Heat Transfer &. Solidification Model CON1D

Ya Meng

Department of Materials Science &. Engineering
University of Illinois at Urbana-Champaign

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Improvements to CON1D6.2

- Microsegregation model
- Spray zone model
- Oil casting heat flux model
- New format of input file
- New output files (18 total)
- Updated manual, source codes & input, output example files can be downloaded from website

Microsegregation Model

- First developed by Y.M. Won
- 14 elements has been taken into account
- Has been incorporated into CON1D (optional)
- User inputs cooling rate, interested position
- CON1D calculates liquidus and solidus temperature (.ext), which are used for whole simulation
- CON1D output 5 information-only files:

  - .seg: solidification time, CR, SDAS, T_{sol} from shell surface to inside
  - .liq: liquid concentration at shell surface
  - .lqi: liquid concentration at at some distance under shell surface
  - .sol: solid concentration at shell surface
  - .sli: solid concentration at some distance under shell surface

Equilibrium partition coefficients, diffusion coefficients and liquidus line slopes of the 14 solute elements

Element	$k^{\delta/L}$	$k^{\gamma/L}$	D^{δ} (cm^2/sec)	D^{γ} (cm^2/sec)	m (^{o}C/%)	n (^{o}C/%)
C	0.19	0.34	0.0127exp(-19450/RT)	0.0761exp(-32160/RT)	78.0	-1122
Si	0.77	0.52	8.0exp(-59500/RT)	0.3exp(-60100/RT)	7.6	60
Mn	0.76	0.78	0.76exp(-53640/RT)	0.055exp(-59600/RT)	4.9	-12
P	0.23	0.13	2.9exp(-55000/RT)	0.01exp(-43700/RT)	34.4	140
S	0.05	0.035	4.56exp(-51300/RT)	2.4exp(-53400/RT)	38.0	160
Cr	0.95	0.86	2.4exp(-57310/RT)	0.0012exp(-52340/RT)	1.04	13.4
Ni	0.83	0.95	1.6exp(-57360/RT)	0.34exp(-67490/RT)	4.69	-28.6
Cu	0.53	0.88	2.6exp(-57360/RT)	0.7exp(-68350/RT)	5.32	-10.4
Mo	0.80	0.585	3.47exp(-57690/RT)	0.068exp(-59000/RT)	2.6	77.6
Ti	0.38	0.33	3.15exp(-59200/RT)	0.15exp(-59980/RT)	10.24	120.5
V	0.93	0.63	4.8exp(-57360/RT)	0.284exp(-61900/RT)	12.95	85.5
Nb	0.40	0.22	50.2exp(-60220/RT)	0.83exp(-63690/RT)	10.24	70.8
W	0.85	0.45	1.57exp(-58200/RT	0.13exp(-57300/RT)	0.24	18.8
N	0.25	0.48	0.008exp(-18900/RT)	0.91exp(-40270/RT)	60.0	-

Notes : R is gas constant of 1.987 cal/mol-K and T is temperature in K.

Spray zone model

- Enhanced user-control spray zone parameters for parametric study

  - natural convection heat transfer coefficient

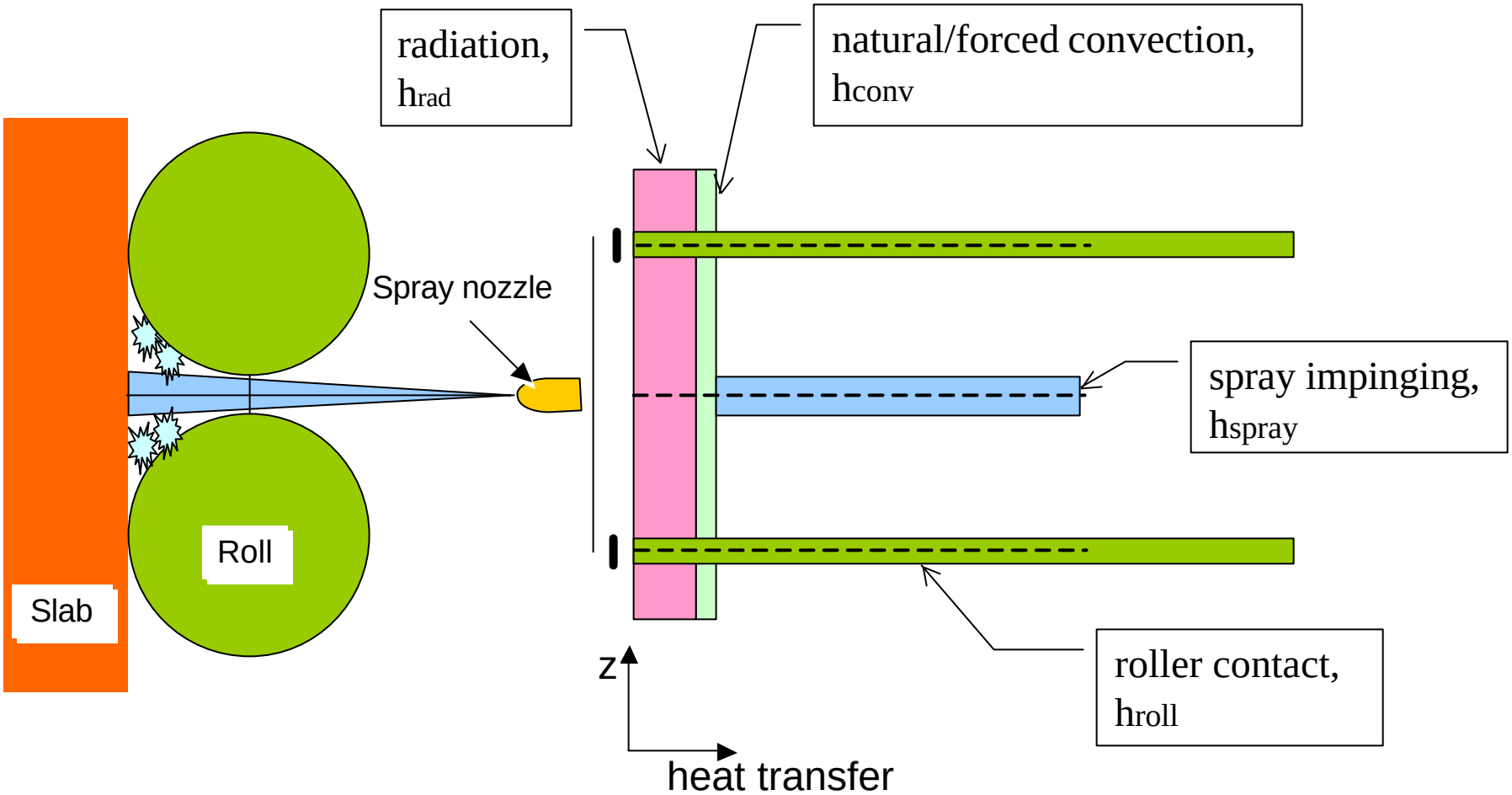
  - user-input spray coefficient, convection coefficient, ambient temperature for different spray zones

