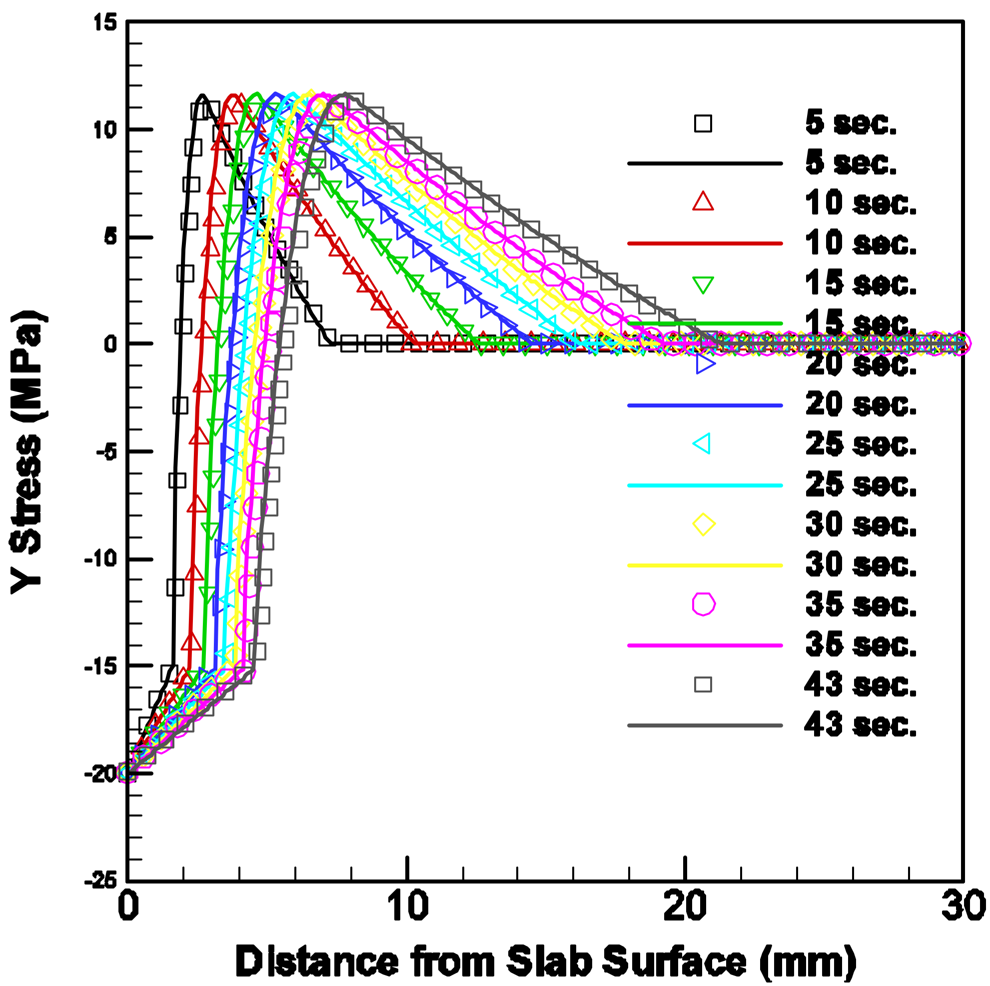
Heat Transfer Model Validation



- *Lines: Boley & Weiner's analytical solution**
- *Symbols: CON2D computation results*

** J. H. Weiner and B. A. Boley, J. Mech. Phys. Solids, 1963, Vol. 11, pp145-154*

Stress Model Validation



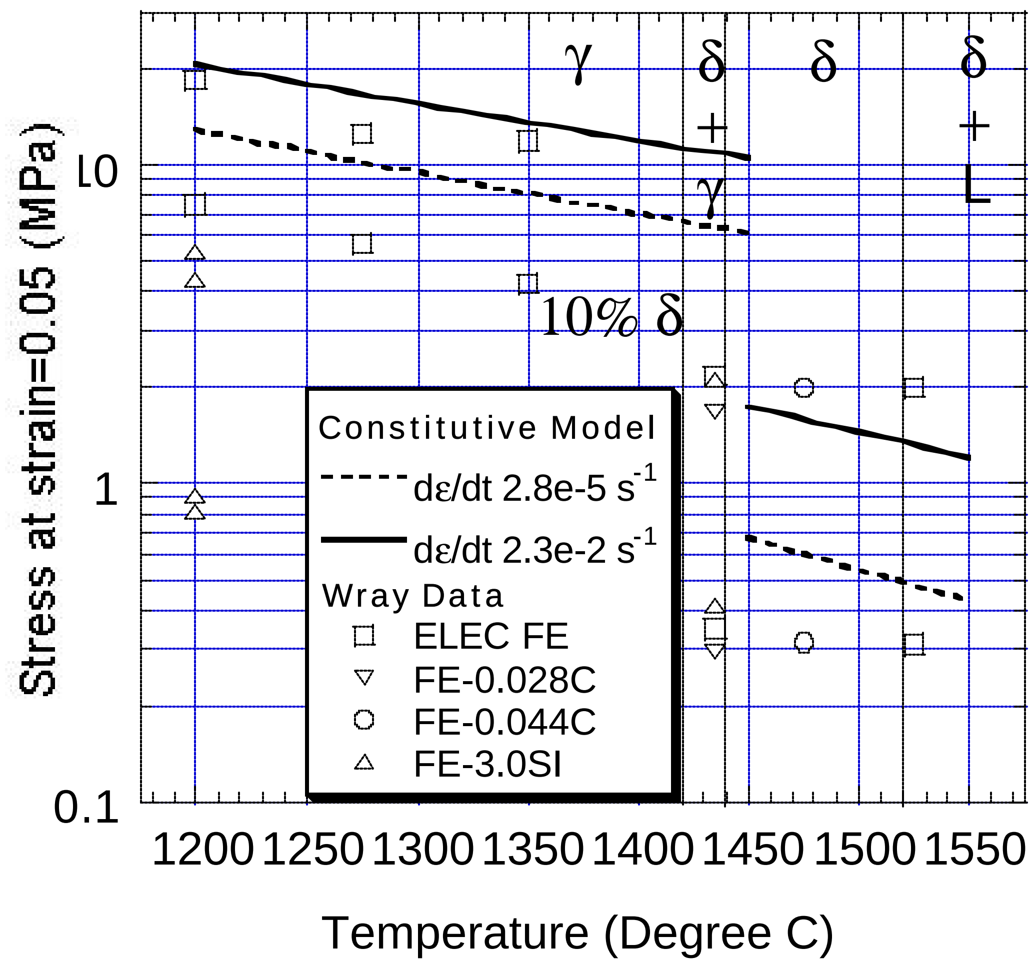
- *Lines: Boley & Weiner's analytical solution**
- *Symbols: CON2D computation results*

** J. H. Weiner and B. A. Boley, J. Mech. Phys. Solids, 1963, Vol. 11, pp145-154*

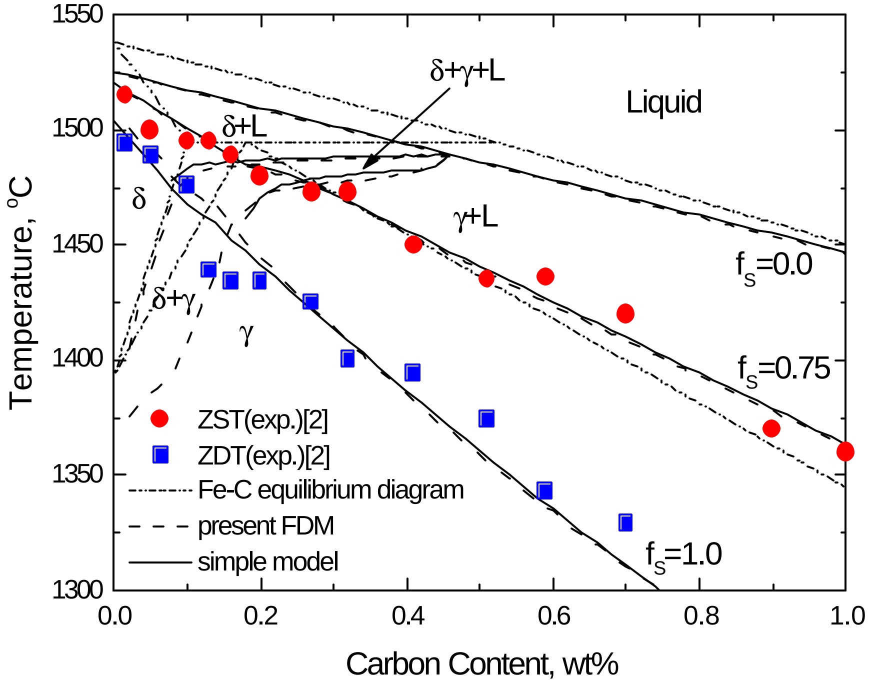
Steel Properties Assumed

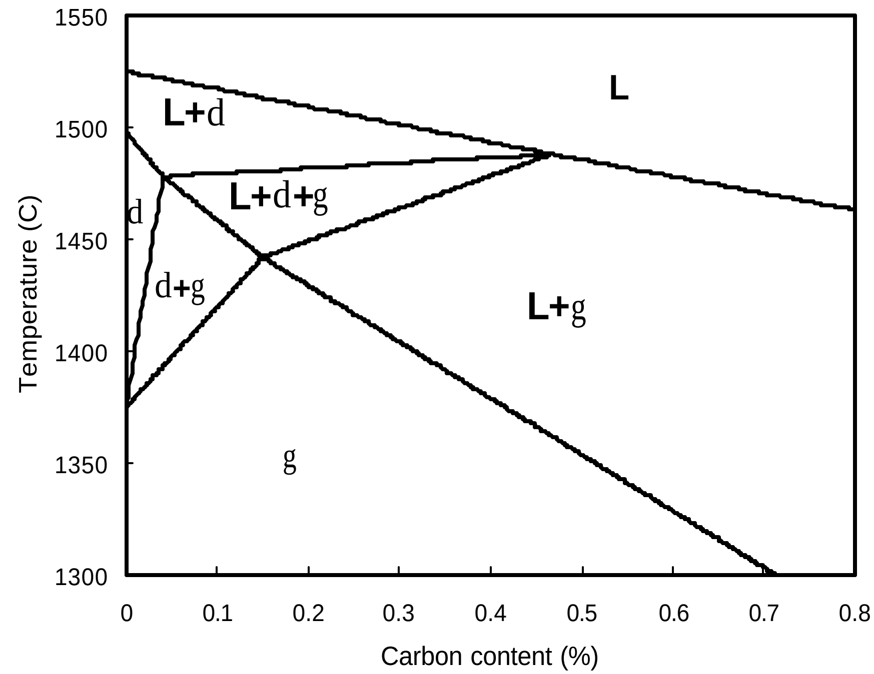
- *Mizukami elastic modulus data*
- *Temperature dependent conductivity, enthalpy and thermal linear expansion.*
- *Super creep model for liquid elements to treat them as solid without generating unphysical stress in liquid.*
- *Kozlowski constitutional equations for austenite, and modified model for delta-ferrite:*
  - *Kozlowski Model for Austenite*
  - *Modified Power Law Model for d-ferrite*

Constitutive Model



Non-equilibrium phase diagram of plain carbon steels** used in CON2D*

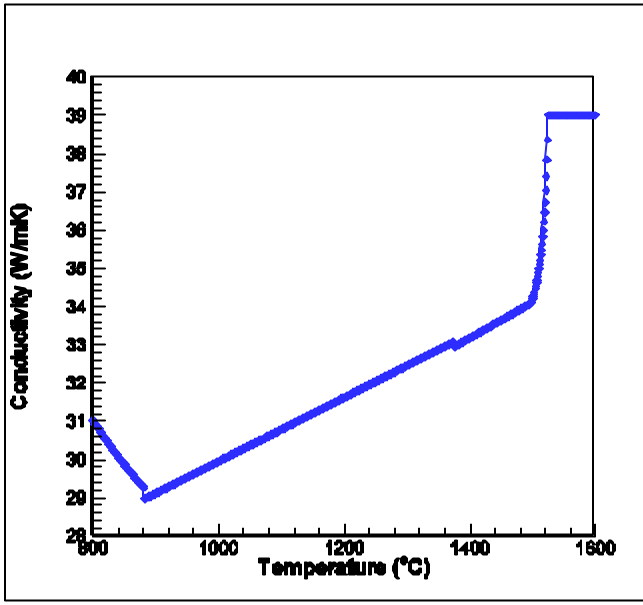




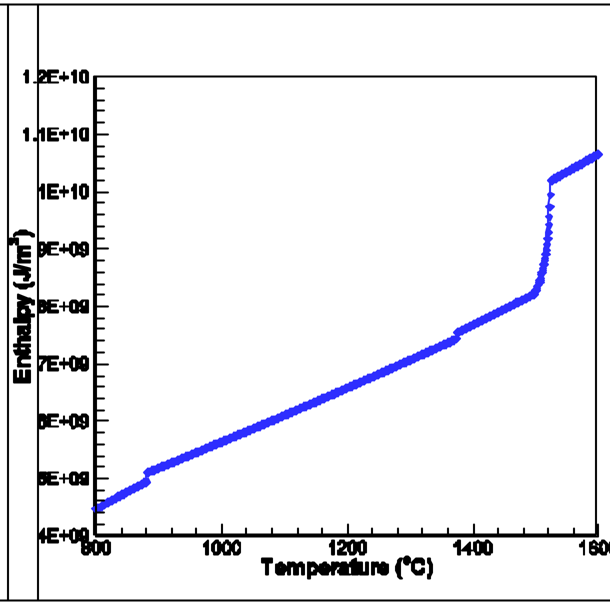
- *Young Mok WON et. al., Effect of Cooling Rate on ZST, LIT, ZDT of Carbon Steels Near Melting Point", ISIJ International, Vol. 38, 1998, No. 10, pp. 1093 –1099
- **Other Steel Components: 1.52%Mn, 0.34%Si, 0.015%S, 0.012%P

