Maximum Casting Speed for CC steel billets with no submold support

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Objective

- Analyze bulging below the mold due to ferrostatic pressure
- Determine critical casting speed as a function of section size and mold length

Model Descriptions

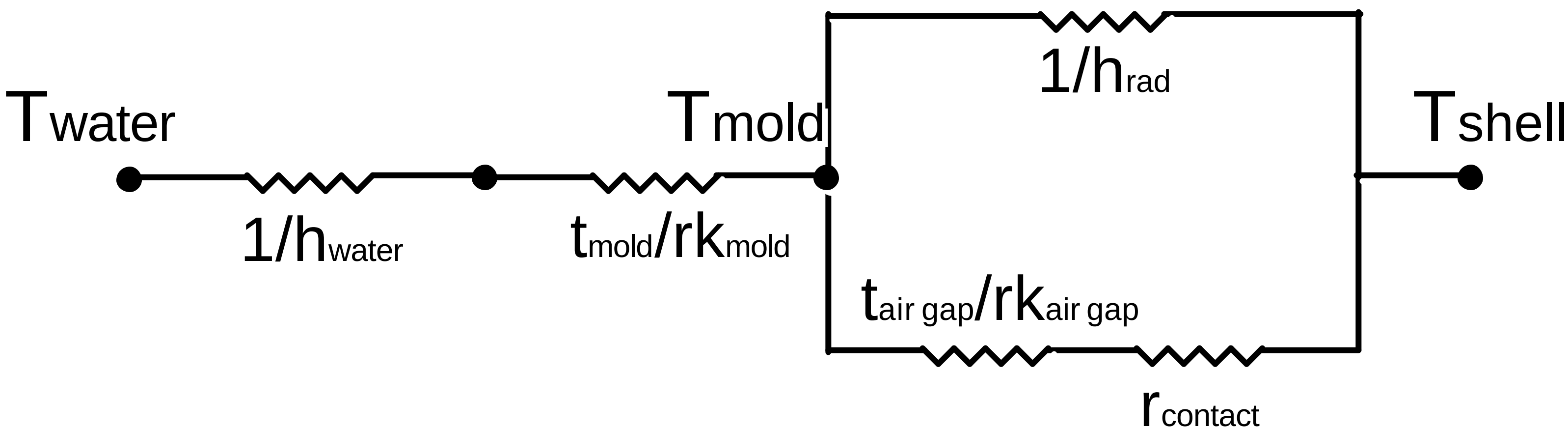
- Finite element thermal stress model
- Phase fractions from non-equilibrium Fe-C phase diagram for plain carbon steel
- Recalescence and kinetics neglected
- Linear phase fraction model between liquidus and solidus for ferritic and austenitic stainless steels
- 2-D generalized plane strain

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

Model Descriptions

- Mizukami elastic modulus data
- Kozlowski constitutional equations for austenite, and modified model for delta-ferrite:
  - Kozlowski Model for Austenite
  - Modified Power Law Model for δ-ferrite

Heat Transfer Model



$$h_{rad} = \frac{s\left(T_{shell} + T_{mold}\right)\left(T_{shell}^{2} + T_{mold}^{2}\right)}{\frac{1}{e_{steel}} + \frac{1}{e_{mold}} - 1}$$

Heat Transfer Model

Where, T_{shell} = surface temperature of the steel shell (°C)

T_{mold} = surface temperature of the mold (outermost coating layer) (°C)

T_{water} = cooling water temperature, reading from CON1D output (°C)

h_{rad} =effective radiation heat transfer coefficient (W/m^{2}K)

h_{water} =effective heat transfer coefficient between cooling water and mold cold face , reading from CON1D output (W/m^{2}K)

$r_{contact}$ = strand/mold contact resistance, 5.6e-4

t_{mold} = thickness of the mold wall, 6mm

$t_{air\ gap}$ = thickness of the air gap (mm)

rk_{mold} = conductivity of the copper mold, 360W/mK

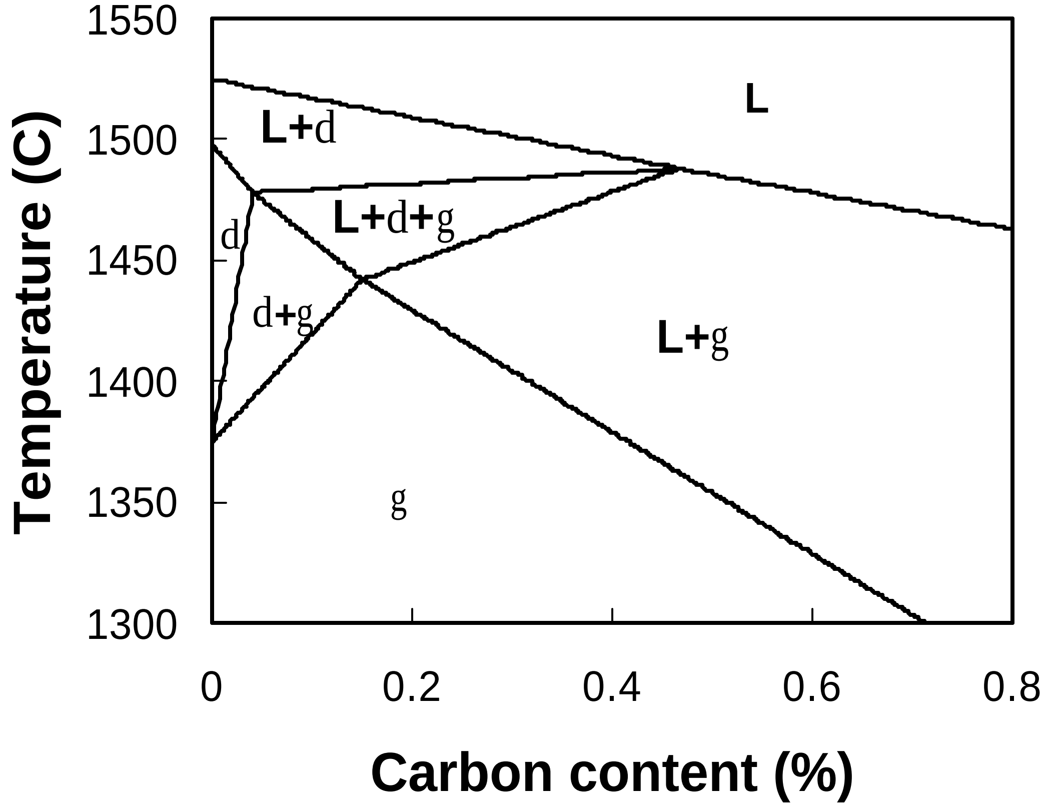
$rk_{air\ gap}$ = conductivity of the air gap, 0.1W/mK

σ = Stefan Boltzman constant, 5.67e-8W/m^{2}K^4

ε_{steel} = steel surface emissivity, 0.8

ε_{mold} = mold surface emissivity, 0.5

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

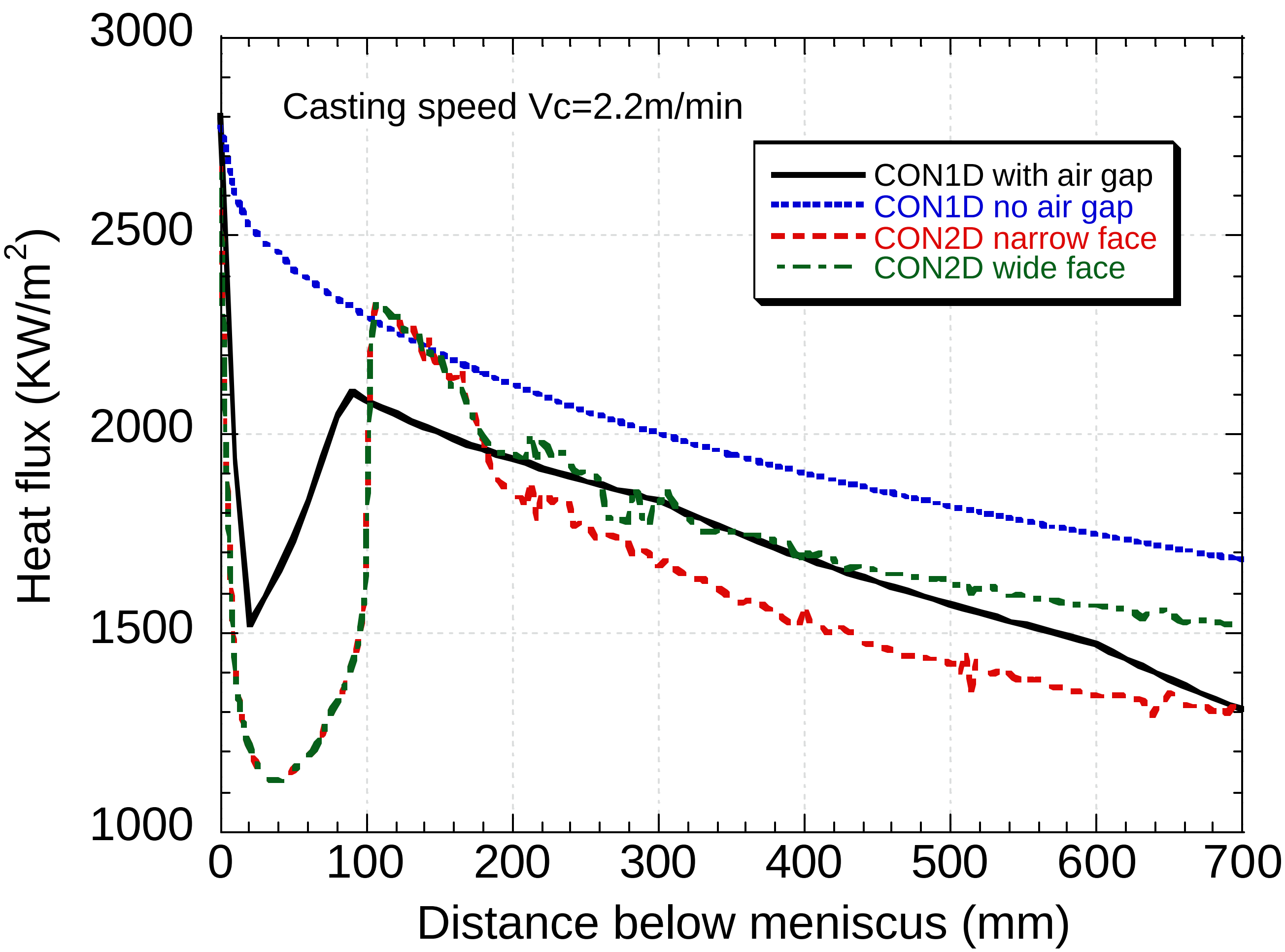


- *Young Mok WON et. al., Effect of Cooling Rate on ZST, LIT, ZDT of Carbon Steels Near Melting Point", ISIJ International, Vol. 38, 1998, No. 10, pp. 1093 –1099
- **Other Steel Components: 1.52%Mn, 0.34%Si, 0.015%S, 0.012%P

