Influence of Mold Geometry on Mold Heat Transfer and Thermocouple Temperature

Melody Langeneckert

Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign

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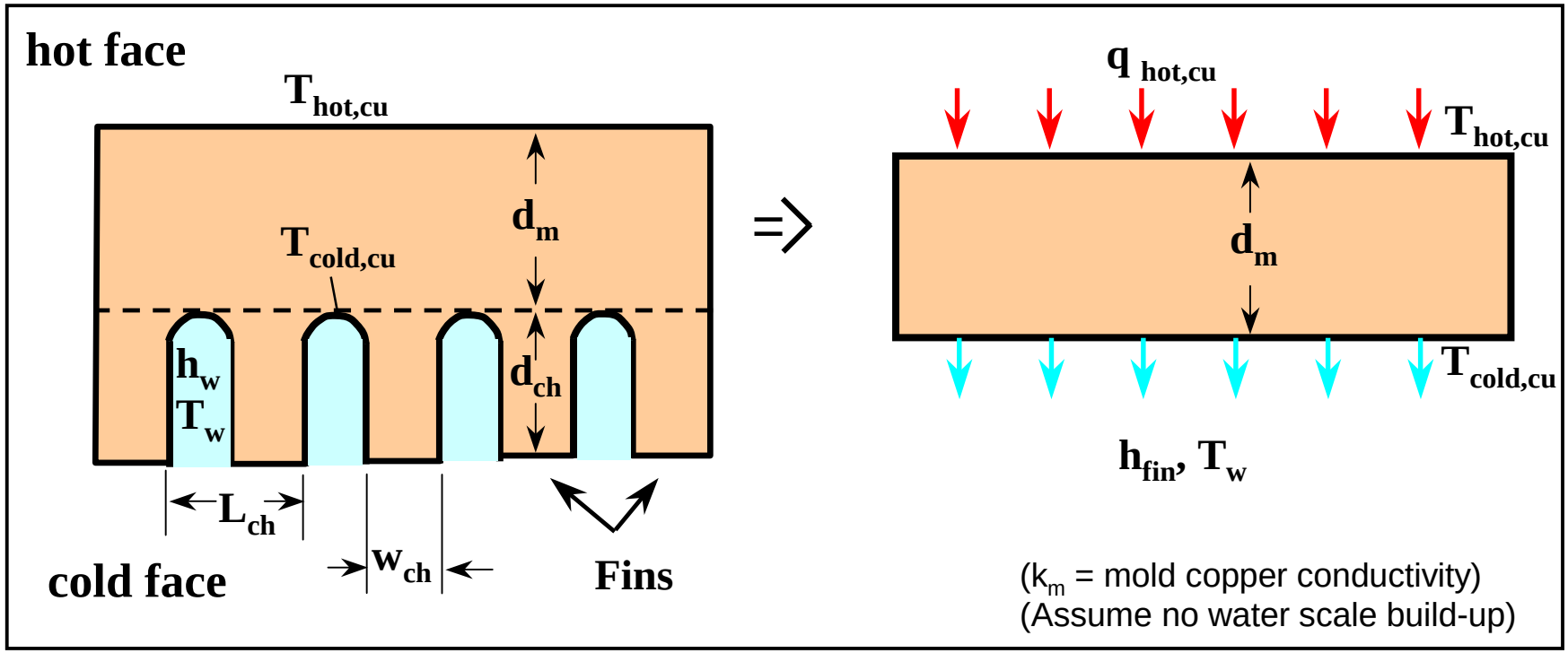
Agenda

- Background – **1D Mold heat transfer using CON1D**
- Problem – **2D conduction due to changes in geometry**
- Improving CON1D capability
  - **estimating mold corner temperature**
  - **3D accuracy, using an offset, to interpret thermocouple temperatures**
- Conclusion - **Implementing improvements to CON1D**
- Future work

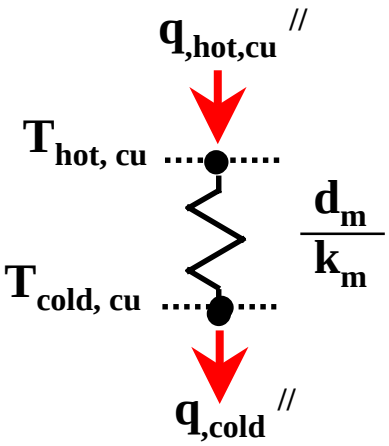
Background

Water Slot - Fin Analogy

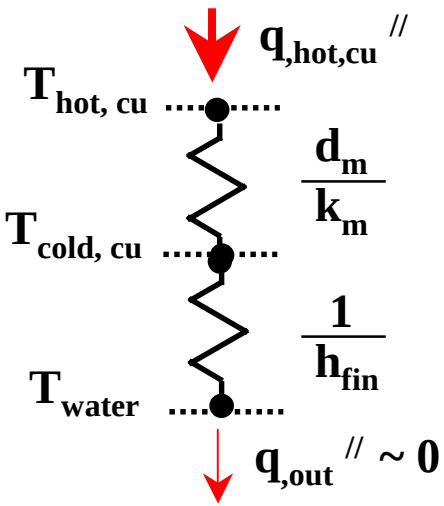


$$h_{fin} = \frac{h_w w_{ch}}{L_{ch}} + \frac{\sqrt{2h_w k_m (L_{ch} - w_{ch})}}{L_{ch}} tanh \sqrt{\frac{2h_w d_{ch}^2}{k_m (L_{ch} - w_{ch})}}$$

Background
CON1D Equations



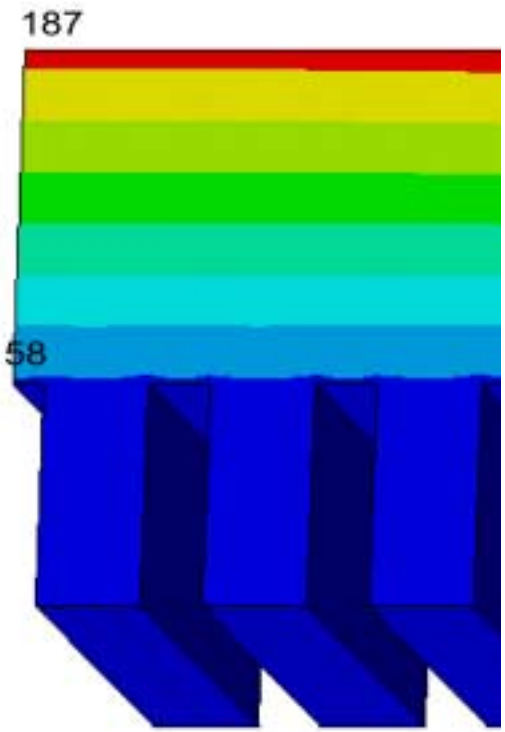
$(q_{,hot,cu}^{//} = q_{,cold}^{//})$

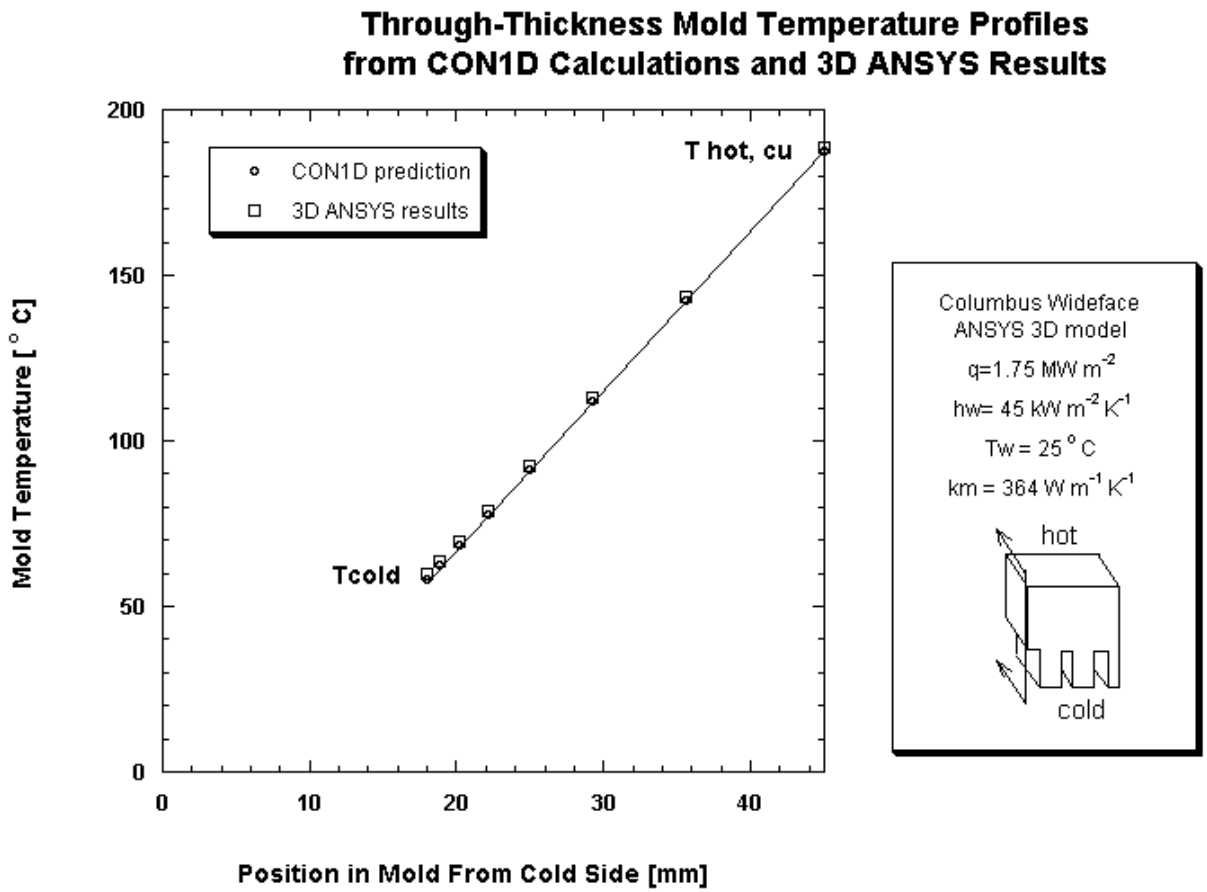


$$T_{hot,cu} = T_{water} + q''_{hot,cu}\left(\frac{1}{h_{fin}} + \frac{d_m}{k_m}\right)$$

$$T_{cold} = T_{water} + \frac{q''_{cold}}{h_{fin}}$$

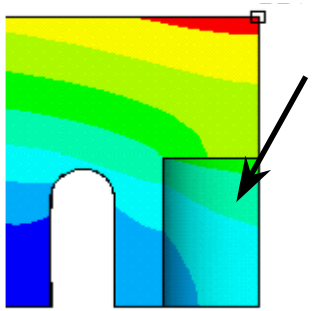
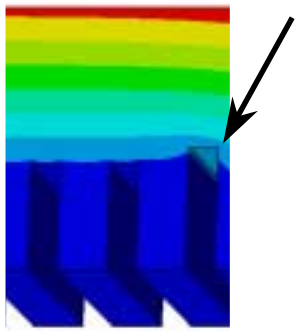
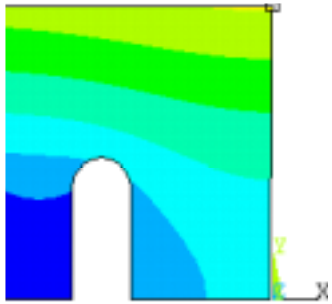
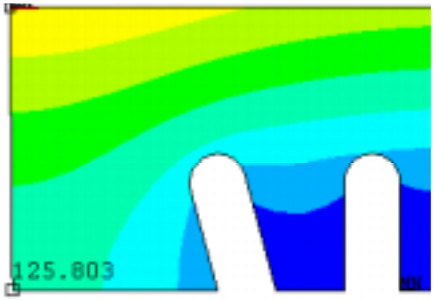
Background
CON1D and 3D ANSYS results





