MechSE

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Calibration of Mold Heat Transfer Models with Breakout Shell Measurements

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Outline

1. The Circumstances of Breakout
2. Estimation of Flow Rate and Solidification time
3. Heat Transfer Model – Calibration for Geometry Differences
4. CON1D Model Verification with Plant
5. Conclusions

1. The Circumstances of Breakout

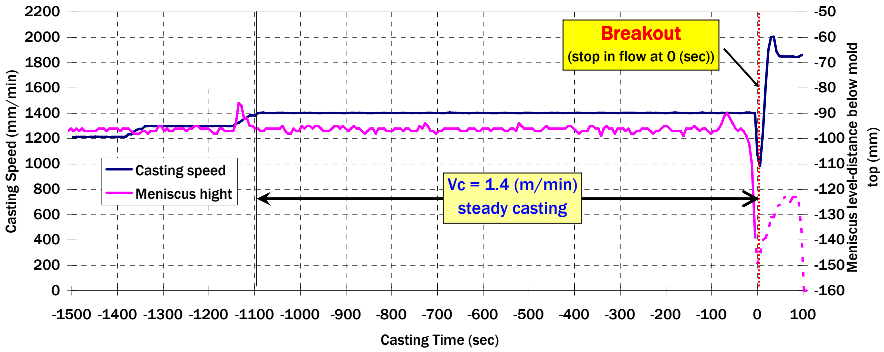
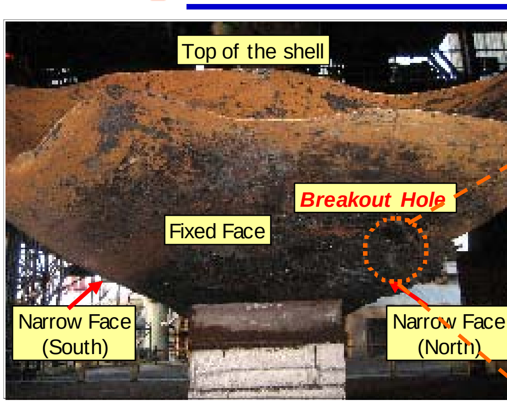


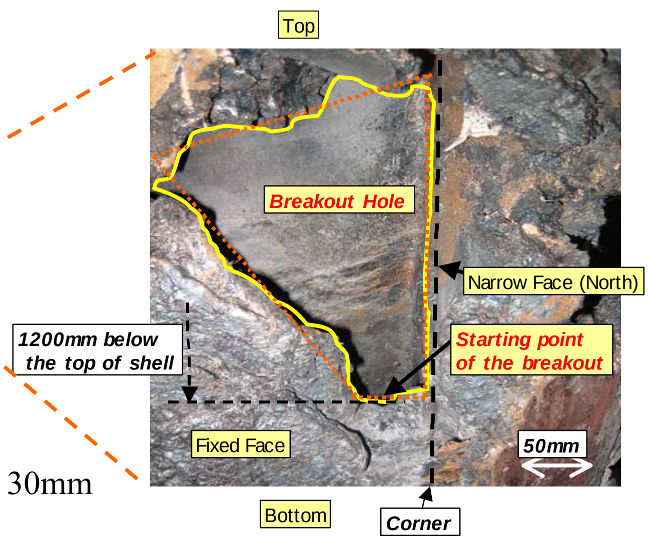
Figure 1. History of recorded Casting Conditions

Table 1. Casting Condition

		Steel Composition	
Casting speed	23.4 mm/s		
Strand thickness	252 mm	0.16	%C
Strand width	1360 mm	0.71	%Mn
SEN submergence depth	230 mm	0.016	%P
Pour temperature	1540 ℃	0.006	%S
Meniscus dist. From mold top	96 mm	0.02	%Si
Mold conductivity (WF)	242 W/mK	0.039	%Al
(NF)	355 W/mK		

1. The Circumstances of Breakout





Breakout Point

- Fixed Face, North side off corner 30mm
- 1200mm below the top of shell
- Hole size = 34107 mm^2

Figure 2. Breakout shell and hole

1. The Circumstances of Breakout

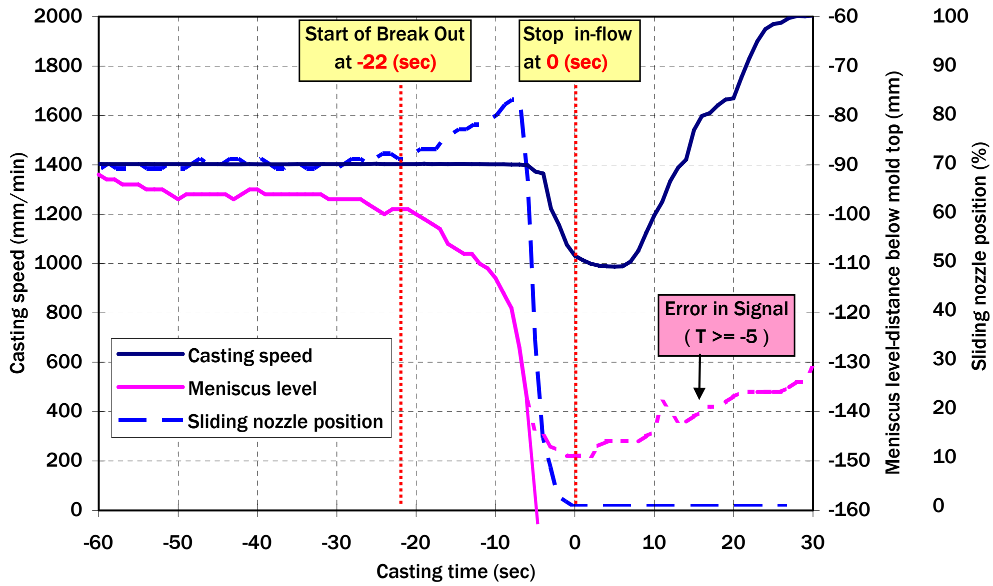
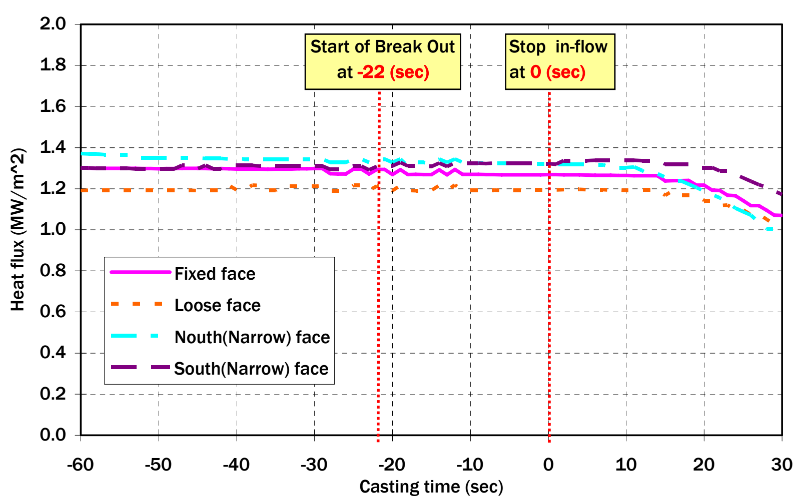


Figure 3. History of recorded Casting Conditions during Breakout

1. The Circumstances of Breakout



~constant q:

1.279MW/m² (Fixed face)

1.195MW/m2 (Loose face)

1.336MW/m2 (Nouth face)

1.294MW/m2 (South face)

(Average from -1000s to -23s
; Vc = 1.4 m/min ~ constant)