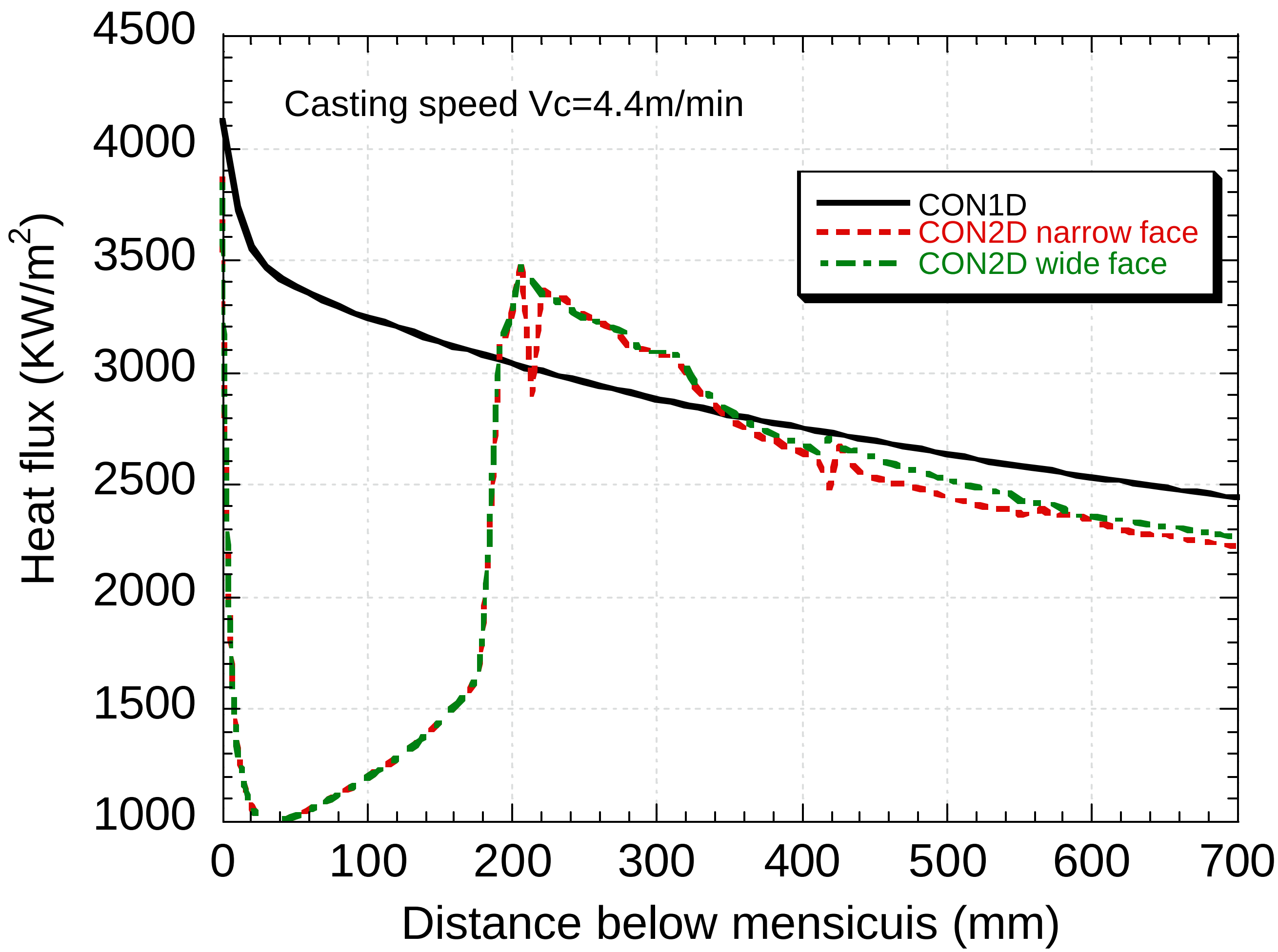
Conditions

	Case 1	Case 2	Unit
Casting Speed:	**2.2**	**4.4**	**m/min**
Pour Temperature:	**1540**	**1540**	**ºC**
Slab Geometry:	**120 *120**	**120*120**	**mm*mm**
Meniscus Level:	**100**	**100**	**mm**
Working Mold Length:	**700**	**700**	**mm**
Carbon Content:	**0.1**	**0.27**	**wt%**
Liquidus Temperature:	**1516.01**	**1500.72**	**ºC**
Solidus Temperature:	**1460.72**	**1411.79**	**ºC**
Mold Thickness (with Water Channel):	**6**	**6**	**mm**
Mold Taper:	**0.75**	**0.75**	**%/m**
Mold Conductivity:	**360**	**360**	**W/mK**
Initial Mold Cooling Water Temperature:	**30**	**30**	**ºC**
Cooling Water Flow rate:	**1100**	**1100**	**l/m**
Cooling Water Velocity:	**6.6**	**6.6**	**m/s**
Air Conductivity:	**0.1**	**0.06**	**W/mK**
Contact Resistance:	**5.6e-4**	**3.5e-5**	**m^2K/W**