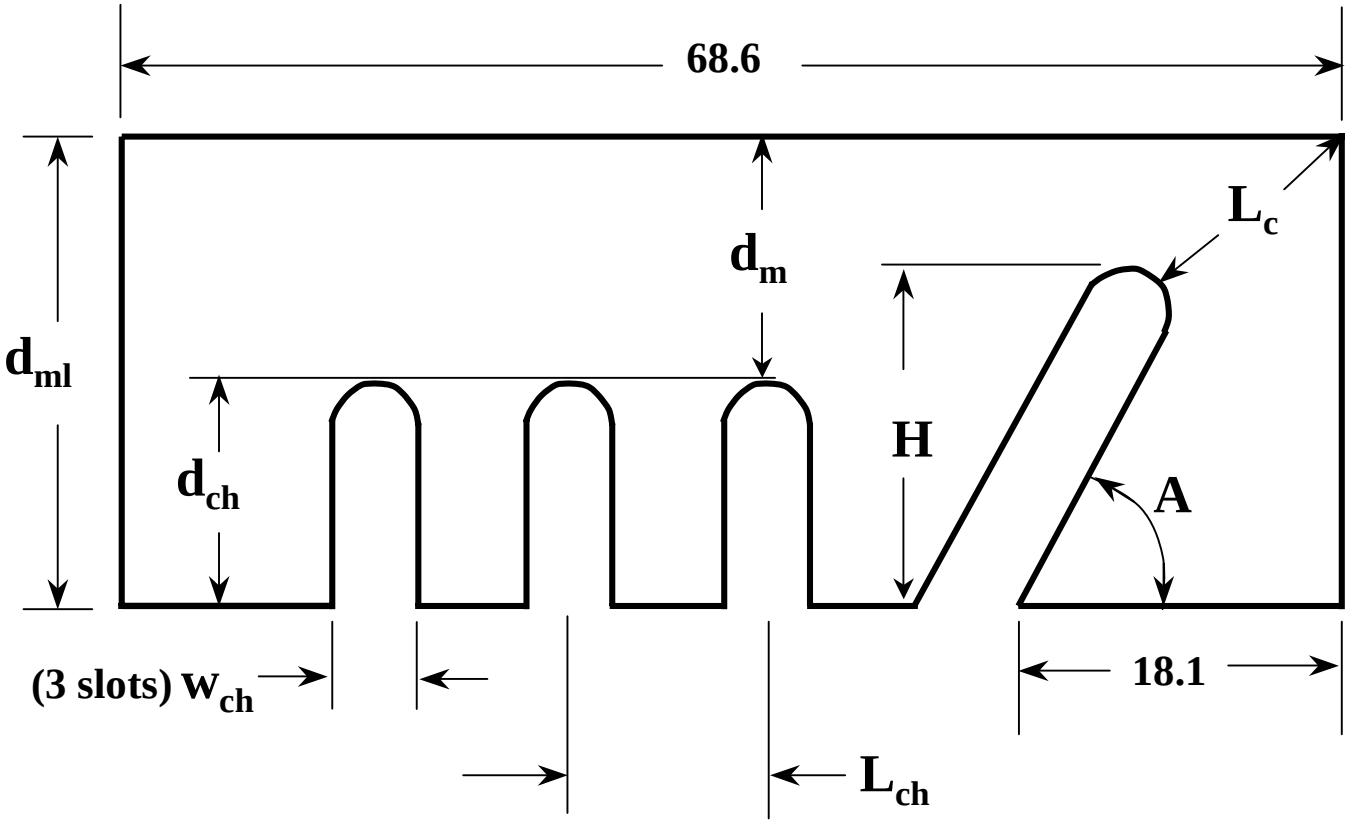
Problem

2D Conduction due to changes in geometry

Bolts	Deep end slot
	
Mold edges	**Angled slots**
	

Estimating mold corner temperature based on angled water slot geometry

2D Model Geometry



Typical Dimensions

d_{ml} = 25 mm

d_{ch} = 11 mm

w_{ch} = 5 mm

d_m = 13 mm

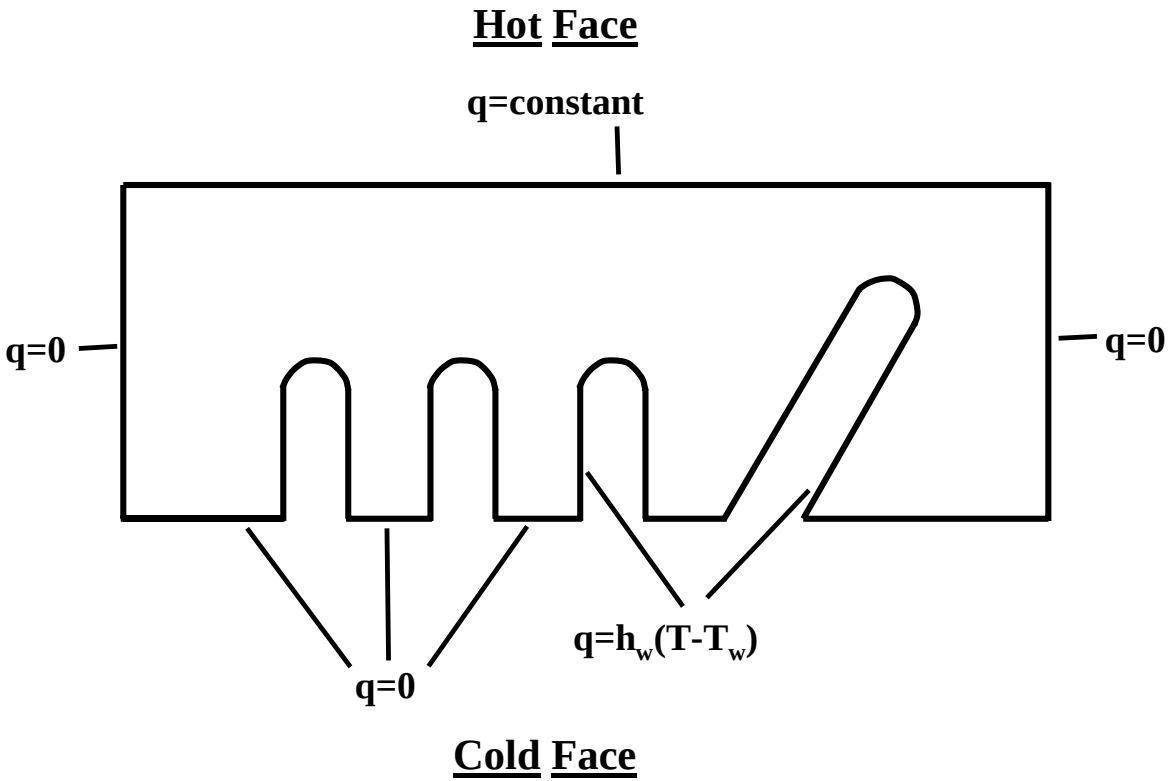
L_c = 13.5 mm

L_{ch}=16 mm

A= 75 °

(Based on Armco narrow face)

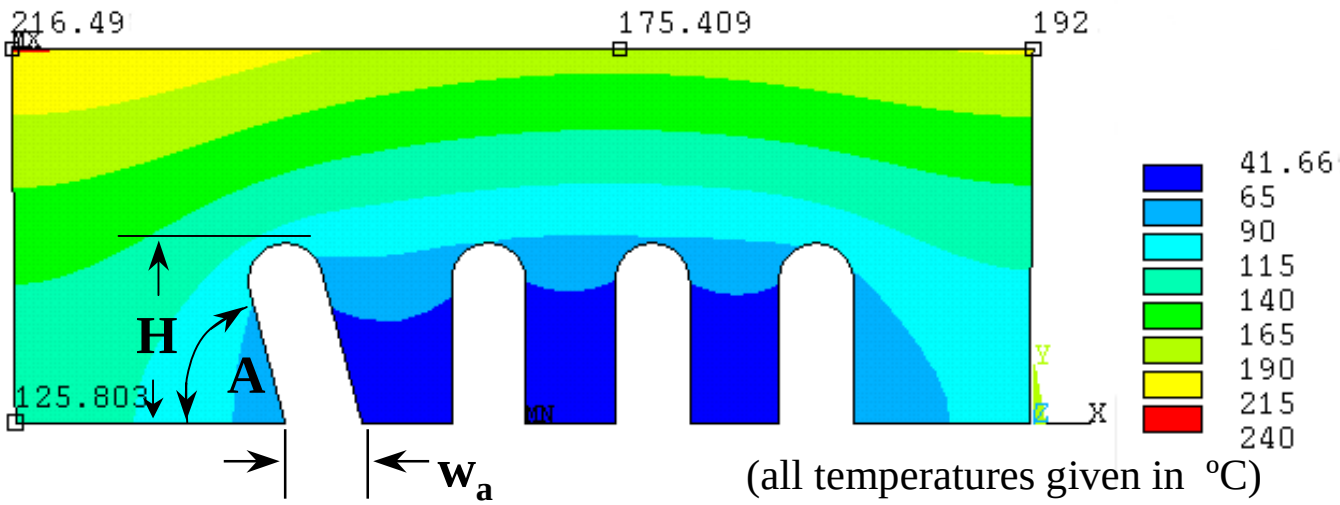
2D Model Boundary Conditions



2D Model Results

Eight geometries were chosen for the angled water slot varying:

- the angle (A), [45º ,80º]
- the height, (H) [16 mm, 11 mm]
- and the width (w_a), [9 mm, 4 mm]



(all temperatures given in ºC)