  - can simulate air mist spray cooling zones

- Validated by China steel measured data

  - input conditions and measured data from **LIN, Kuan-Ju**

Schematic of Spray Zones Region



Spray zone model

$$h_{rad} = s \cdot e_{steeel} \cdot \left(T_s + T_{amb}\right) \cdot \left(T_s^{\ 2} + T_{amb}^{\ 2}\right)$$

$$h_{conv} = user\ input$$

$$h_{spray} = Coeff \cdot A \cdot Q_w^{\ n} \cdot \left(1 - b \cdot T_{amb}\right)$$

$$h_{roll} = \frac{\left(h_{rad} + h_{conv} + h_{spray}\right) \cdot L_{spray} + \left(h_{rad} + h_{conv}\right) \cdot \left(Pitch - L_{spray} - L_{roll\ contact}\right)}{L_{roll\ contact} \cdot \left(1 - q\right)} \cdot q$$

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

ε_{steel} = steel emissivity (-)

T_s , T_{amb} = steel surface temperature, ambient temperature (K)

Q_w = water flux (l/m^{2}sec)

Coeff, A, n, b = coefficients for spray heat transfer (-)

L_{spray}, $L_{roll\ contact}$ = spray length, roll contact length (m)

q = fraction of heat flow per zone going to roll (-)

Model Validation:China Steel

Casting Conditions

	Water Spray only	**Air Mist**
Casting Speed: (m/min)	0.55	0.56
Pour Temperature: (^oC)	1510	1522
Slab Geometry: (mm*mm)	1560*270	1880*270
Nozzle Submergence Depth: (mm)	200	200
Working Mold Length: (mm)	600	600
Carbon Content: (%)	0.45	0.45
Mold Oscillation Frequency: (cpm)	120	120
Oscillation Stroke: (mm)	4	4
Mold Thickness (with Water Channel): (mm)	51	51
Initial Mold Cooling Water Temperature: (^oC)	35	35
Water Channel Geometry (depth*width*distance): (mm^3)	25*5*28	21*6*28
Cooling Water Flow rate: (m/s)	7.62	6.41

Model Validation:China Steel

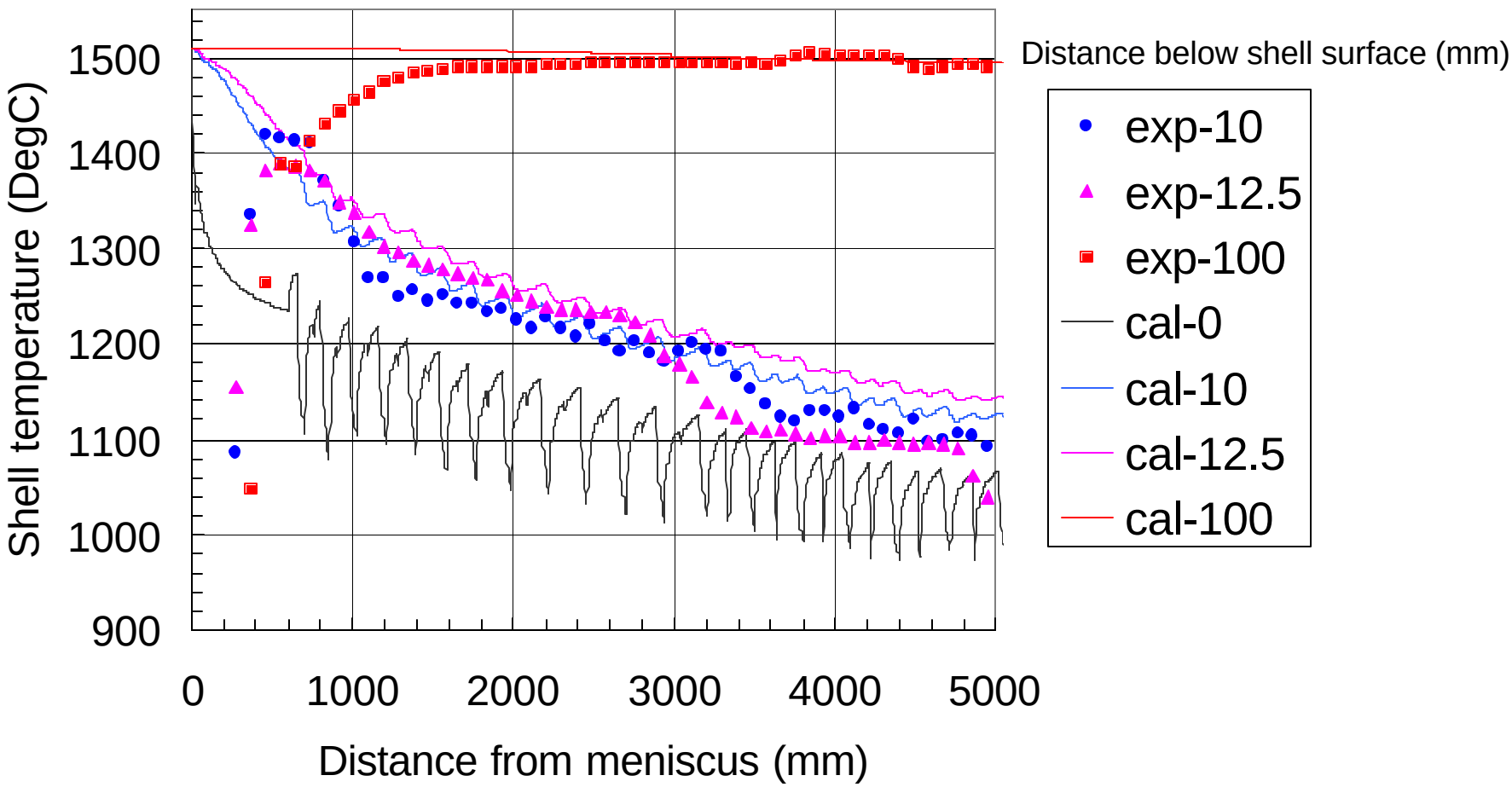
Spray Zones Variables

Ambient temperature below spray zones: 35°C
Spray zone coefficients: A=1.57, n=0.55, b=0.0075
Minium convection heat transfer coefficient (natural): 8.7(W/m^2K)