Figure 4. History of recorded Heat Flux during Breakout

2. Estimation of Flow Rate and Solidification time

2.1. Estimation of Flow Rate

$$Q_{in} + Q_{drop} = Q_{out} + Q_{drain} \quad \cdots (1)$$

$t < -22 : Q_{drain} = 0$

$t > 0 \quad : Q_{in} = 0$

- Q_{in} : Input from sliding nozzle gate
- Q_{drop} : Flow rate of Drop in level
- Q_{out} : Output by casting speed
- Q_{drain} : Drainage from breakout hole
- t : Casting time (sec)

(Use Eulerian reference frame based on steady-meniscus position)

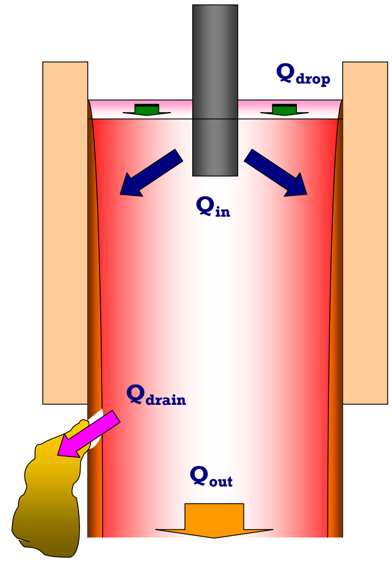


Figure 5. Schematic of Mass Balance

2.1. Estimation of Flow Rate

Qin ; Input from Sliding Nozzle Gate

Second order approximation

$$Q_{in} = 0.0002 X_t^{\,2} + 0.0368 X_t \quad \cdots (2)$$

{X : SN position at time t (%)

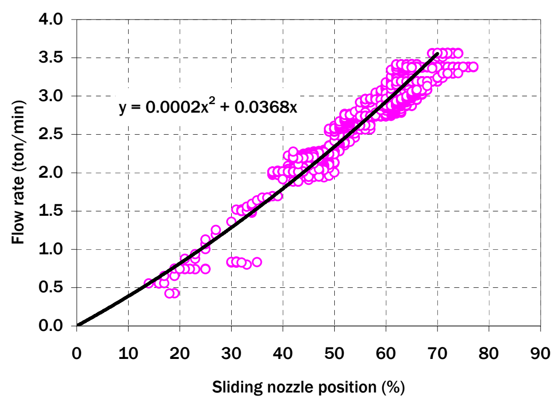


Figure 6. Real date of Flow Rate from Sliding Nozzle

Q_{out} ; Output by Casting Speed

$$Q_{out} = \rho \times W \times Y \times V_{C-t} \quad \cdots (3)$$

- ρ : steel density (ton/m^3) = 7.4
- W : slab width (m)
- Y : slab tickness (m)
- $V_{C\text{-}t}$: casting speed at time t (m/min)

2.1. Estimation of Flow Rate

t < -5

Q_{drop} ; Flow Rate of Drop in Level

$$Q_{drop} = \rho \times W \times Y \times \frac{(z_t - z_{t-1})}{(t-(t-1))} \quad \ldots (4)$$

Q_{drain} ; Drainage from Breakout Hole

$$Q_{drain} = Q_{out} - (Q_{in} + Q_{drop}) \quad \ldots (1)'$$

$$S_t = \frac{Q_{drain}}{\rho \times v_t} \quad \ldots (5)$$

$$v_t = \sqrt{2gh_{t-1}} \quad \ldots (6)$$

$$h_{t-1} = z_{hole-t-1} - z_{t-1} \quad \ldots (7)$$

- ρ : steel density (ton/m^3) = 7.4
- W : slab width (m)
- Y : slab tickness (m)
- z_t : distance below steady state meniscus to liquid level at time t (m)
- $z_{hole-t-1}$: distance below steady state meniscus to breakout hole at time t-1sec (m)
- t : casting time (min)
- S_t : hole size at time t (m^2)
- v_t : speed of running fluid from breakout hole at time t (m/sec)
- g : gravitational acceleration (m/sec^2) = 9.8
- h_{t-1} : liquid height from liquid level to breakout hole at time t-1sec (m)

2.1. Estimation of Flow Rate

t >= -5

Q_{drain} ; Drainage from Breakout Hole

Exponential approximation

$$S_t = 3713.7e^{0.2119t} \quad \ldots (8)$$

$$Q_{drain} = \rho \times S_t \times v_t \quad \ldots (5)'$$

$$v_t = \sqrt{2gh_{t-1}} \quad \ldots (6)$$

$$h_{t-1} = z_{hole-t-1} - z_{t-1} \quad \ldots (7)$$

Q_{drop} ; Flow Rate of Drop in Level

$$Q_{drop} = Q_{out} + Q_{drain} - Q_{in} \quad \ldots (1)''$$

$$z_t = z_{t-1} + \frac{Q_{drop}}{\rho \times W \times Y}(t-(t-1)) \quad \ldots (4)'$$

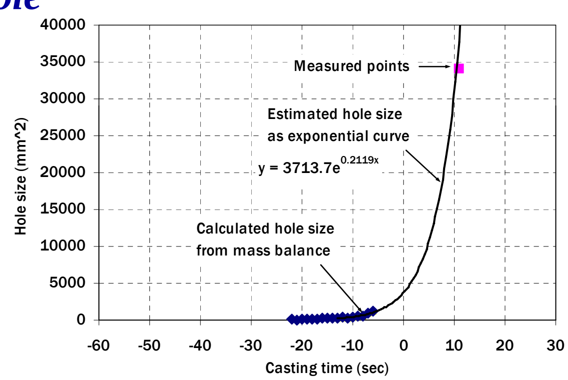


Figure 7. Estimated Hole size

2.1. Estimation of Flow Rate

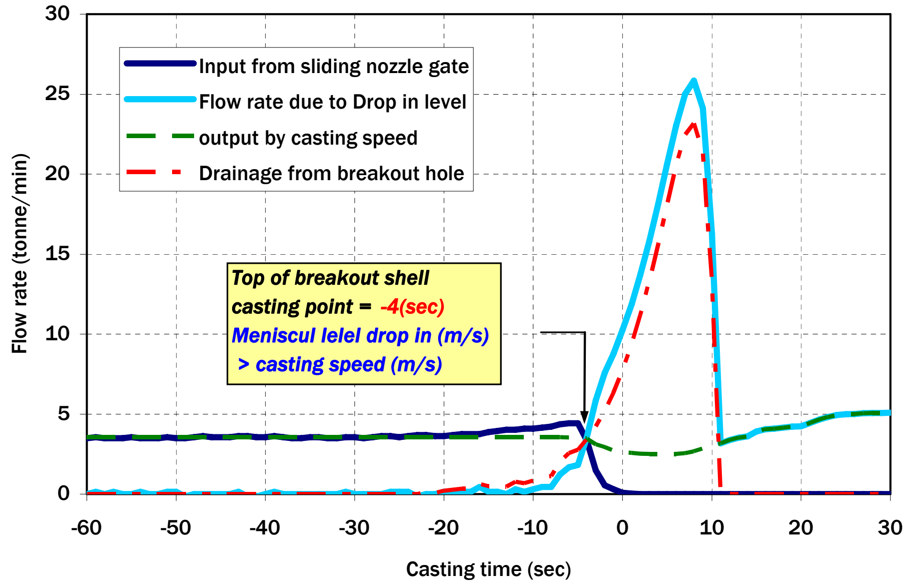


Figure 8. Estimated Flow Rate

2.2. Estimated Solidification Time

Note: Eulerian frame of reference (based on steady-meniscus position)