Typical design

$A = 75^o$

$L_c = 22$ mm

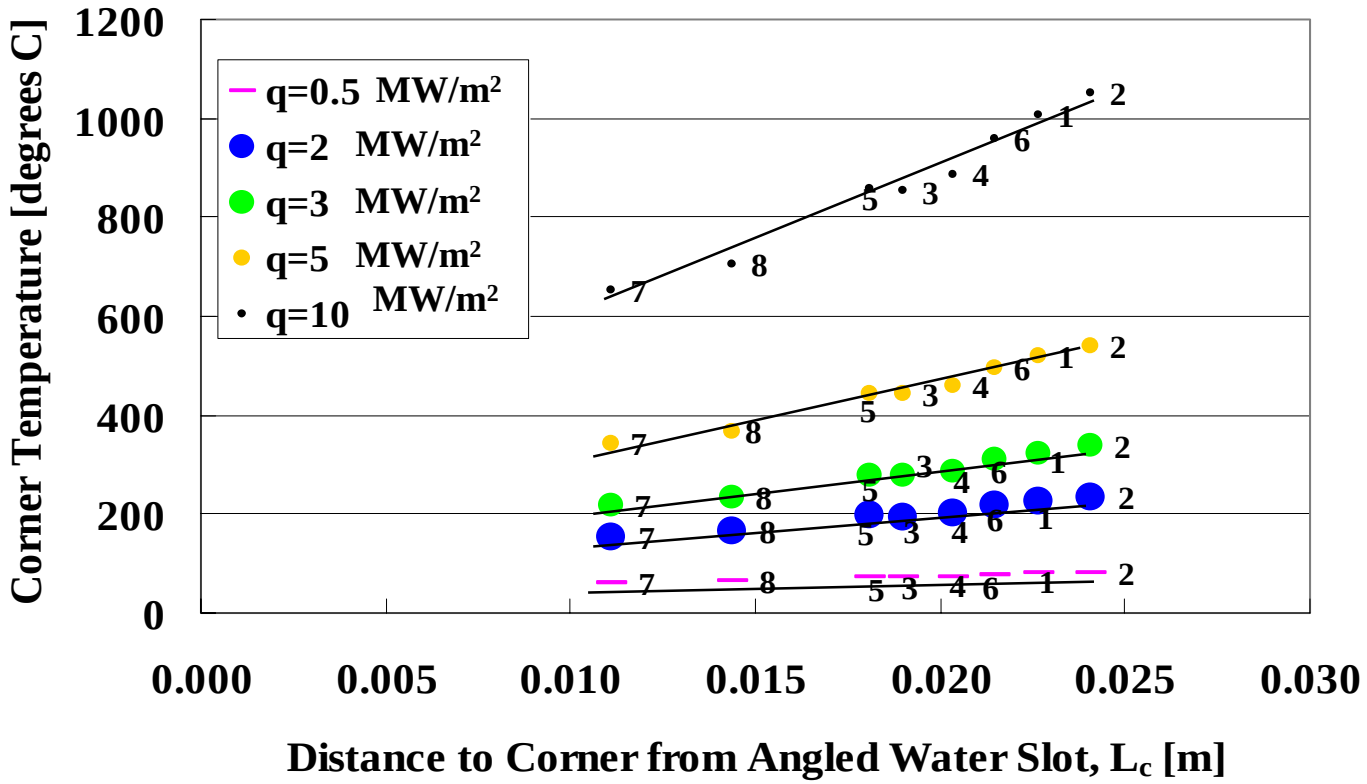
$w_a = 5$ mm

$q = 2.5$ MW m^{-2}

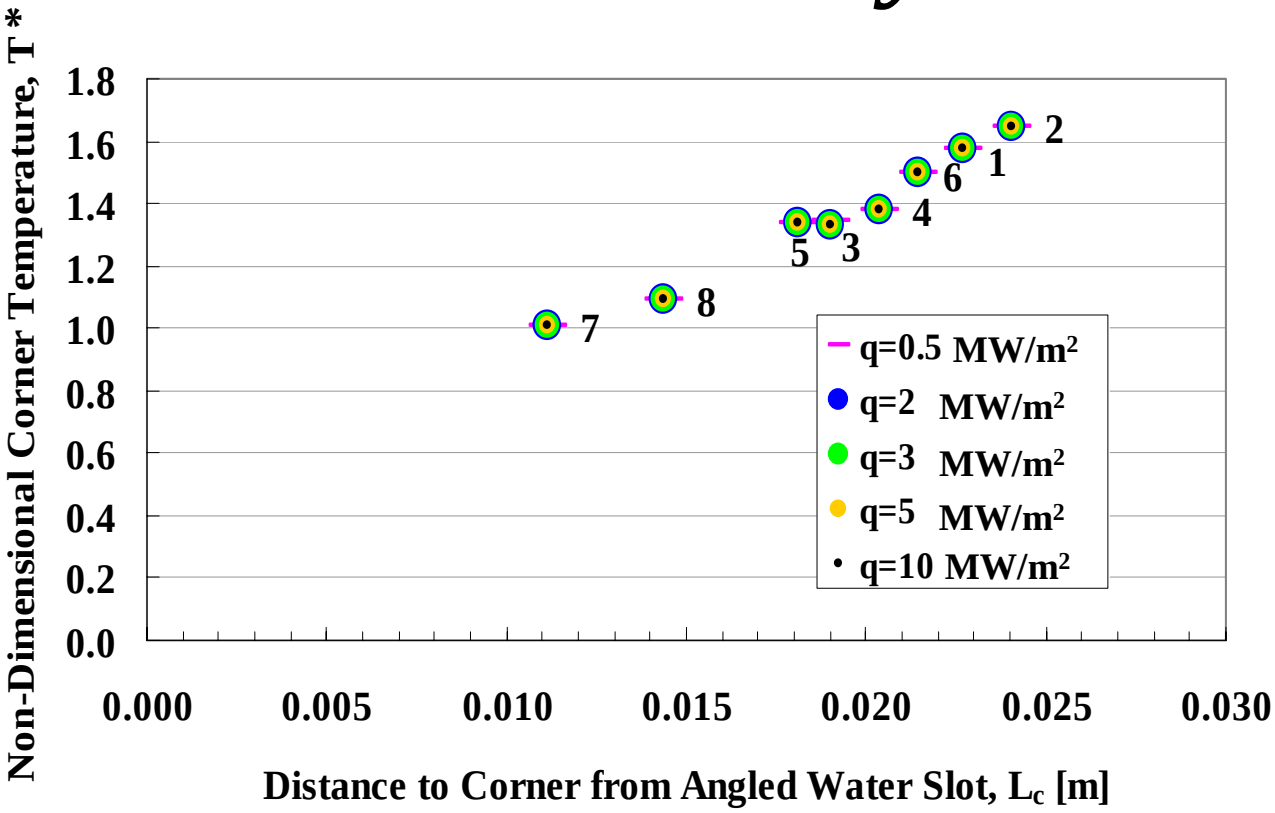
$h_w = 35$ kW m^{-2} K^{-1}

$T_w = 30$ ^oC

Heat Flux and L_c Influence Corner Temperature



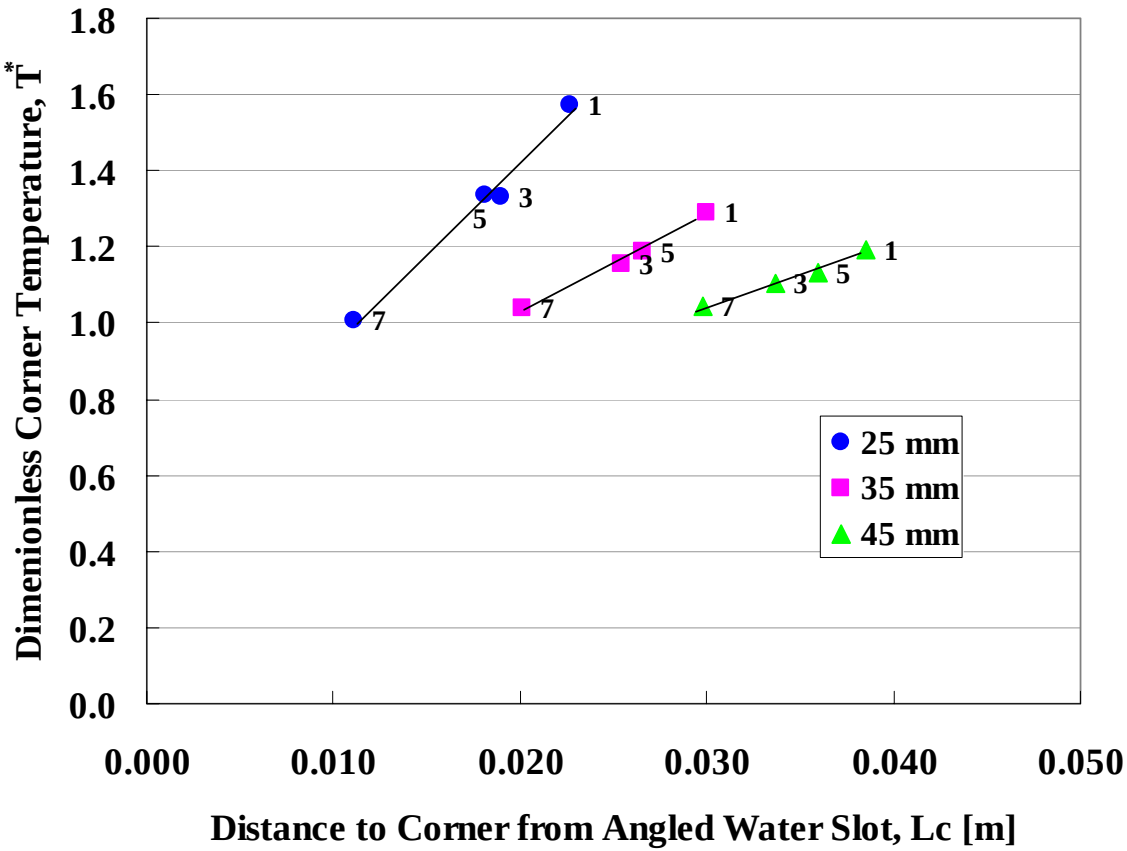
Corner Temperature Normalized by Heat Flux