No.	zone starts (mm)	rol. #	rad. (m)	water flowrate (l/min/row)	spray width (m)	spray length (m)	contct angle (Deg)	frac.of q thr rol	spray coeff	conv. coeff. (W/m^2K)	amb. temp. (DegC)
Water Spray only											
1	600.0	2	.0700	27.500	1.300	.050	7.00	.050	0.25	8.7	35
2	906.9	5	.0700	14.860	1.200	.050	7.00	.050	0.25	8.7	35
3	1840.8	5	.1000	14.860	1.200	.050	7.00	.050	0.25	8.7	35
4	3034.3	5	.1250	11.840	1.200	.050	7.00	.200	0.25	8.7	35
5	4520.5	10	.1500	8.800	1.200	.050	7.00	.200	0.25	8.7	35
6	7977.9	10	.1750	7.150	1.200	.050	7.00	.200	0.25	8.7	35
7	11883.1	11	.2100	2.500	2.000	.050	7.00	.200	0.25	8.7	35
8	17050.7	18	.2400	0.000	9.999	.050	7.00	.200	0.25	8.7	400
	26440.7	End of last spray zone (mm)									
Air Mist											
1	600.0	2	.0700	20.000	1.600	.040	7.00	.050	0.25	8.7	35
2	891.2	5	.0700	11.100	1.600	.060	7.00	.050	0.25	138.0	35
3	1824.2	5	.1000	9.800	1.600	.060	7.00	.050	0.25	121.0	35
4	3018.4	5	.1250	12.100	1.400	.060	7.00	.200	0.25	150.0	35
5	4491.8	10	.1500	8.300	1.400	.060	7.00	.200	0.25	103.0	35
6	7908.6	12	.1400	5.333	1.400	.060	7.00	.200	0.25	66.0	35
7	11878.4	15	.1550	0.000	1.200	.060	7.00	.330	0.25	8.7	400
8	17111.0	9	.2400	0.000	9.999	.060	7.00	.250	0.25	8.7	400
	21678.1	End of last spray zone (mm)									