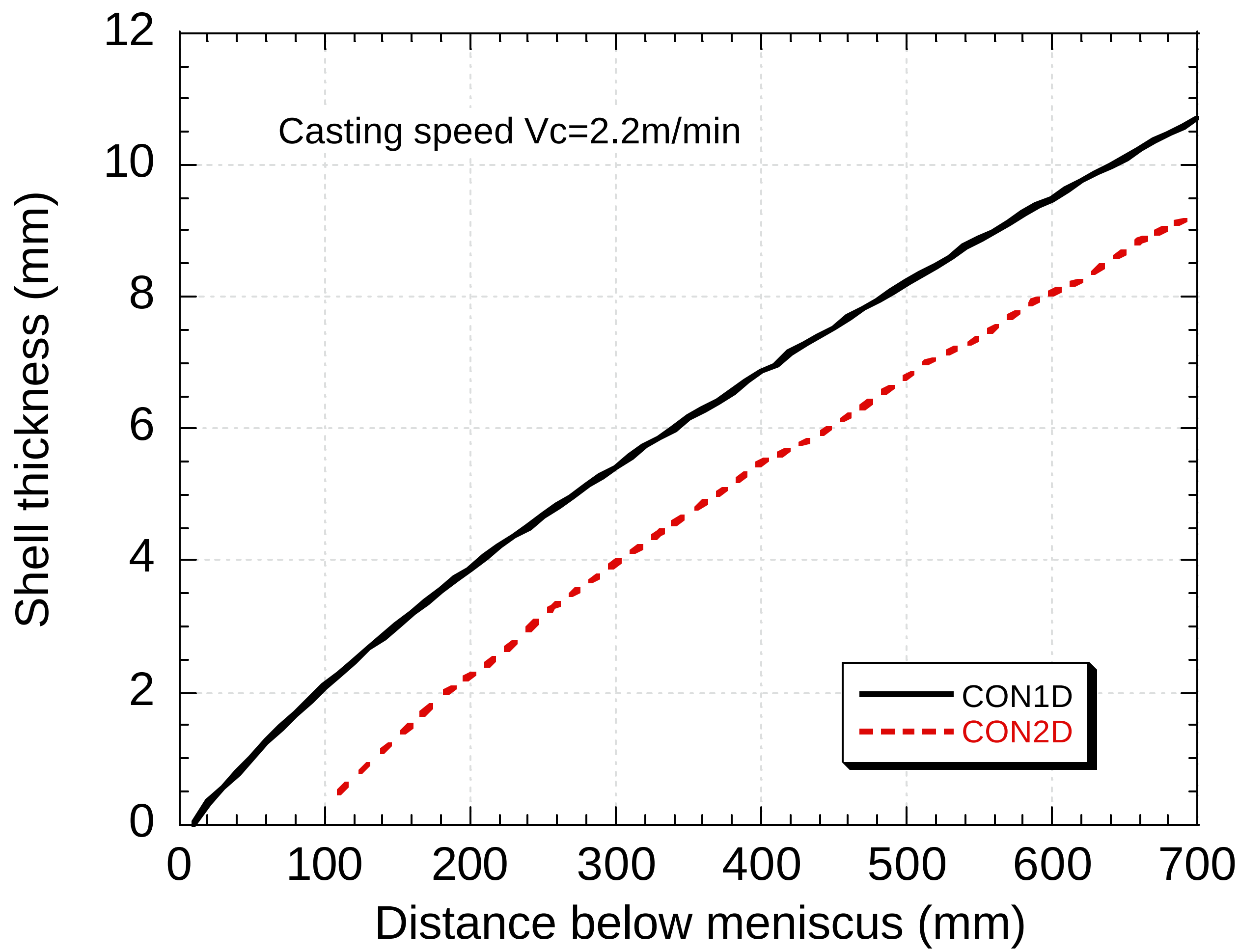
Heat Flux Comparison: Case 1



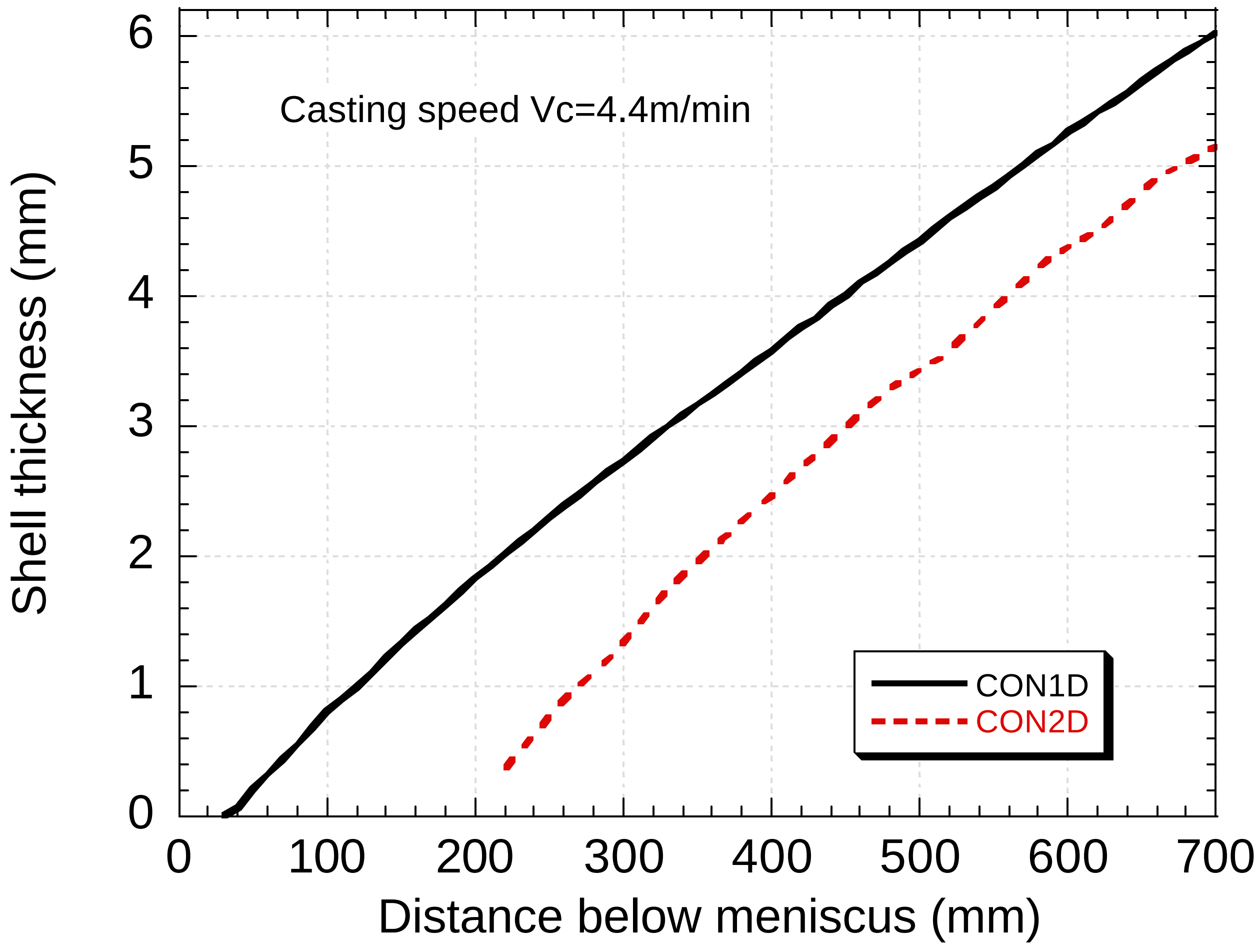
Heat Flux Comparison: Case 2



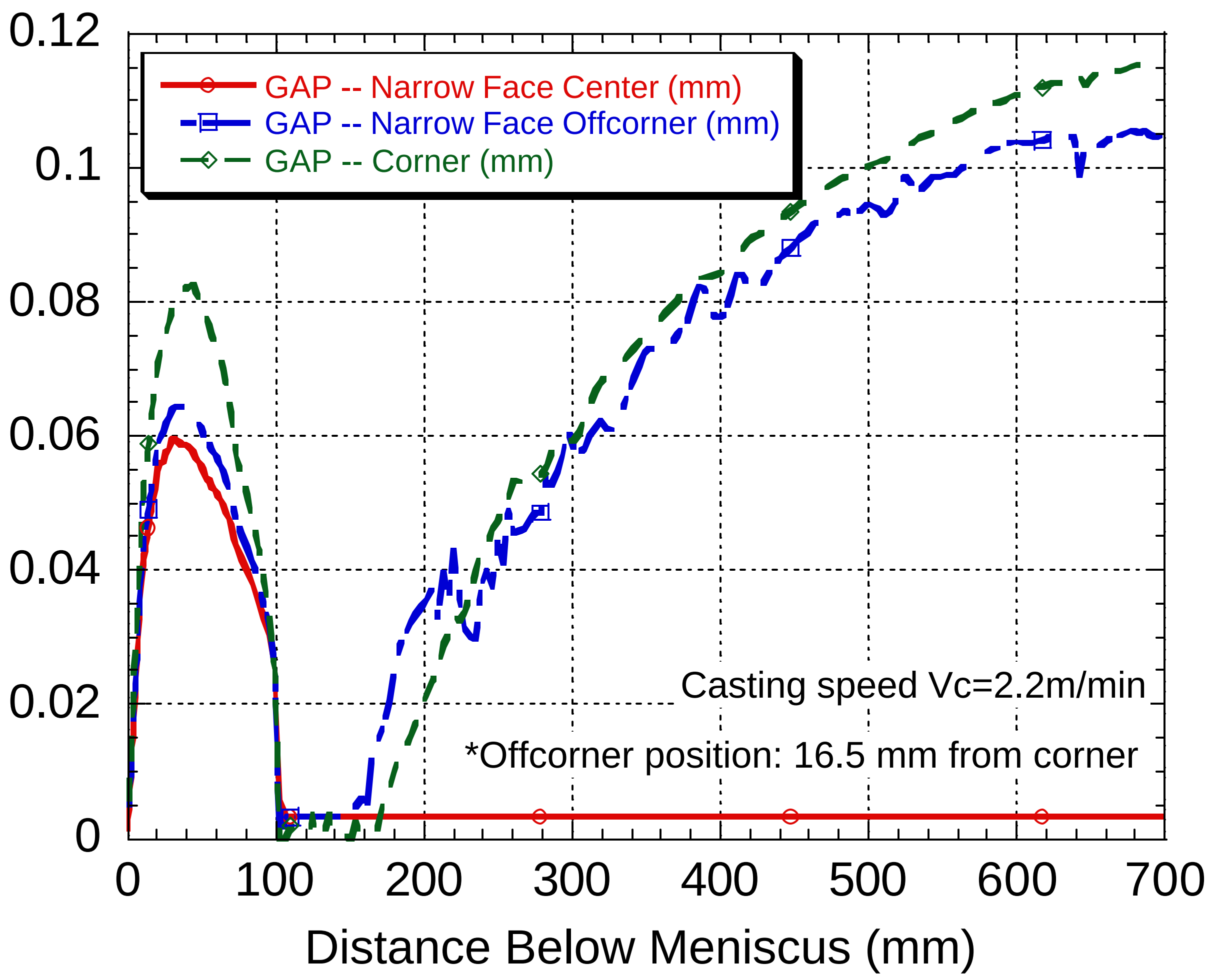
Shell Thickness Comparison: Case 1



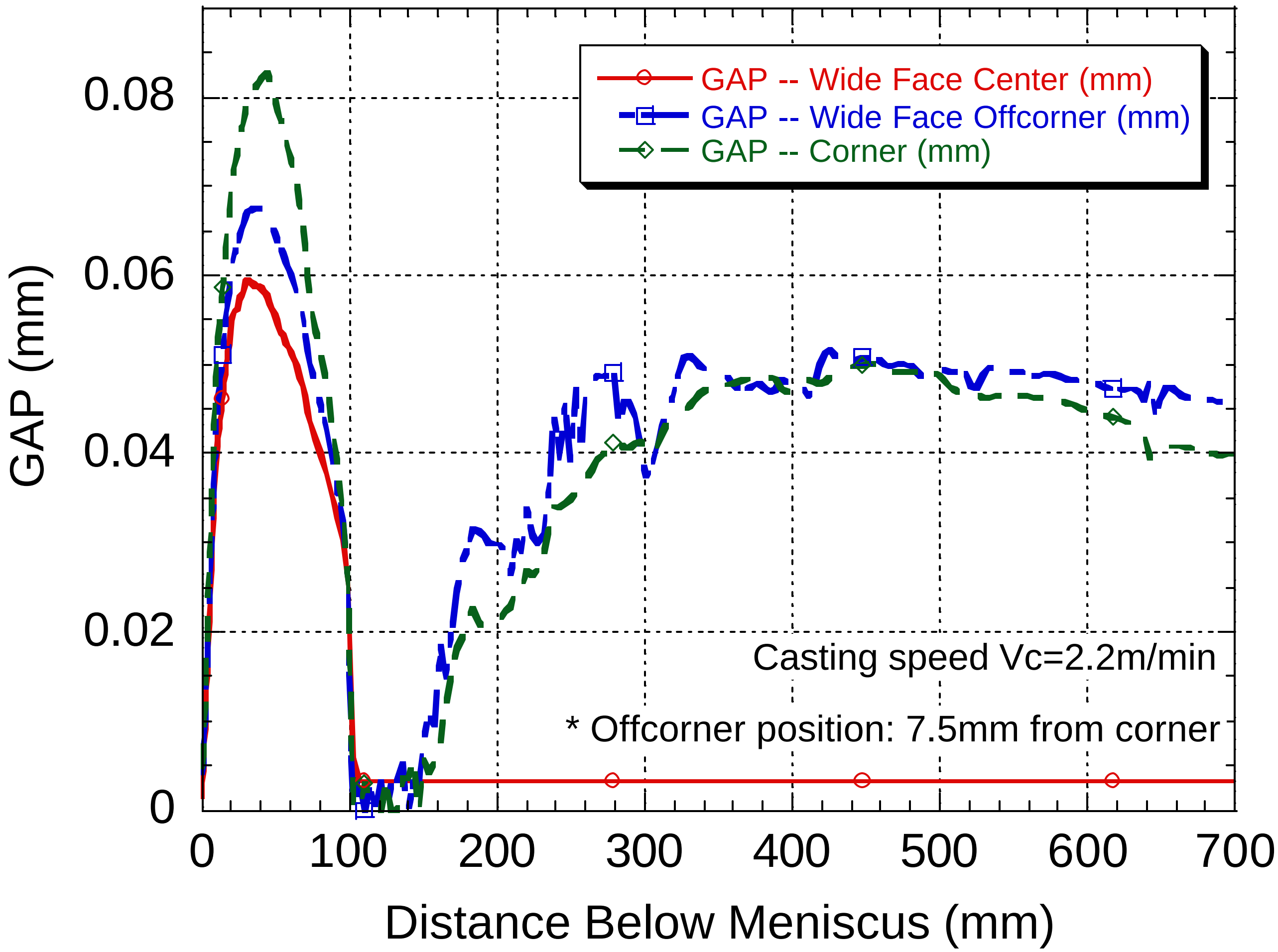
Shell Thickness Comparison: Case 2