$$T^* = \frac{k(T_c - T_{water})}{qL_{eff}}$$

$$L_{eff} = \frac{k_m}{h_{fin}} + d_m$$

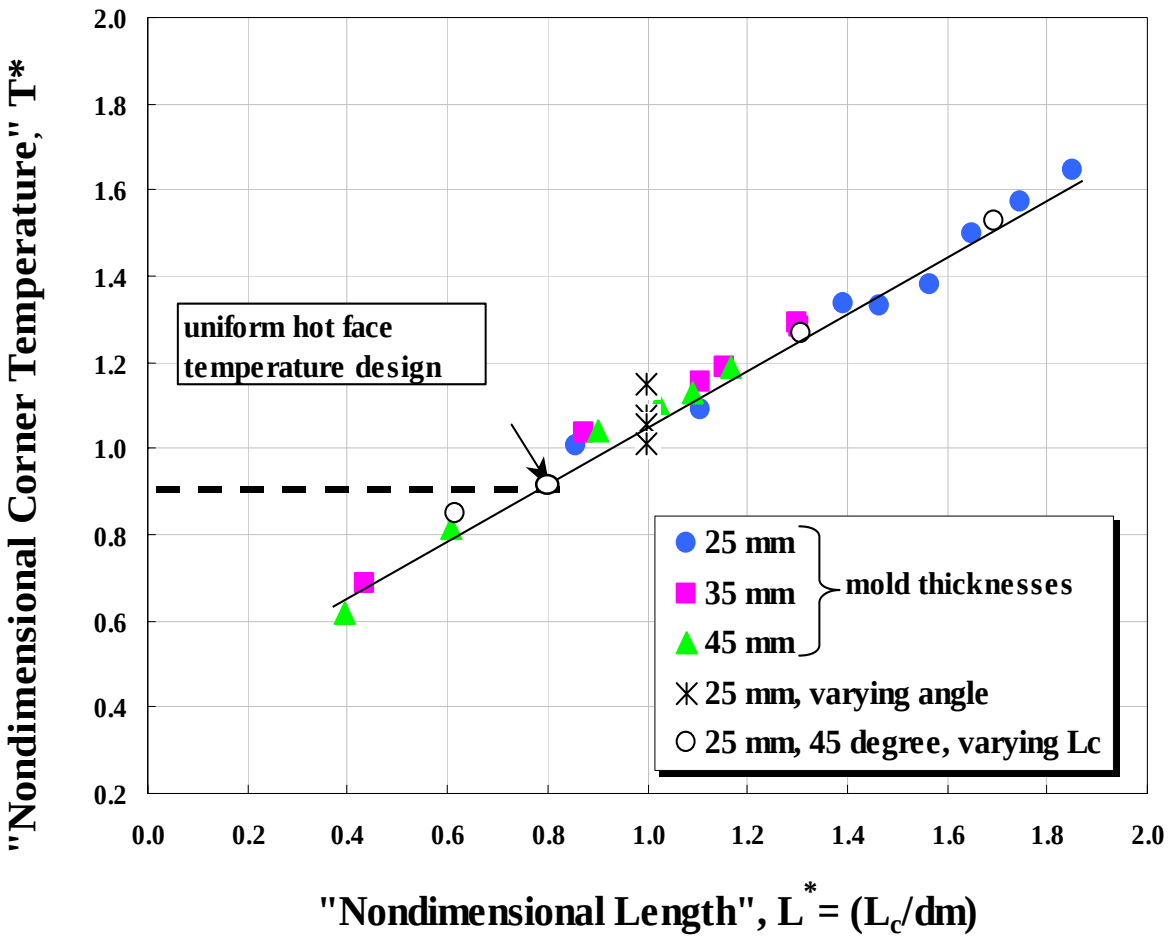
Mold Thickness Affects T_c



$$T^* = \frac{k\left(T_c - T_{water}\right)}{qL_{eff}}$$

$$L_{eff} = \frac{k_m}{h_{fin}} + d_m$$

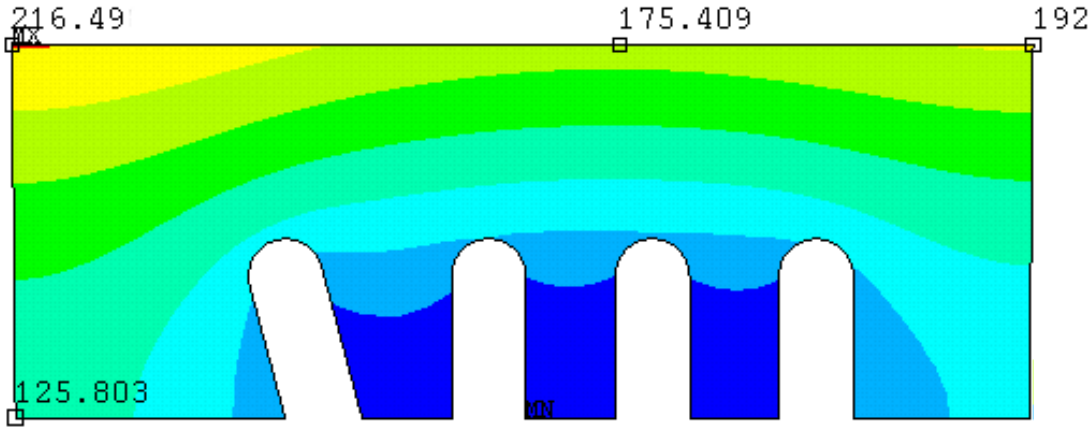
Corner Temperature Estimation



$$L^* = \frac{L_c}{d_m}$$

$$T^* = \frac{k\left(T_c - T_{water}\right)}{qL_{eff}}$$

$$\boxed{T^* = 0.65L^* + 0.42}$$



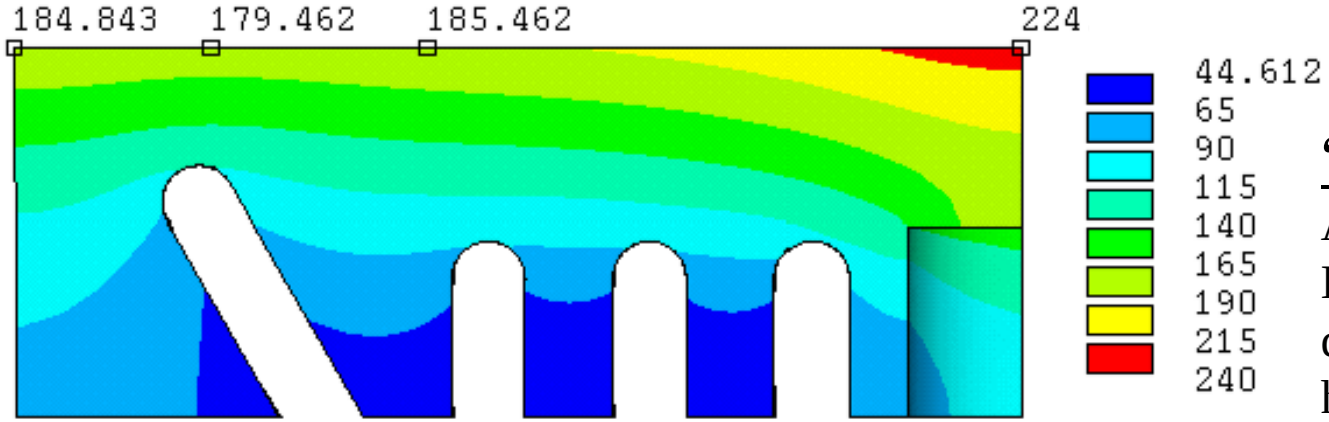
Typical design

$A = 75^o$

$L_c = 22$ mm

$q = 2.5$ MW m^{-2}

$h_w = 35$ kW m^{-2} K^{-1}



"Optimized" design

$A = 60^o$

$L_c = 11.4$ mm

$q = 2.5$ MW m^{-2}

$h_w = 35$ kW m^{-2} K^{-1}

Calculating T_c

$$L^* = \frac{L_c}{d_m} \qquad (1)$$

$$T^* = \frac{k(T_c - T_{water})}{qL_{eff}} \qquad (2)$$

$$L_{eff} = \frac{k_m}{h_{fin}} + d_m \qquad (3)$$

$$T^* = 0.65L^* + 0.42 \qquad (4)$$

$$T_{hot,cu} = T_{water} + q''_{hot,cu}\left(\frac{1}{h_{fin}} + \frac{d_m}{k_m}\right) \qquad (5)$$

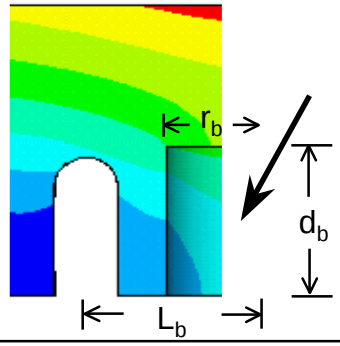
$$\boxed{T_c = \left(0.65\frac{L_c}{d_m} + 0.42\right)\left(T_{hot,cu} - T_w\right) + T_w} \qquad (6)$$