Properties

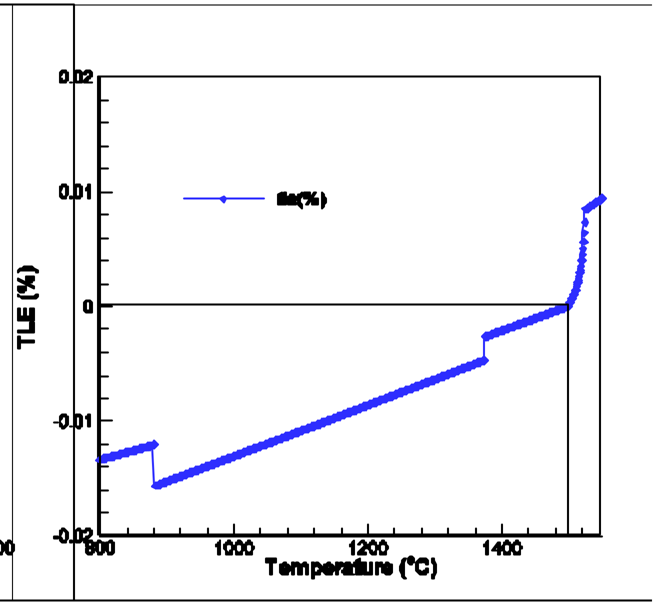
Conductivity



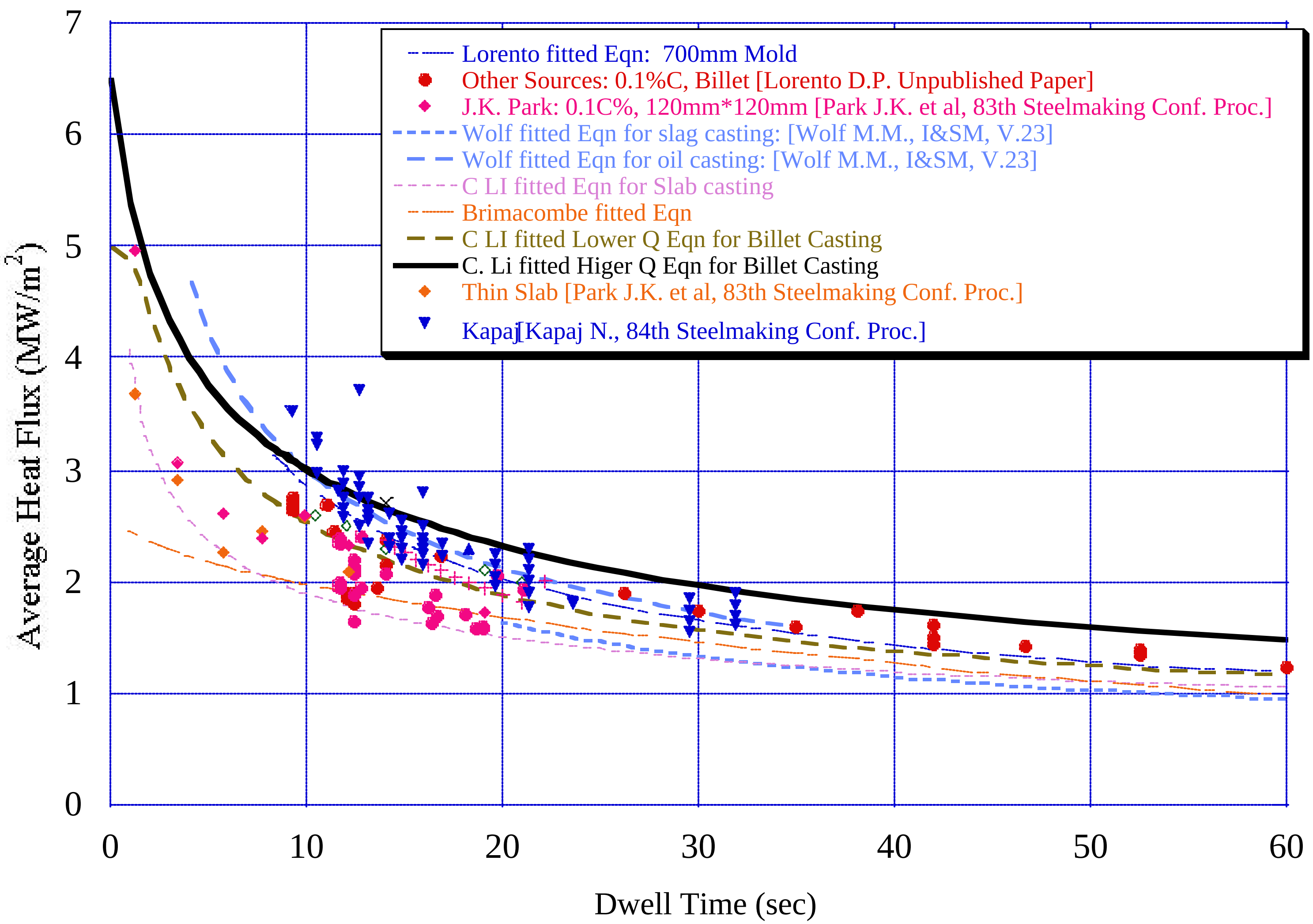
Enthalpy



TLE



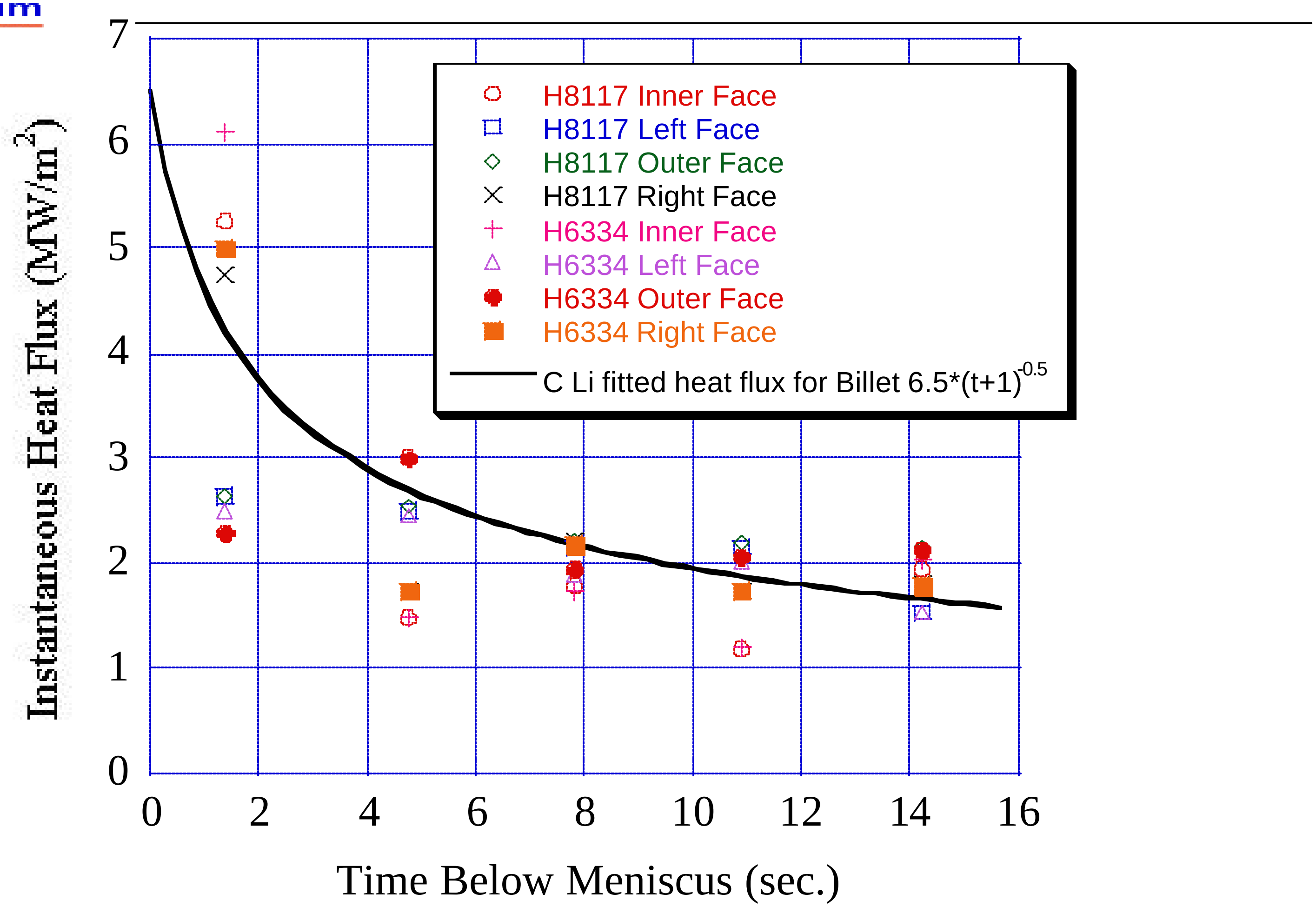
Mold Heat Flux



Mold Heat Flux Data

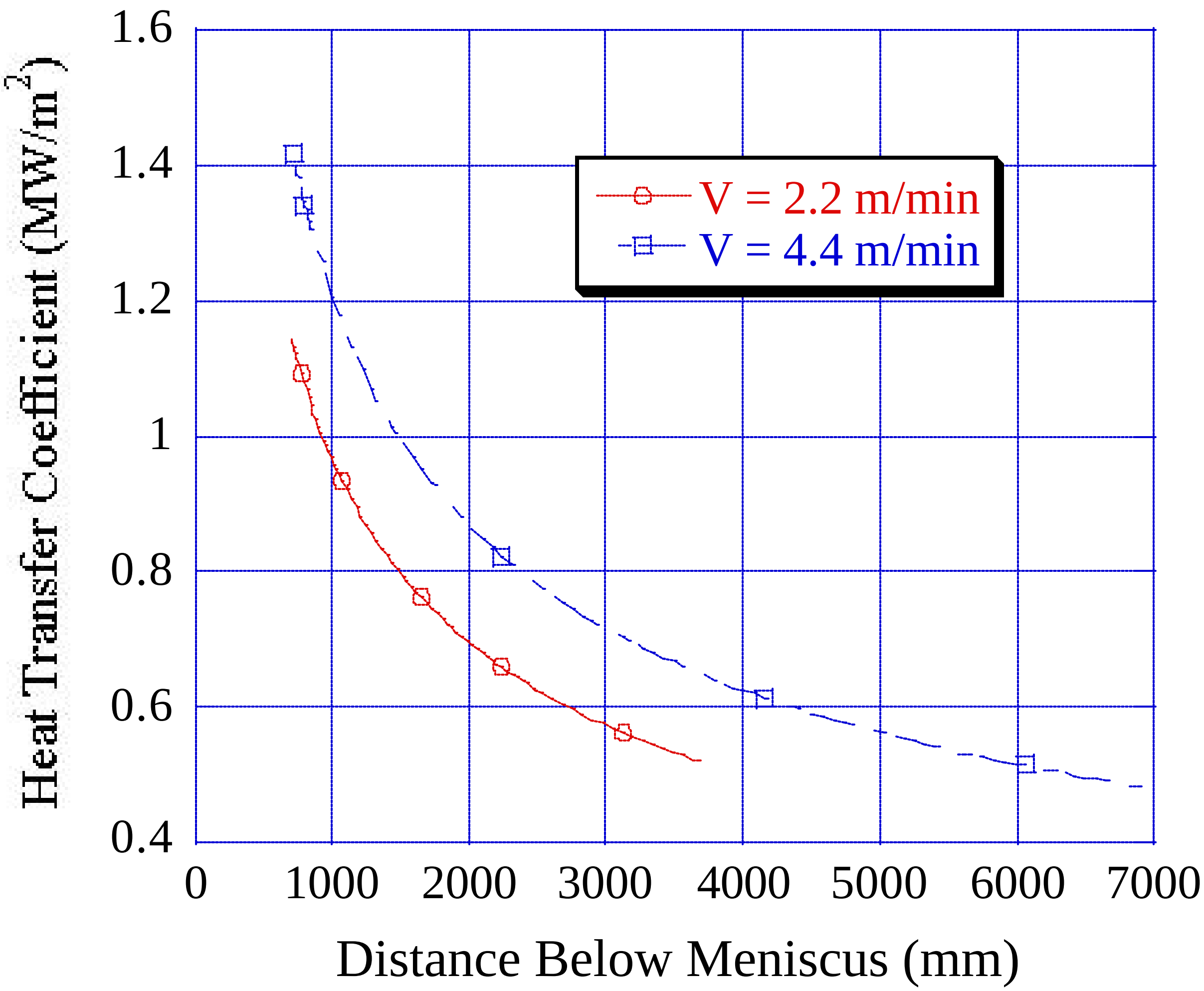
	Instantaneous Heat Flux (MW/m^2)	Averaged Heat Flux (MW/m^2)
Wolf Eqn for Slag Casting		$7.3t(s)^{-0.5}$
Wolf Eqn for Oil Casting		$9.5t(s)^{-0.5}$
Brimacombe		$2.68-0.222t(s)^{0.5}$
C. Li Eqn for Slab Casting		$4.05t(s)^{-0.33}$
C. Li Lower Q Eqn for Billet	$5-0.2444t(s)$, $t<1$ $4.7556t(s)^{-0.504}$, $t>=1$	$9.5779t(s)^{-0.504}-4.625t(s)^{-1}$
C. Li higher Q Eqn for Billet	$6.5(t(s)+1)^{-0.5}$	$13t(s)^{-1}((t(s)+1)^{0.5}-1)$
Lorento		$1.4V_c(m/min)^{0.5}$

Instantaneous Heat Flux Assumed



*Instantaneous data is from: I.V. Samarasekera et. al., *"High Speed Casting of High Quality Billets"*, Strategic Project Report, Sep. 1998

Spray Water Heat Convection Coefficient Assumed



Coefficient calculated from Nozaki Model:

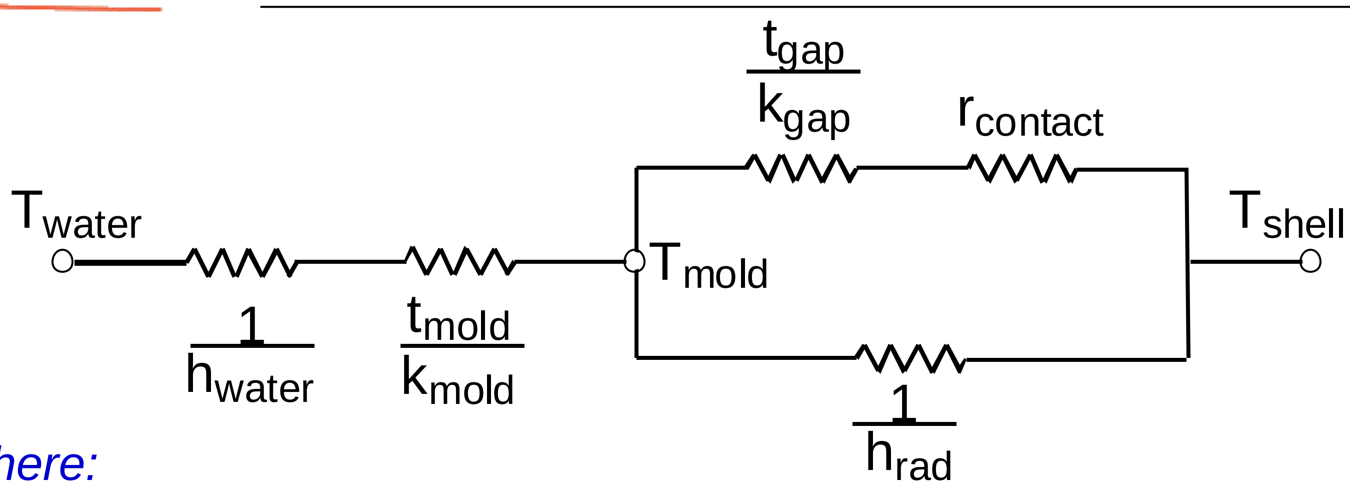
$$h = \frac{1.57}{a} \dot{W}^{0.55} \left(1 - 0.0075 T_w\right)$$

where

$$\dot{W} = A \cdot z\left(mm\right)^{-0.86} \left(l / m^2 s\right)$$

$$a = 4,\ A = \begin{cases} 3500, V_c = 2.2 m / min \\ 5250, V_c = 4.4 m / min \end{cases}$$

Interfacial Layer Heat Transfer Model



Where:

h_{water}: *heat transfer coefficient between mold cold face and cooling water*

t_{mold}: *mold wall thickness*

k_{mold}: *mold wall heat conductivity*

t_{gap}: *gap between mold hot face and shell surface*

k_{gap}: *gap heat conductivity*

$r_{contact}$: *contact heat resistance between mold wall and shell surface*

h_{rad}: *heat radiation coefficient between mold hot face and shell surface*

$$h_{rad} = \frac{s}{1/e_m + 1/e_s - 1}\left(T_{surf}^2 + T_{mold}^2\right)\left(T_{surf} + T_{mold}\right)$$

Parameters of Heat Transfer Model

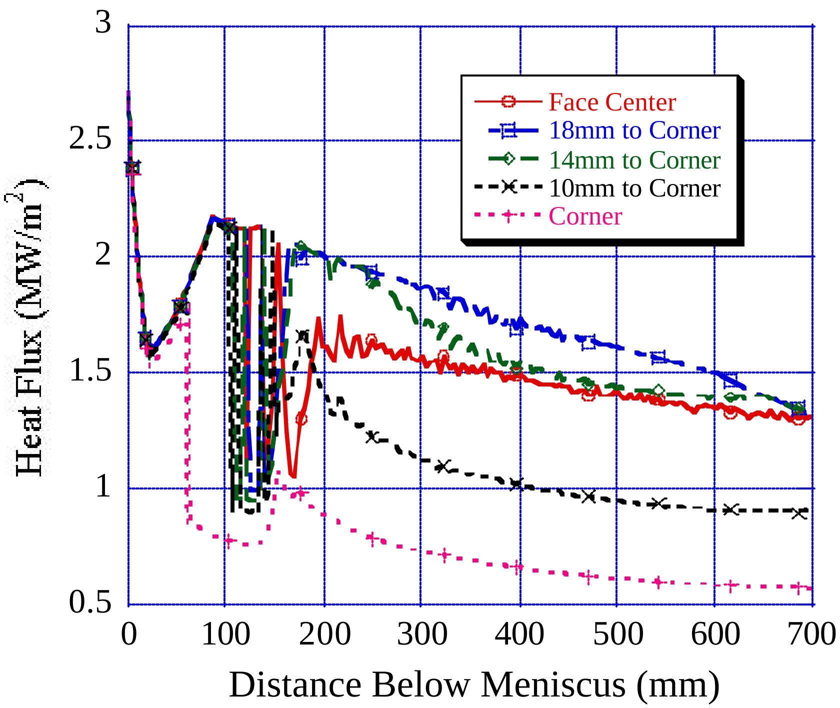
Heat Convection Coefficient (W/m^2K)	22,000 (at meniscus) ~ 25,000 (at mold exit)
Cooling Water Temperature (^oC)	30 (at meniscus) ~ 42 (at mold exit)
Water Flow Rate (l/s)	4.583
Mold Wall Thickness (mm)	6
Mold Wall Conductivity (W/mK)	360
Gap Conductivity (W/mK)	0.1
Contact Resistance (m^2K/W)	5.6×10^{-4}
σ, Stefan Boltzman Constant (W/m^2K^4)	5.67×10^{-8}
ε_m, Mold Wall Surface Emissivity	0.5
ε_s, Steel Surface Emissivity	0.8

Conditions of 2D Simulation

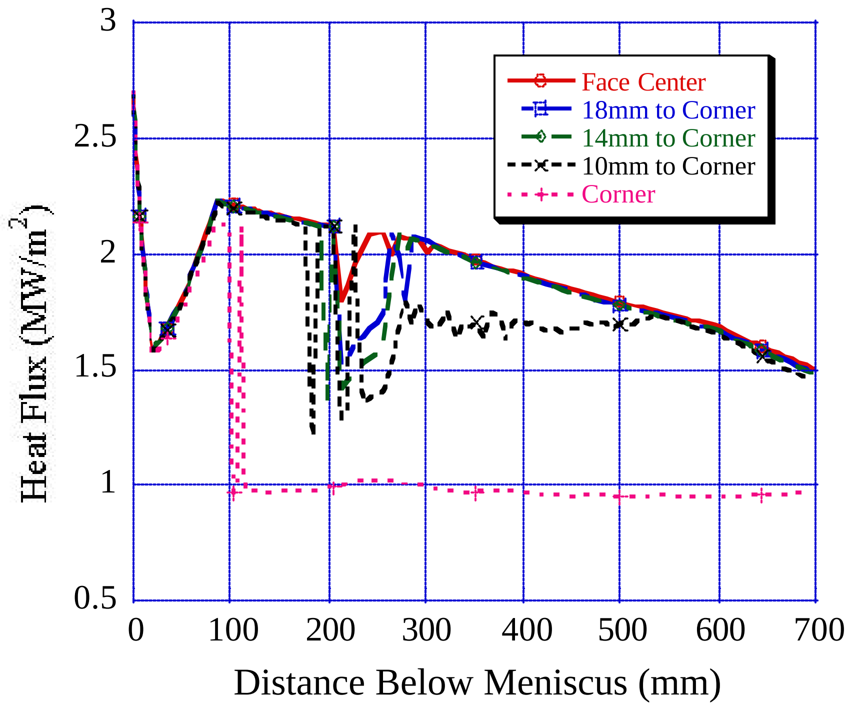
Material Composition (wt%)	0.27C, 1.52Mn, 0.34Si, 0.015S, 0.012P
Billet Section Size (mm x mm)	**120x120**
Working Mold Length (mm)	**700**
Total Mold Length (mm)	**800**
Taper (%/m)	0.75 (on both faces)
Time of Turning on Ferrostatic Pressure (sec.)	**0.3**(Run# 3~6), **3.5**(Run# 1,2)
Mesh Size (mm x mm)	0.1x1.0 (at surface), 1.4x1.0 (at center)
Node Number	7381
Element Number	7200
Time Step (sec.)	0.001 ~ 0.05
Pouring Temperature (^oC)	1540.0
Solidus Temperature (^oC)	1411.79
Liquidus Temperature (^oC)	1500.72
70% Solid Temperature (^oC) (Shell Thickness)	1477.02
90% Solid Temperature (^oC) (Damage strain accumulation begins)	1459.90