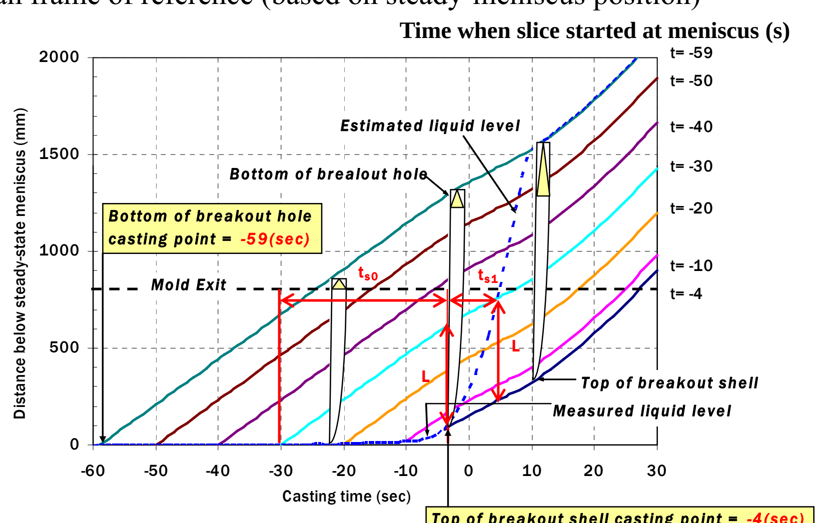


Figure 9. Distance traveled by different points on the shell surface relative to the dropping

2.2. Estimated Solidification Time

$$t_s = t_{s0} + t_{s1} \qquad \text{... (9)}$$

$$\int_{t_{s0}}^{t_{-4}} V_C \, dt = L \qquad \text{... (10)}$$

$$\int_{t_{-4}}^{t_{s1}} \left(\frac{dz}{dt} - V_C\right) dt = L \qquad \text{... (11)}$$

Cubic curve approximation

$$t_{s1} = 15.778L^3 - 34.956L^2 + 30.803L \qquad \text{... (12)}$$

- t_s : solidification time at L (sec)
- t_{s0} : solidification time at L before -4 (sec)
- t_{s1} : solidification time at L after -4 (sec)
- V_C : casting speed (m/min)
- z : distance below steady state maniscus to liquid level(m)
- L : distance from the top of shell (m)

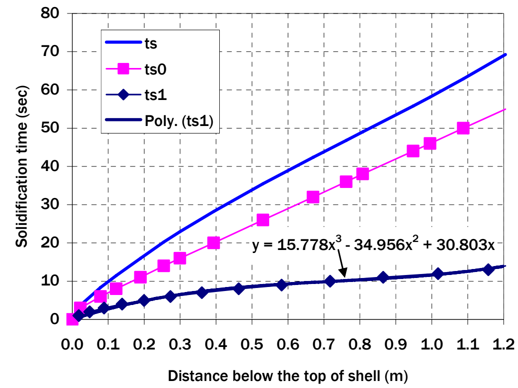


Figure 10. Solidification time

3. Heat Transfer Model – Calibration for Geometry Differences

3. 1. Mold Geometry Simplification with CON1D

Wide Face

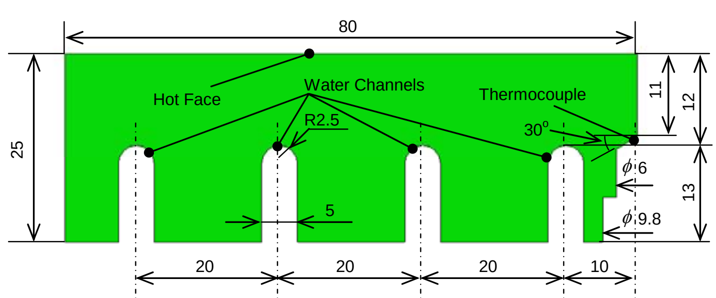


Figure 11. Wide face mold geometry

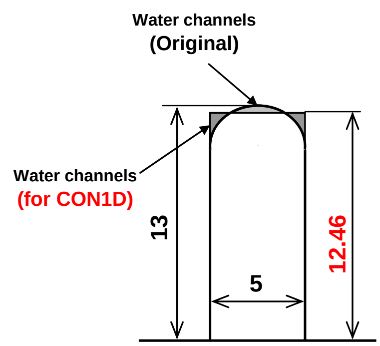


Figure12 . Wide face Water channel & CON1D Simplification

3. 1. Mold Geometry Simplification with CON1D

Narrow Face

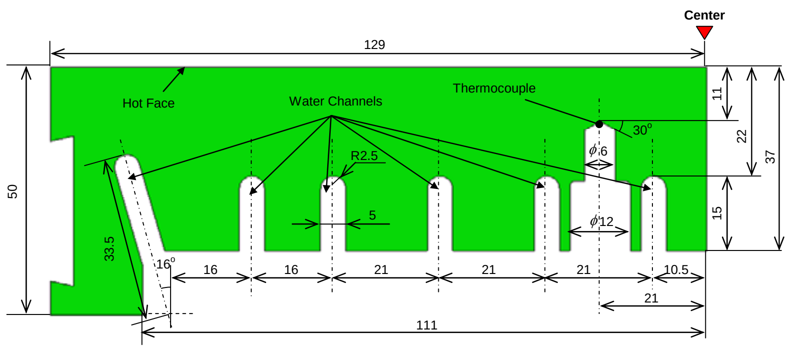


Figure 13. Narrow face mold geometry

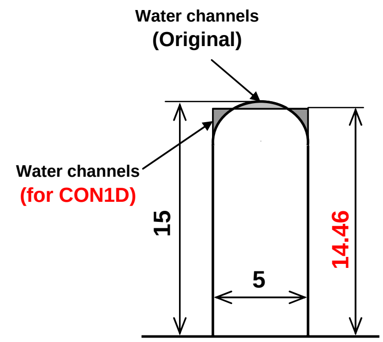


Figure 14. Narrow face Water channel & CON1D Simplification

3. 2. CON1D Model Offset Determination with ABAQUS

3. 2. 1. Procedure of Offset

CON1D
- Heat Flux
- Cooling water Temperature
- Hot Face and Cold Face Temperatures

→ ABAQUS (2D)

→ CON1D Offset - 1
- **Influence of Heat Transfer Coefficient difference between CON1D and ABAQUS-2D model**

→ ABAQUS (3D)

→ CON1D Offset - 2
- **Influence of Thermocouple Hole geometry**

Heat Transfer Coefficient Formula

CON1D

$$h_{water} = 1 / \left(\frac{d_{scale}}{k_{scale}} + \frac{1}{h_{fin}} \right) \quad \text{... (13)}$$

$$h_{fin} = \frac{h_w w_{ch}}{L_{ch}} + \frac{\sqrt{2 h_w k_{mold} \left(L_{ch} - w_{ch} \right)}}{L_{ch}} \tanh \sqrt{\frac{2 h_w d_{ch}^2}{k_{mold} \left(L_{ch} - w_{ch} \right)}} \quad \text{... (14)}$$

- h_{water} : heat transfer coefficient using CON1D (W/m^2K)
- d_{scale} : scale thickness of water scale at mold cold face (m)
- k_{scale} : conductivity of water scale at mold cold face (W/mK)
- h_w : heat transfer coefficient between water and sides of water channels (W/m^2K) (using ABAQUS 2D and 3D model shown in formura 3 on next slide)
- k_{mold} : conductivity of mold (W/mK)
- Lch, wch, dch : geometry parameters shown in Figure 5 (m)