Adding 3D accuracy to CON1D

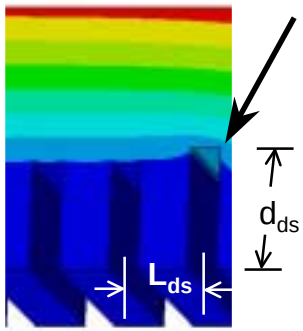
to interpret thermcouple temperatures

Nomenclature

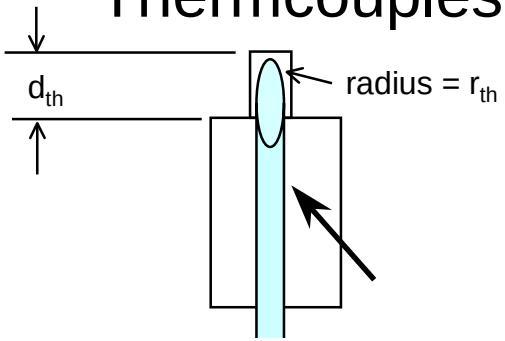
Bolt holes



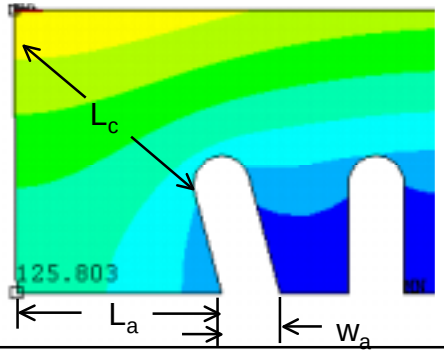
Deep end slot



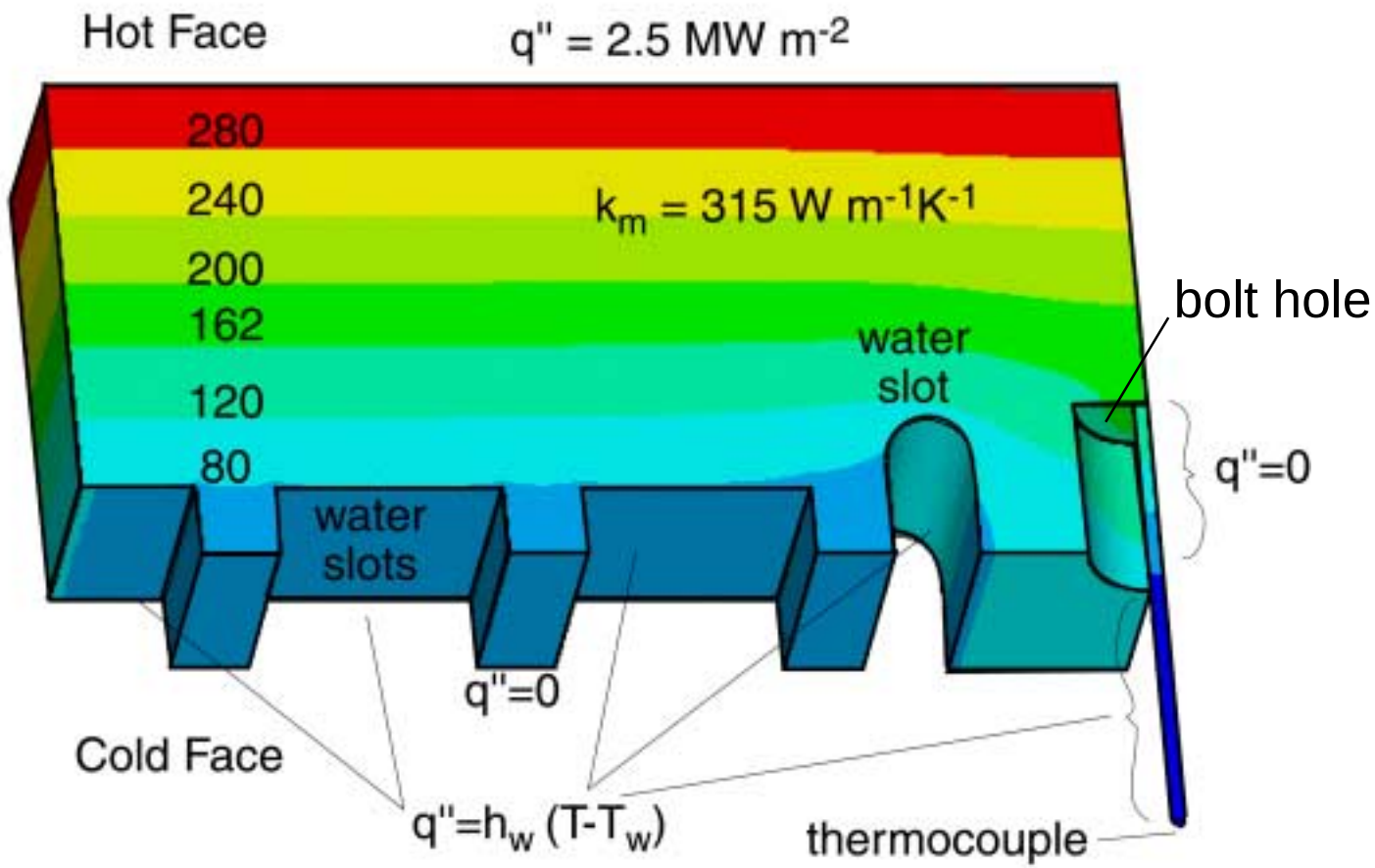
Thermcouples



Angled slots



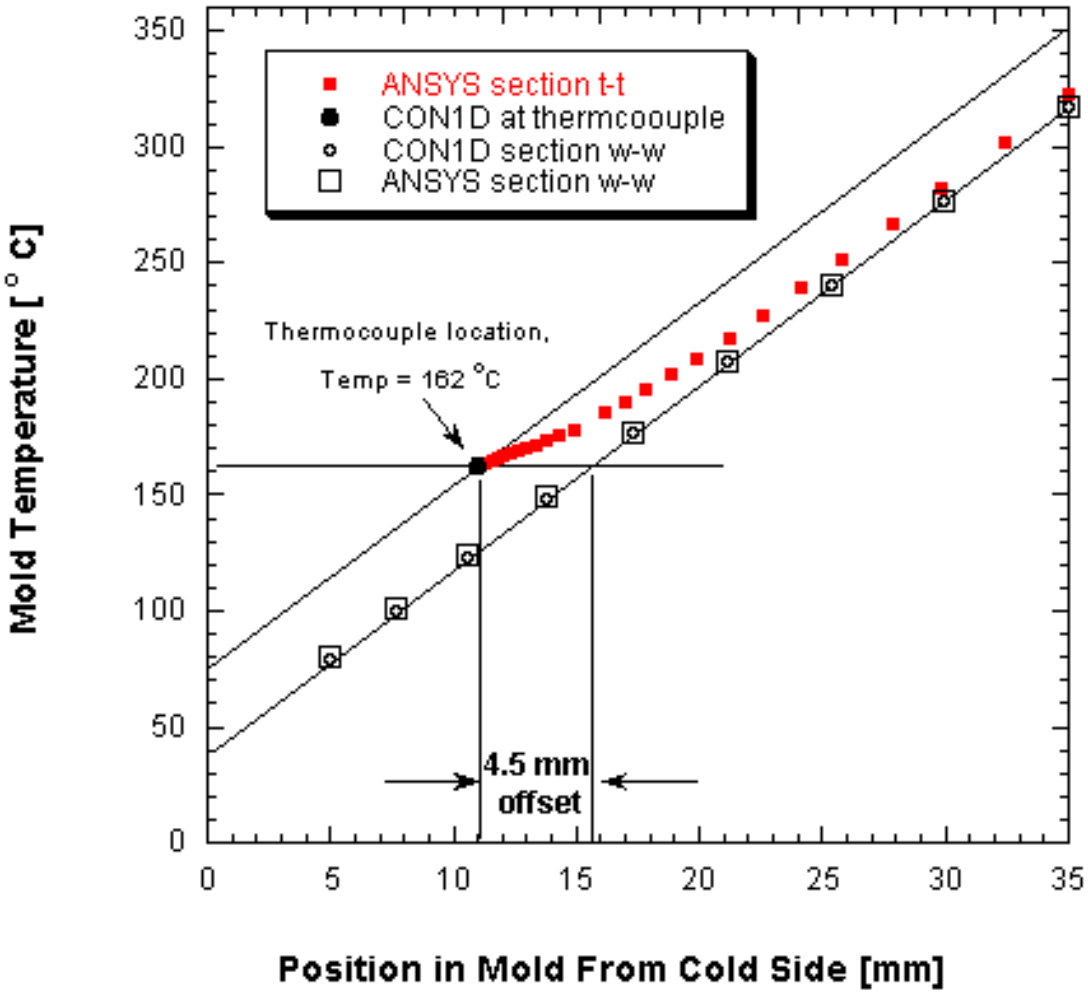
3D ANSYS Model Description



$h_w = 54$ kW m^{-2} K^{-1}
$T_w = 35$ °C

all temperatures [°C]
q''=0 where not specified

Through-Thickness Mold Temperature Profiles
Comparing 3D and CON1D Predicitons
Near the Water Slots and Near the Thermocouple