Fully Coupled Simulation
corresponding to real mold operation
producing hot corner
Run # 1 – 2.2m/min
Run # 2 – 4.4 m/min

Heat Flux Predicted



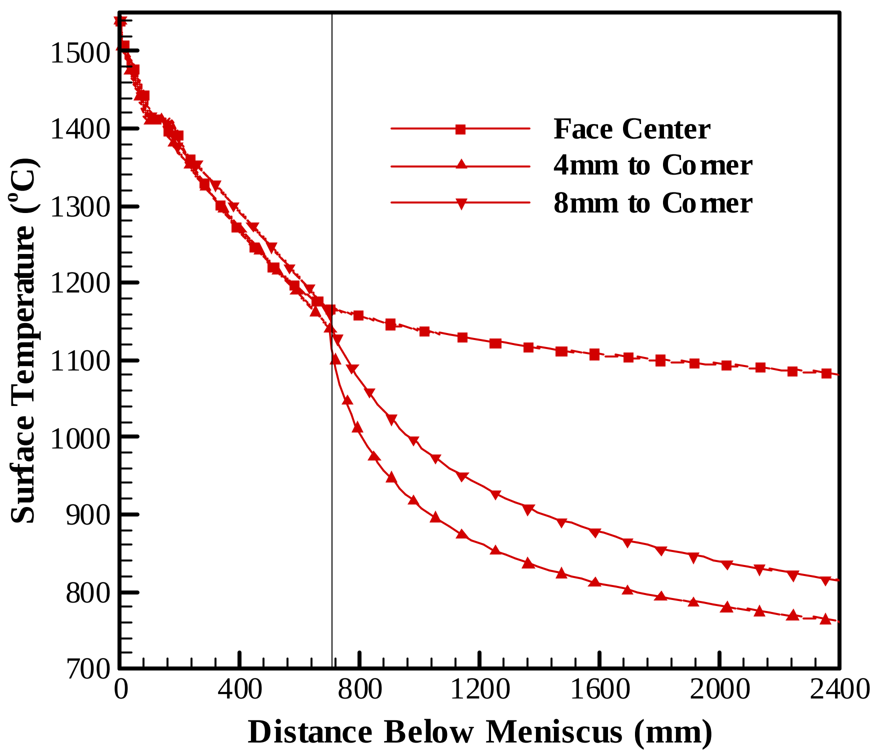
V = 2.2 m/min



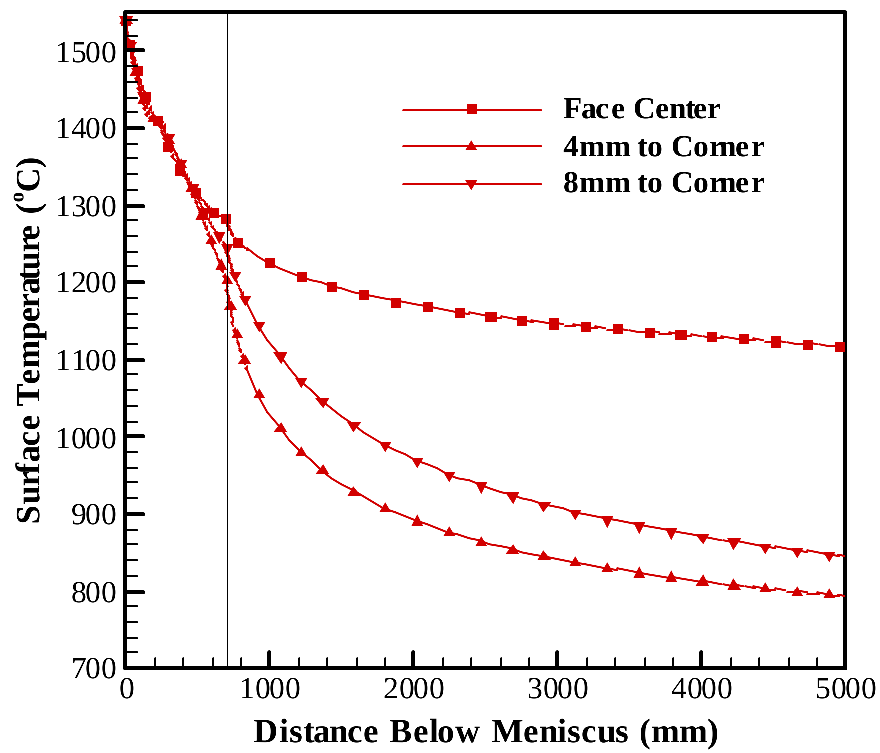
V = 4.4 m/min

Surface Temperature History

fully coupled cases 1,2



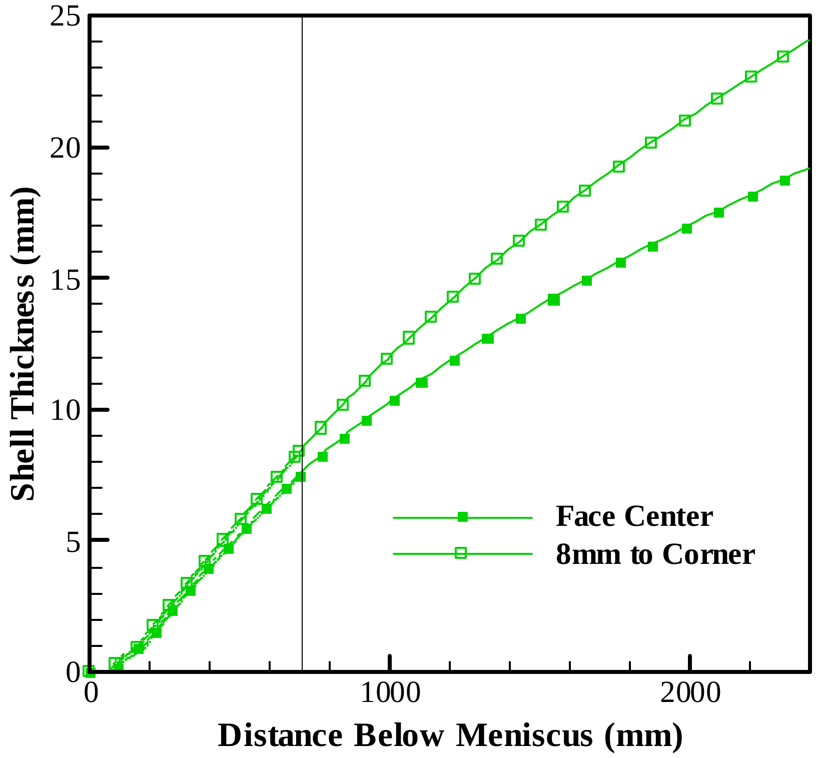
V = 2.2 m/min

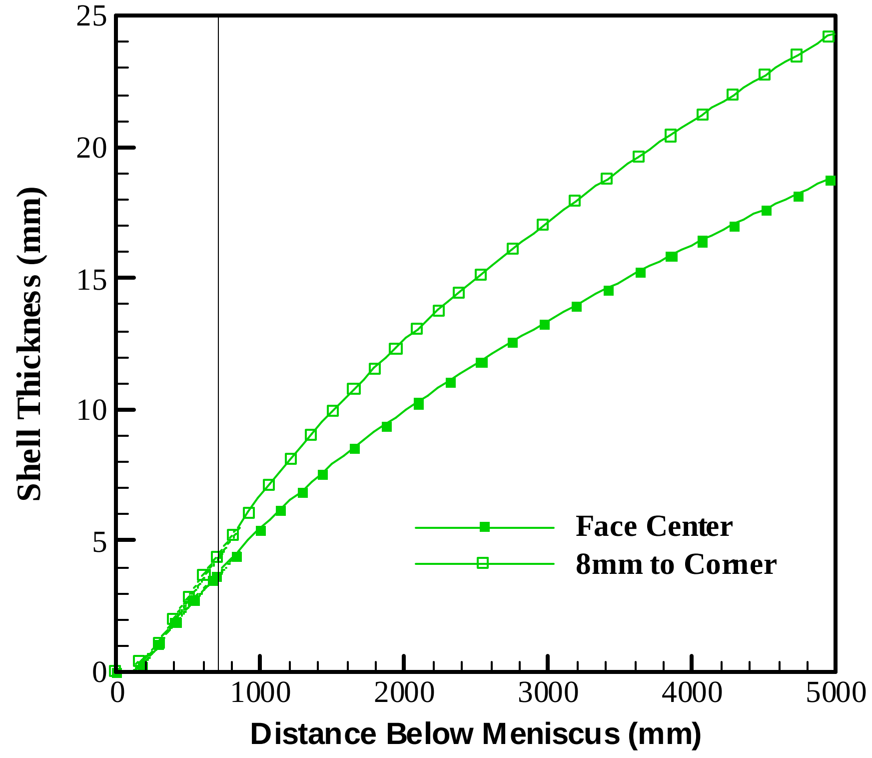


V = 4.4 m/min

Shell Thickness History

fully coupled cases 1,2



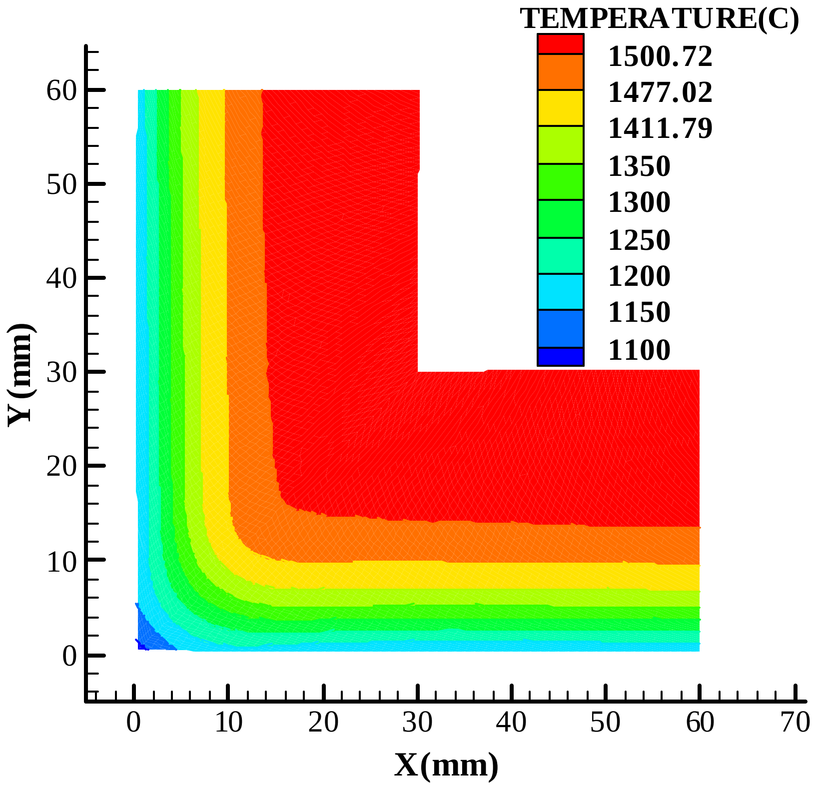


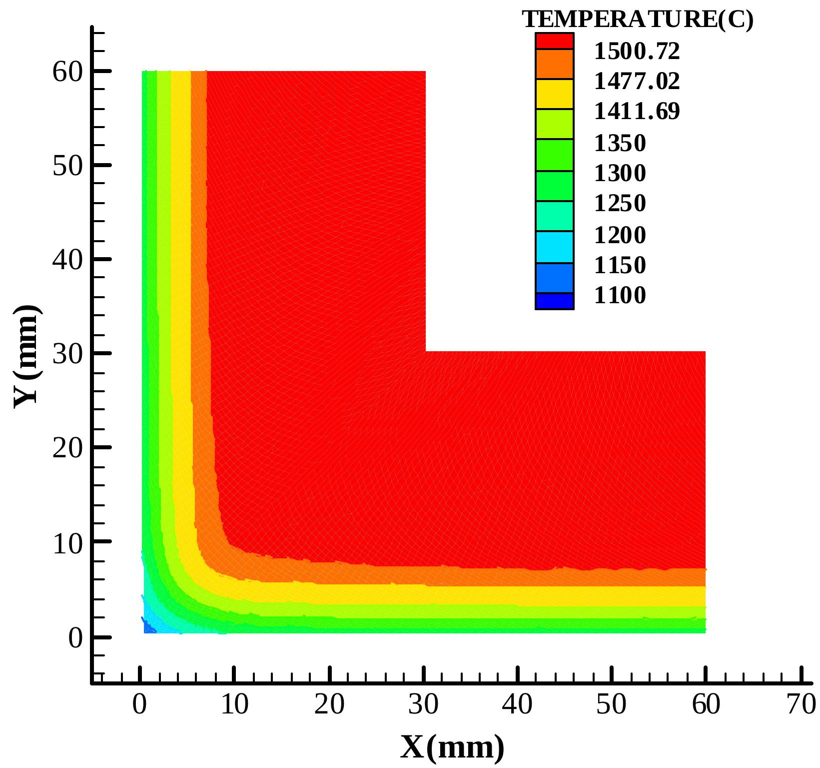
V = 2.2 m/min *V = 4.4 m/min*

Temperature Contour and Distorted Shape

(Mold Exit)

fully coupled cases 1,2





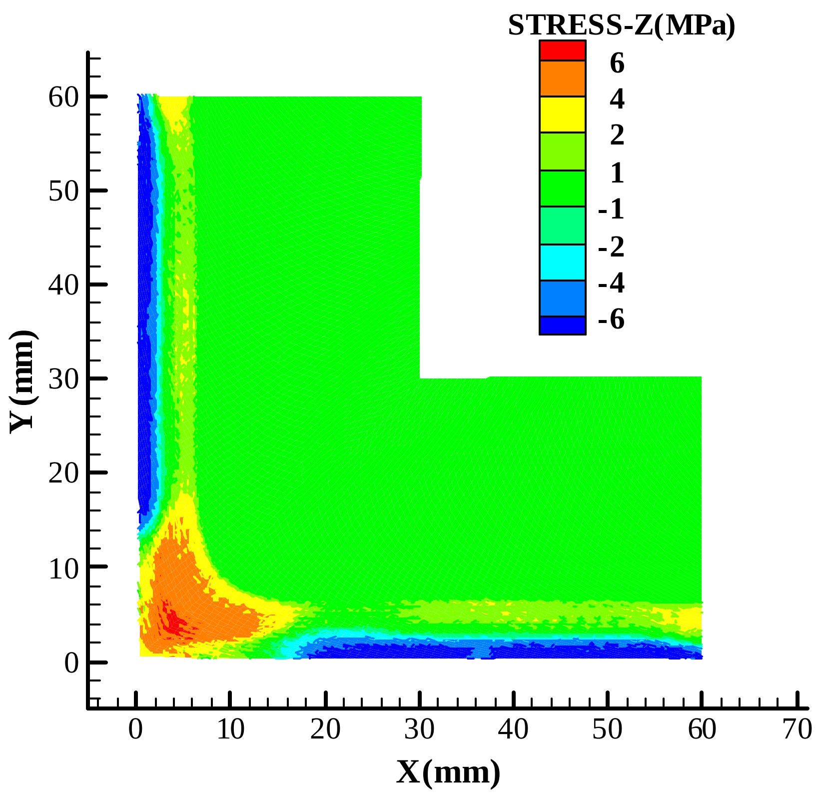
V = 2.2 m/min

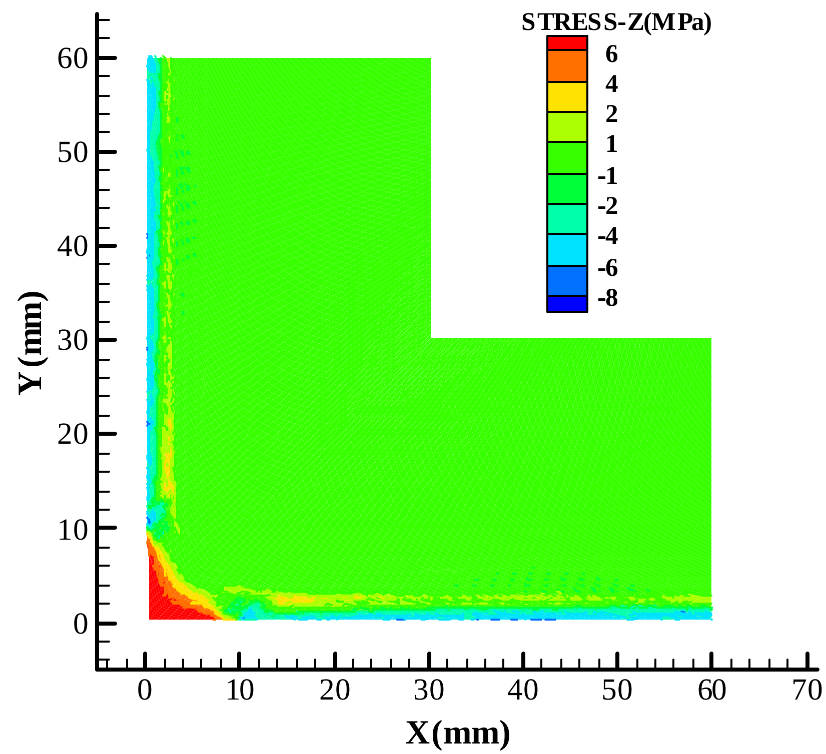
V = 4.4 m/min

Stress along Z dir. and Distorted Shape

(Mold Exit)