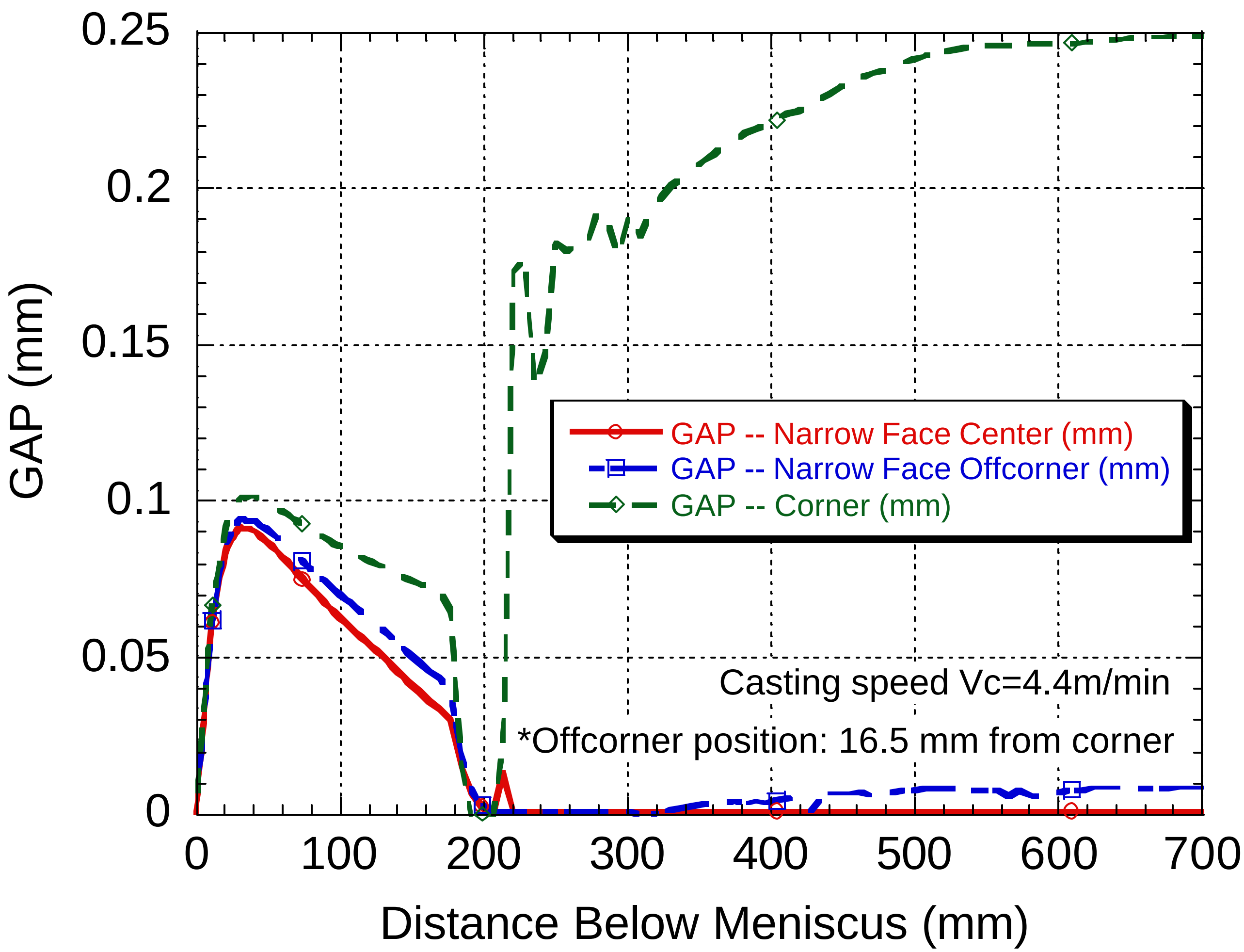
Narrow Face Gaps: Case 1



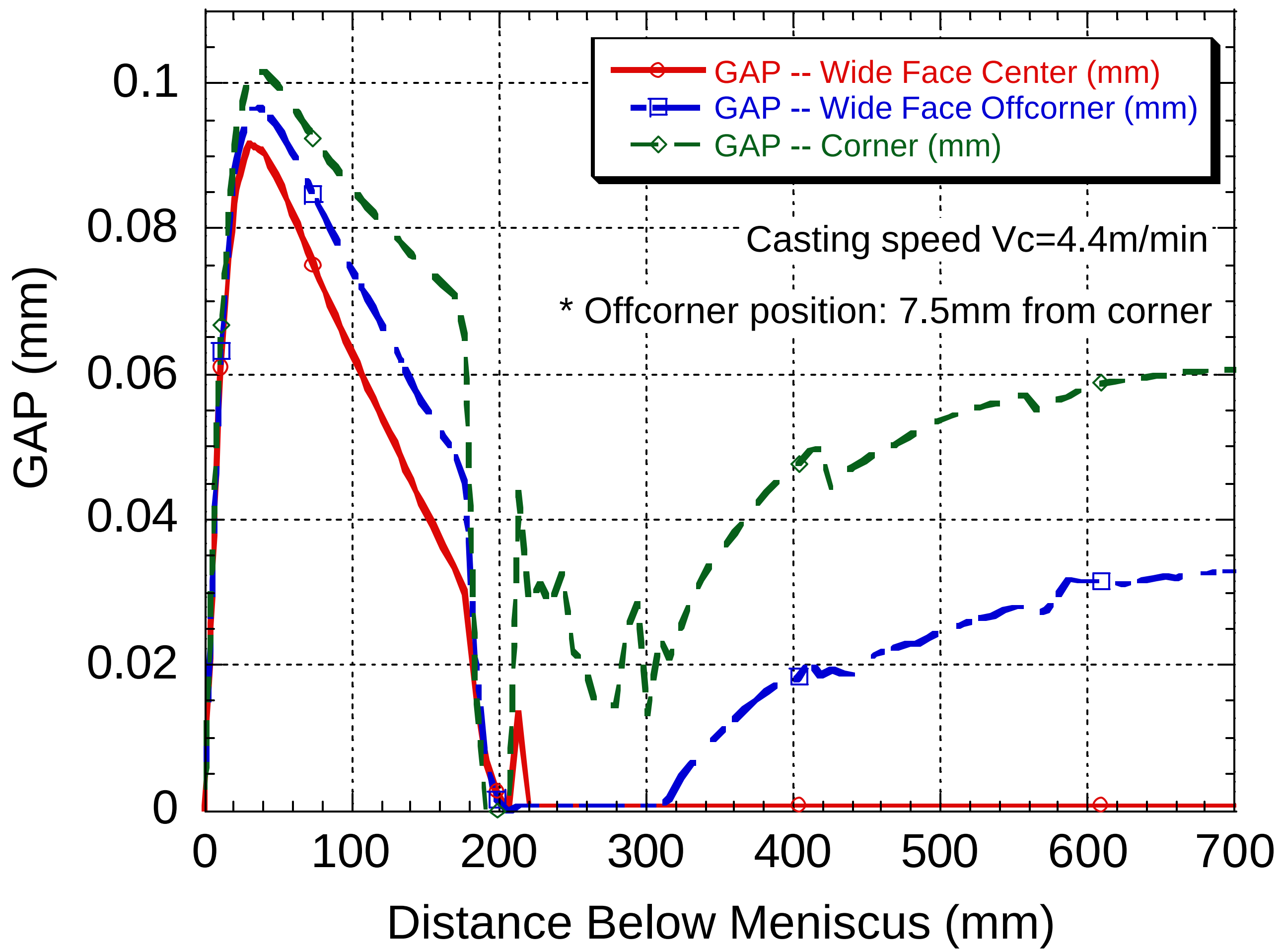
Wide Face Gaps: Case 1

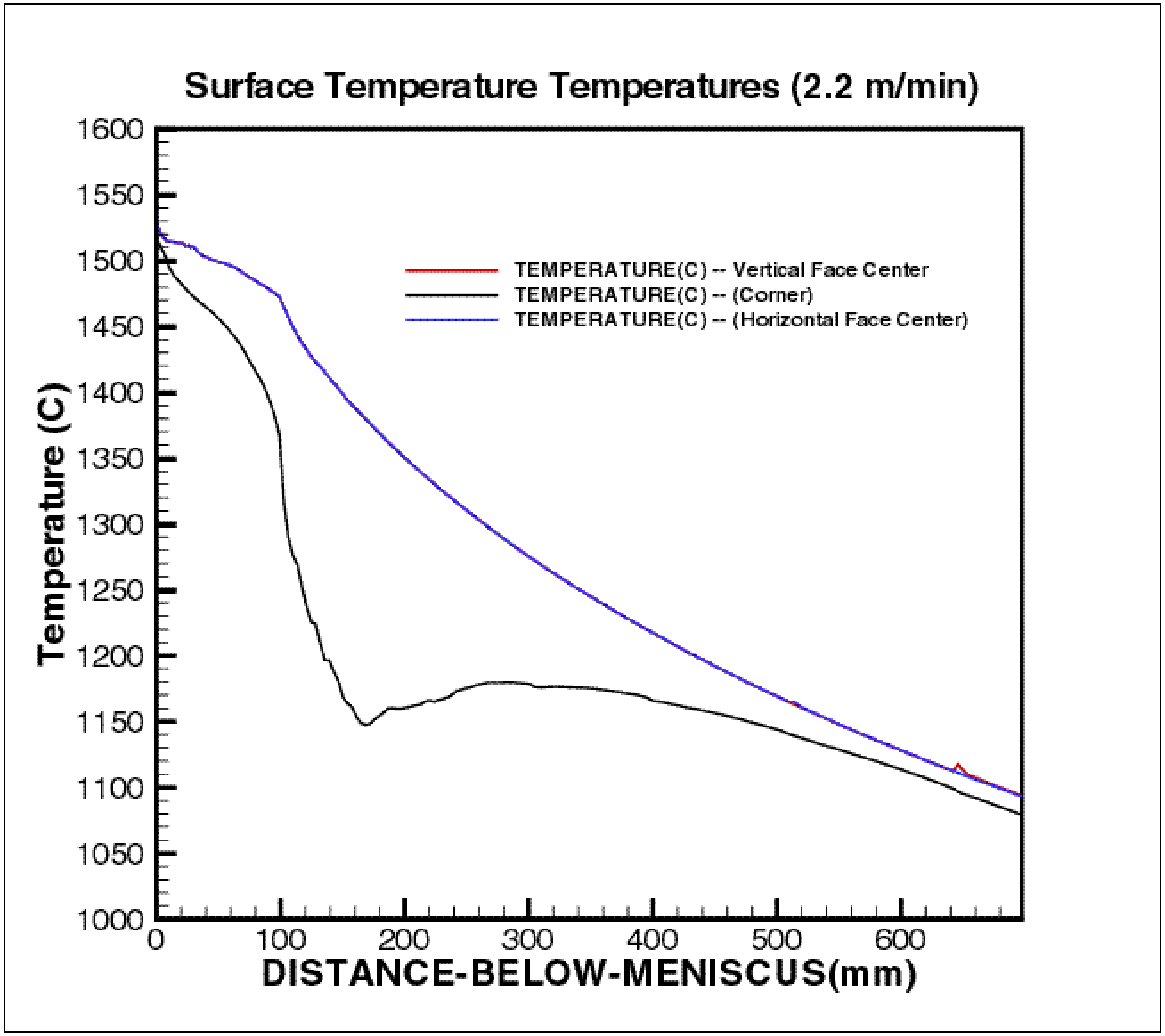


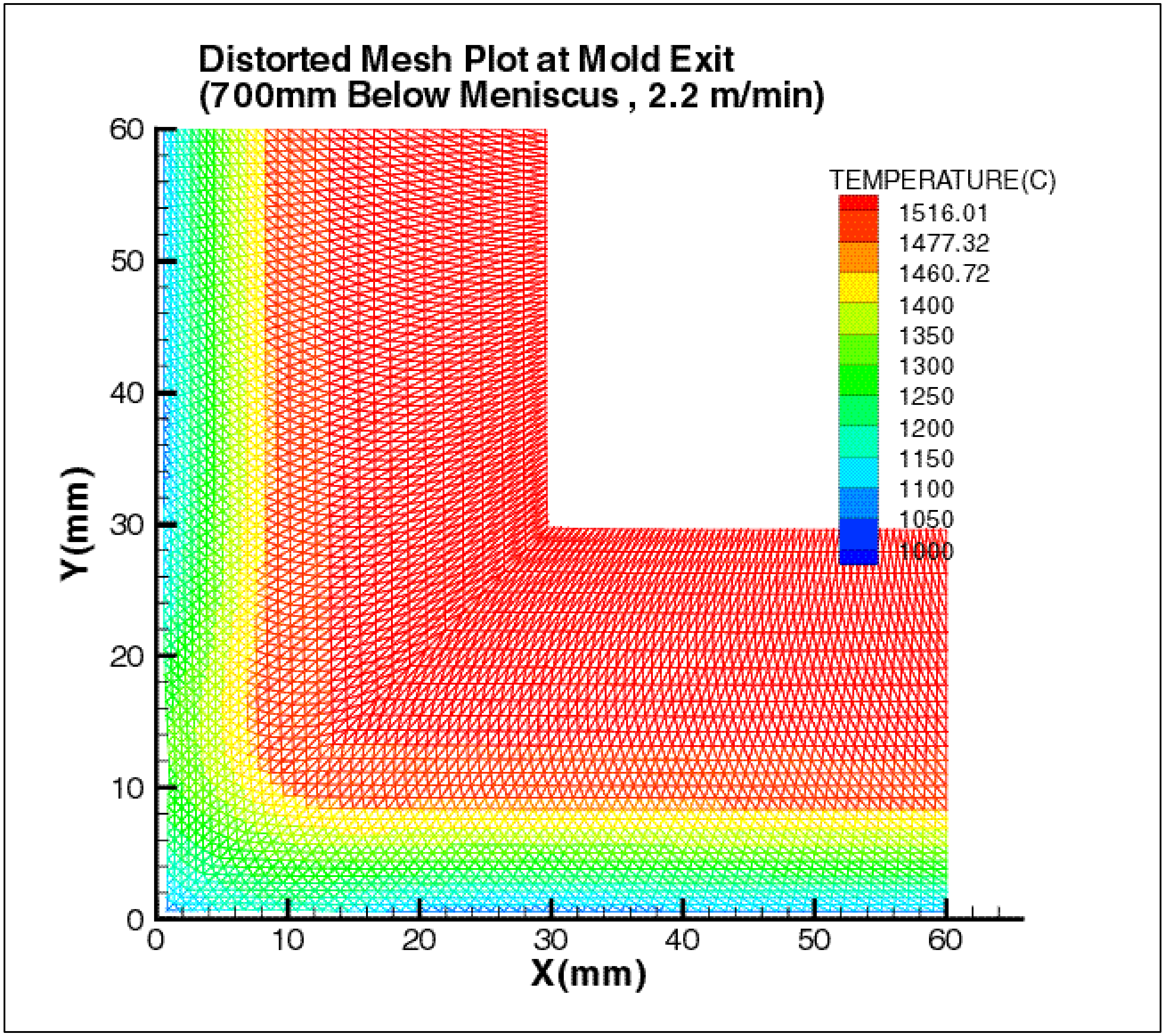
Narrow Face Gaps: Case 2

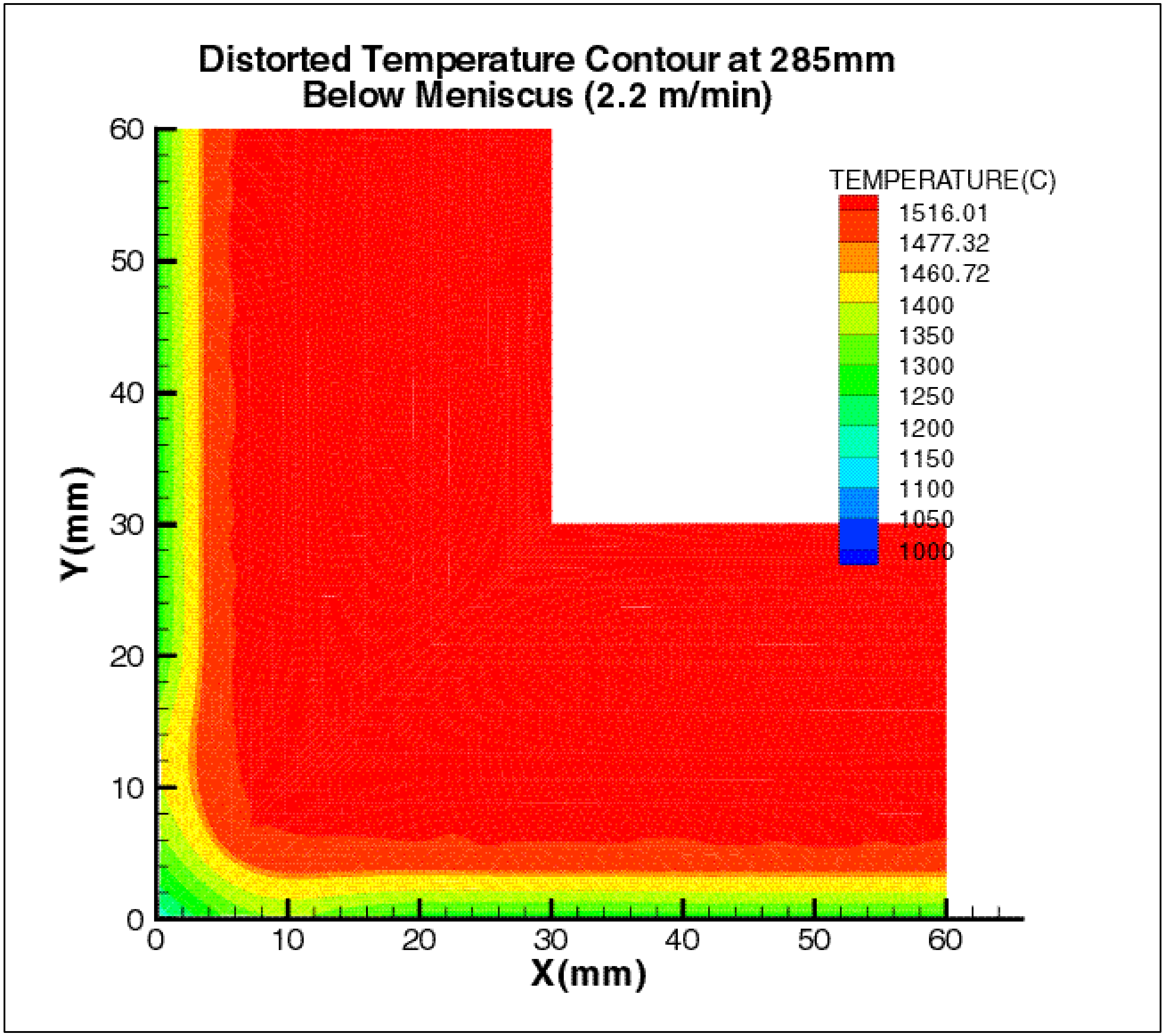


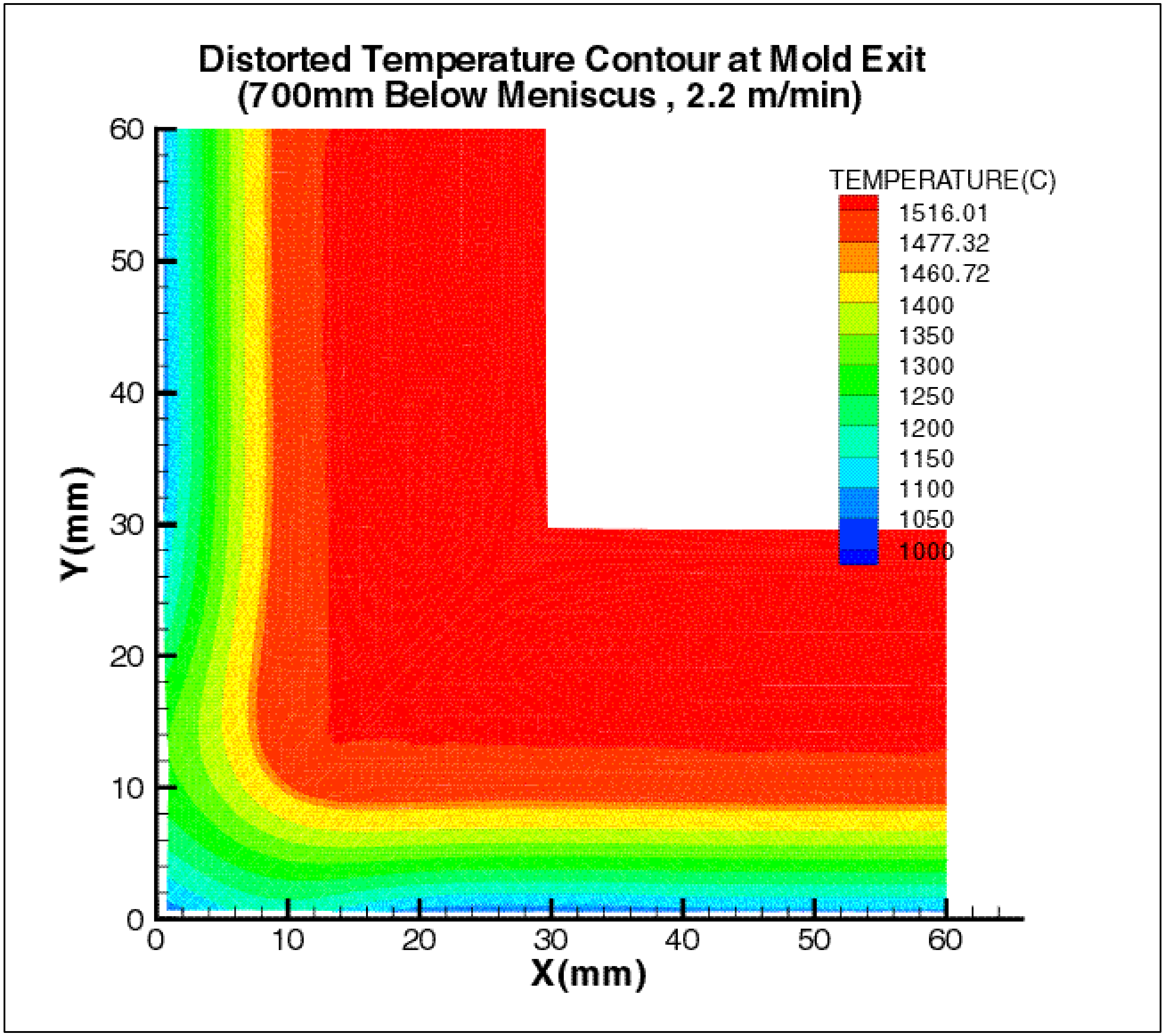