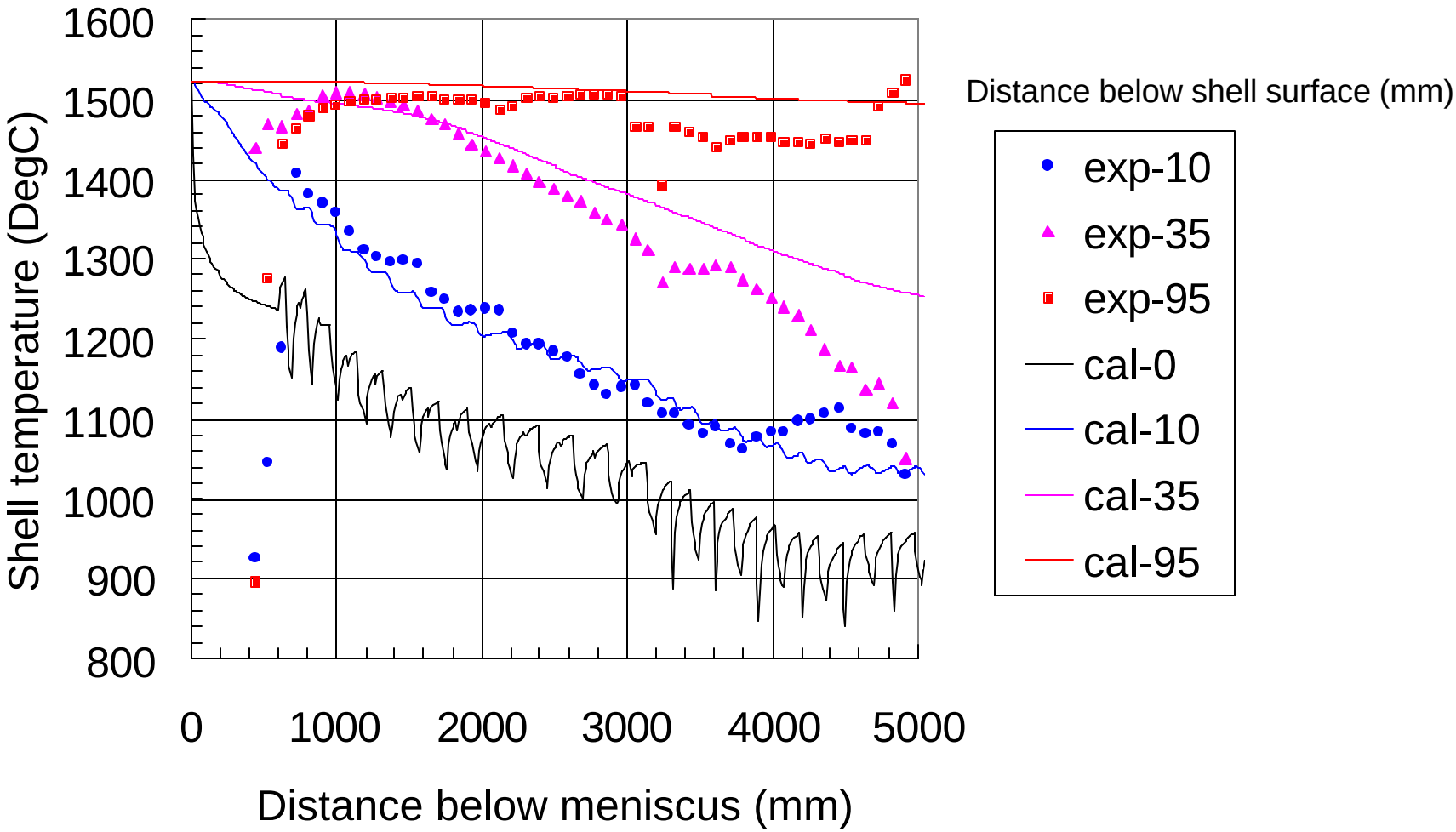
Model Validation: China Steel

Shell Temperature for Water Spray Only Case



Model Validation: China Steel

Shell Temperature for Air Mist Case



Heat Transfer Model for Billet Casting

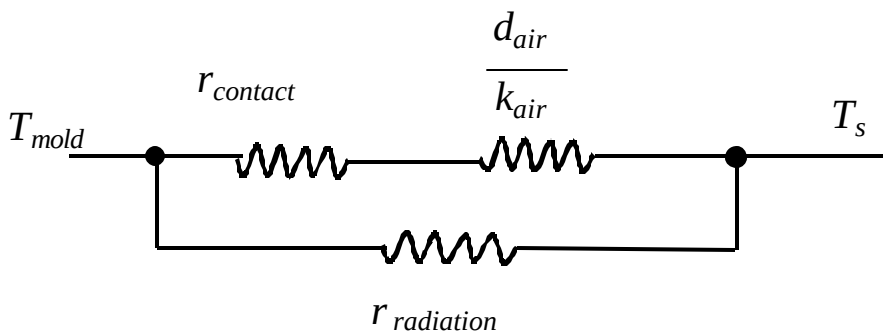
- User chosen heat transfer model
  - oil casting
  - mold powder casting
  - user input heat flux
- Validated by trial at POSCO
  - input conditions and measured data from **PARK, J.K.**

Model Description

$$q_{\text{int}} = (h_{rad} + h_{conv})(T_s - T_{mold})$$

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

$$h_{conv} = \frac{1}{r_{contact} + \frac{d_{air}}{k_{air}}}$$



Where, q_{int} = heat flux transferred across gap (W/m^2)

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

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

T_s = surface temperature of the steel shell (°C)

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

$r_{contact}$ = strand/mold contact resistance(m^{2}K/W)

d_{air} = thickness of the air gap (mm)

k_{air} = conductivity of the air gap (W/mK)

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

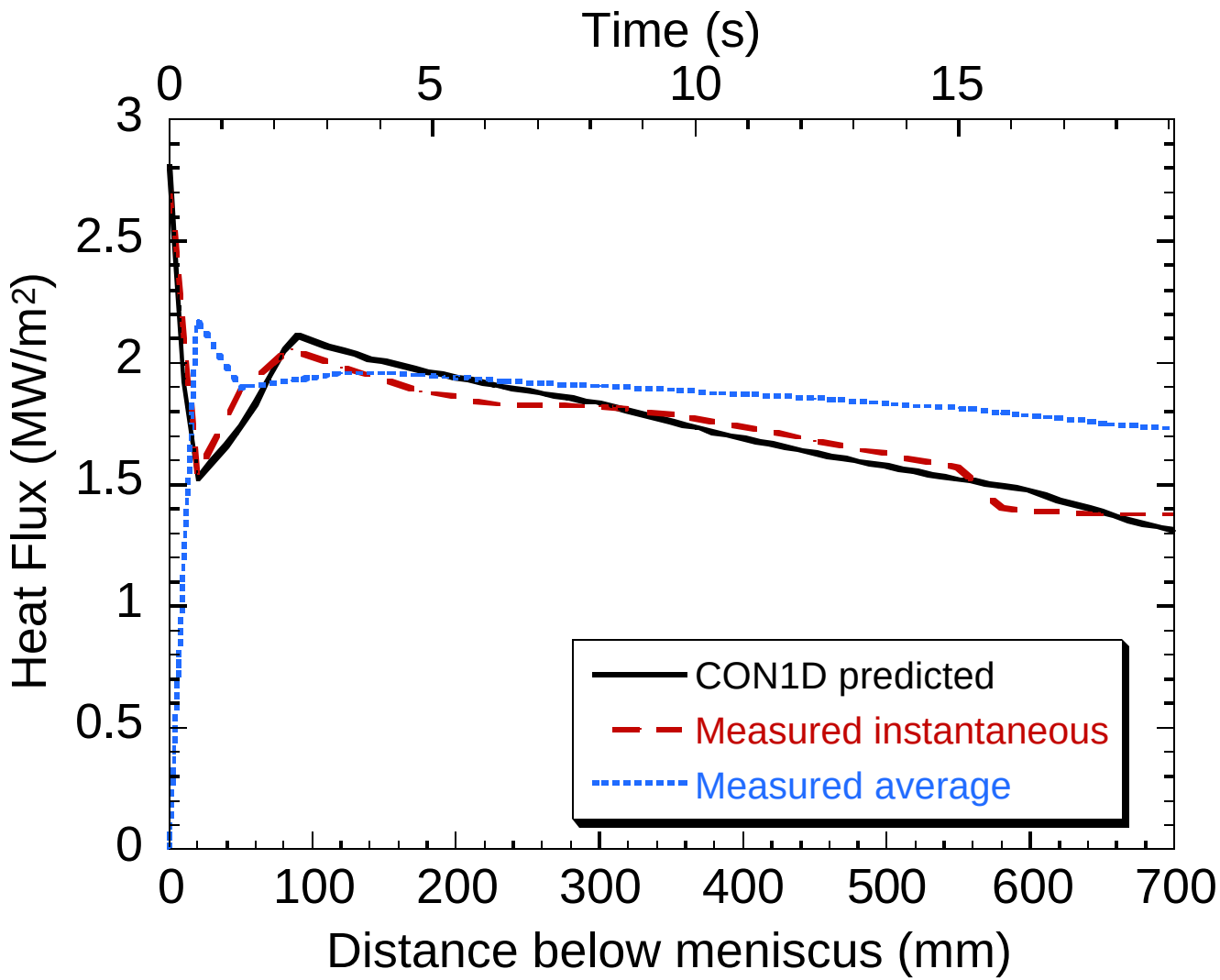
ε_{steel}, ε_{mold} = steel, mold surface emissivity (-)