fully coupled cases 1,2





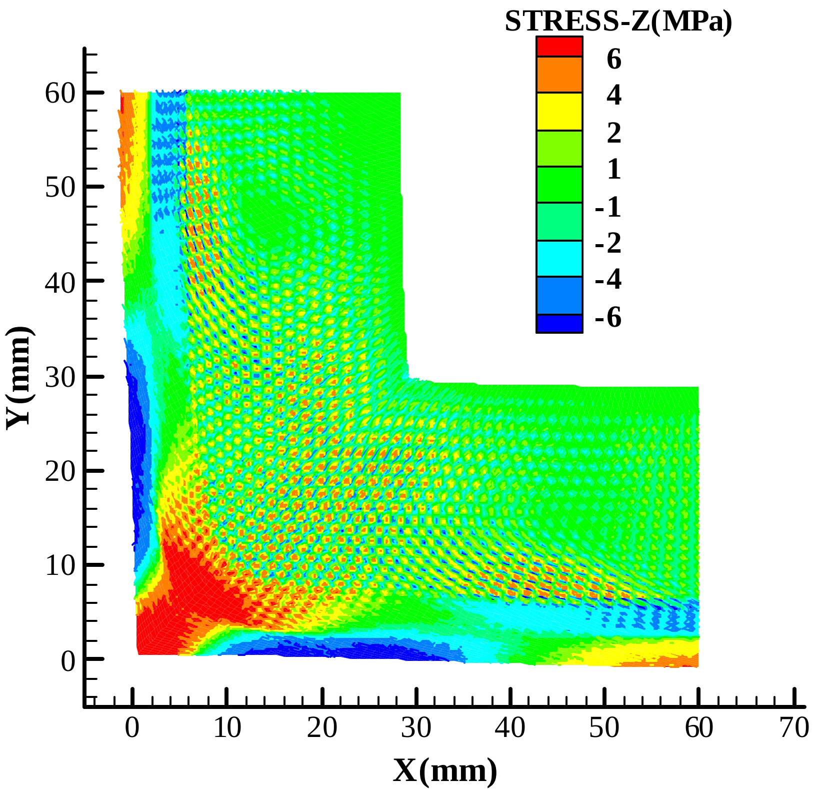
V = 2.2 m/min

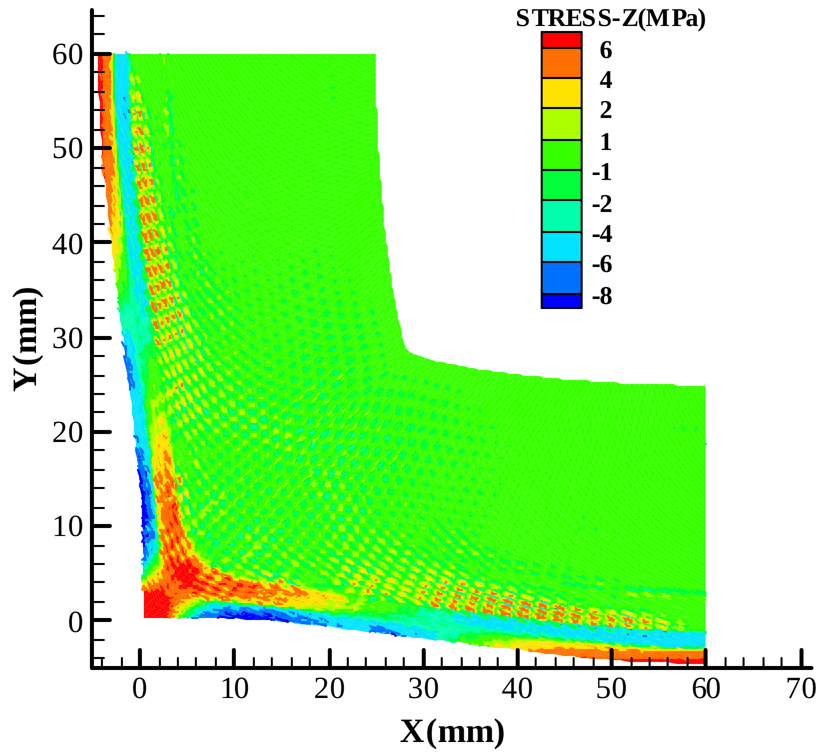
V = 4.4 m/min

Stress along Z dir. and Distorted Shape

(100mm Below Mold Exit)

fully coupled cases 1,2





V = 2.2 m/min

V = 4.4 m/min

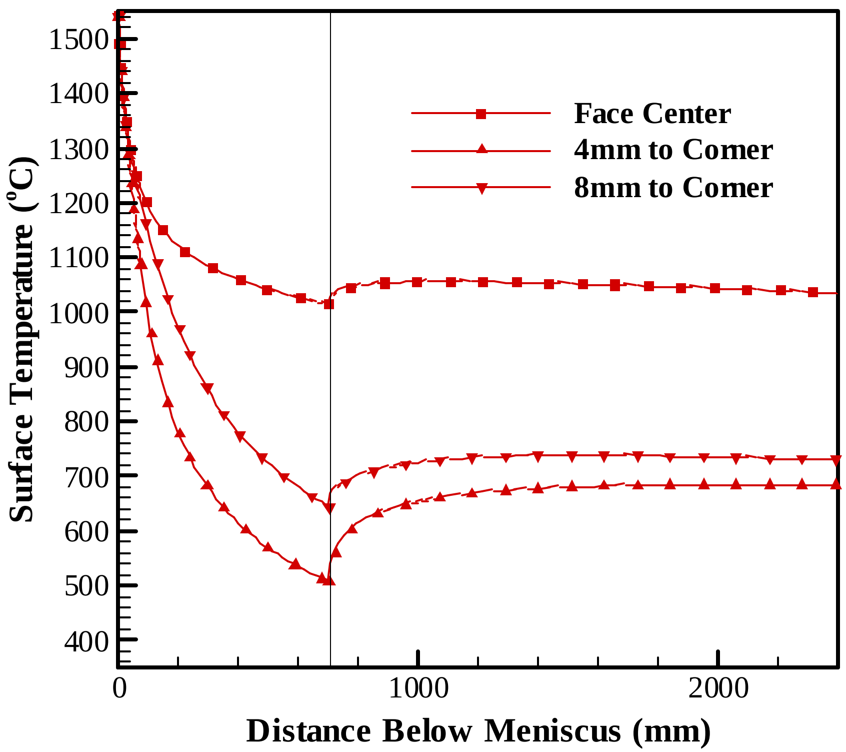
Simulation with uniform heat flux around perimeter corresponding to ideal mold operation (no air gap) producing cold corner

Run # 3 – 2.2m/min

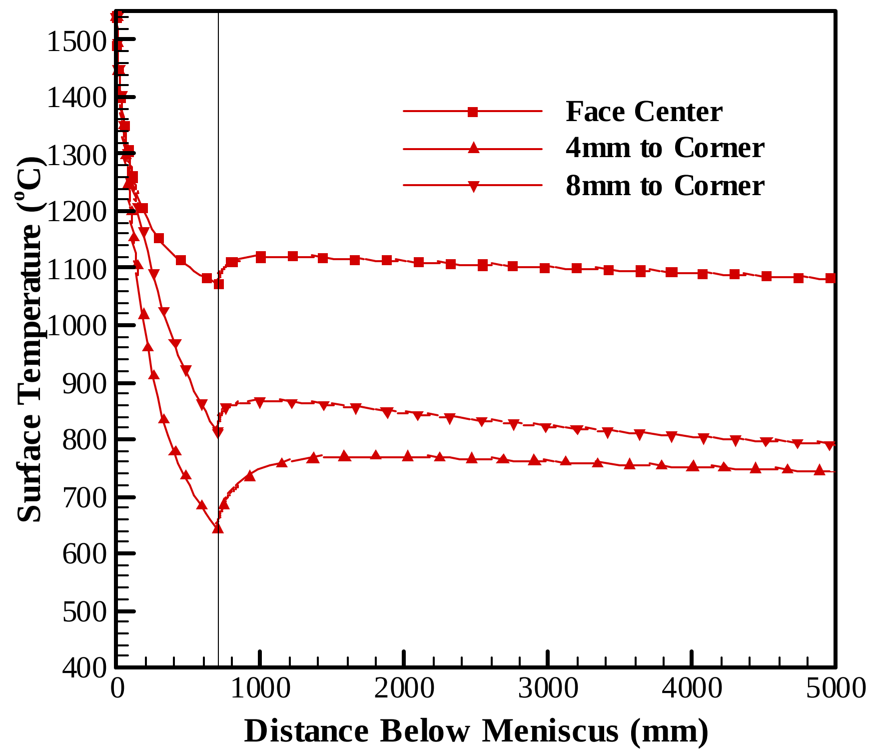
Run # 4 – 4.4 m/min

Surface Temperature History

uniform heat flux cases 3,4



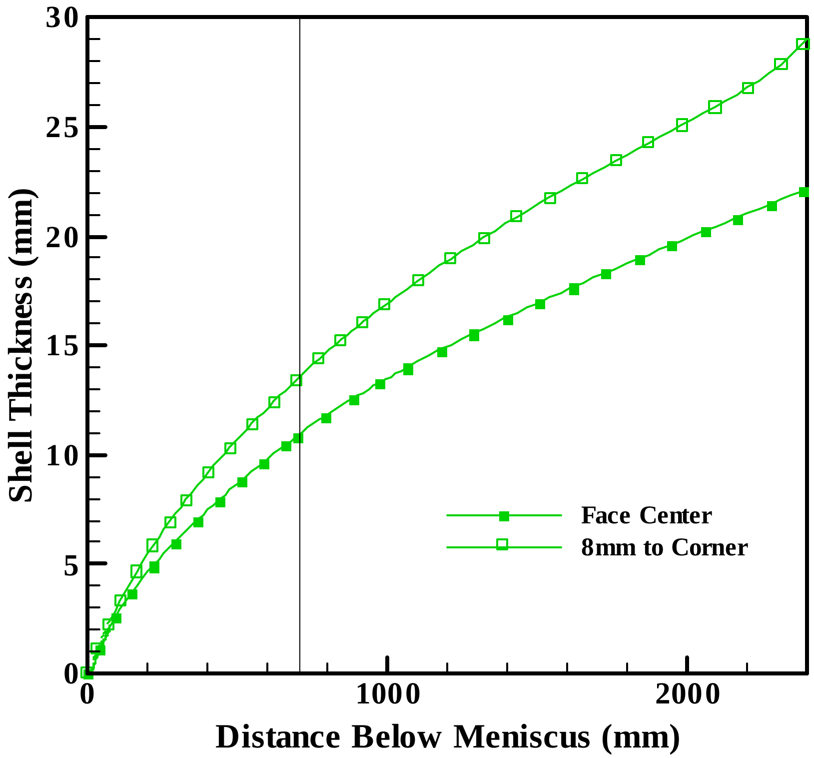
V = 2.2 m/min

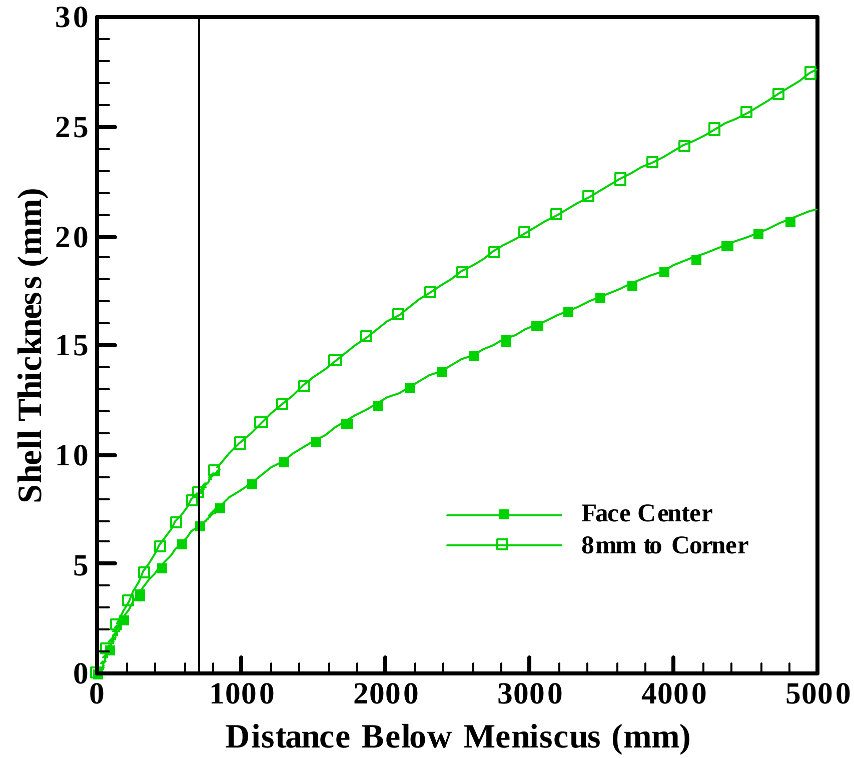


V = 4.4 m/min

Shell Thickness History

uniform heat flux cases 3,4





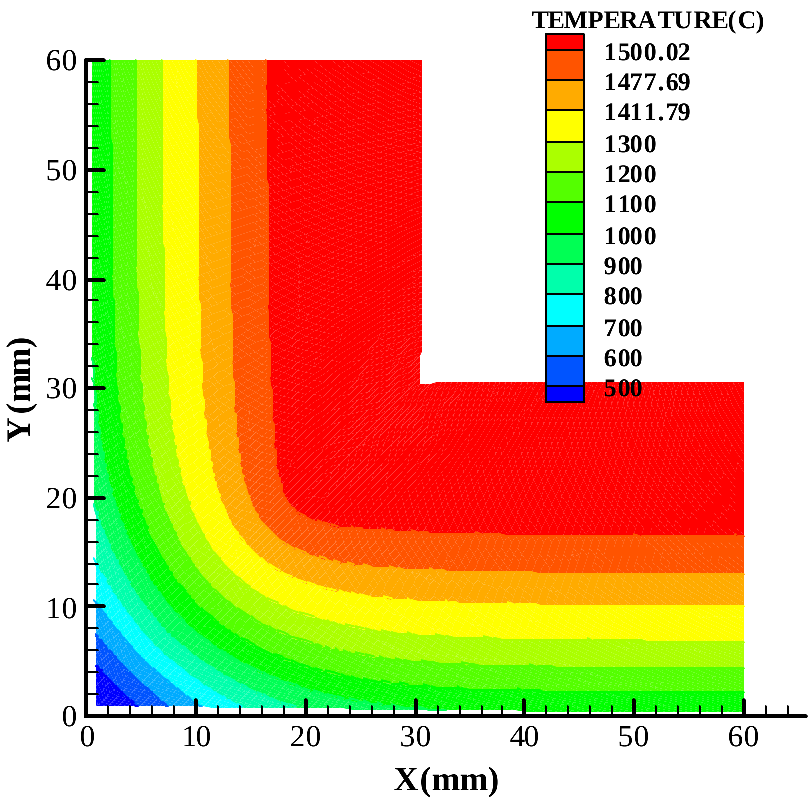
V = 2.2 m/min

V = 4.4 m/min

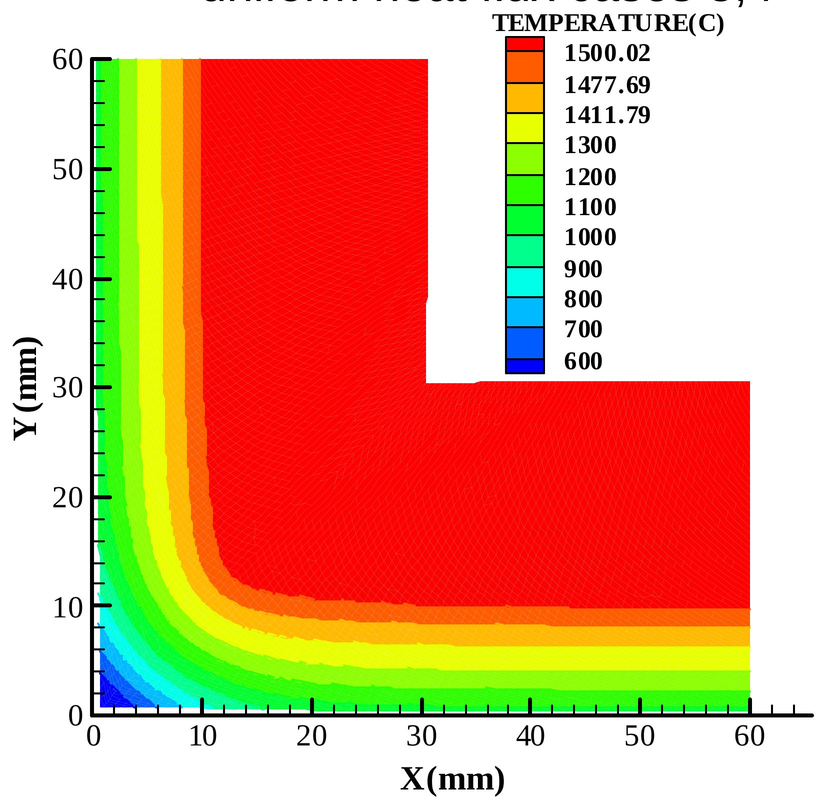
Temperature Contour and Distorted Shape

(Mold Exit)