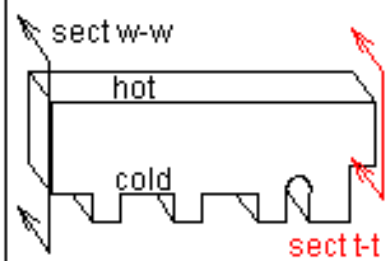
Armco Wideface
ANSYS 3D model

$q = 2.5\ MW\ m^{-2}$

$hw = 54\ kW\ m^{-2}\ K^{-1}$

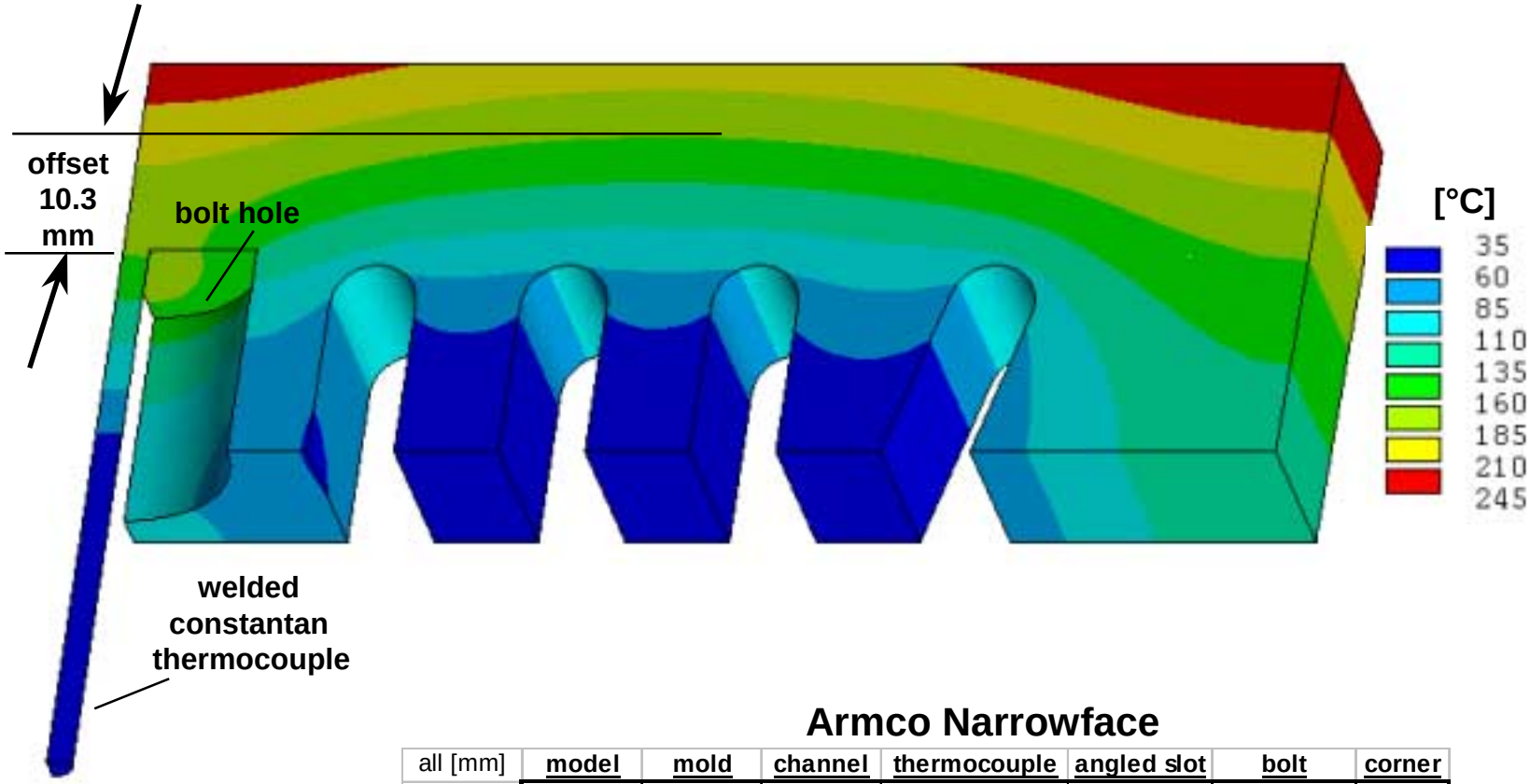
$Tw = 35\ ^{\circ}C$

$km = 315\ W\ m^{-1}\ K^{-1}$



3D ANSYS Results

Armco Narrowface

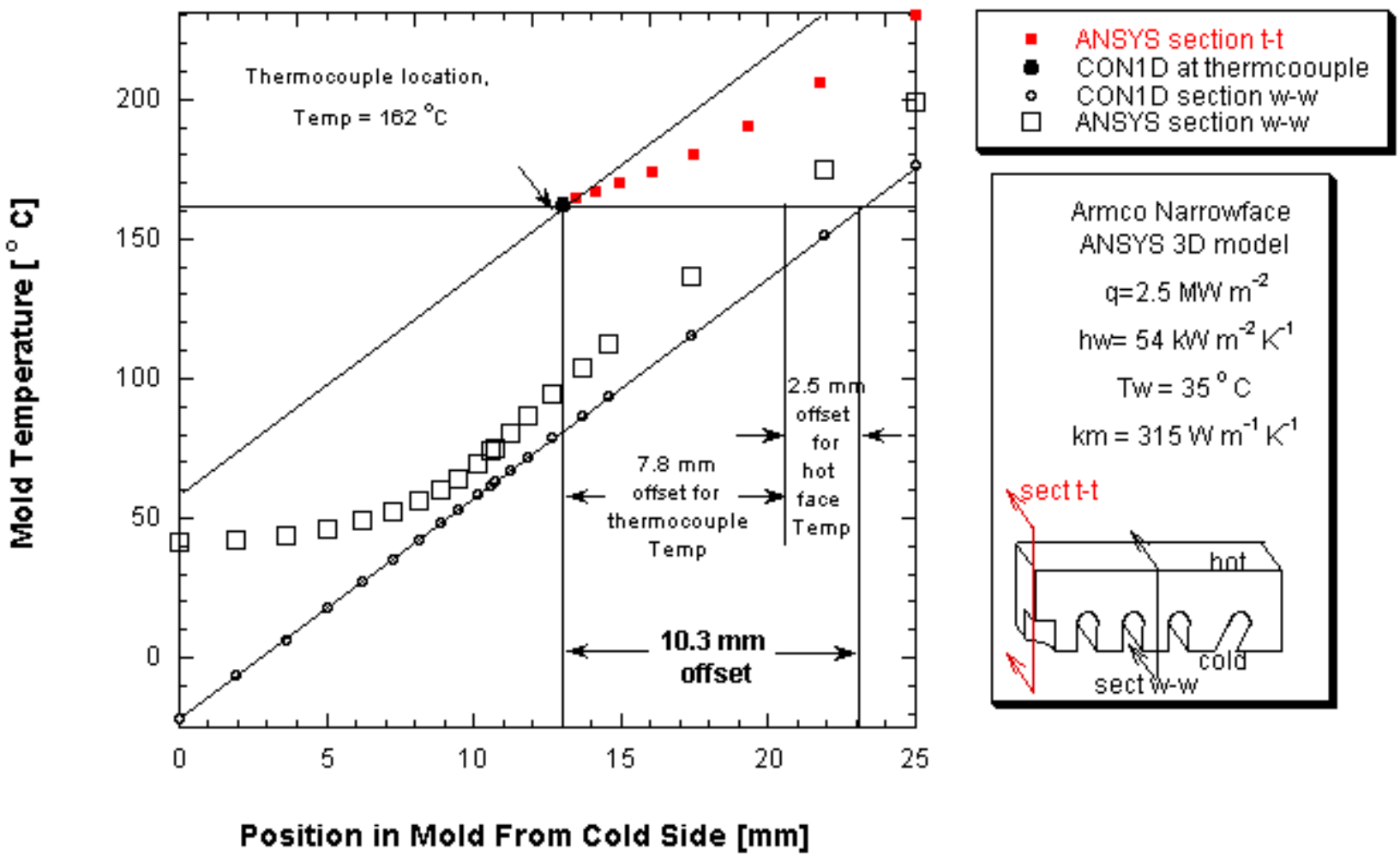


q, hot cu = 2.5 MW m^{-2}
hw = 54 kW m^{-2} K^{-1}
Tw = 35 °C
km = 315 W m^{-1} K^{-1}
kth = 218 W m^{-1} K^{-1}

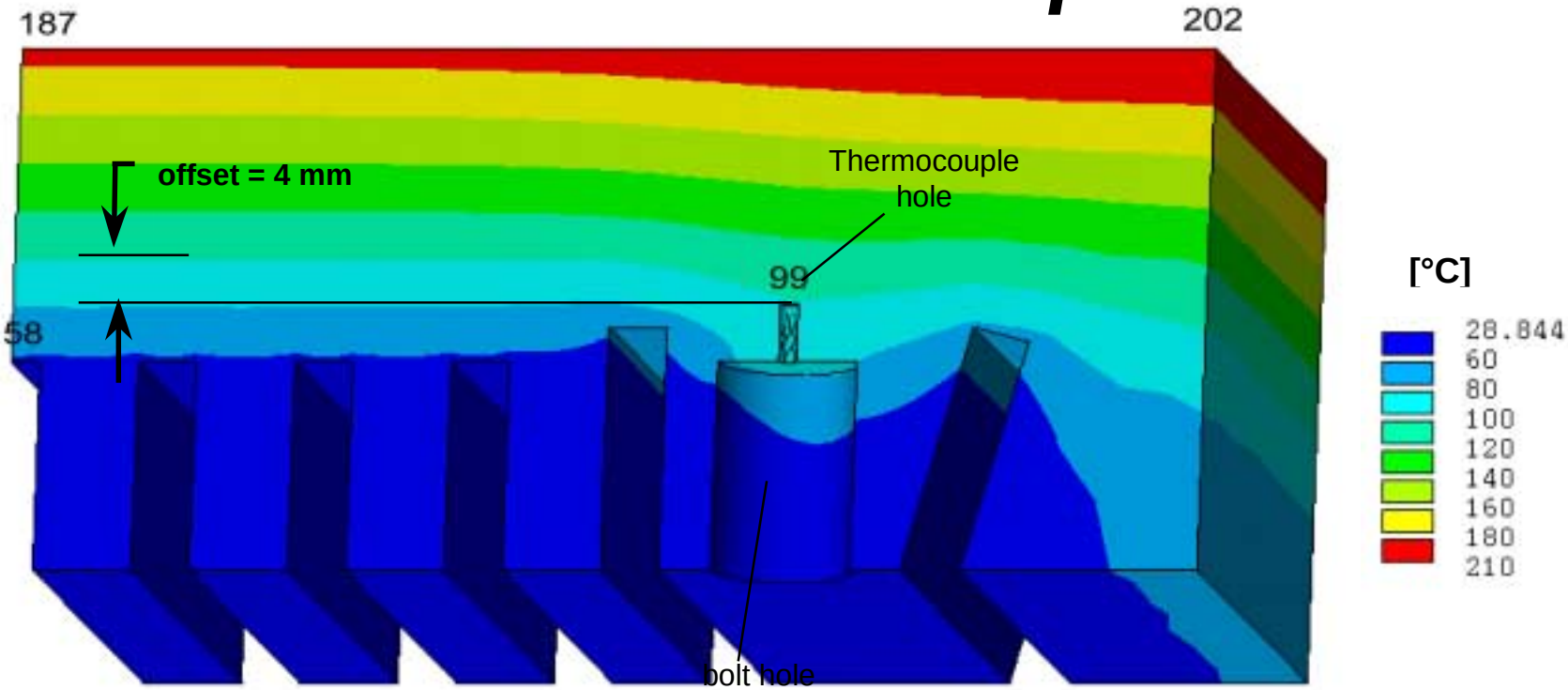
Armco Narrowface

all [mm]	model	mold	channel	thermocouple	angled slot	bolt	corner
depth	**dml**	**dm**	**dch**		**H**	**db**	
	25	13	12		12	13	
length	**Lml**		**Lch**		**La**	**Lb**	**Lc**
	68.6		11		18.1	14.8	21.4
width (or radius)			**wch**	**rth**	**wa**	**rb**	**A**
			5	1	5	8	75 °

Through-Thickness Mold Temperature Profiles Comparing 3D and CON1D Predicitons Near the Water Slots and Near the Thermocouple



3D ANSYS Results
Columbus Narrowface

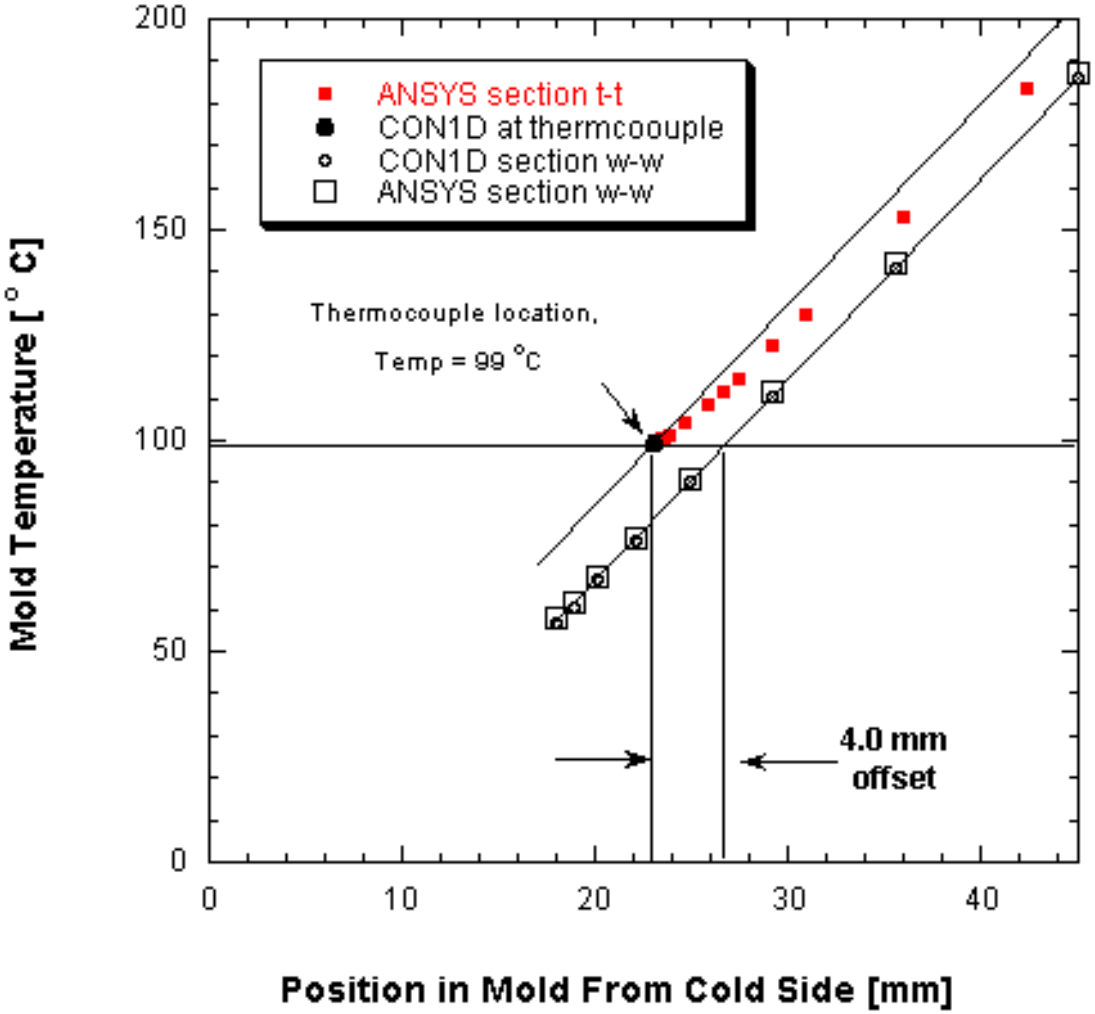


Columbus Narrow Face

q, hotcu = 1.75 MW m^{-2}
hw = 45 kW m^{-2} K^{-1}
Tw = 25 °C
km = 364 W m^{-1} K^{-1}

all [mm]	model	mold	channel	thermocouple	deep slot	angled slot	bolt	corner
depth	**dml**	**dm**	**dch**	**dth**	**dds**	**da**	**db**	
	45	27	18	5	21	21	18	
length	**Lml**		**Lch**		**Lds**	**La**	**Lb**	**Lc**
	103		13.5		13	20.5	10.4	29.5
width (or radius)			**wch**	**rth**	**wds**	**wa**	**rb**	
			5	0.75	5	5	6	

Through-Thickness Mold Temperature Profiles Comparing 3D and CON1D Predicitons Near the Water Slots and Near the Thermocouple