Wide Face Gaps: Case 2

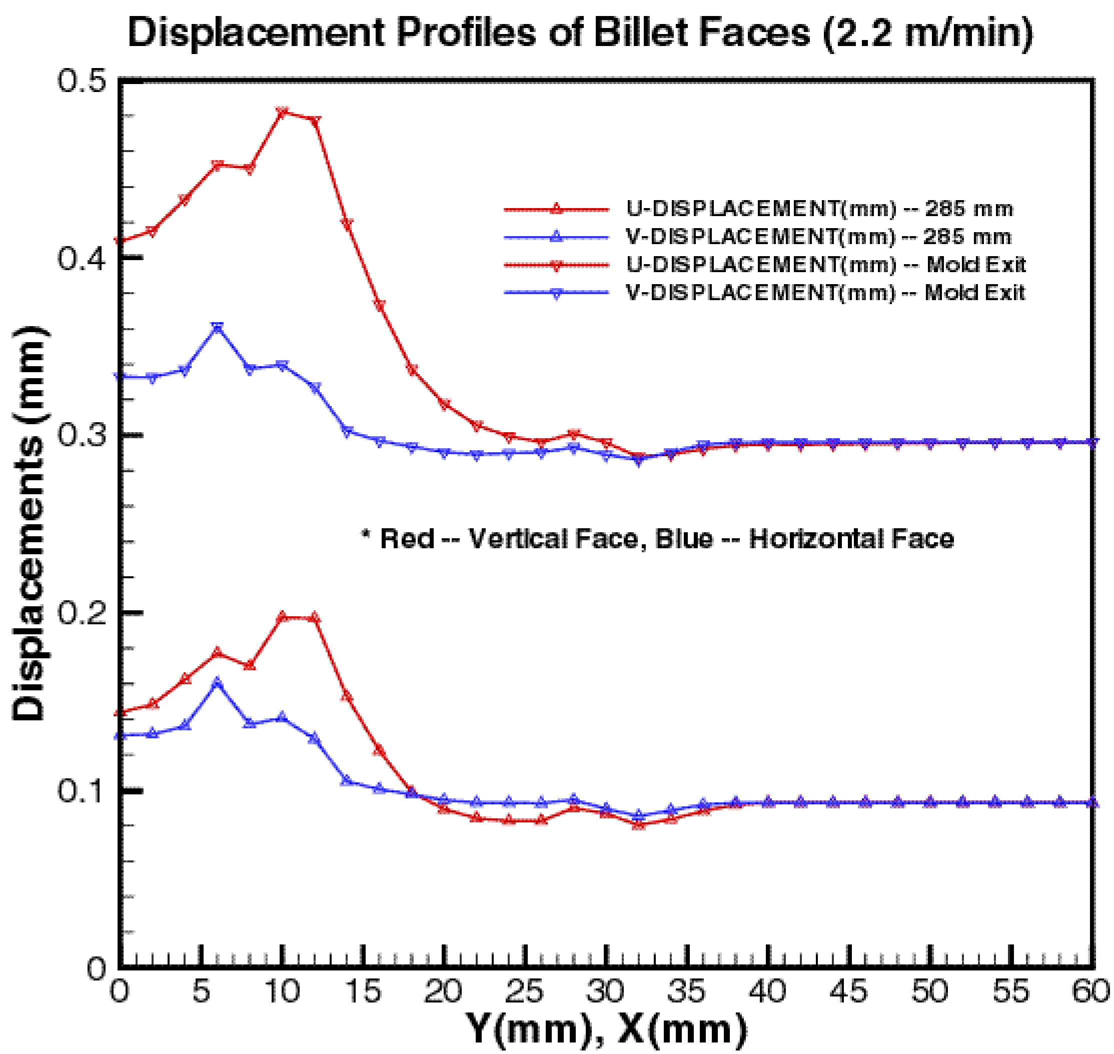


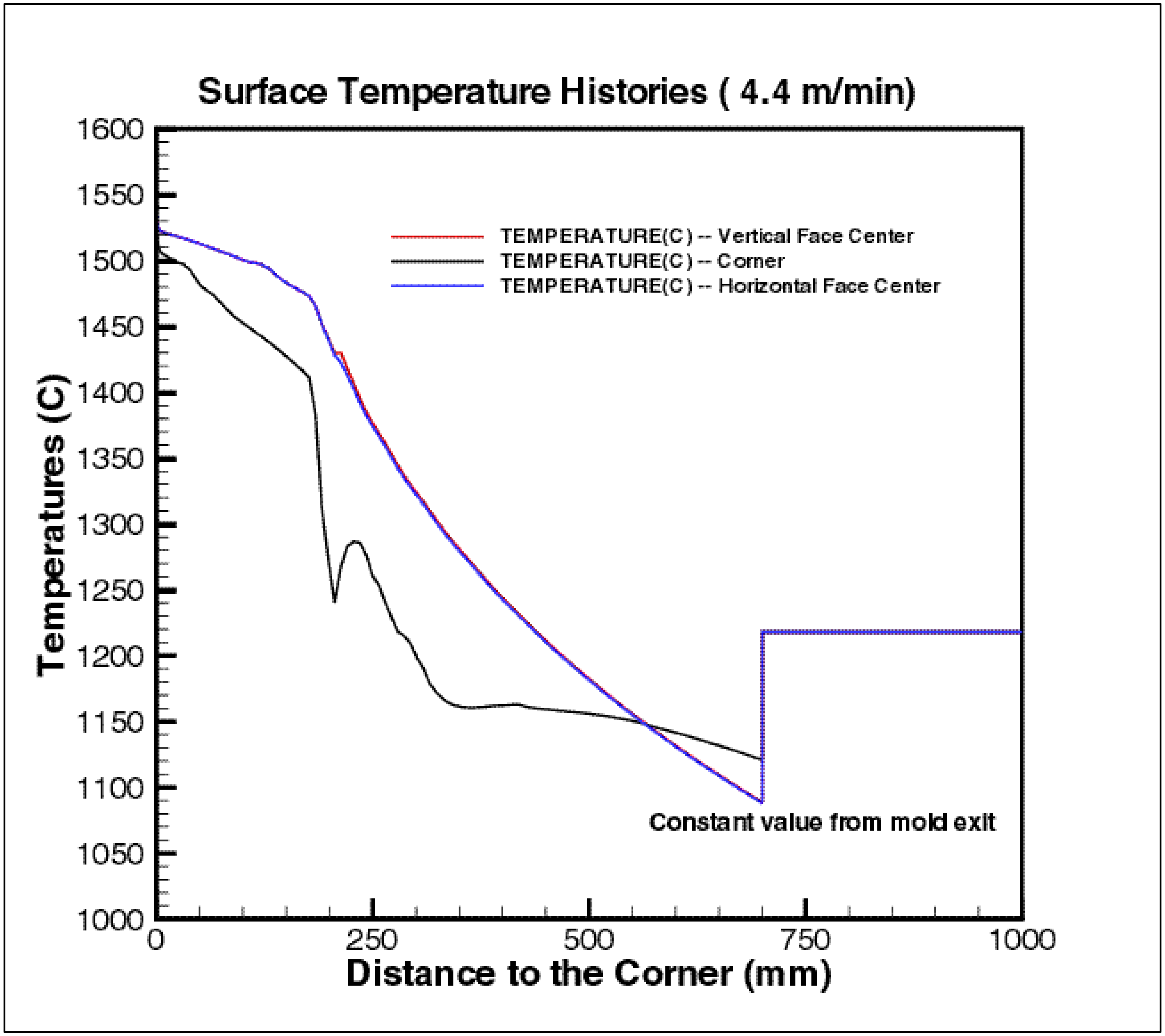

Surface Temperature Temperatures (2.2 m/min)
TEMPERATURE(C) -- Vertical Face Center
TEMPERATURE(C) -- (Corner)
TEMPERATURE(C) -- (Horizontal Face Center)
Temperature (C)