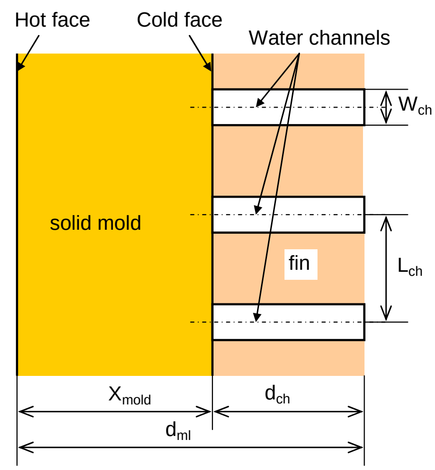


Figure15. Water channel in the mold

ABAQUS (2D and 3D)

$$h_w = \frac{k_{waterm}}{D} \left(5 + 0.015 \mathrm{Re}_{waterf}^{c_1} \, \mathrm{Pr}_{waterw}^{c_2} \right) \quad \text{... (15)}$$

$$D = \frac{2 W_{ch} d_{ch}}{W_{ch} + d_{ch}} \quad \text{... (16)}$$

$$c_1 = 0.88 - 0.24 / \left(4 + \mathrm{Pr}_{waterw} \right) \quad \text{... (17)}$$

$$c_2 = 0.333 + 0.5 e^{-0.6 \mathrm{Pr}_{waterw}} \quad \text{... (18)}$$

$$\mathrm{Re}_{waterf} = \frac{\rho_{water} v_{water} D}{\mu_{waterf}} \quad \text{... (19)}$$

$$\mathrm{Pr}_{waterw} = \frac{\mu_{waterw} Cp_{water}}{k_{waterw}} \quad \text{... (20)}$$

[C. A. Sleicher and M. W. Rouse, Int. J. Heat Mass Transf. V. 18, pp. 677-683, 1975]

$$k_{waterm} = 0.59 + 0.001 T_{water} \quad \text{... (21)}$$

$$k_{waterw} = 0.59 + 0.001 T_{cold} \quad \text{... (22)}$$

$$\mu_{waterf} = 2.062 * 10^{-9} \rho_{water} * 10^{\left(\frac{792.42}{T_{film} + 273.15} \right)} \quad \text{... (23)}$$

$$\mu_{waterw} = 2.062 * 10^{-9} \rho_{water} * 10^{\left(\frac{792.42}{T_{cold} + 273.15} \right)} \quad \text{... (24)}$$

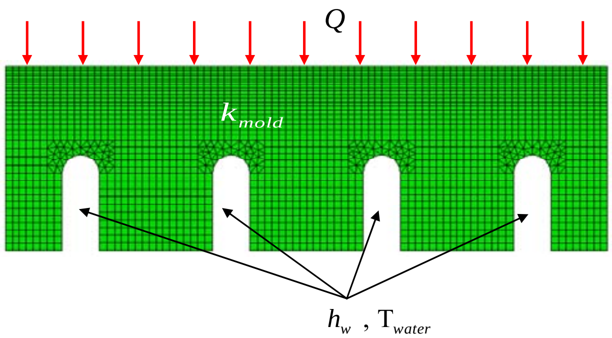
$$T_{film} = 0.5 (T_{water} + T_{cold}) \quad \text{... (25)}$$

- k_{water} : conductivity of water (W/mK)
- μ_{water} : water viscosity (Pa s)
- v_{water} : cooling water velocity (m/s)
- ρ_{water} : water density (kg/m^3) = 995.6
- Cp_{water} : water heat capacity (J/kg) = 4179
- T_{water} : cooling water temperature (°C)
- T_{cold} : cold face temperature (°C)

3. 2. 2. Offset - 1 - *Influence of Mold Heat Transfer difference between CON1D and ABAQUS-2D model -*

ABAQUS 2D model

- Boundary conditions and properties



Wide Face

Parameter	Value	Units
Q	1.443	MW/m^2
h_w	37.31	$kW/m^2 K$
T_{water}	33.71	^oC
k_{mold}	242	W/m K

Narrow Face

Parameter	Value	Units
Q	1.443	MW/m^2
h_w	50.73	$kW/m^2 K$
T_{water}	37.86	^oC
k_{mold}	355	W/m K

Figure 16. boundary conditions and properties

3. 2. 2. Offset - 1 - *Influence of Mold Heat Transfer difference between CON1D and ABAQUS-2D model -*

Temperature profiles

Wide Face

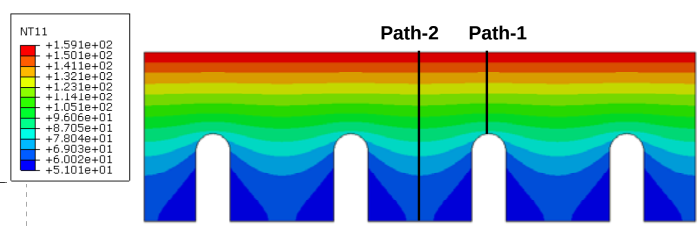
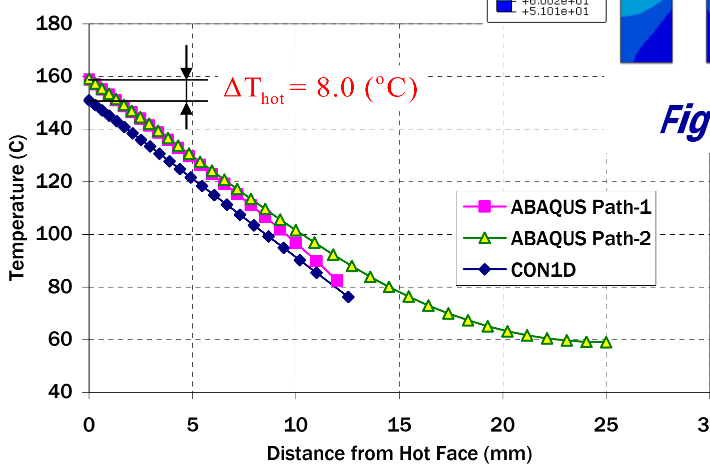


Figure 17. Calibration results



$$\Delta T_{hot} = \frac{\left(T_{hot-path1} - T_{hot-path2}\right)}{2} - T_{hot-CON1D} \quad \text{... (26)}$$

- ΔT_{hot} : Hot Face temperature difference between CON1D and ABAQUS (°C)
- T_{hot} : Hot Face temperature (°C)

Figure 18. Temperature profiles in Wide face

3. 2. 2. Offset - 1 - *Influence of Mold Heat Transfer difference between CON1D and ABAQUS-2D model -*

Determination of Offset-1

Wide Face

$$d_{offset-1} = \Delta T_{hot} \frac{dx}{dT} \quad \text{... (27)}$$

- $d_{offset-1}$: offset-1 distance (mm)
- ΔT_{hot} : Hot Face temperature difference between CON1D and ABAQUS (°C)
- dx/dt : inverse of the temperature gradient from CON1D (mm/°C)

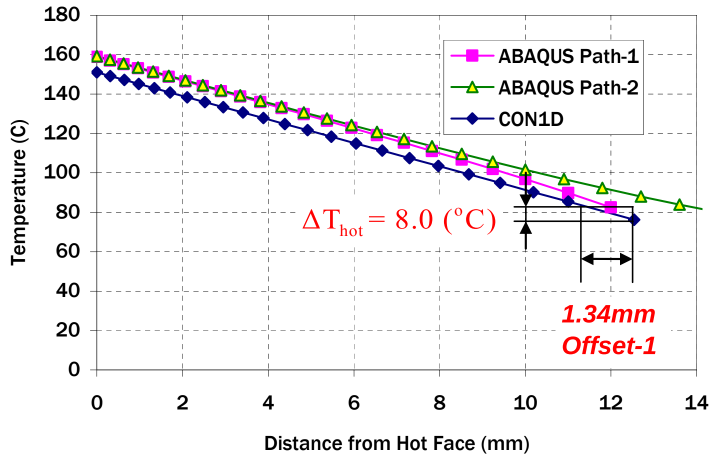


Figure 19. Determination of Offset-1 in Wide Face

3. 2. 2. Offset - 1 - *Influence of Mold Heat Transfer difference between CON1D and ABAQUS-2D model -*