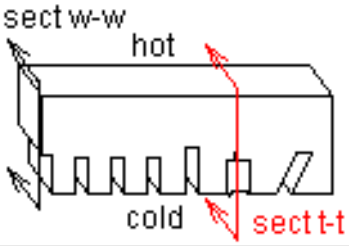
Columbus Narrowface
ANSYS 3D model

$q = 1.75\ MW\ m^{-2}$

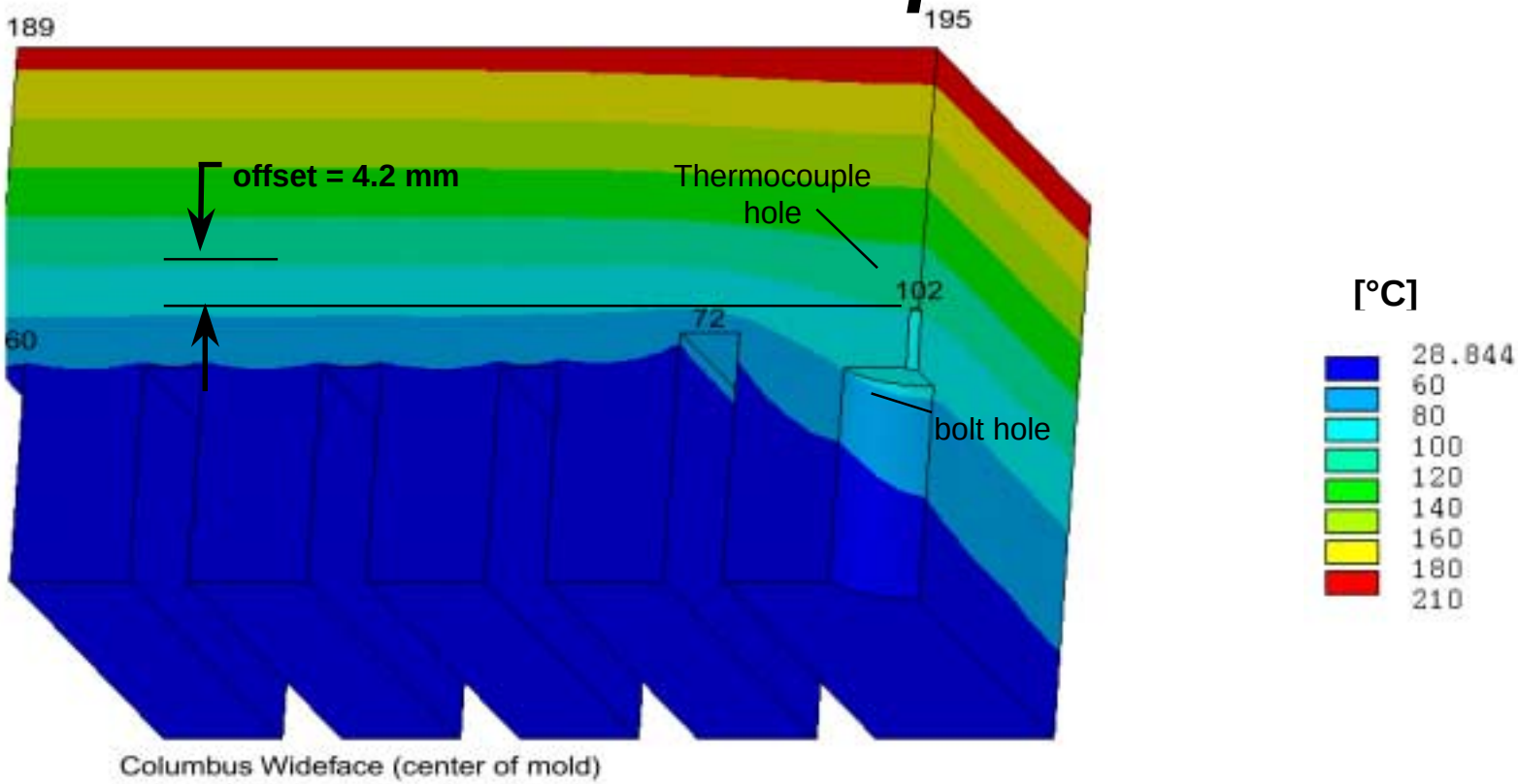
$hw = 45\ kW\ m^{-2}\ K^{-1}$

$Tw = 25\ ^{\circ}C$

$km = 364\ W\ m^{-1}\ K^{-1}$



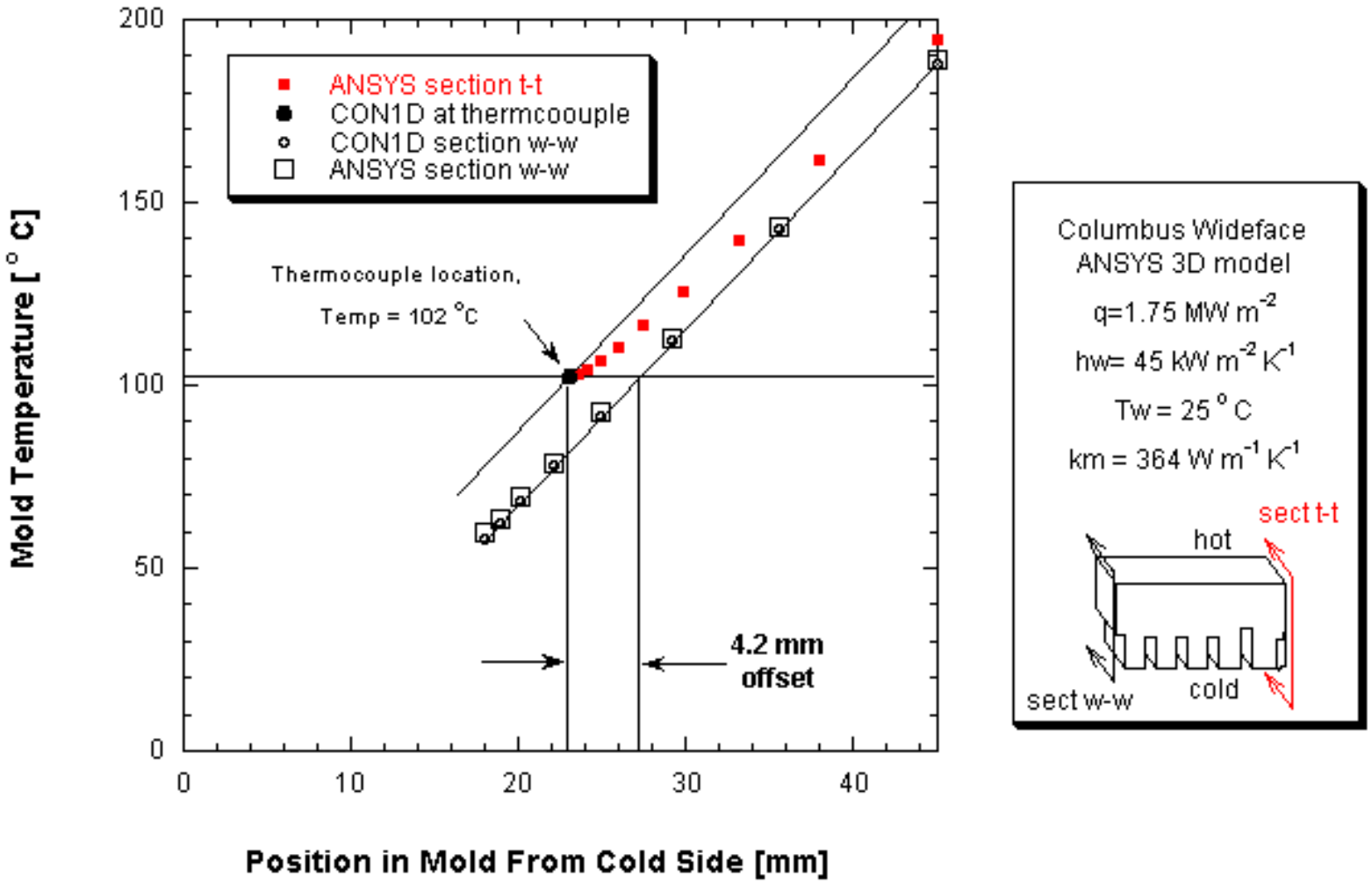
3D ANSYS Results
Columbus Wideface



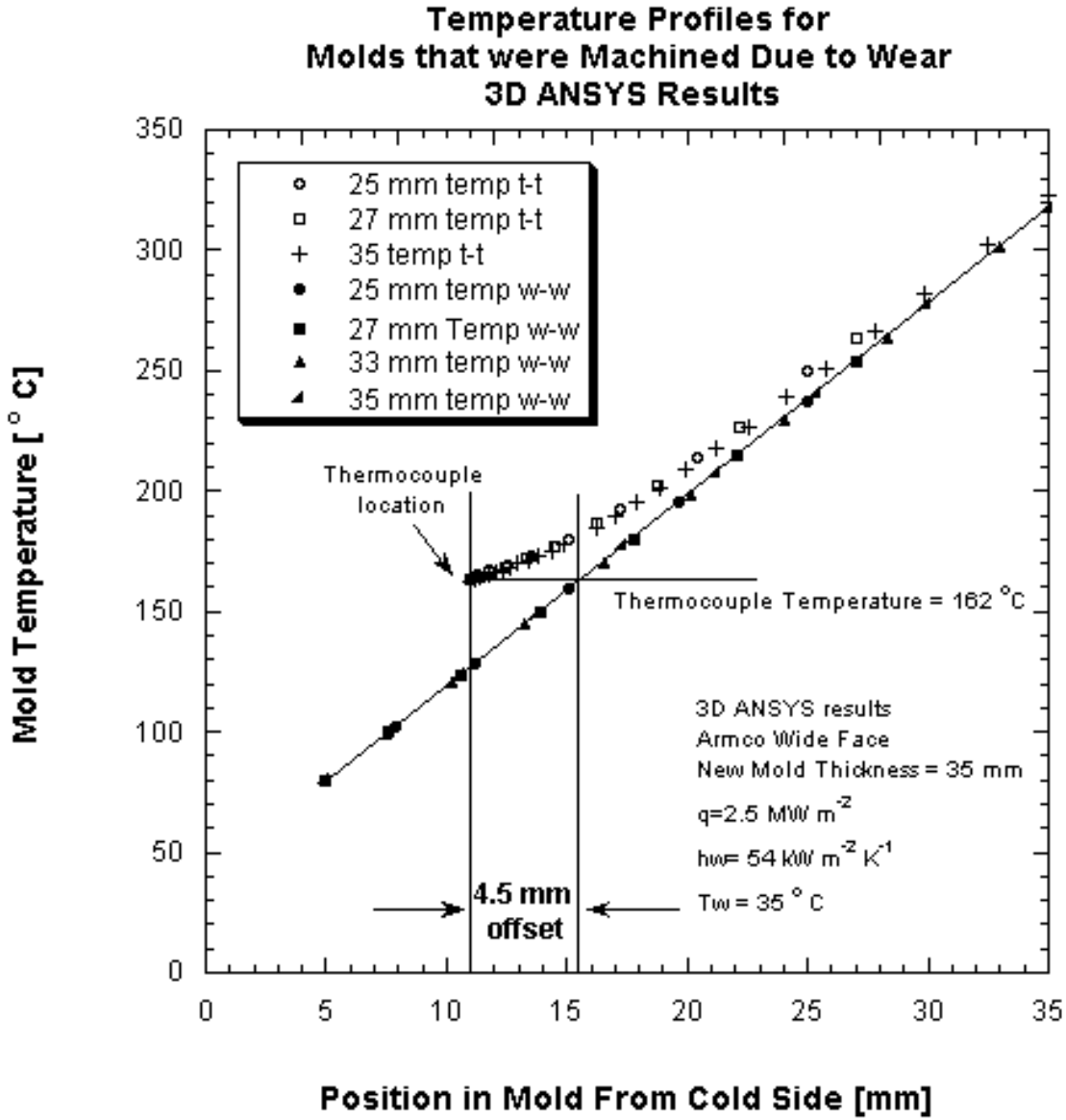
q, hotcu = 1.75 MW m^{-2}
hw = 45 kW m^{-2} K^{-1}
Tw = 25 ^{o}C
km = 364 W m^{-1} K^{-1}

all [mm]	model	mold	channel	thermocouple	deep slot	bolt
depth	**dml**	**dm**	**dch**	**dth**	**dds**	**db**
	45	27	18	5	21	18
length	**Lml**		**Lch**		**Lds**	**Lb**
	60.5		14.5		14.5	14.5
width (or radius)			**wch**	**rth**	**wds**	**rb**
			5	0.75	5	8