uniform heat flux cases 3,4



V = 2.2 m/min

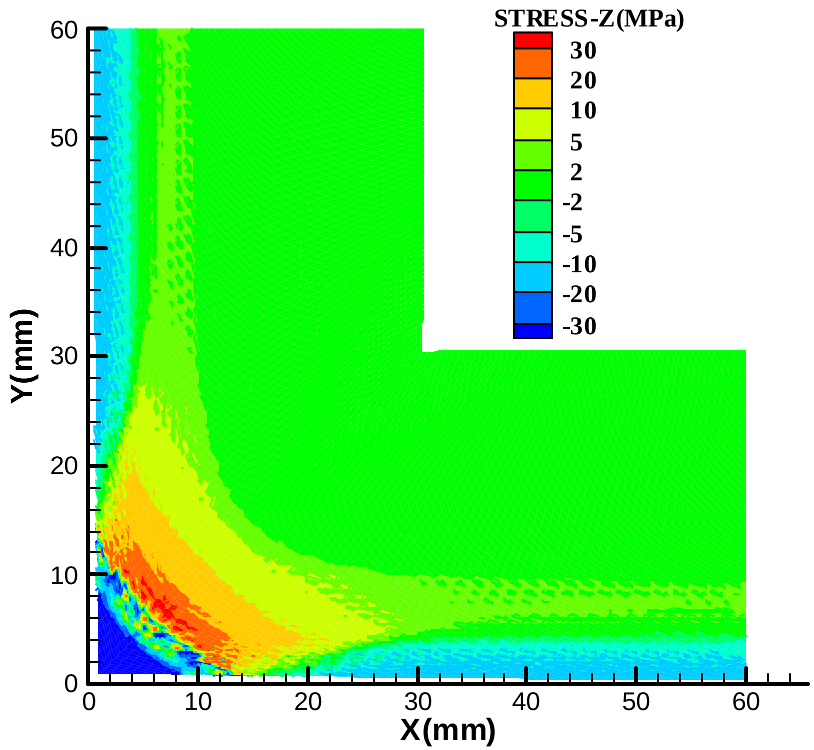


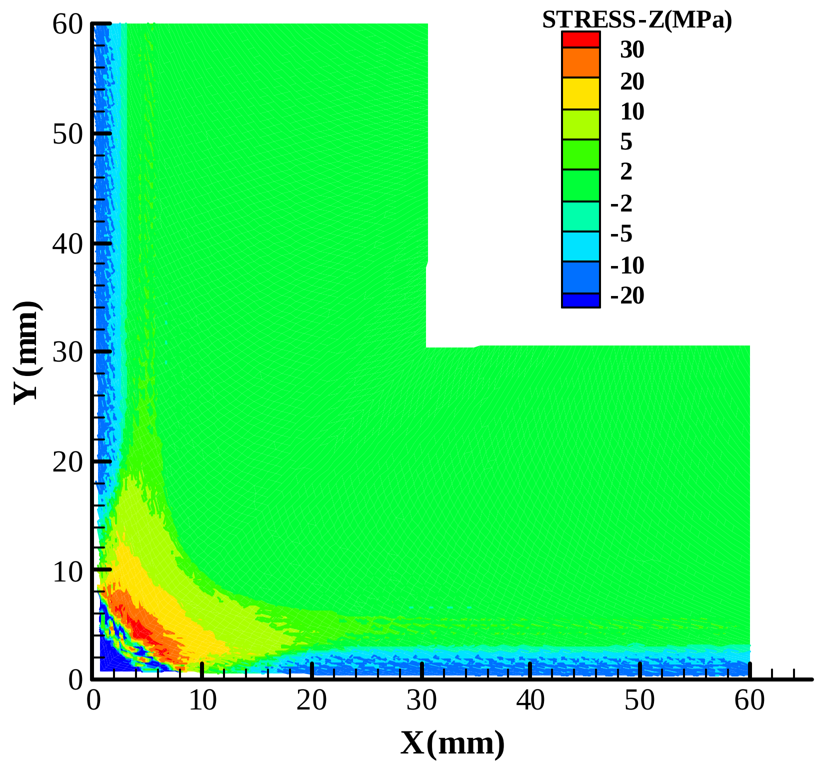
V = 4.4 m/min

Stress along Z dir. and Distorted Shape

(Mold Exit)

uniform heat flux cases 3,4

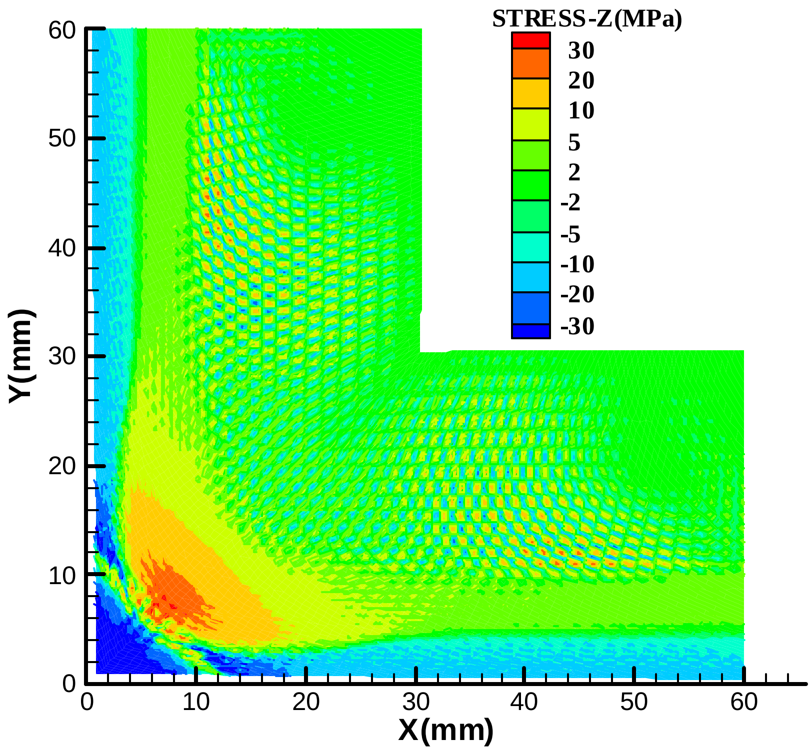


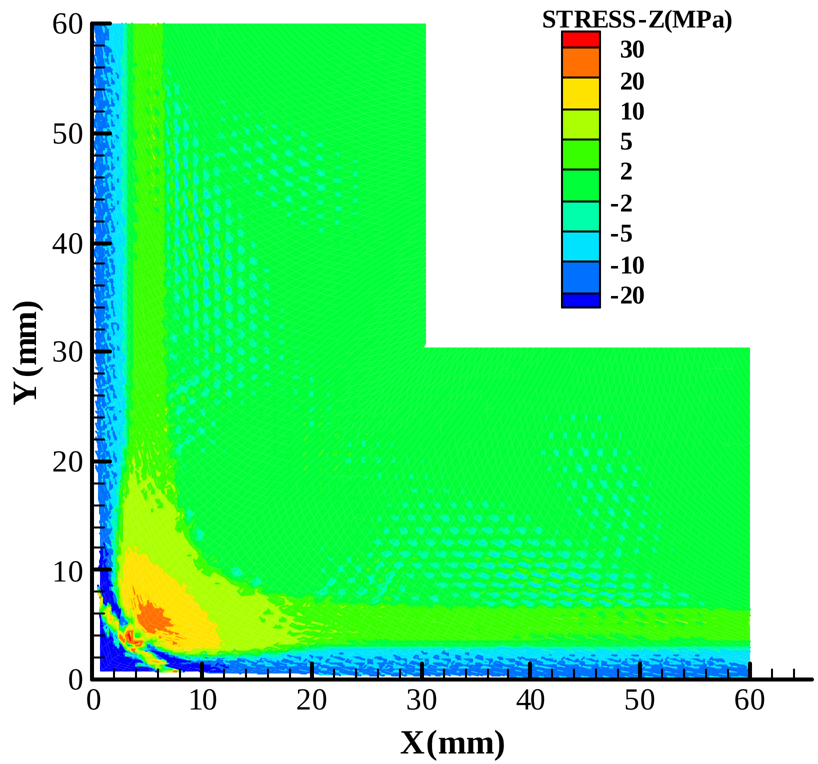


V = 2.2 m/min *V = 4.4 m/min*

Stress along Z dir. and Distorted Shape
(100mm Below Mold Exit)

uniform heat flux cases 3,4





V = 2.2 m/min

V = 4.4 m/min

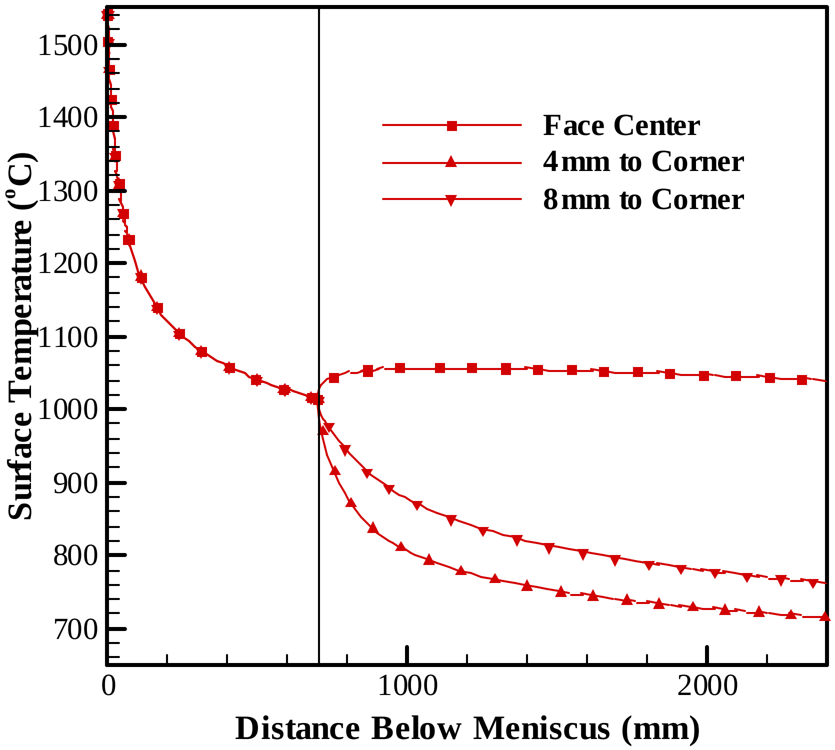
Simulation with uniform temperature around perimeter corresponding producing uniform corner

Run # 5 – 2.2m/min

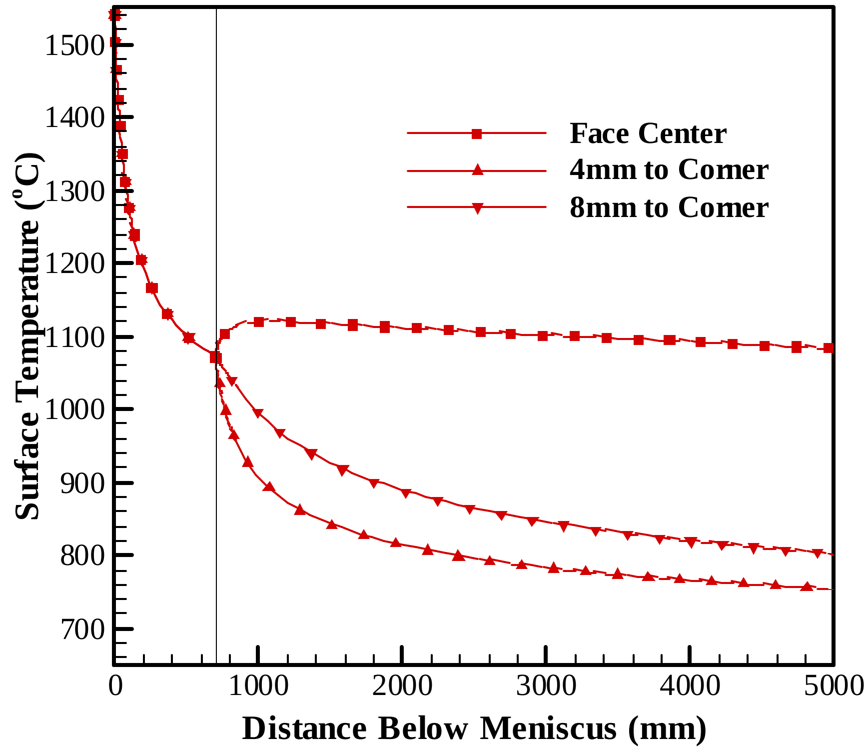
Run # 6 – 4.4 m/min

Surface Temperature History

uniform temperature cases 5,6



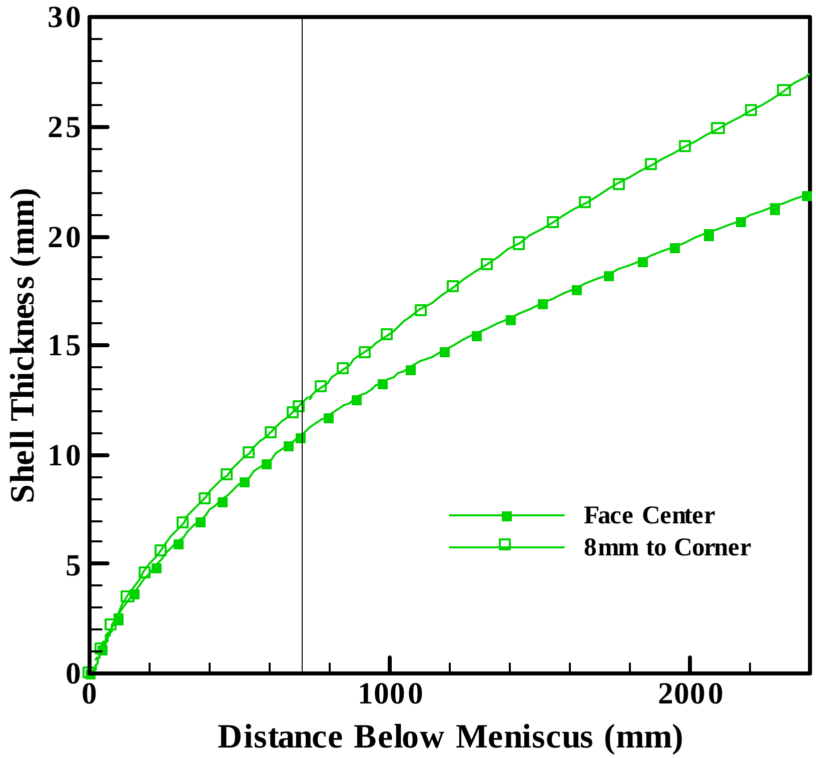
V = 2.2 m/min

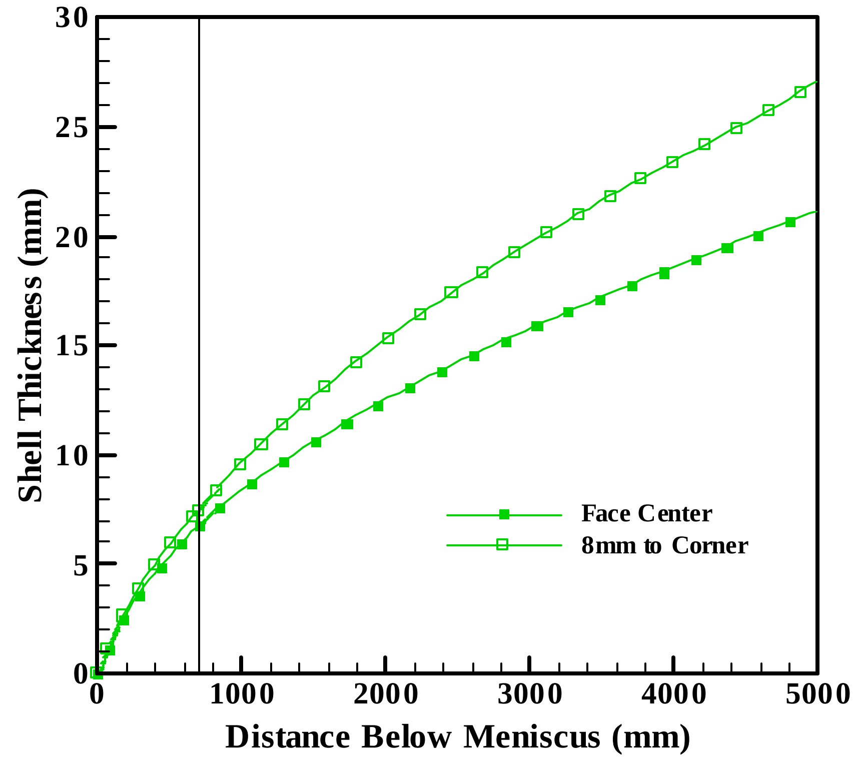


V = 4.4 m/min

Shell Thickness History

uniform temperature cases 5,6

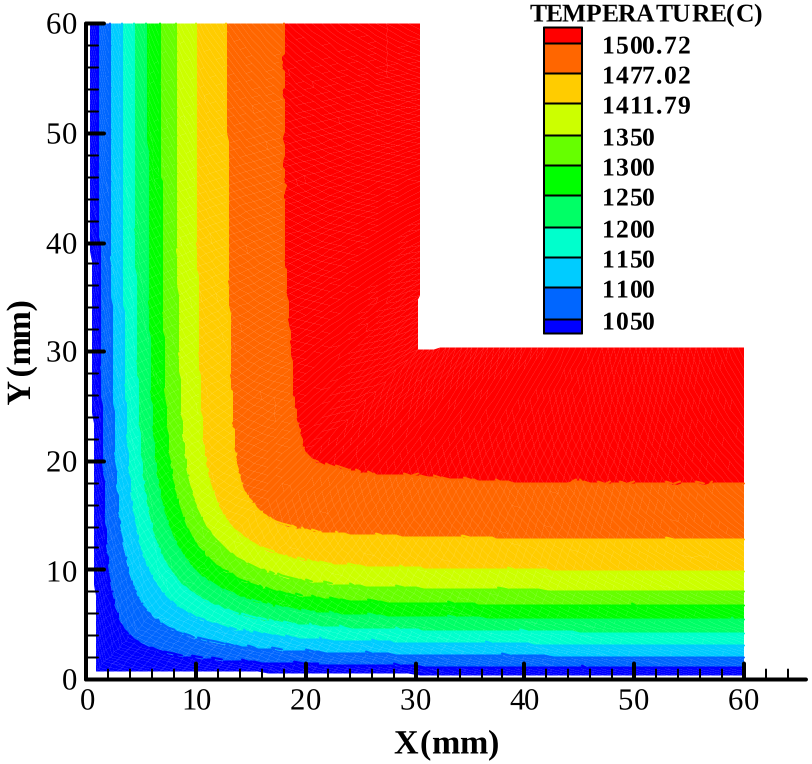




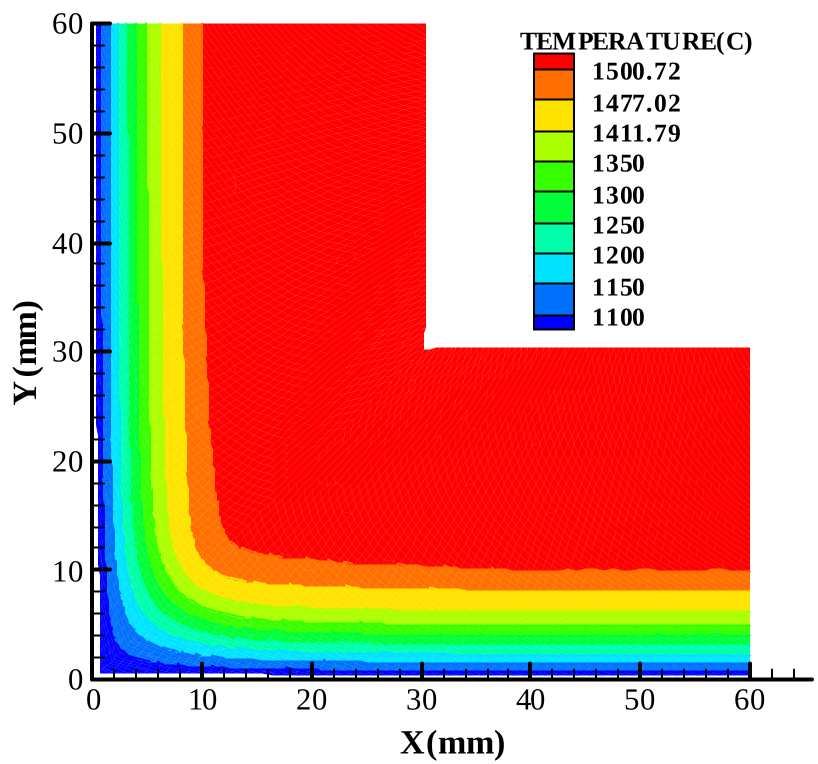
V = 2.2 m/min *V = 4.4 m/min*

Temperature Contour and Distorted Shape
(Mold Exit)