Temperature profiles

Narrow Face

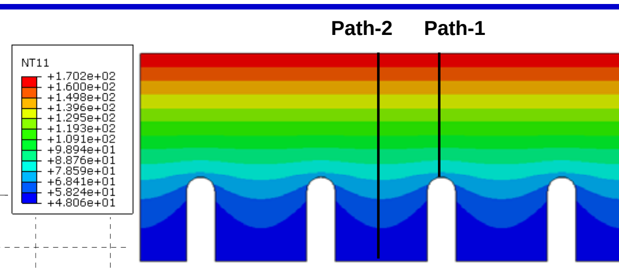
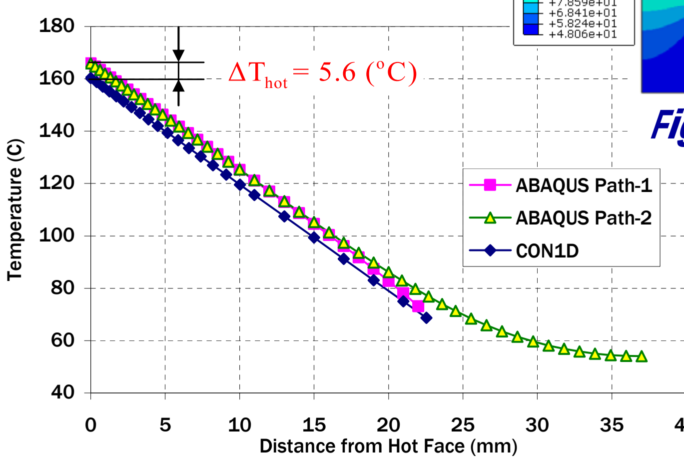


Figure 20. Calibration results



$$\Delta T_{hot} = \frac{\left(T_{hot-path1} - T_{hot-path2}\right)}{2} - T_{hot-CON1D} \quad \text{... (26)}$$

- ΔT_{hot} : Hot Face temperature difference between CON1D and ABAQUS (°C)
- T_{hot} : Hot Face temperature (°C)

Figure 21. Temperature profiles in Narrow face

3. 2. 2. Offset - 1 - *Influence of Mold Heat Transfer difference between CON1D and ABAQUS-2D model -*

Determination of Offset-1

Narrow Face

$$d_{offset-1} = \Delta T_{hot} \frac{dx}{dT} \quad \ldots (27)$$

- $d_{offset-1}$: distance of offset-1 (mm)
- ΔT_{hot} : Hot Face temperature difference between CON1D and ABAQUS (°C)
- dx/dt : inverse of the temperature gradient from CON1D (mm/°C)

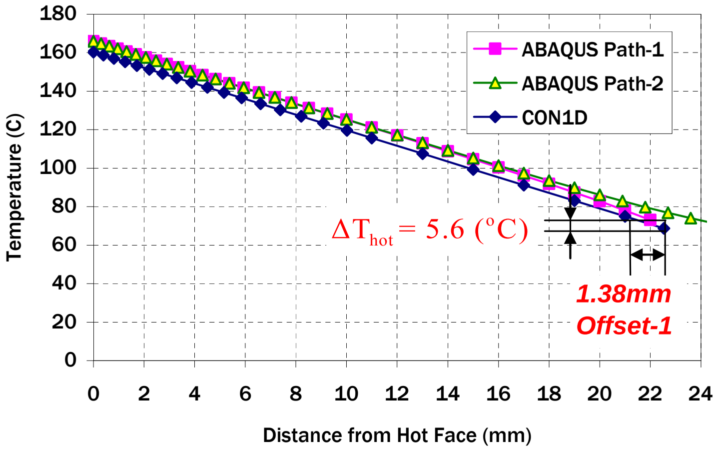
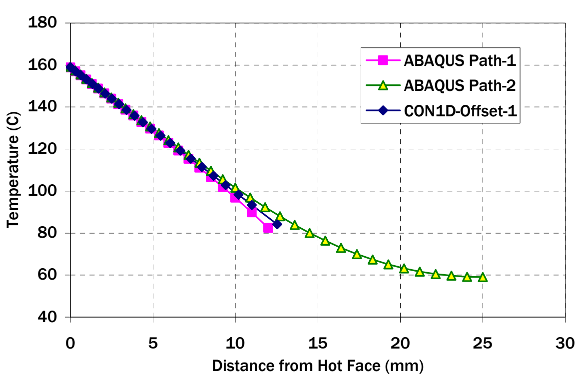


Figure 22. Determination of Offset-1 in Narrow Face

3. 2. 2. Offset - 1 - *Influence of Mold Heat Transfer difference between CON1D and ABAQUS-2D model -*

Temperature profiles with Offset-1

Wide Face



Narrow Face

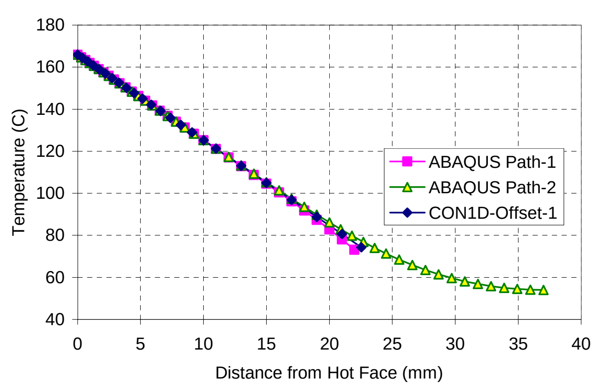
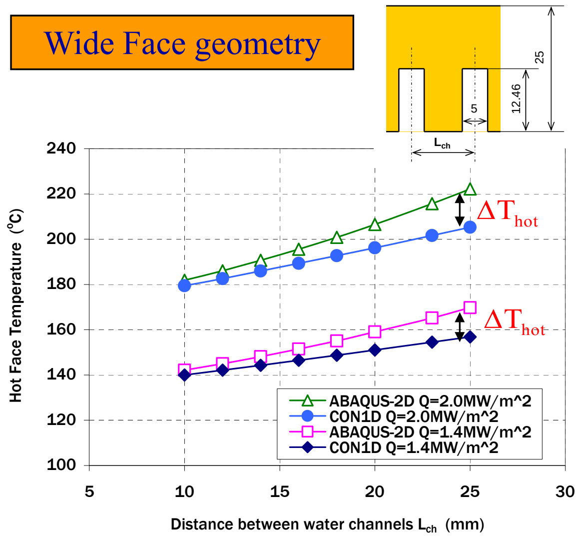


Figure 23. Temperature profiles with Offset-1

Generalization of Offset-1 by water channel geometry

Wide Face geometry



Narrow Face geometry

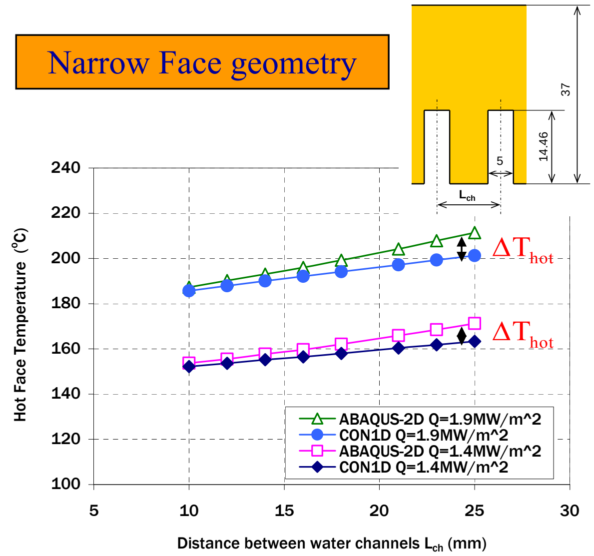


Figure 24. Relation of distance between water channel to Hot Face temperature with CON1D and ABAQUS-2D

3. 2. 2. Offset - 1 - Influence of Mold Heat Transfer difference between CON1D and ABAQUS-2D model -