Model Validation:Trial at POSCO

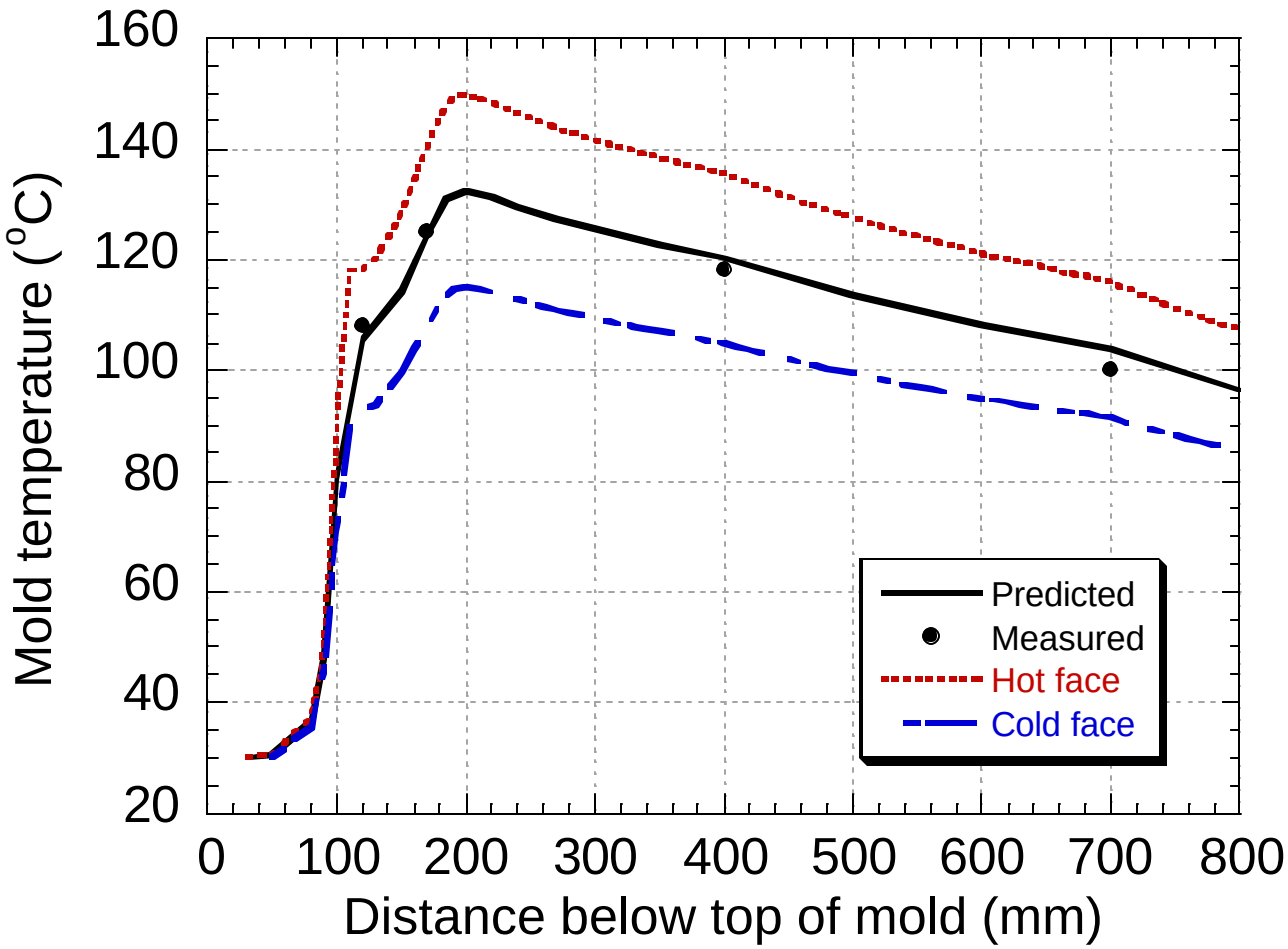
Simulation Parameters

Casting Speed:	2.2 m/min
Pour Temperature:	1540 ^{o}C
Slab Geometry:	120 mm*120 mm
Meniscus Level:	100 mm
Working Mold Length:	700 mm
Carbon Content:	0.1 wt%
Mold Thickness (with Water Channel):	6 mm
Mold Taper:	0.75 %/m
Mold Conductivity:	360 W/mK
Initial Mold Cooling Water Temperature:	30 ^{o}C
Cooling Water Flow rate:	1100 l/m
Cooling Water Velocity:	6.6 m/s
Air Conductivity:	0.1 W/mK
Contact Resistance:	5.6e-4 m^2K/W