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
0
100
200
300
400
500
600
DISTANCE-BELOW-MENISCUS(mm)

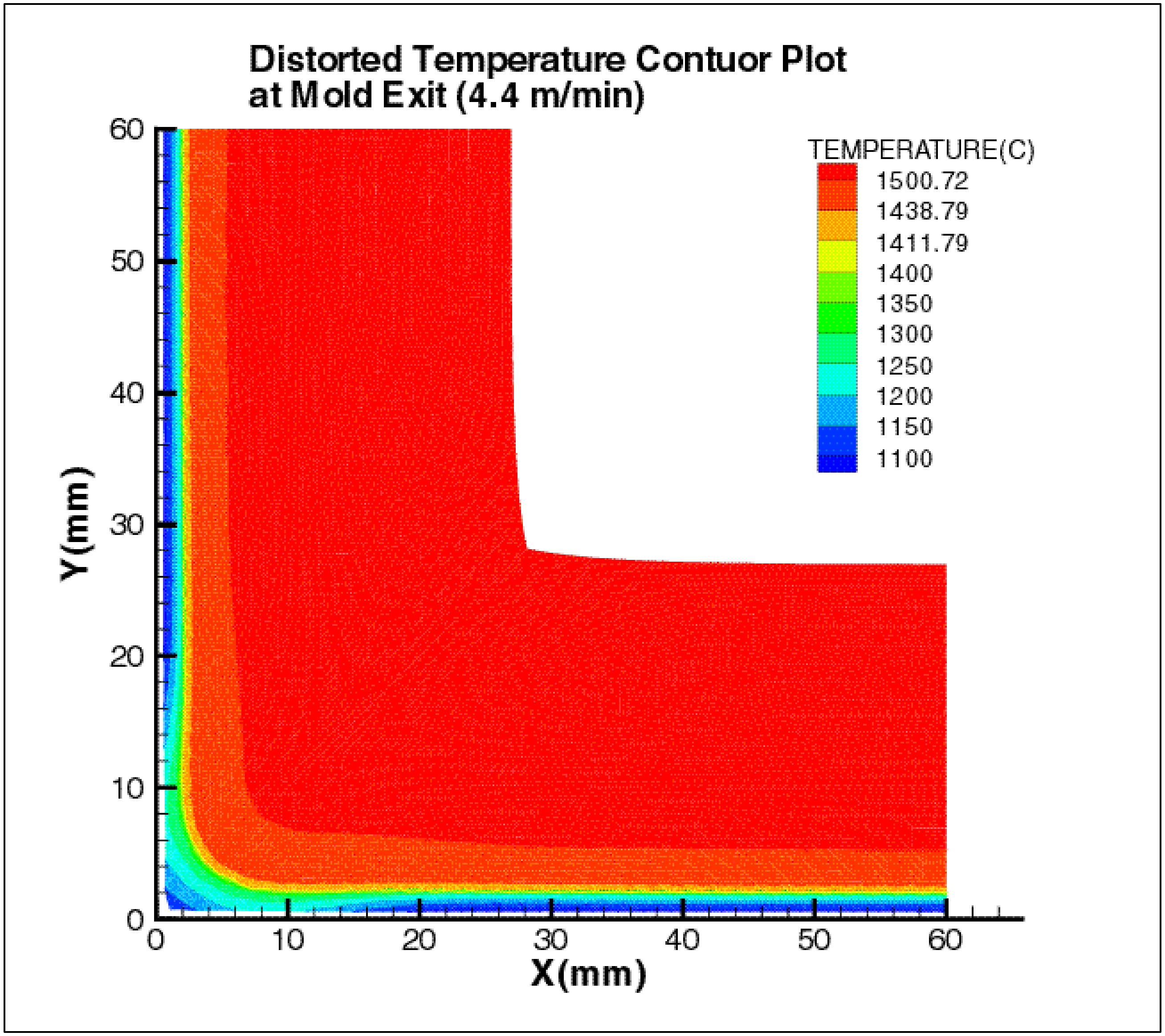

Distorted Mesh Plot at Mold Exit
(700mm Below Meniscus , 2.2 m/min)
TEMPERATURE(C)
1516.01
1477.32
1460.72
1400
1350
1300
1250
1200
1150
1100
1050
1000
Y(mm)
X(mm)
0
10
20
30
40
50
60