uniform temperature cases 5,6



V = 2.2 m/min

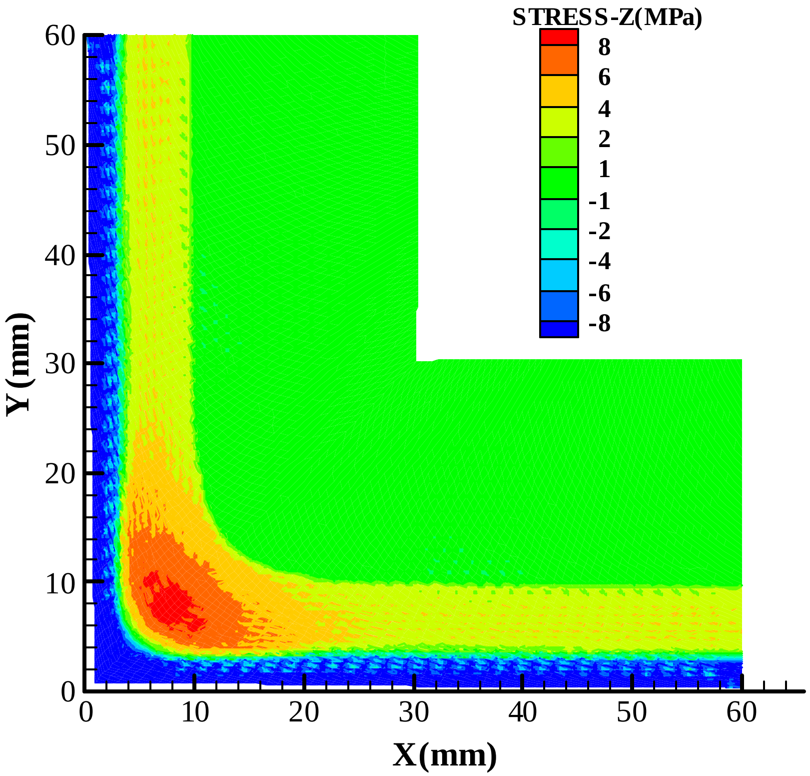


V = 4.4 m/min

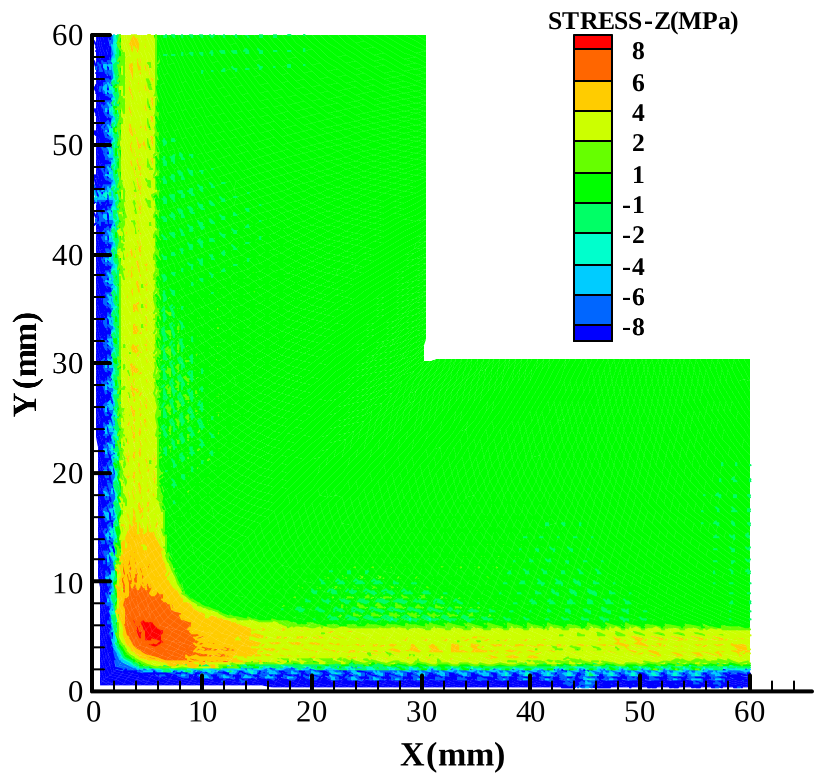
Stress along Z dir. and Distorted Shape

(Mold Exit)

uniform temperature cases 5,6



V = 2.2 m/min

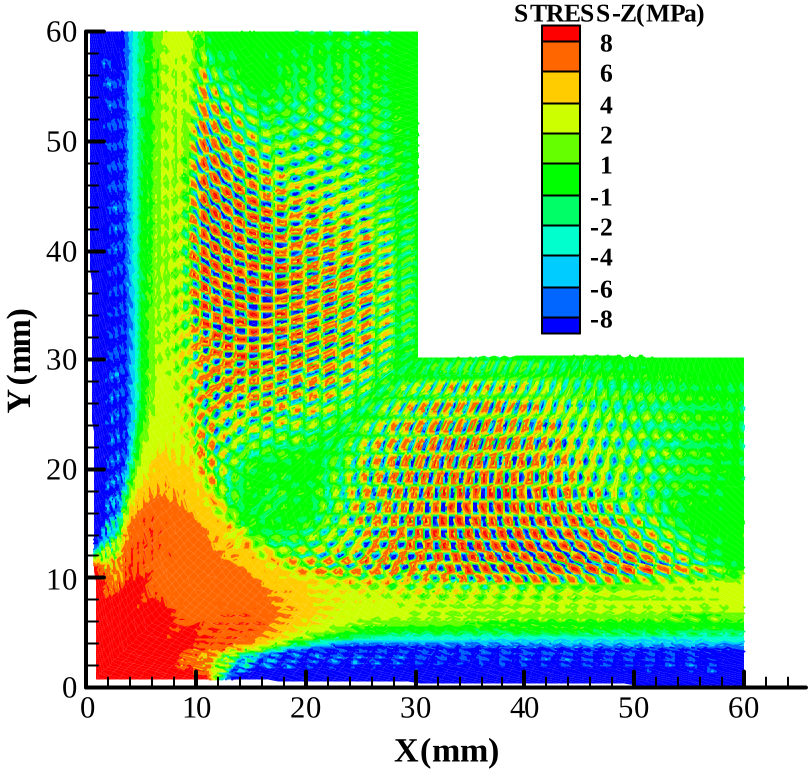


V = 4.4 m/min

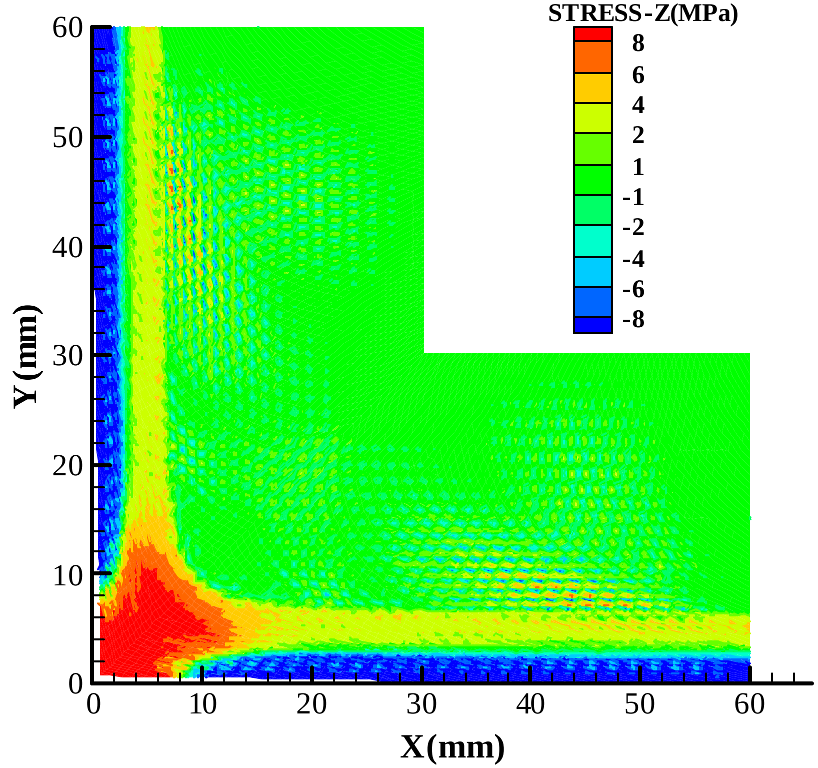
Stress along Z dir. and Distorted Shape

(100mm Below Mold Exit)

uniform temperature cases 5,6



V = 2.2 m/min



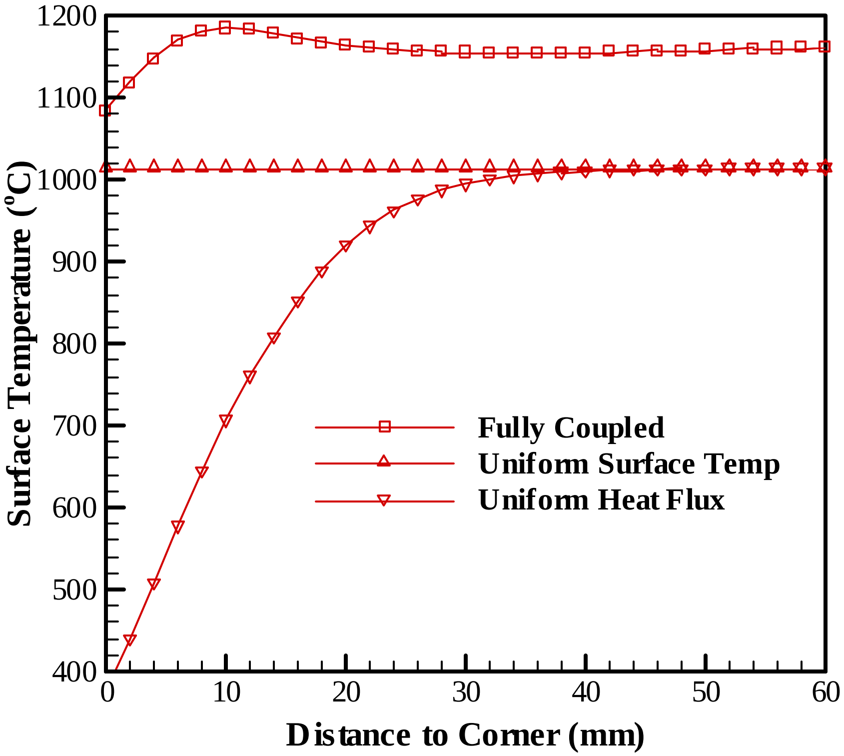
V = 4.4 m/min

Observations

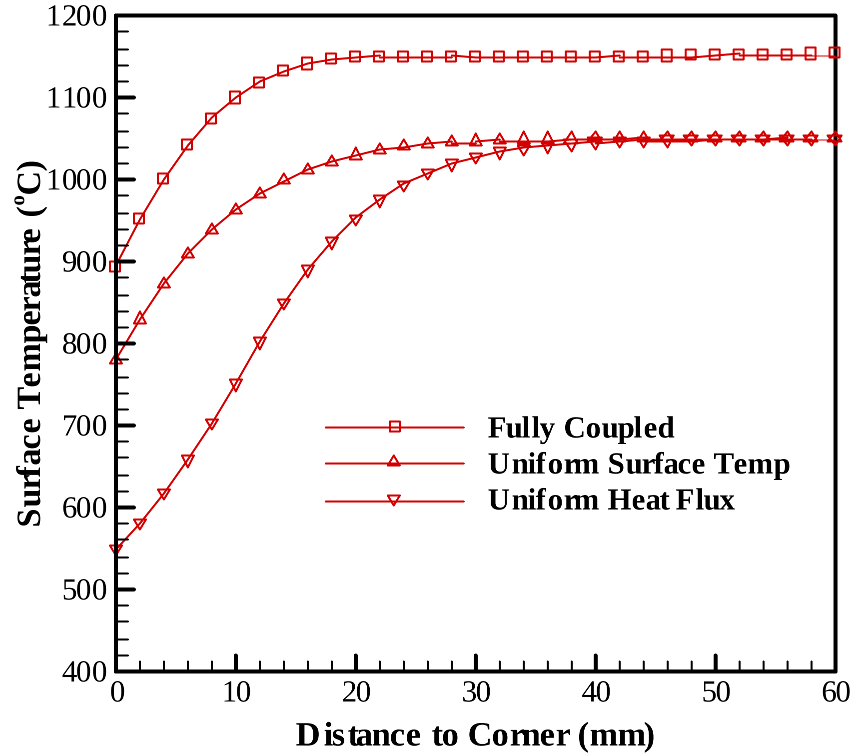
- *Mold operation resulting hotter corners in the mold leads to hot and weak corner which could not withstand the shell bending around corner due to ferrostatic pressure as the billet is out of the mold. As simulation predicted, billet fails at 4.4m/min casting speed.*
- *Mold operation producing uniform or cold corner could support the ferrostatic pressure after mold exit without much bulging.*
- *Hot and uniform corners suffer overcooling in spray zones due to 2D heat convection near the corner. This leads to substantial tensile stress along casting direction which might cause transverse corner cracks at surface.*
- *Cold corner formed in the mold produces large tensile stress along the casting direction around corner region which might lead to transverse corner cracks in mold.*