Generalization of Offset-1 by water channel geometry

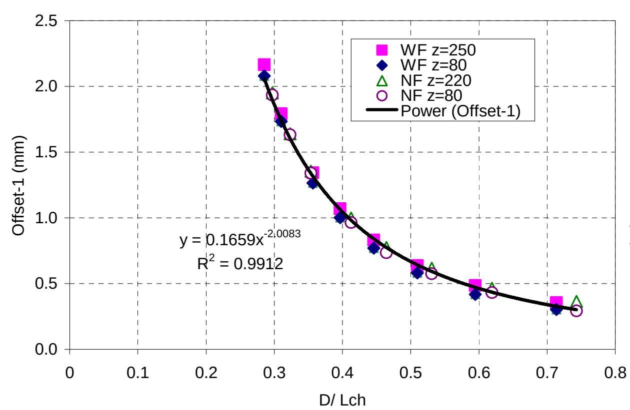


Figure 25. Relation of water channel geometry parameter X to Offset-1

$$d_{offset-1} = \Delta T_{hot} \frac{dx}{dT} \quad \text{... (27)}$$

$$X = \frac{D}{L_{ch}} \quad \text{... (28)}$$

$$D = \frac{2 W_{ch} d_{ch}}{W_{ch} + d_{ch}} \quad \text{... (16)}$$

Power approximation

$$d_{offset-1} = 0.1659 X^{-2.0083} \quad \text{... (29)}$$

- $d_{offset-1}$: distance of offset-1 (mm)
- k_{mold} : conductivity of mold (W/mK)
- ΔT_{hot} : Hot Face temperature difference between CON1D and ABAQUS (°C)
- X : water channel geometry parameter
- d_{ch} : water channel depth (mm)
- L_{ch} : distance between water channel (mm)
- W_{ch} : water channel width (mm)

3. 2. 2. Offset - 1 - *Influence of Mold Heat Transfer difference between CON1D and ABAQUS-2D model -*

Error of generalized Offset-1

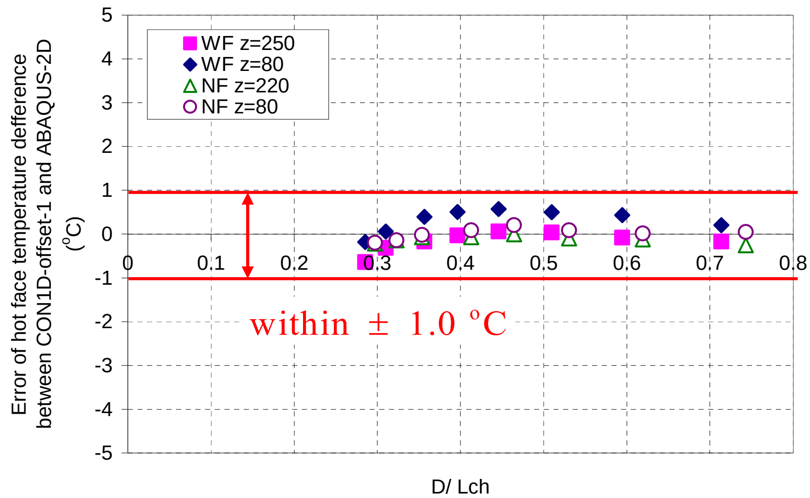
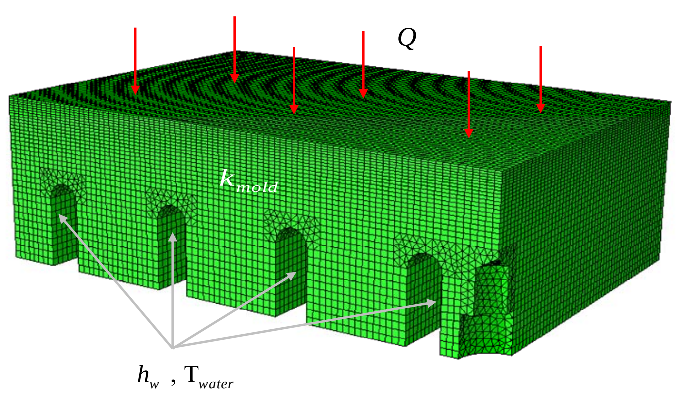


Figure 26. Error of hot face temperature between CON1D-generalized offset-1 to ABAQUS-2D

3. 2. 3 Offset - 2 - *Influence of Thermocouple Hole geometry -*

ABAQUS 3D model - Boundary conditions and properties

Wide Face



Parameter	Value	Units
Q	1.443	MW/m^2
h_w	37.31	$kW/m^2\ K$
T_{water}	33.71	^oC
k_{mold}	242	W/m K

Number of elements : 196598 (hexahedrons, tetrahedrons)

Figure 27. Wide face boundary conditions and properties

Temperature profiles

Wide Face

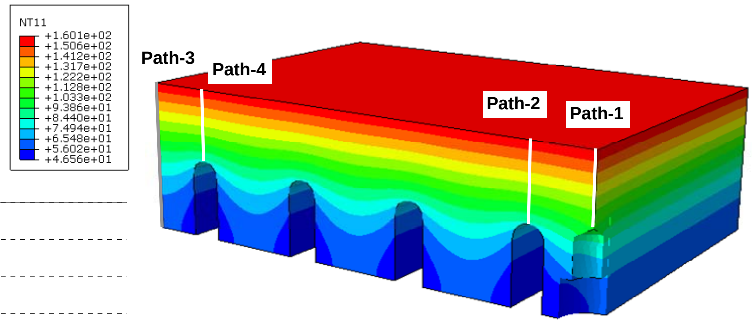


Figure 28. Calibration results

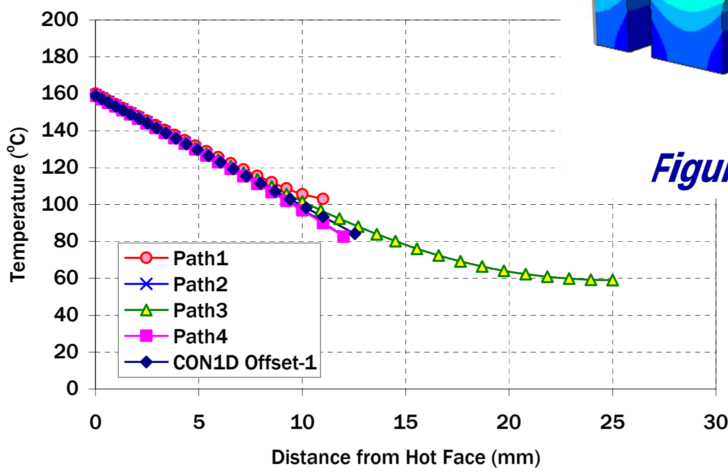
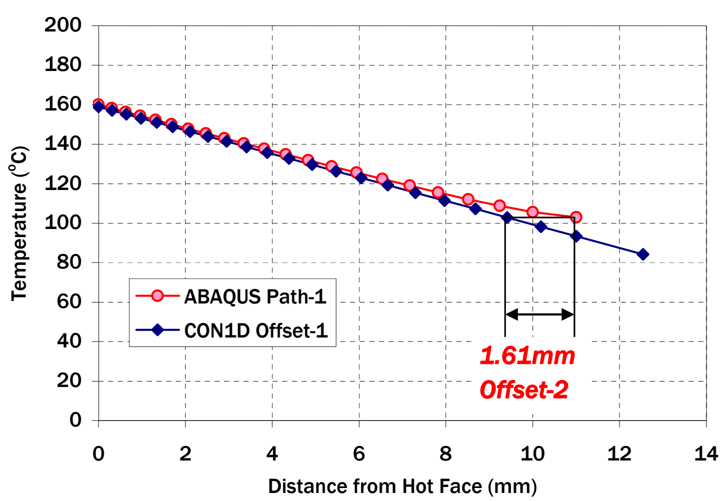