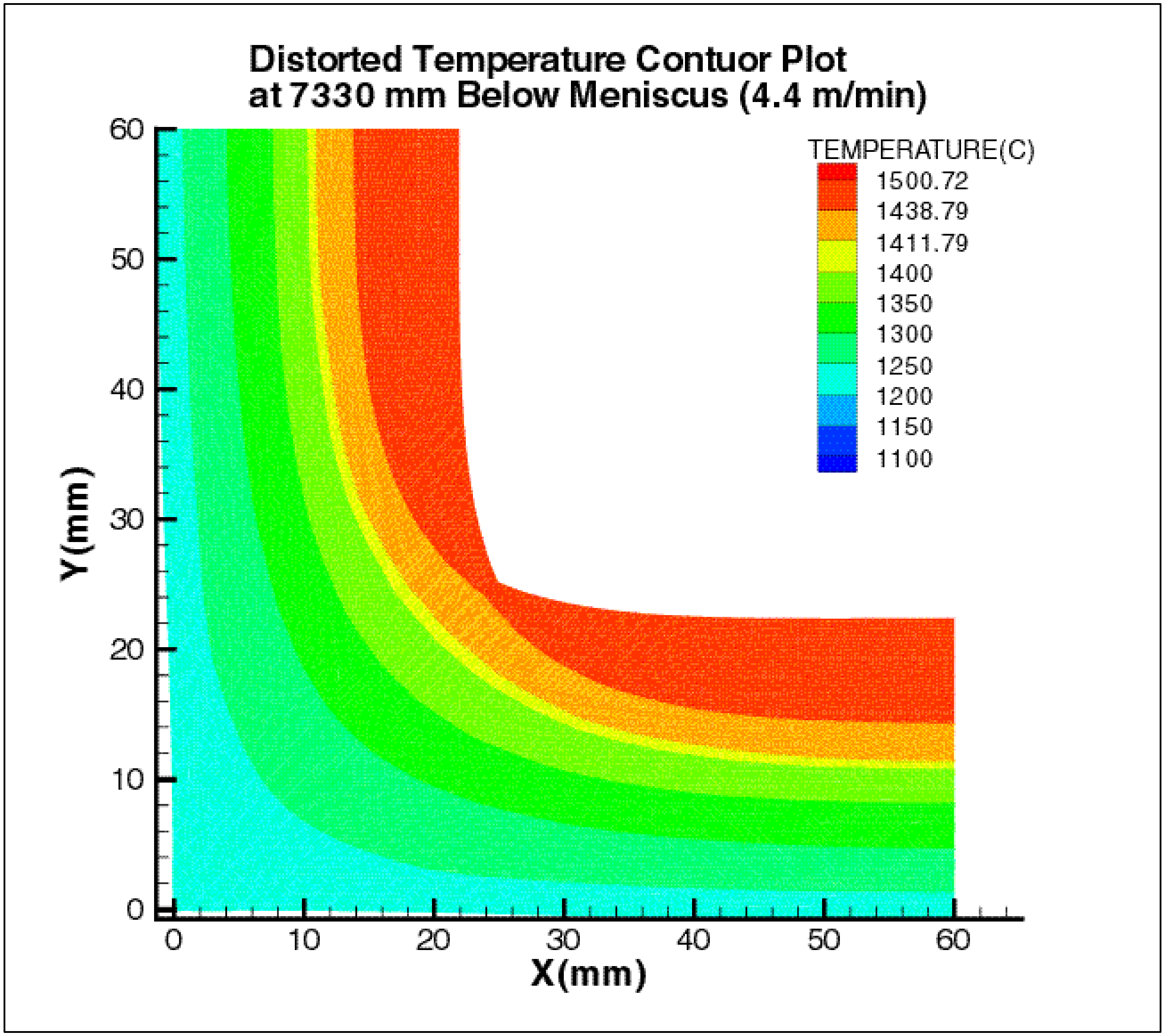

Distorted Temperature Contour at 285mm
Below Meniscus (2.2 m/min)
TEMPERATURE(C)
1516.01
1477.32
1460.72
1400
1350
1300
1250
1200
1150
1100
1050
1000
Y(mm)
X(mm)
0
10
20
30
40
50
60

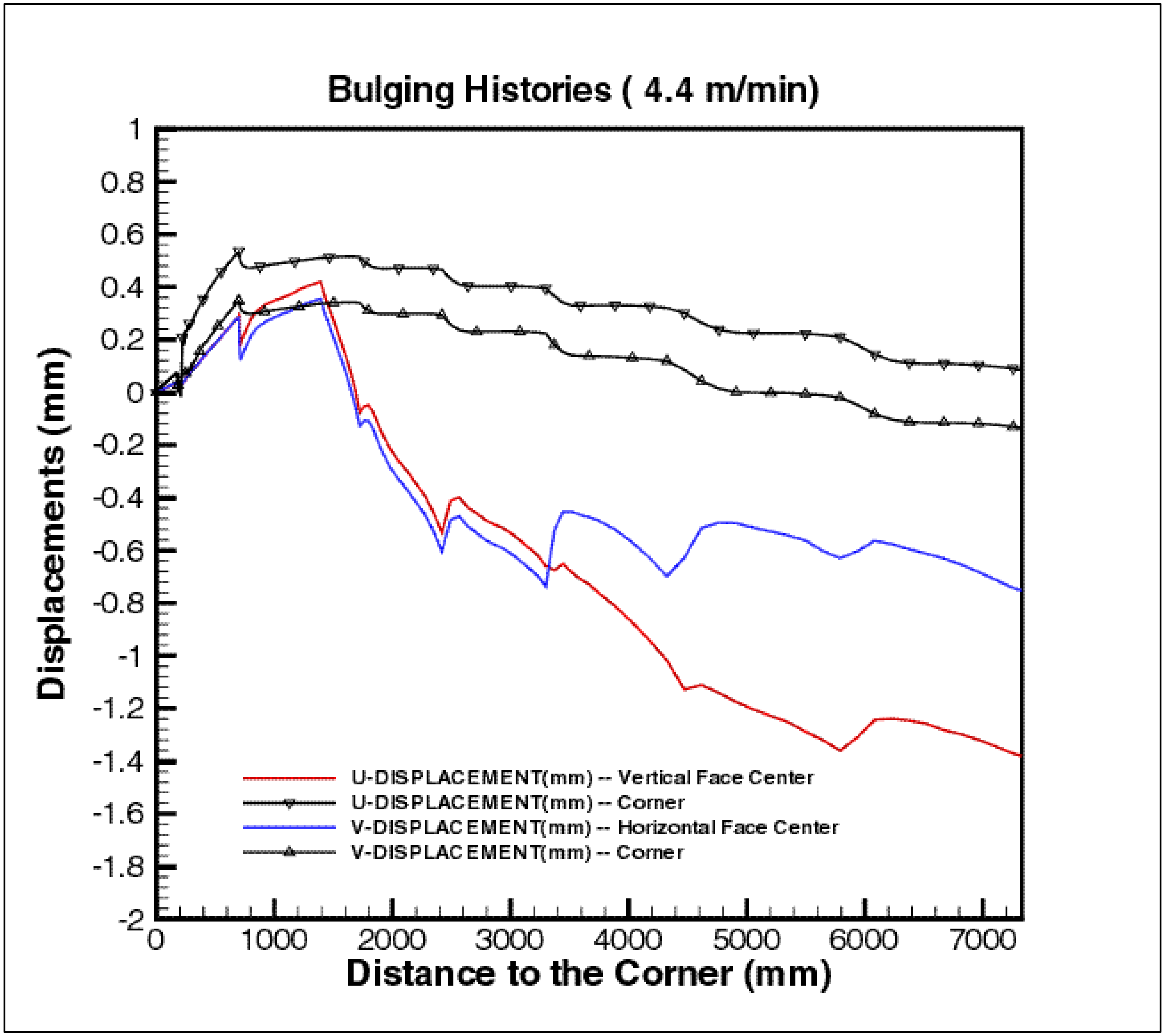

Distorted Temperature Contour at Mold Exit
(700mm Below Meniscus , 2.2 m/min)
TEMPERATURE(C)
1516.01
1477.32
1460.72
1400
1350
1300
1250
1200
1150
1100
1050
1000
Y(mm)
X(mm)
0
10
20
30
40
50
60

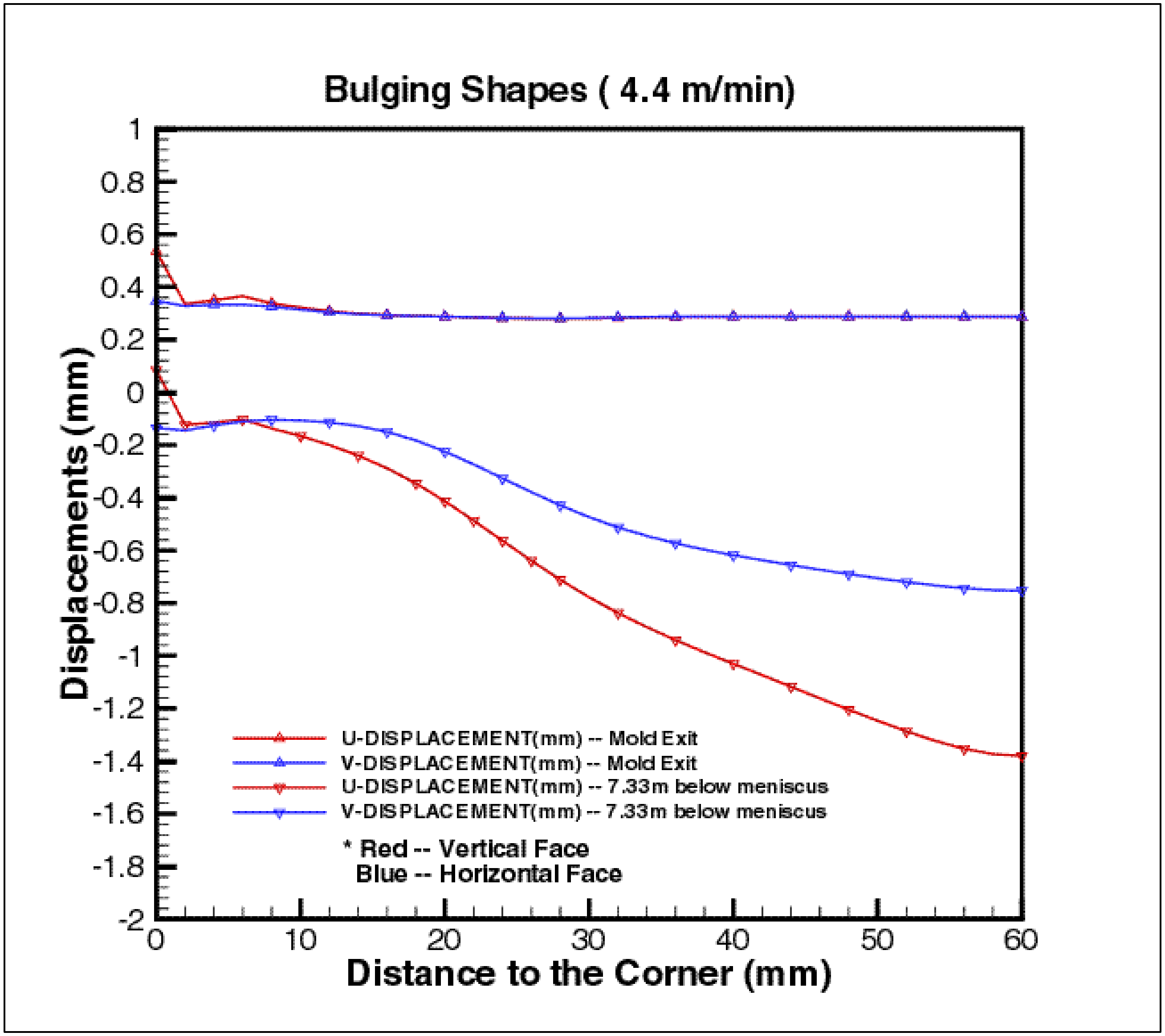

Displacement Profiles of Billet Faces (2.2 m/min)
U-DISPLACEMENT(mm) -- 285 mm
V-DISPLACEMENT(mm) -- 285 mm
U-DISPLACEMENT(mm) -- Mold Exit
V-DISPLACEMENT(mm) -- Mold Exit
* Red -- Vertical Face, Blue -- Horizontal Face
Displacements (mm)
Y(mm), X(mm)
0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20
25
30
35
40
45
50
55
60