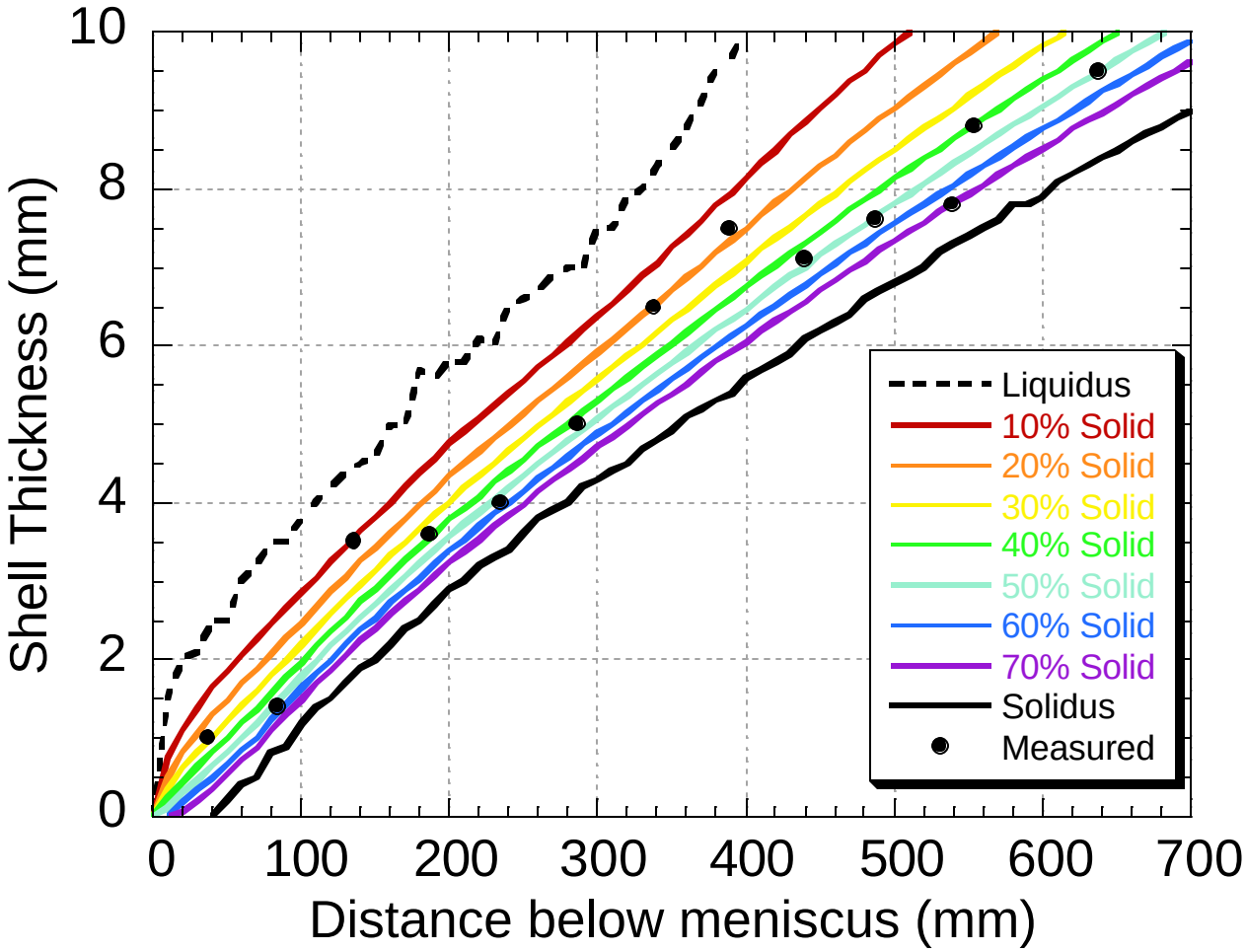
Model Validation: Heat Flux



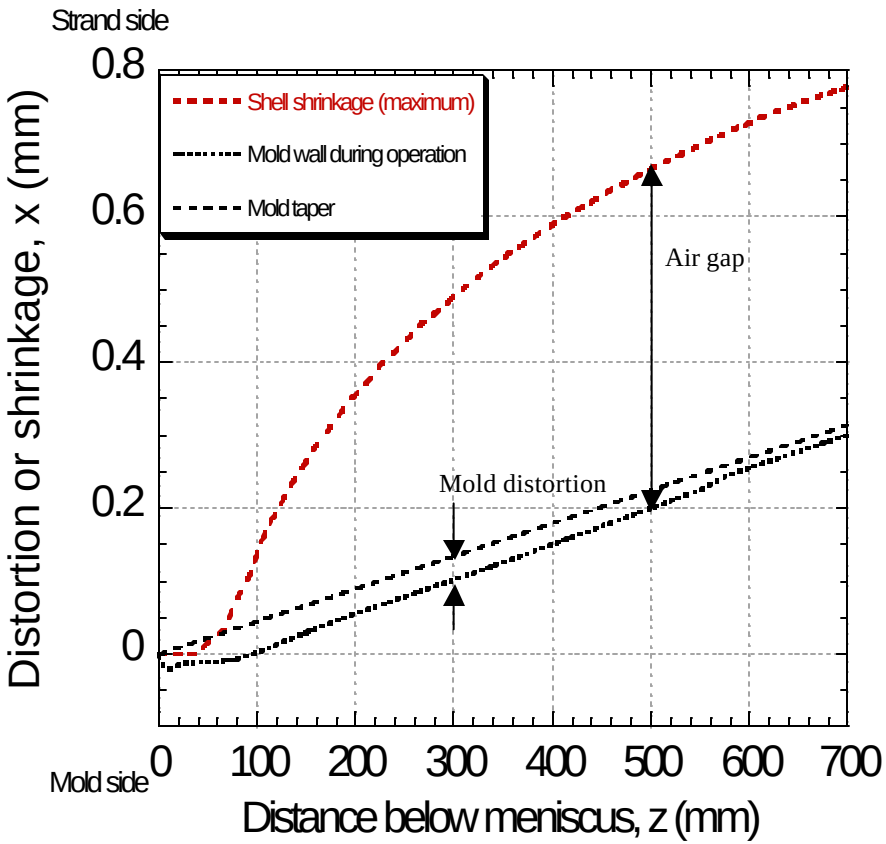
Model Validation: Mold Temperature

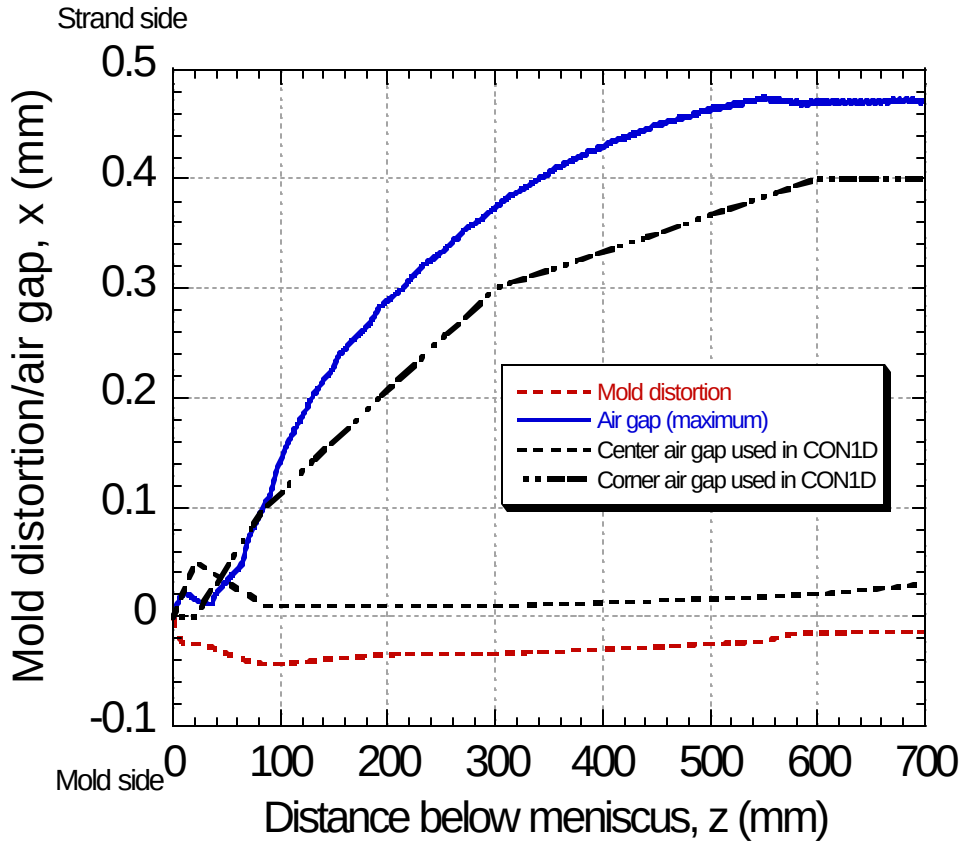


Model Validation: Shell Thickness (Center)