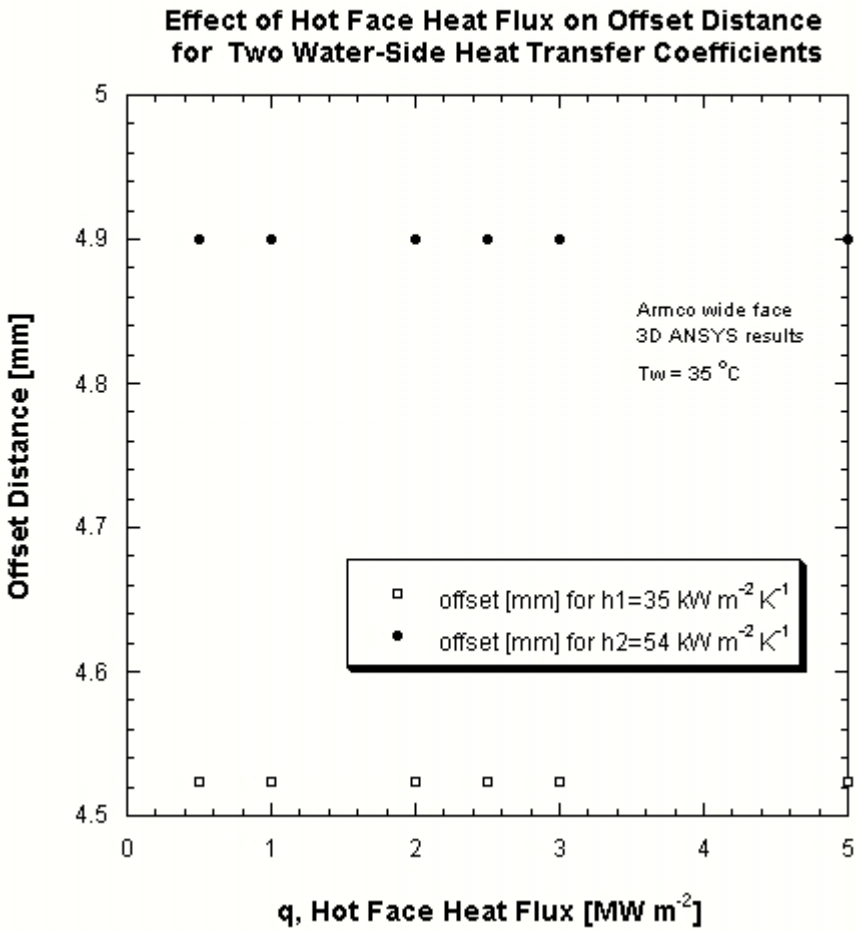
Through-Thickness Mold Temperature Profiles Comparing 3D and CON1D Predicitons Near the Water Slots and Near the Thermocouple

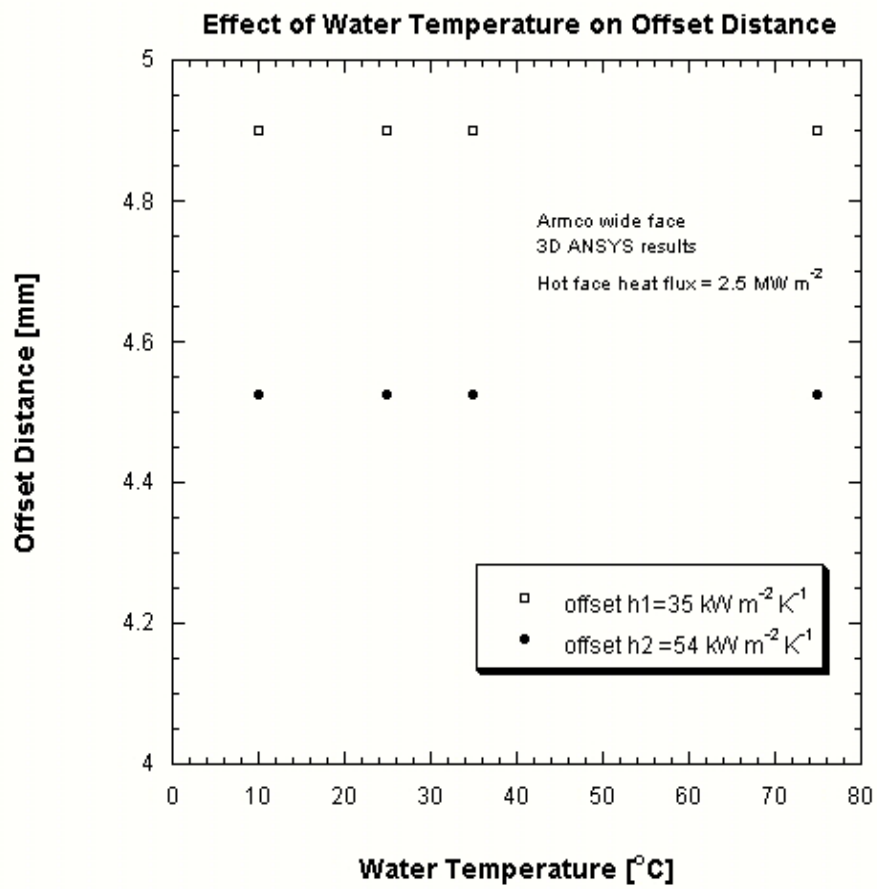


Effect of Mold Thickness on Offset

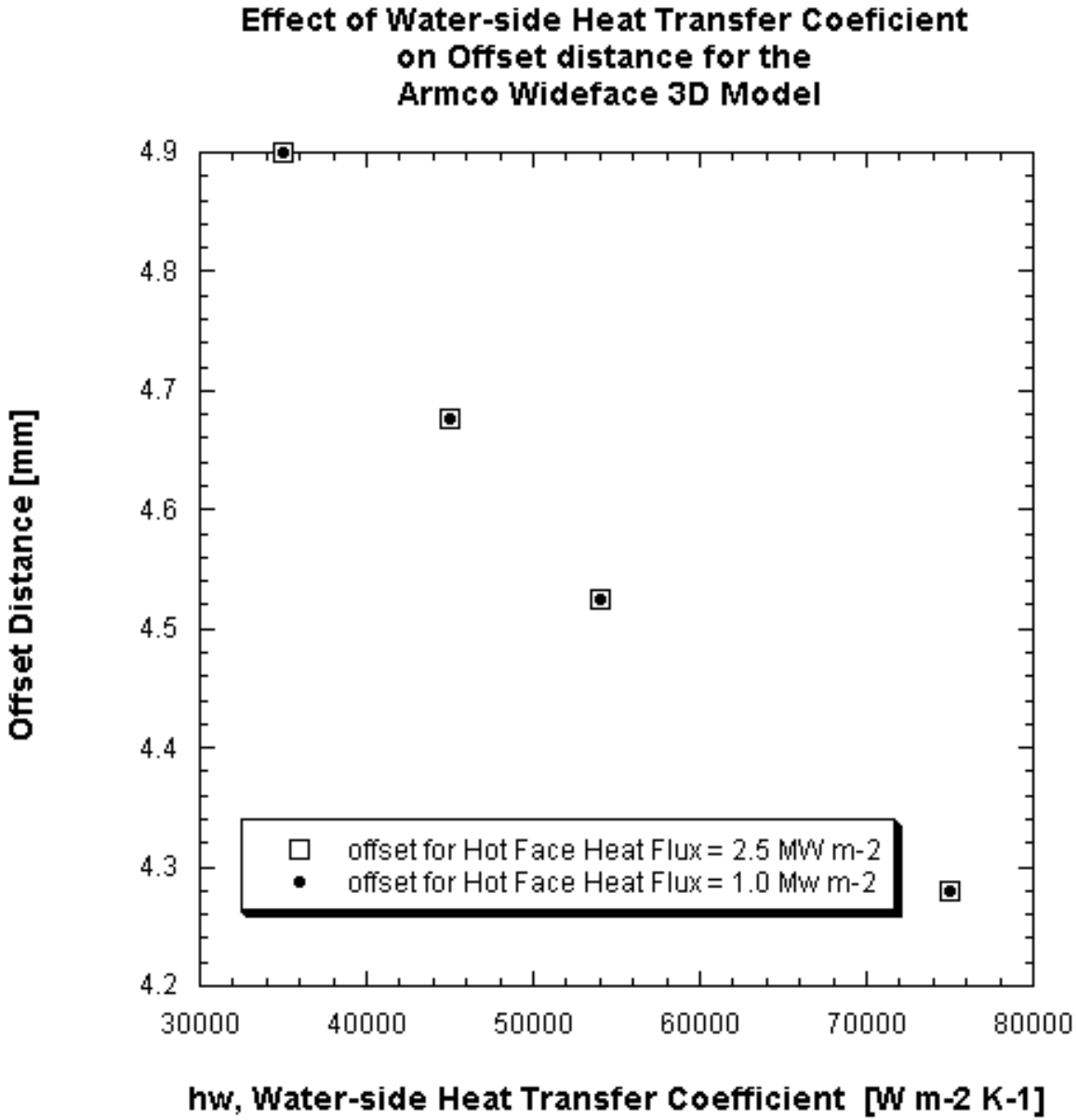


Dependence of Offset on Boundary Conditions





Dependence of Offset on Boundary Conditions



Calculate Offset Using CON1D Equations

$$T_{hot,cu} = T_{water} + q_{hot,cu}\left(\frac{1}{h_{fin}} + \frac{d_m}{k_m}\right)$$

(Assume no scale buildup
So $h_{fin}=h_{water}$)

$$T_{cold} = T_{water} + \frac{q_{cold}}{h_{fin}}$$

$$X_t = d_m - \left[\frac{\left(T_{thcpl} - T_{cold}\right)}{T_{hot,cu} - T_{cold}} d_m\right]$$

$$\boxed{offset = d_{thcpl} - X_t}$$

Using equations 1 and 2, find a value for q_{int}, so that T_{thcpl} matches plant data.
Recalculate h_{fin} since it is a function of hw which depends on T_{cold}.
Iterate until convergence.

Conclusion
CON1D Improvements

Hot face corner temperature can be estimated based on angled end water slot geometry

$$T_c = \left(0.65 \frac{L_c}{d_m} + 0.42 \right) \left(T_{hot,cu} - T_w \right) + T_w$$

Thermocouple temperatures vary based on mold geometry (and boundary conditions). They can be predicted by CON1D using an offset distance.

Offset distance

- based primarily on mold geometry
- milling a worn mold will not change the offset distance
- independent of hot face heat flux and water temperature
- depends slightly on water-side heat transfer coefficient

Future Work

- Modify equation for corner temperature to depend on end slot angle (A)

- Use new equation to predict hot face temperature near a bolt hole, which has the same geometry as a straight end water slot.