Surface Temperature Histories (4.4 m/min)
TEMPERATURE(C) -- Vertical Face Center
TEMPERATURE(C) -- Corner
TEMPERATURE(C) -- Horizontal Face Center
Constant value from mold exit
Temperatures (C)
Distance to the Corner (mm)
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
0
250
500
750
1000


Distorted Temperature Contuor Plot
at Mold Exit (4.4 m/min)
TEMPERATURE(C)
1500.72
1438.79
1411.79
1400
1350
1300
1250
1200
1150
1100
Y(mm)
X(mm)
0
10
20
30
40
50
60


Distorted Temperature Contuor Plot
at 7330 mm Below Meniscus (4.4 m/min)
TEMPERATURE(C)
1500.72
1438.79
1411.79
1400
1350
1300
1250
1200
1150
1100
Y(mm)
X(mm)
0
10
20
30
40
50
60


Bulging Histories (4.4 m/min)
Displacements (mm)
Distance to the Corner (mm)
U-DISPLACEMENT(mm) -- Vertical Face Center
U-DISPLACEMENT(mm) -- Corner
V-DISPLACEMENT(mm) -- Horizontal Face Center
V-DISPLACEMENT(mm) -- Corner
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0
1000
2000
3000
4000
5000
6000
7000


Bulging Shapes (4.4 m/min)
Displacements (mm)
Distance to the Corner (mm)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
0
10
20
30
40
50
60
U-DISPLACEMENT(mm) -- Mold Exit
V-DISPLACEMENT(mm) -- Mold Exit
U-DISPLACEMENT(mm) -- 7.33m below meniscus
V-DISPLACEMENT(mm) -- 7.33m below meniscus
* Red -- Vertical Face
Blue -- Horizontal Face

Critical Fracture Strain

Critical strain for 0.27%C steel is 4%*

$$e_c = \frac{j}{\dot{e}^{m^*} \Delta T_B^{n^*}}$$

$$where:$$

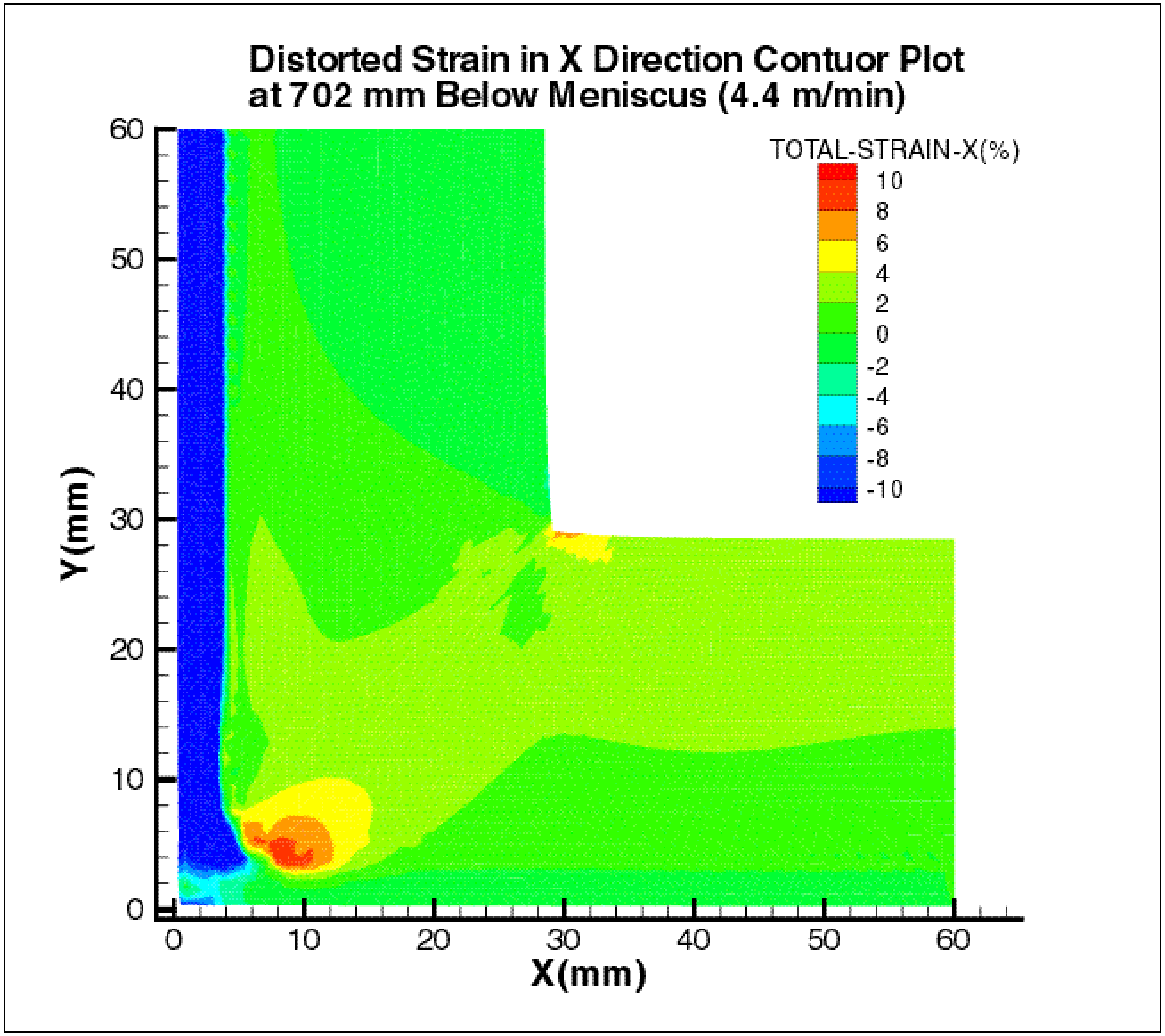
$$\Delta T_B = T(f_s = 0.9) - T(f_s = 0.99)$$

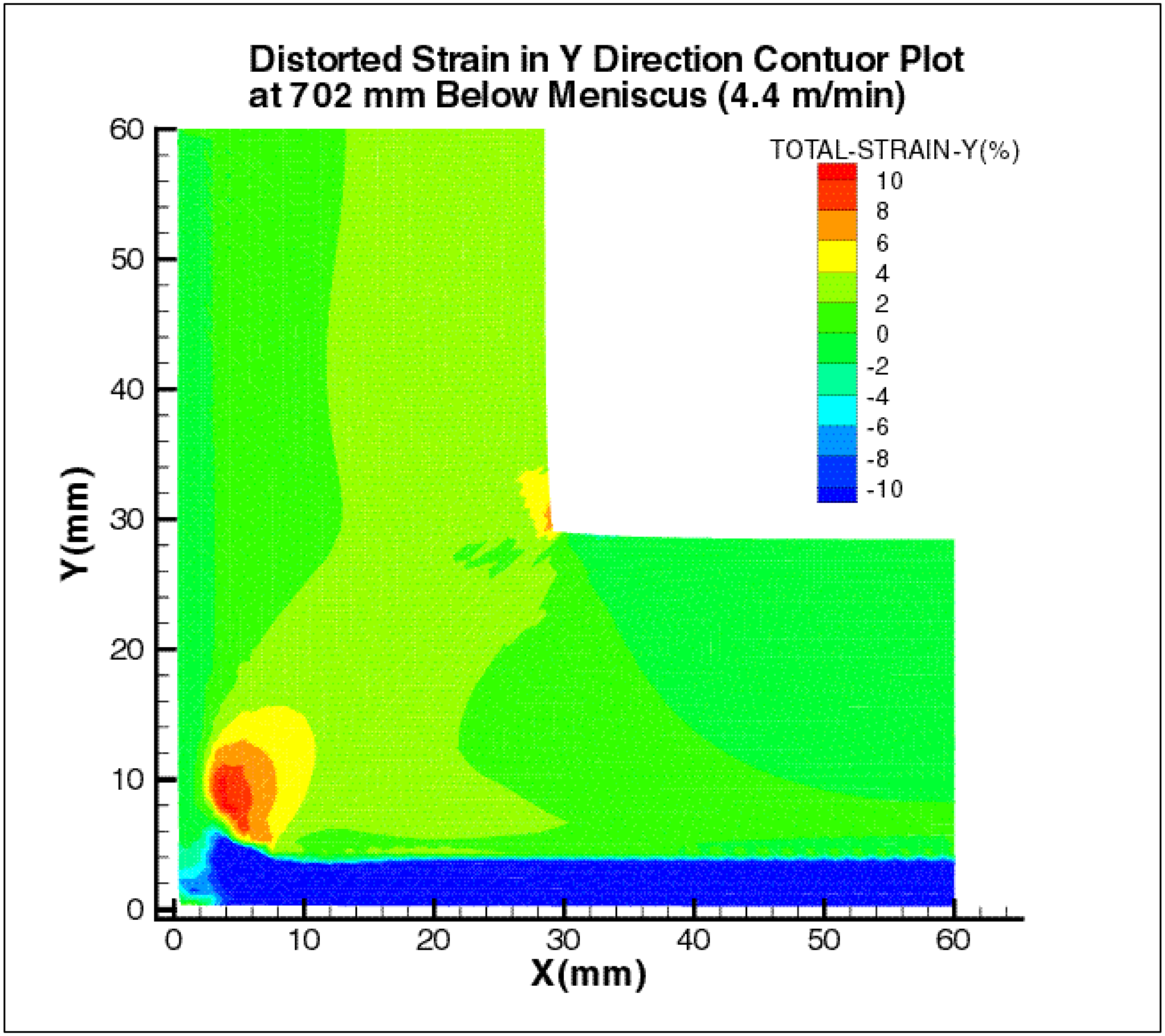
$$m^* = 0.3131,\ n^* = 0.8638,\ j = 0.02821$$

$$for\ \ 0.27\%C\ \ steel$$

$$\Delta T_B = 9^o C,\ \dot{e} = 7.0e-4s^{-1}$$

** Critical fracture strain is calculated based on the empirical equation above by Y.M. WON et. al. which is to be published in Met. Trans.*


Distorted Strain in X Direction Contuor Plot
at 702 mm Below Meniscus (4.4 m/min)
TOTAL-STRAIN-X(%)
10
8
6
4
2
0
-2
-4
-6
-8
-10
Y(mm)
60
50
40
30
20
10
0
0
10
20
30
40
50
60
X(mm)


Distorted Strain in Y Direction Contuor Plot
at 702 mm Below Meniscus (4.4 m/min)
TOTAL-STRAIN-Y(%)
10
8
6
4
2
0
-2
-4
-6
-8
-10
Y(mm)
60
50
40
30
20
10
0
X(mm)
0
10
20
30
40
50
60