Figure 29. Temperature profiles in Wide face

Determination of Offset-2

Wide Face



$$d_{offset-2} = \left(T_{TC} - T_{hf}\right)\frac{dx}{dT} - d_{TC} \quad \text{... (30)}$$

- $d_{offset-2}$: distance of offset-2 (mm)
- T_{TC} : thermocouple temperature from ABAQUS (°C)
- T_{hf} : thermocouple temperature from CON1D (°C)
- dx/dt : inverse of the temperature gradient from CON1D (mm/°C)
- d_{TC} : actual depth of the thermocouple from Hot Face (mm)

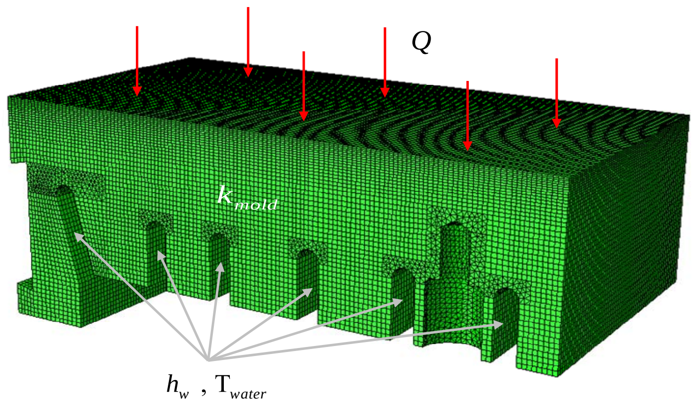
Figure 30. Determination of Offset-2 in Wide Face

Continuous Casting Consortium

3. 2. 3 Offset - 2 - *Influence of Thermocouple Hole geometry* -

ABAQUS 3D model - Boundary conditions and properties

Narrow Face



Parameter	Value	Units
Q	1.443	MW/m^2
h_w	50.73	$kW/m^2\ K$
T_{water}	37.86	^oC
k_{mold}	355	W/m K

Number of elements : 481590 (hexahedrons, tetrahedrons)

Figure 31. Narrow face boundary conditions and properties

Continuous Casting Consortium

3. 2. 3 Offset - 2 - *Influence of Thermocouple Hole geometry* -

Temperature profiles

Narrow Face

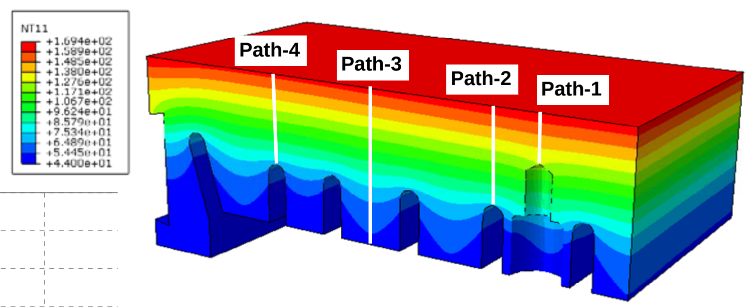


Figure 32. Calibration results

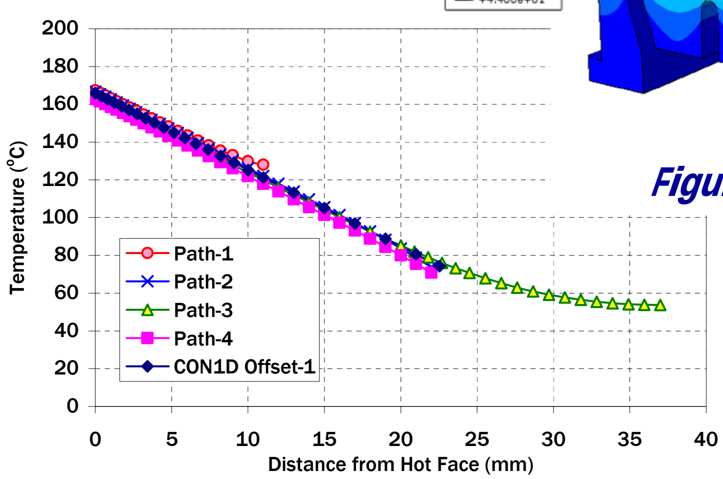
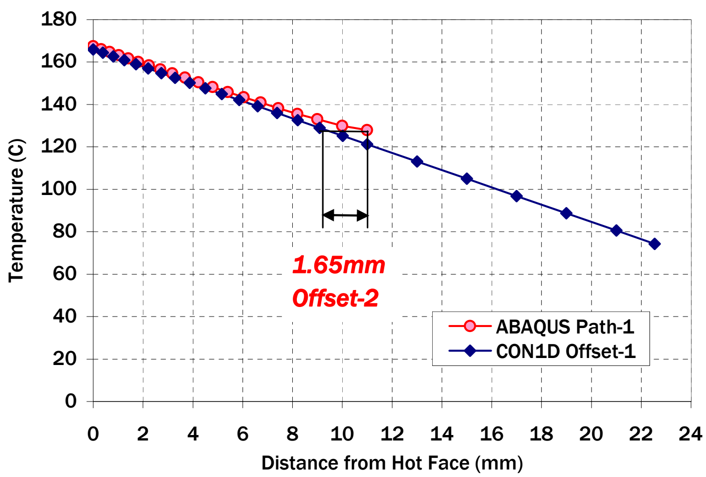


Figure 33. Temperature profiles in Narrow face

3. 2. 3 Offset - 2 - *Influence of Thermocouple Hole geometry -*

Determination of Offset-2

Narrow Face



$$d_{offset-2} = \left(T_{TC} - T_{hf}\right)\frac{dx}{dT} - d_{TC} \quad \text{... (30)}$$

- $d_{offset-2}$: distance of offset-2 (mm)
- T_{TC} : thermocouple temperature from ABAQUS (°C)
- T_{hf} : thermocouple temperature from CON1D (°C)
- dx/dt : inverse of the temperature gradient from CON1D (mm/°C)
- d_{TC} : actual depth of the thermocouple from Hot Face (mm)

Figure 34. Determination of Offset-2 in Wide Face

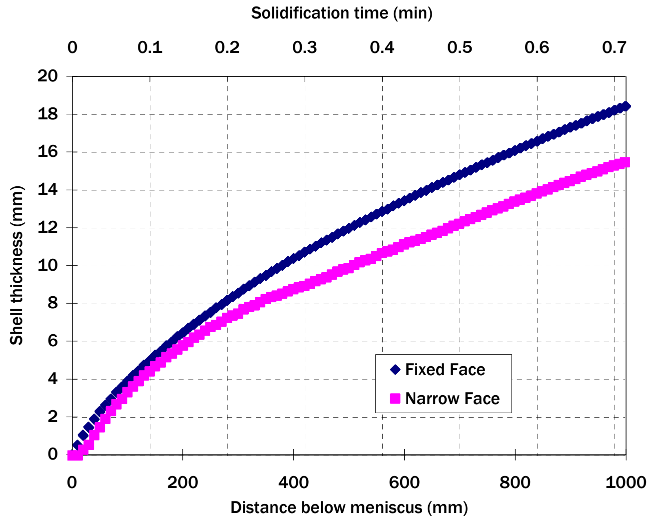
4. CON1D Model Verification with Plant

Table 2. CON1D Fitting Condition

	Fixed face	Narrow face
Simulation shell	Fixed face	
Casting speed	23.4 mm/s	
SEN submergence depth	230 mm	
Pour temperature	1540 ℃	
Meniscus dist. From mold top	96 mm	
Fraction solid for shell thickness location	0.35	
Treatment of superheat	-	1 : default
Mean heat flux in mold - measured	1.279 MW/m^2	1.294 MW/m^2
<u>Fitting Parameters</u>		
- Solid flux conductivity	1.00 W/mK	
- Liquid flux conductivity	1.00 W/mK	
- Location of peak heat flux	-	0.03 m
- Slag rim thickness at metal level	-	2.20 mm
- Slag rim thickness at heat flux peak	-	0.75 mm
- Cold face scale thickness	-	0.002mm
- Constant ratio of solid flux velocity to casting speek	0.085	0.084
<u>CON1D prediction</u>		
- Mean heat flux in mold	1.279 MW/m^2	1.293 MW/m^2