Surface Temperature Profiles

V=2.2m/min



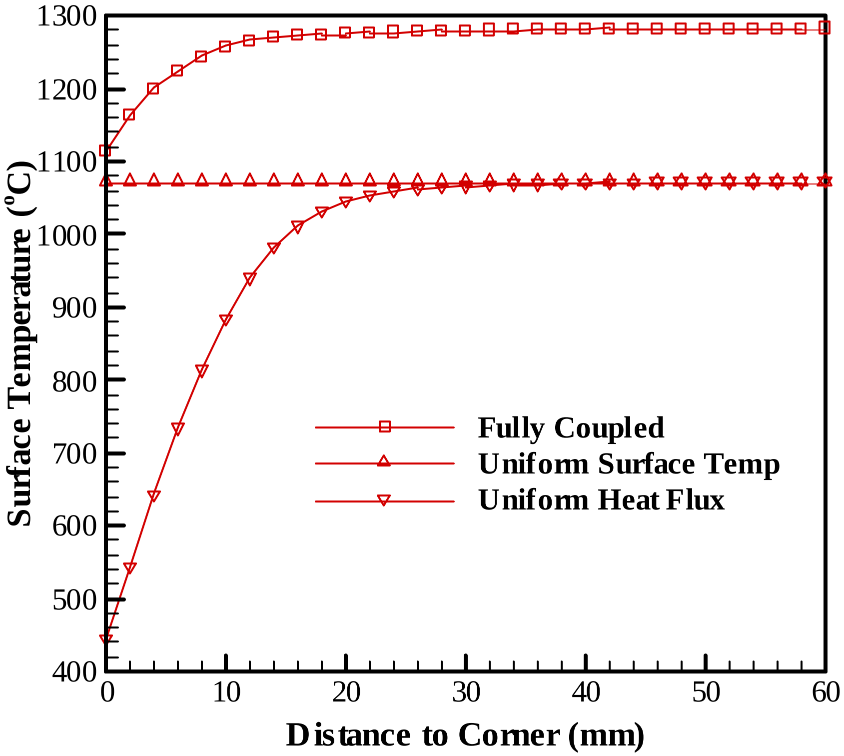
Mold Exit



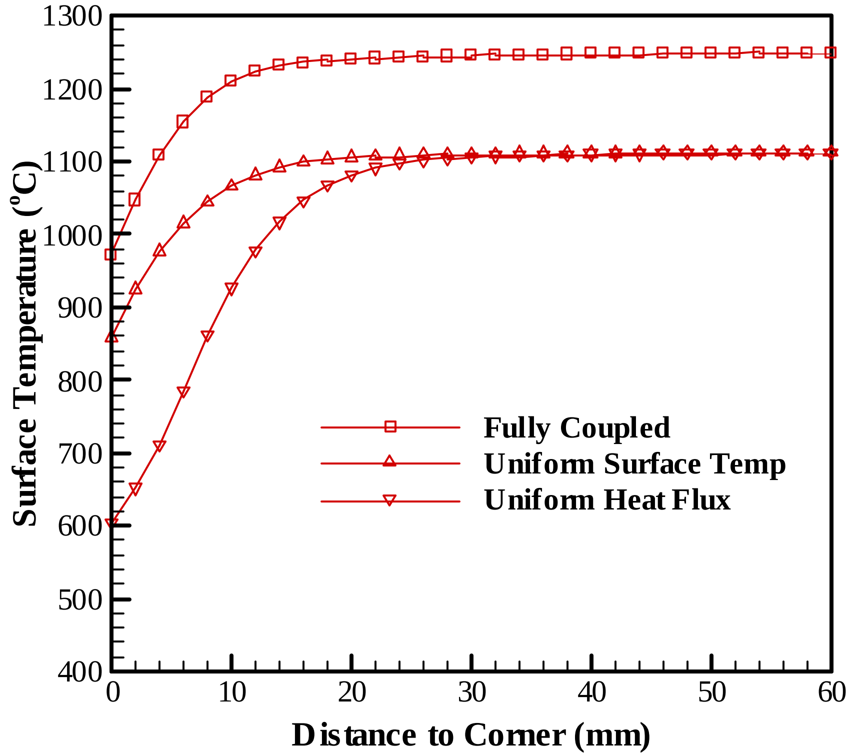
100mm Below Mold Exit

Surface Temperature Profiles

V=4.4m/min



Mold Exit

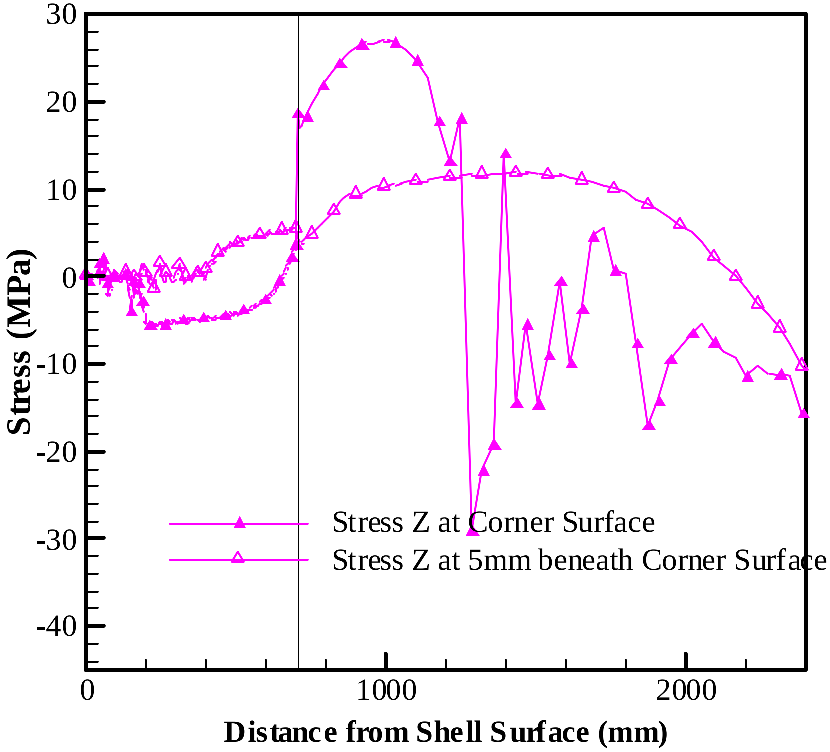


100mm Below Mold Exit

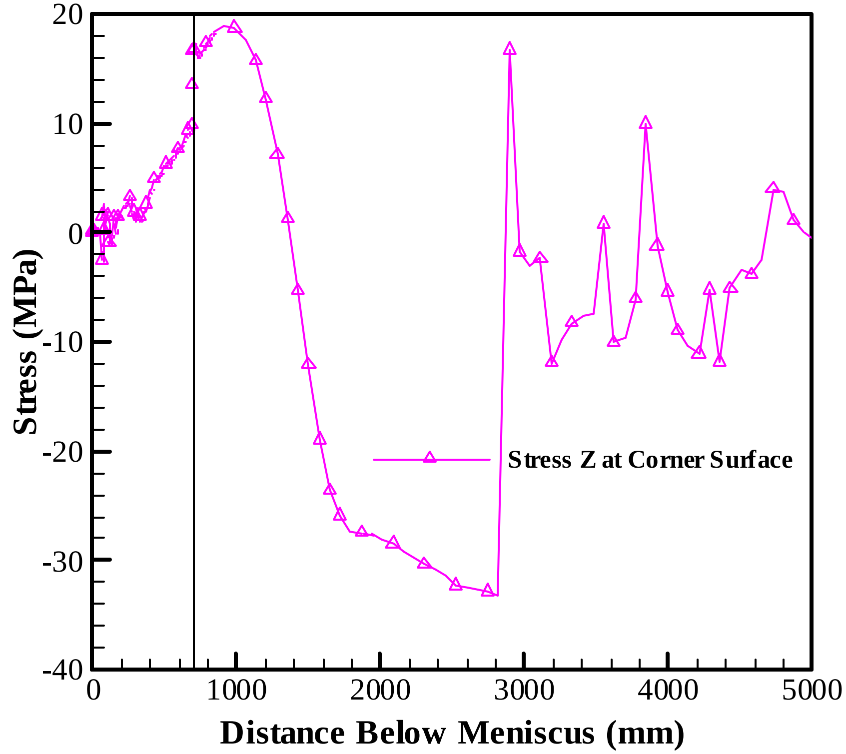
Stress Histories at Corner

(Fully Coupled Simulation in Mold)

fully coupled cases 1,2



V = 2.2 m/min

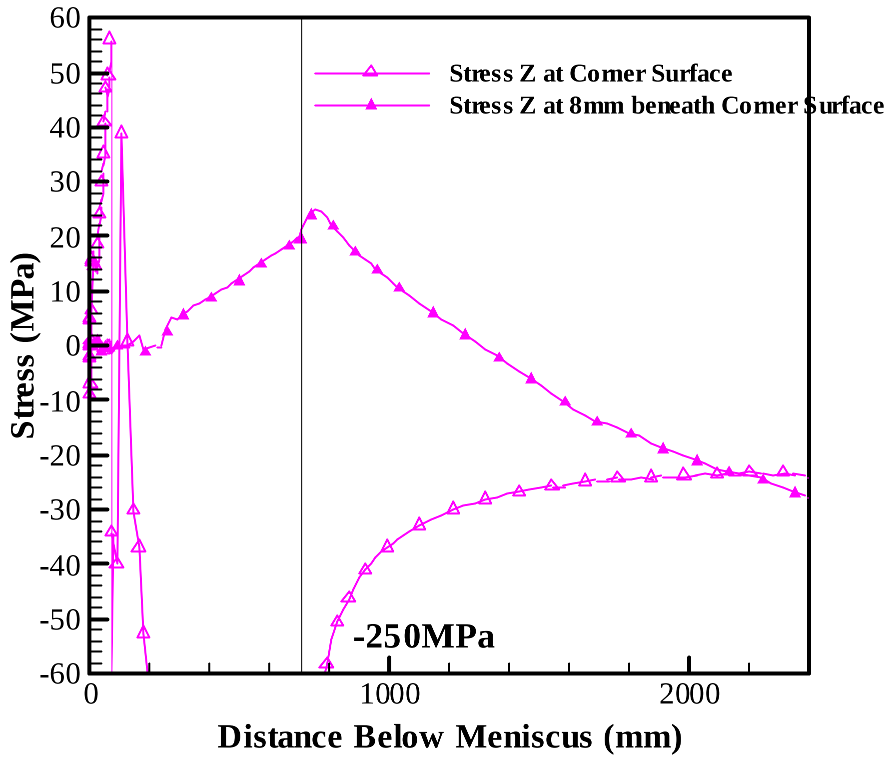


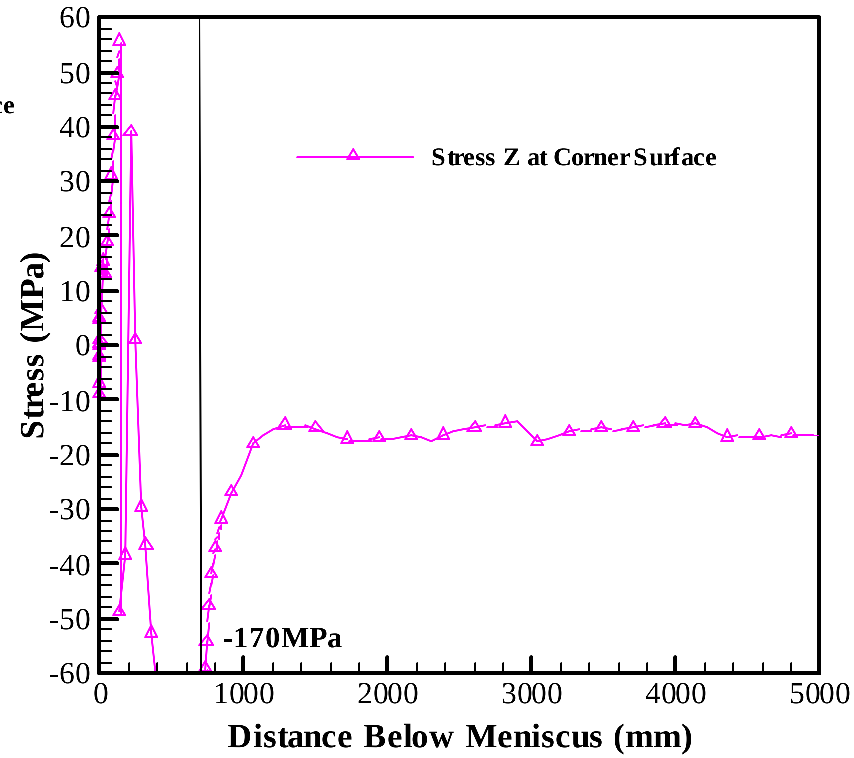
V = 4.4 m/min

Stress Histories at Corner

(Uniform Heat Flux around Perimeter in Mold)

uniform heat flux cases 3,4





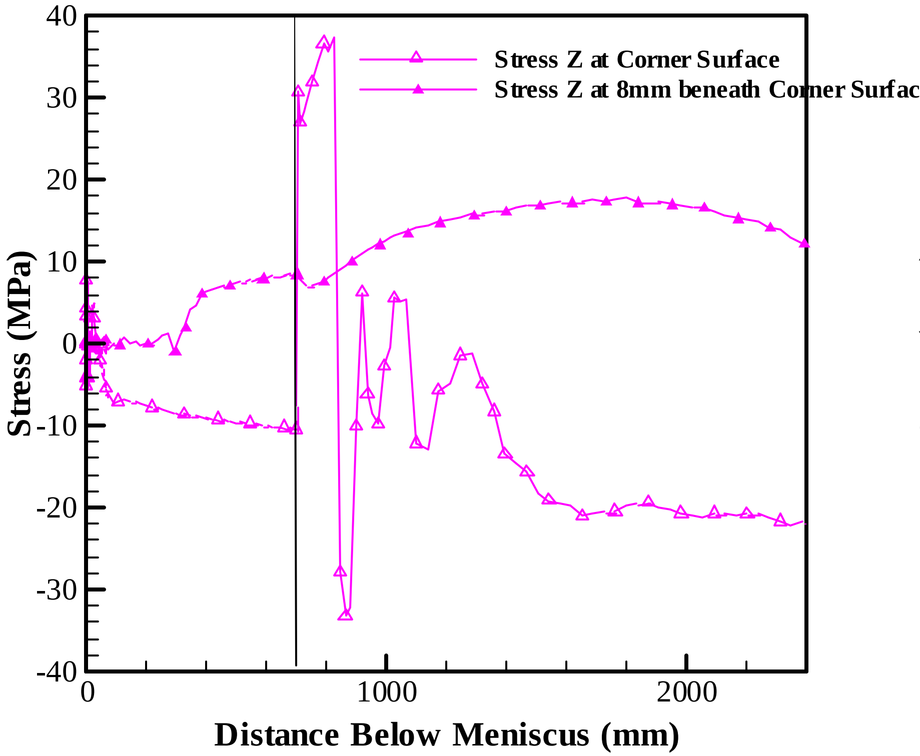
V = 2.2 m/min

V = 4.4 m/min

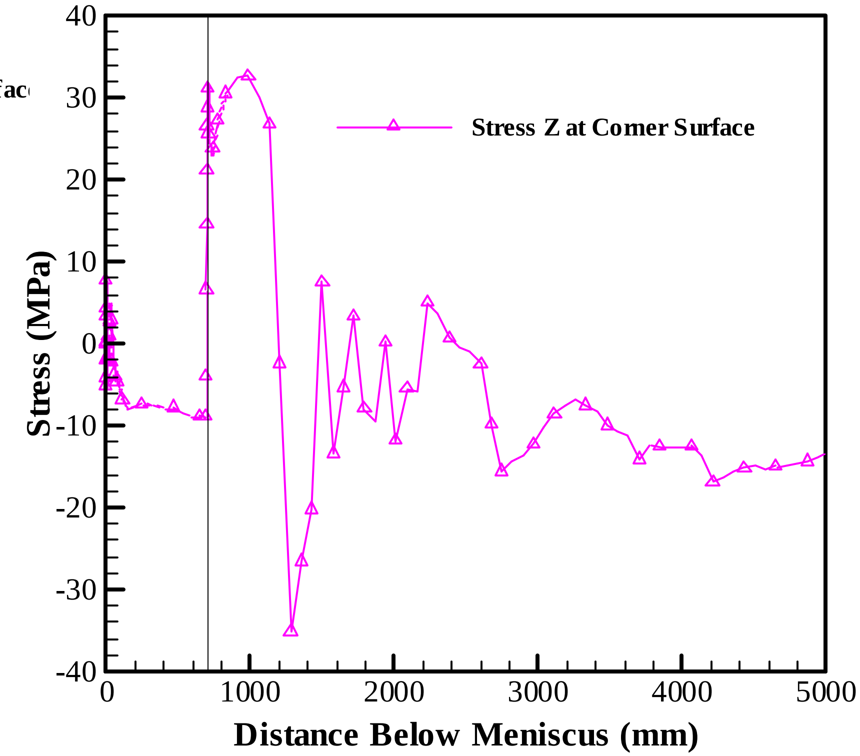
Stress Histories at Corner

(Uniform Temperature around Perimeter in Mold)

uniform temperature cases 5,6



V = 2.2 m/min

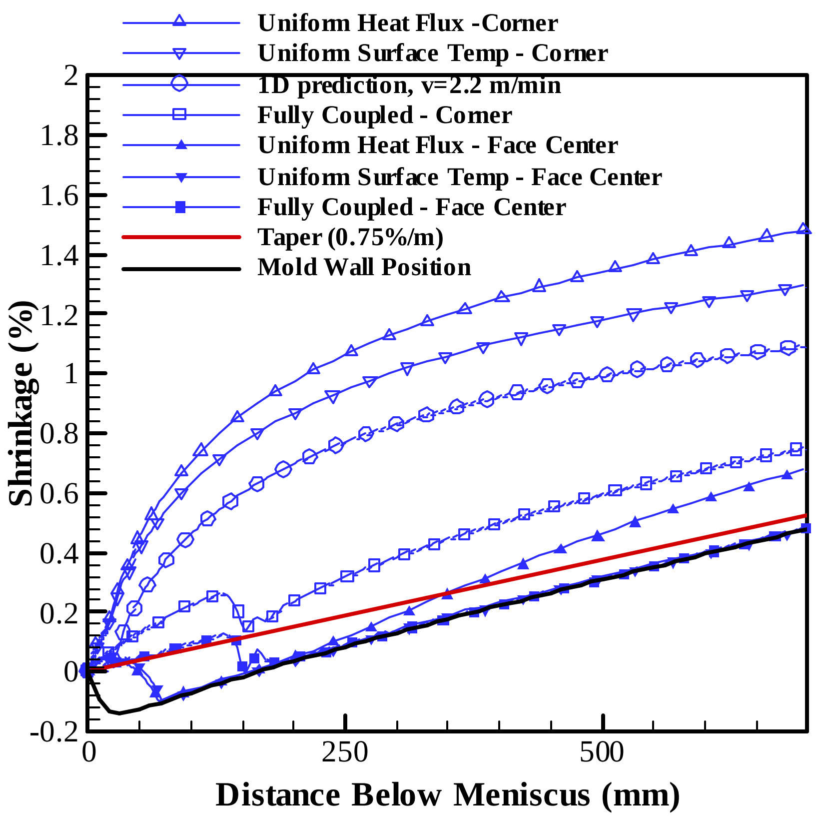


V = 4.4 m/min

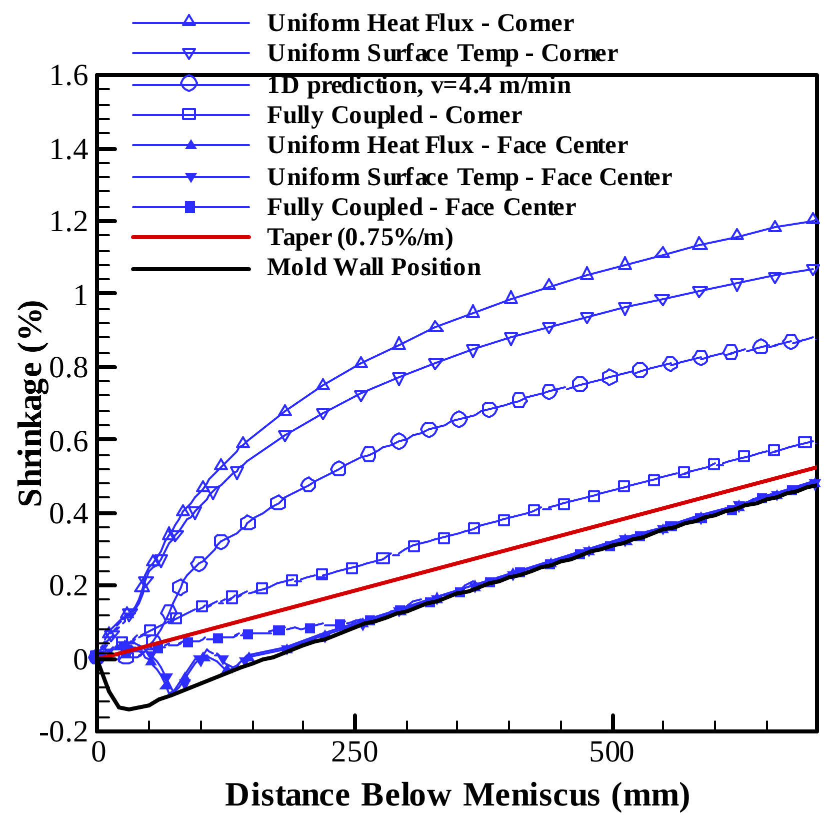
Observations

- *The hot and uniform corner formed in the mold suffer overcooling in the spray zones leading to tensile stress near corner surface. The absolute value stress does not depend on casting speed, but on the amount of temperature decreasing.*
- *Cold corner suffer reheating in the spray region which will increase the tensile stress already built up at sub surface in the mold and lead to sub-surface transverse cracks.*
- *The uniform surface temperature corner is more preferable to prevent either extreme cold or hot corner.*
- *Spray pattern should also be designed in care to prevent severe reheating or overcooling near corner.*
- *Slice domain model is favorable for ideal taper prediction since it provides results close to 2D prediction having uniform surface temperature around perimeter with much lesser computational cost.*