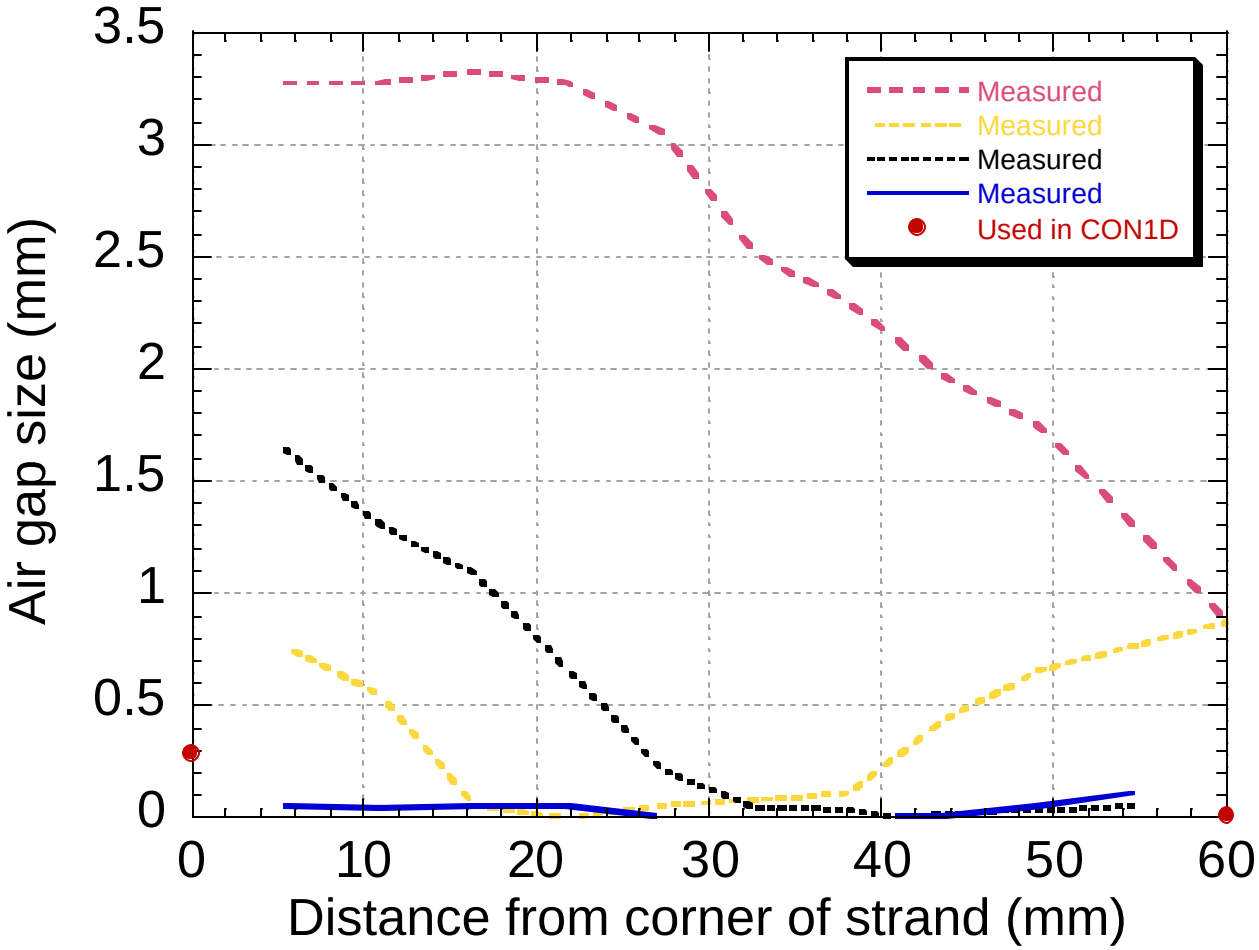


Air Gap Calculation

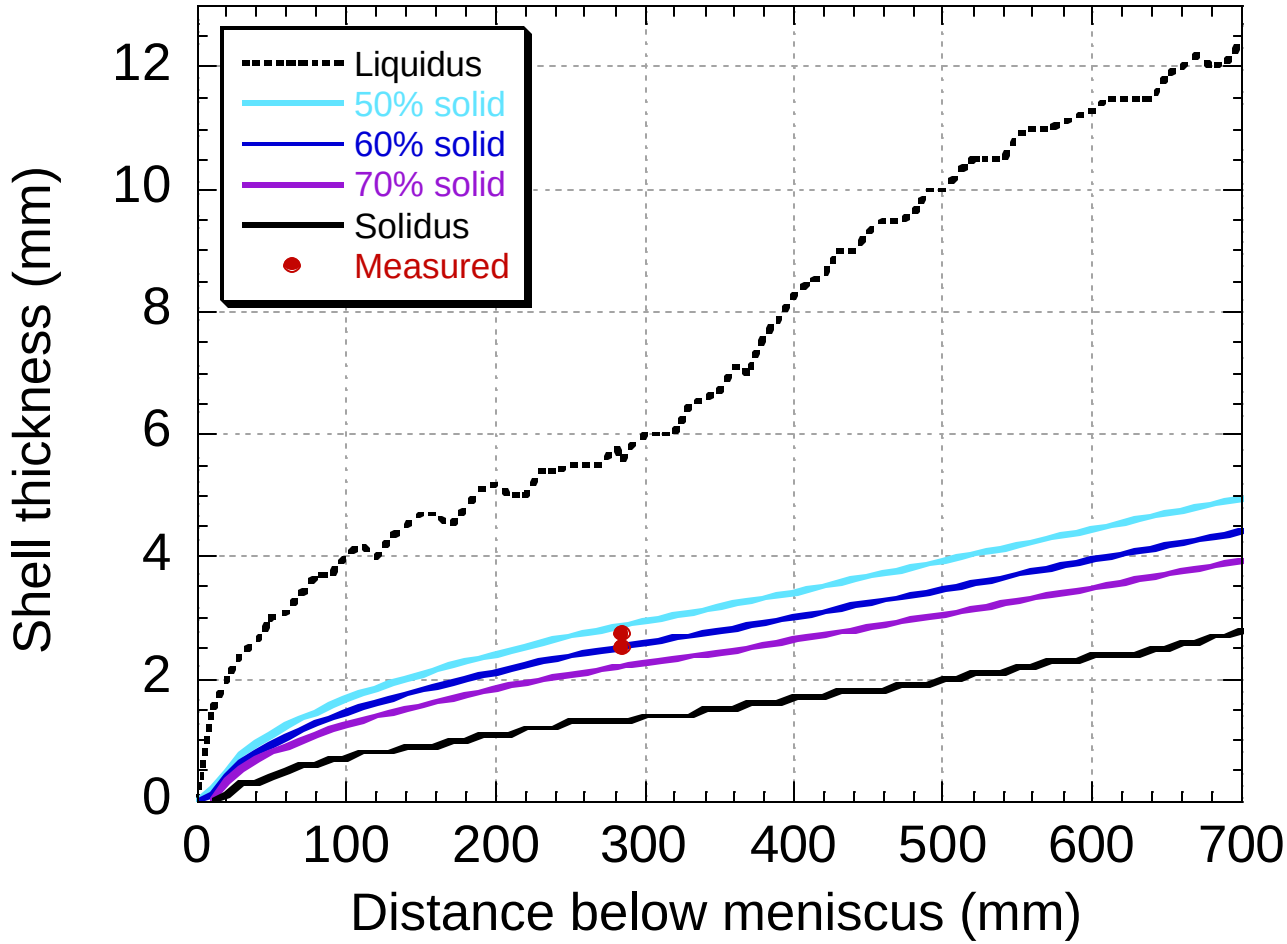




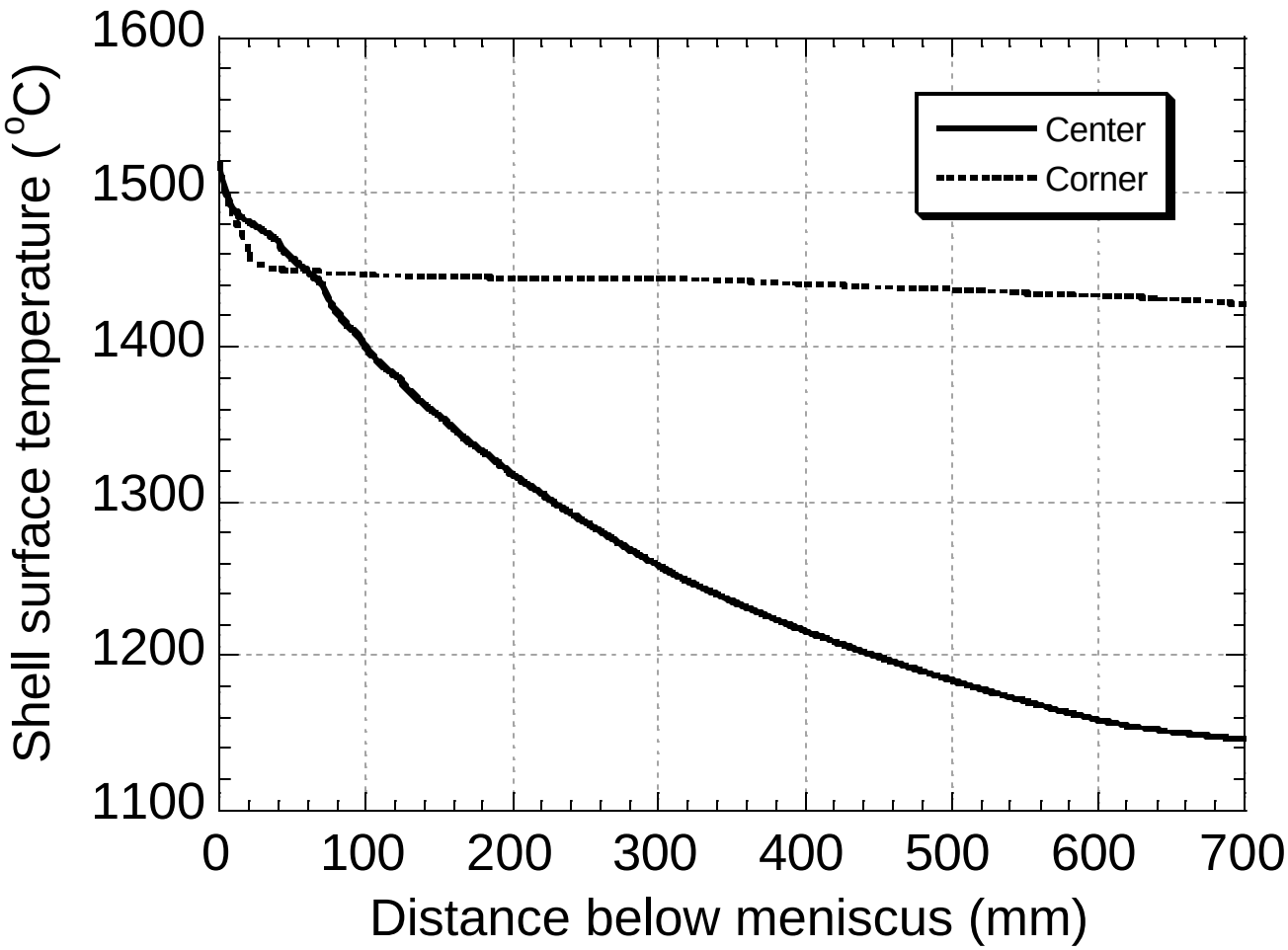
Air Gap Comparison



Model Validation: Shell Thickness (Corner)



Shell Temperature Comparison



Conclusion

- Microsegregation model

  - incorporated 14 elements effects on solidus and liquidus

- Spray zone model

  - calibrated by measured shell temperature at China Steel
  - can simulate both spray water only and air mist cases

- Oil casting heat flux model

  - calibrated by measured data at POSCO:

    mold cooling water temperature

    mold thermocouple temperature

    shell thickness

  - solid fraction for tracer test is 0.6

Future Work

- Improve interface model of CON1D

  - validate mold friction model

  - oil casting heat transfer model
- Mold flux crystallization & viscosity
- Mold temperature fluctuation model
- 2D simulation
- Parametric study