4. CON1D Model Verification with Plant

Solidification History with CON1D (steady state 1.4m/min)



Fixed face

$t_s \le 0.04$

$$S_t = 54.763 t_{sol} + 1.9306 t_{sol}^{0.5} \quad \text{... (26)}$$

$t_s > 0.04$

$$S_t = 25.244 t_{sol}^{0.5} - 3.0216 \quad \text{... (27)}$$

Narrow face

$t_s \le 0.01$

$$S_t = 0 \quad \text{... (28)}$$

$t_s > 0.01$

$$S_t = 20.604 t_{sol}^{0.5} - 2.1854 \quad \text{... (29)}$$

t_s : Solidification time (min)
S_t : Shell thickness (mm)

Figure 35. CON1D calculated thickness profile

4. CON1D Model Verification with Plant

Analyzed Breakout Shell Thickness

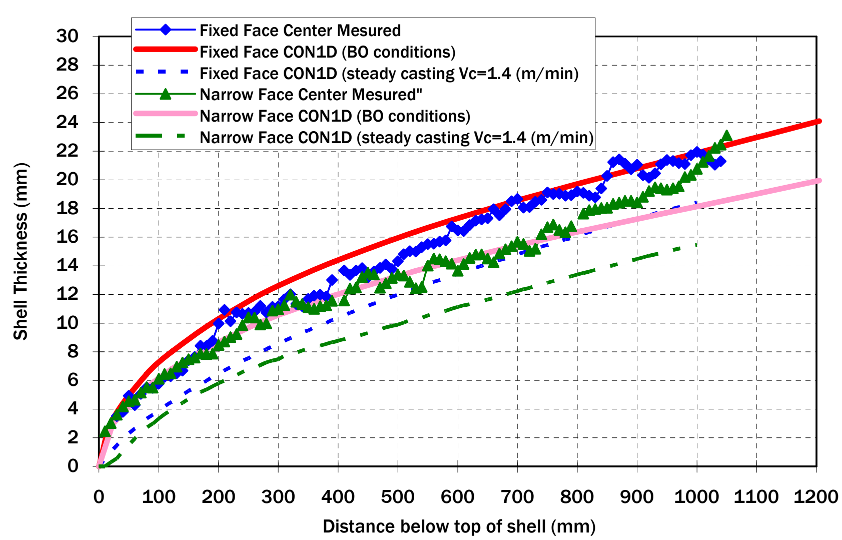


Figure 36. Comparison between CON1D calculated profile and measurements from BO shell

4. CON1D Model Verification with Plant

Analyzed Thermocouple Temperatures

Wide Face

$$d_{offset} = d_{offset-1} + d_{offset-2} \quad \ldots (30)$$

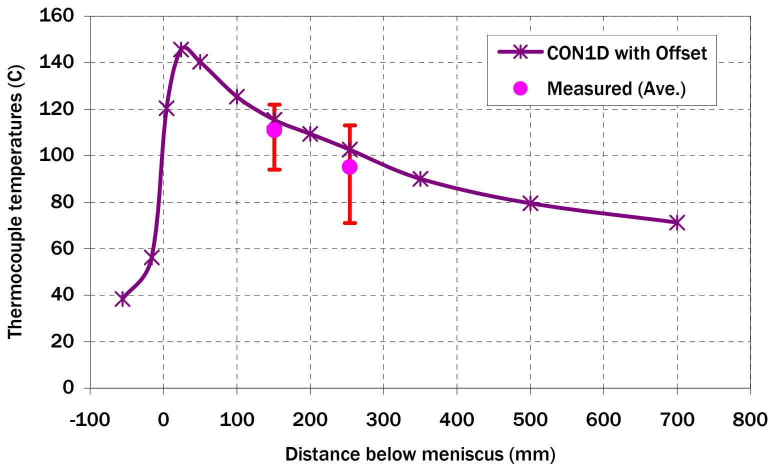


Figure 37. Thermocouple temperatures comparison between CON1D and Measured data

4. CON1D Model Verification with Plant

Narrow Face

$$d_{offset} = d_{offset-1} + d_{offset-2} \quad \ldots (30)$$

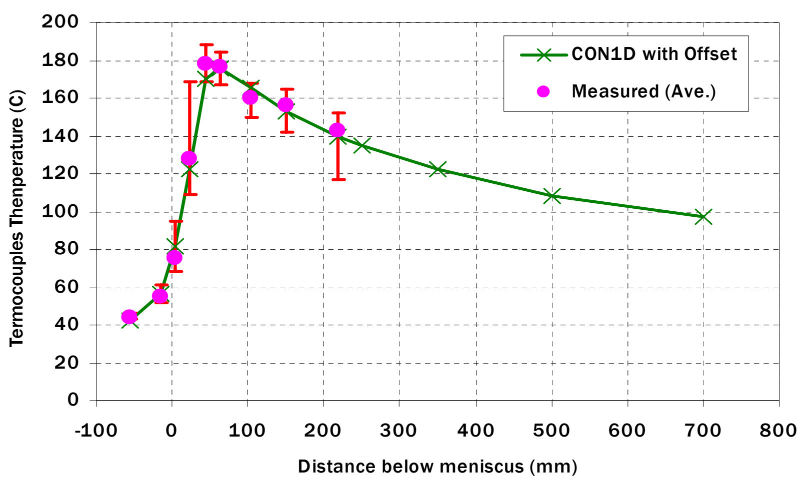


Figure 38. Thermocouple temperatures comparison between CON1D and Measured data

4. CON1D Model Verification with Plant

Table 3. Thermocouple Temperature Comparison

	Distance below	Measured (Ave.)	CON1D with offset	
	Meniscus	Temperature	Temperature	Difference
	mm	°C	°C	°C
Wide Face	151.5	110.9	115.43	**4.5**
	254.0	95.1	102.61	**7.5**
Narrow Face	-56	43.9	42.21	**-1.6**
	-16.0	55.2	56.08	**0.8**
	4.0	75.5	81.65	**6.1**
	24.0	127.8	122.66	**-5.2**
	44.0	178.1	169.86	**-8.2**
	64.0	176.7	175.35	**-1.3**
	104.0	159.7	165.46	**5.7**
	151.5	156.4	152.75	**-3.6**
	219.0	142.8	139.57	**-3.2**

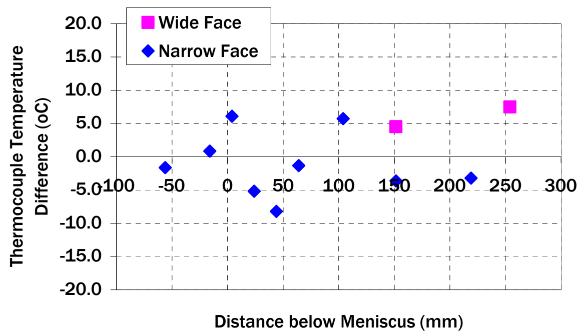


Figure 39. Thermocouple Temperature Difference

5. Conclusions

- Mass balance equation for deriving solidification time and flow-rate history of breakout shell is developed, and applied to understand a real breakout.

- General Offset formula established and applied:
  - 2D ABAQUS heat transfer model to CON1D for hotface
  - 3D ABAQUS heat transfer model to CON1D for TC.

- Analyzed shell thickness with CON1D agreed well with the measured shell thickness from the breakout shell.

- Analyzed thermocouple temperature with CON1D with offset agree well with the measurement thermocouple temperature within 8.2 °C.