Shrinkage Predicted by 2D Model

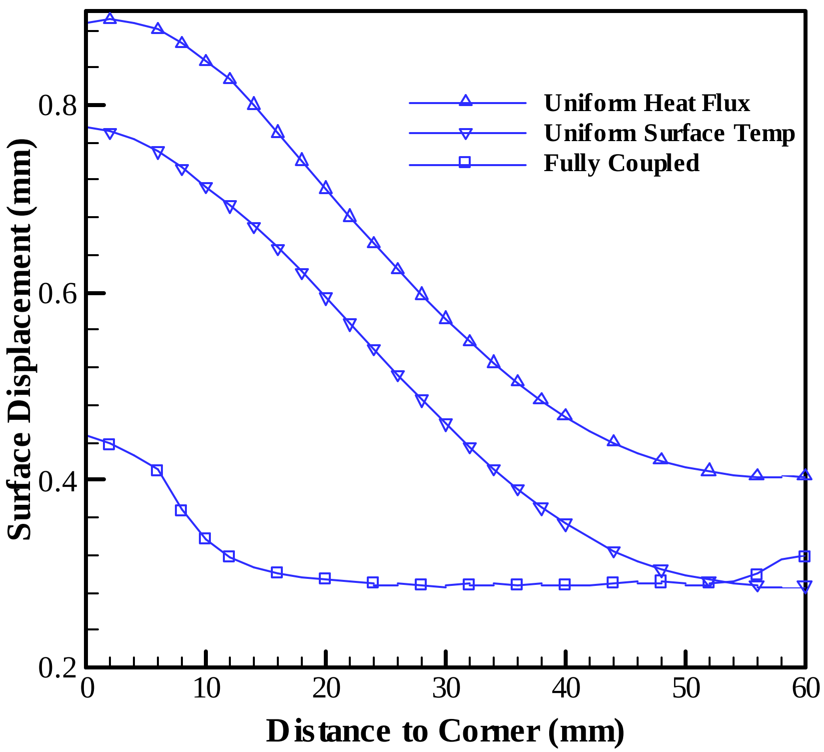


V=2.2m/min

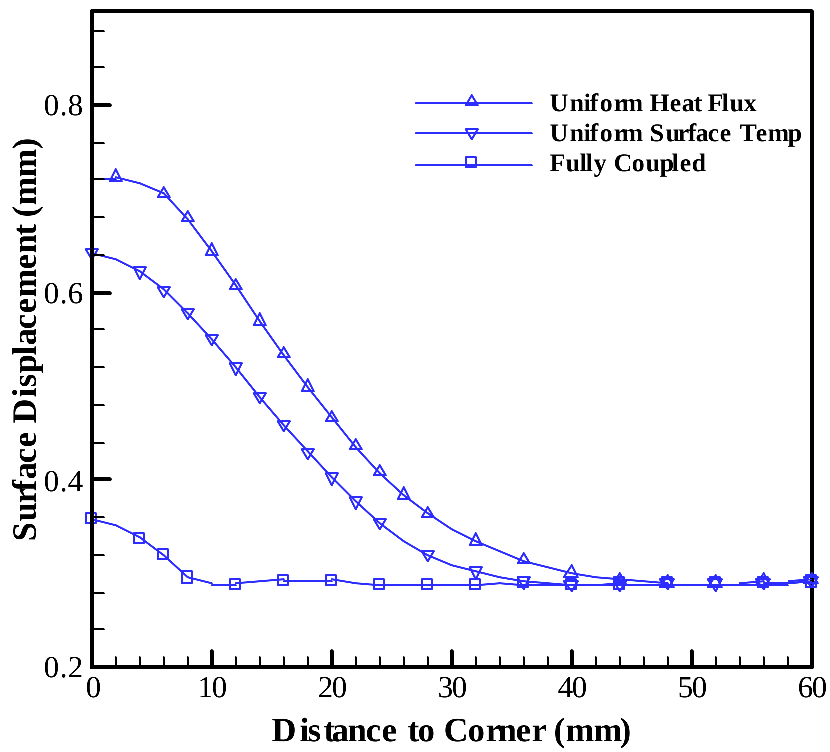


V=4.4m/min

Surface Displacement at Mold Exit

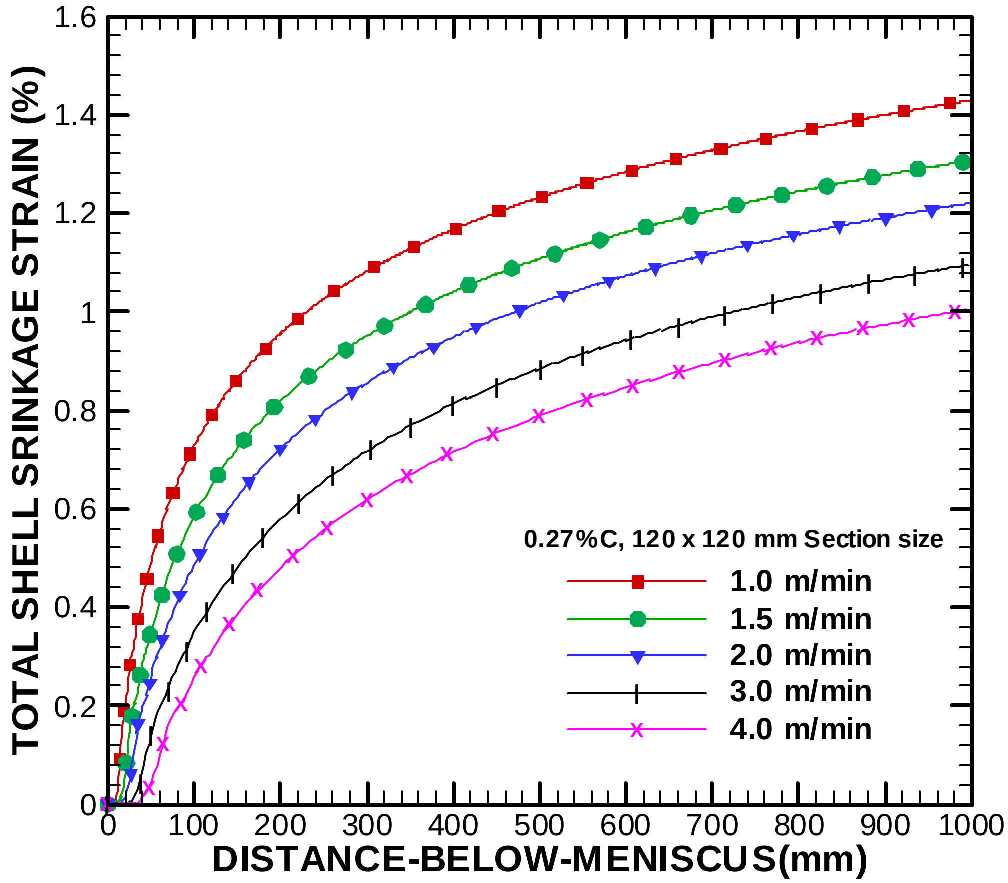


V=2.2m/min

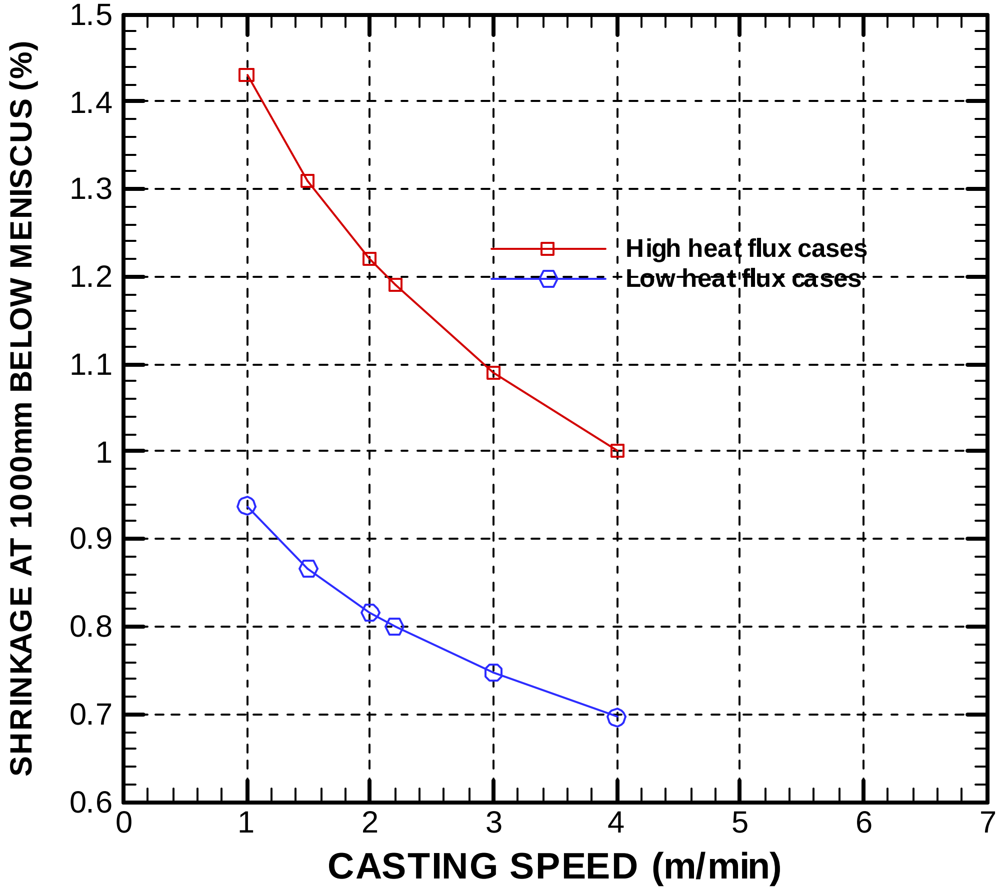


V=4.4m/min

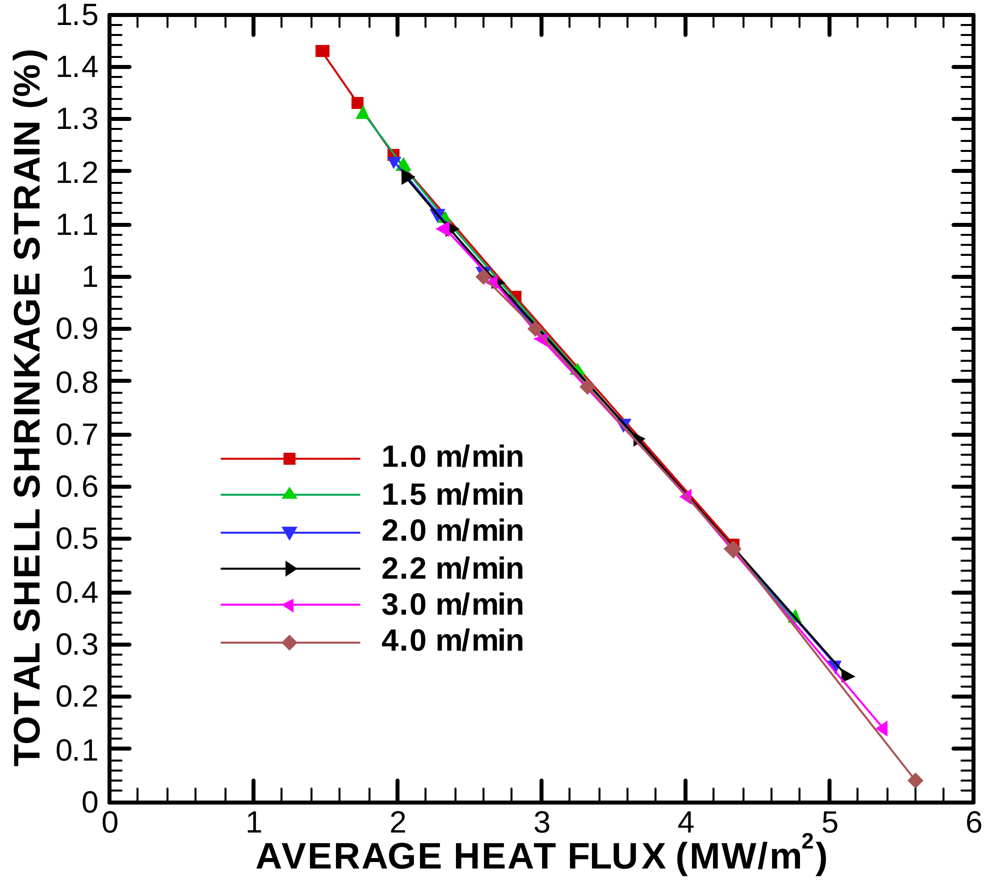
Shrinkage Predicted by Slice Model



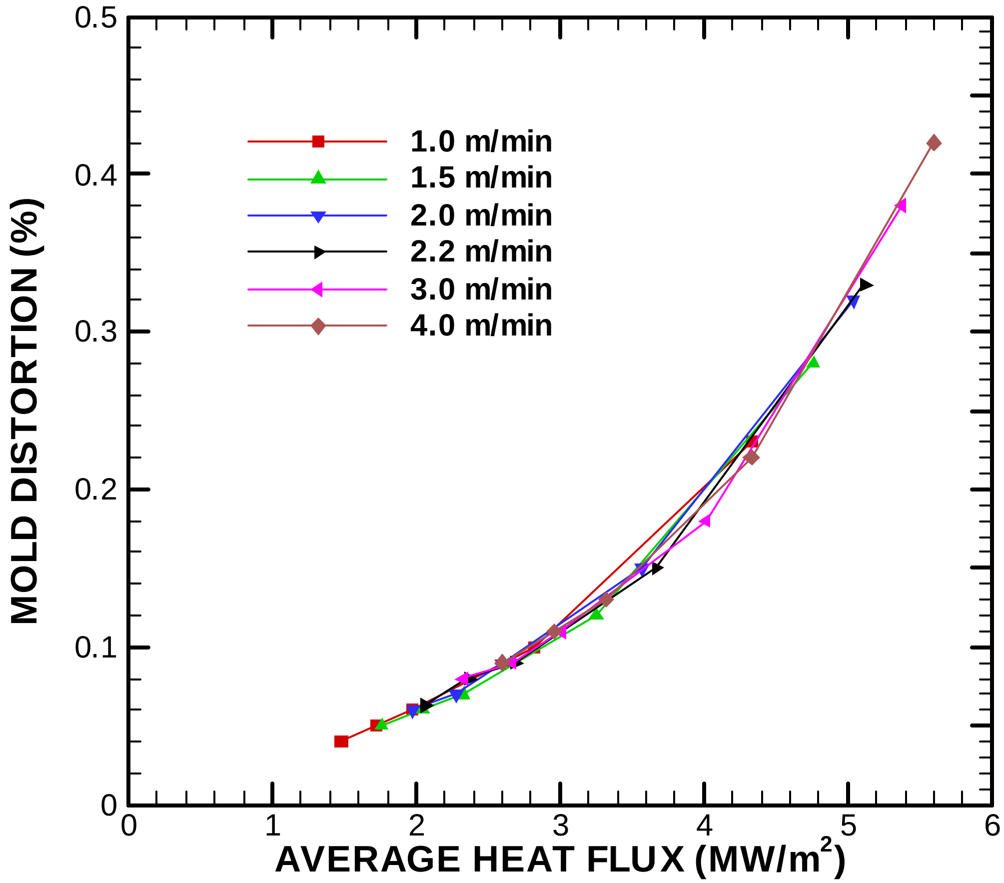
Shrinkage vs. Casting Speed



Shrinkage vs. Average Heat Flux



Mold Distortion vs. Average Heat Flux



* Positive mold distortion means negative taper

Conclusions

- *Optimal mold taper should be able to prevent either very hot or very cold corner region in the mold to avoid the possibility of excessive bulging and transverse surface or subsurface corner cracks .*
- *2D thermal stress analysis with slice domain is preferable for ideal taper investigation.*
- *Lesser amount of mold taper is needed when the casting speed is increased or the total amount of heat extracted by mold is decreased.*

Future Work

- *Further investigate the shell behavior in more realistic spray pattern.*
- *Predict mold shape needed to produce uniform surface temperature around perimeter.*
- *More advanced computational techniques to increase simulation speed and accuracy, such as parallel computation.*