Influence of Mold Geometry on Mold Heat Transfer and Thermocouple Temperature

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September 25, 2000
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

\[ h_{\text{fin}} = \frac{h_w \, w_{ch}}{L_{ch}} + \sqrt{2h_w \, k_m \left(L_{ch} - w_{ch}\right)} \frac{\sqrt{2h_w a_{ch}^2}}{a_{ch}} \, \tanh \sqrt{\frac{2h_w a_{ch}^2}{k_m \left(L_{ch} - w_{ch}\right)}} \]

\( (k_m = \text{mold copper conductivity}) \)
\( (\text{Assume no water scale build-up}) \)
**Background**

**CON1D Equations**

\[
\begin{align*}
T_{\text{hot, cu}} &= T_{\text{water}} + q_{\text{hot, cu}}'' \left( \frac{1}{h_{\text{fin}}} + \frac{d_m}{k_m} \right) \\
T_{\text{cold}} &= T_{\text{water}} + \frac{q_{\text{cold}}}{h_{\text{fin}}} 
\end{align*}
\]
Background

CON1D and 3D ANSYS results

Through-Thickness Mold Temperature Profiles from CON1D Calculations and 3D ANSYS Results

Columbus Wideface
ANSYS 3D model
- $q = 1.75 \text{ MW m}^{-2}$
- $h_w = 45 \text{ kW m}^{-2} \text{ K}^{-1}$
- $T_w = 25 \text{ C}$
- $k_m = 364 \text{ W m}^{-1} \text{ K}^{-1}$

Mold Temperature [°C]

Position in Mold From Cold Side [mm]

CON1D prediction
3D ANSYS results

T_hot, cu
T_cold

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## Problem

2D Conduction due to changes in geometry

<table>
<thead>
<tr>
<th>Bolts</th>
<th>Deep end slot</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Bolts Diagram" /></td>
<td><img src="image2.png" alt="Deep end slot Diagram" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mold edges</th>
<th>Angled slots</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="Mold edges Diagram" /></td>
<td><img src="image4.png" alt="Angled slots Diagram" /></td>
</tr>
</tbody>
</table>
Estimating mold corner temperature based on angled water slot geometry
2D Model Geometry

Typical Dimensions

\[ d_{ml} = 25 \text{ mm} \]
\[ d_{ch} = 11 \text{ mm} \]
\[ w_{ch} = 5 \text{ mm} \]
\[ d_{m} = 13 \text{ mm} \]
\[ L_{c} = 13.5 \text{ mm} \]
\[ L_{ch} = 16 \text{ mm} \]
\[ A = 75^\circ \]

(Based on Armco narrow face)
2D Model Boundary Conditions

Hot Face

\[ q = \text{constant} \]

Cold Face

\[ q = 0 \]

\[ q = h_w(T - T_w) \]
2D Model Results

Eight geometries were chosen for the angled water slot varying:

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

Typical design
A = 75°
Lc = 22 mm
wa = 5 mm
q = 2.5 MW m⁻²
hw = 35 kW m⁻² K⁻¹
Tw = 30 °C
Heat Flux and $L_c$

Influence Corner Temperature

![Graph showing the relationship between corner temperature and distance to corner from angled water slot. The graph plots corner temperature in degrees Celsius against distance to corner in meters, with different lines for heat flux values $q=0.5$, $q=2$, $q=3$, $q=5$, and $q=10$ MW/m$^2$. The graph shows a positive correlation between distance and corner temperature for each heat flux value.]
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 $T_c$

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

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

The graph shows the relationship between the dimensionless corner temperature, $T^*$, and the distance to the corner from the angled water slot, $L_c$, for different mold thicknesses. The equation $T^* = \frac{k(T_c - T_{water})}{qL_{eff}}$ is used to calculate the dimensionless corner temperature, and $L_{eff} = \frac{k_m}{h_{fin}} + d_m$ is used to determine the effective distance to the corner.
Corner Temperature Estimation

\[ L^* = \frac{L_c}{d_m} \]

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

\[ T^* = 0.65L^* + 0.42 \]
**Typical design**

- $A = 75^\circ$
- $L_c = 22$ mm
- $q = 2.5$ MW m$^{-2}$
- $h_w = 35$ kW m$^{-2}$ K$^{-1}$

**“Optimized” design**

- $A = 60^\circ$
- $L_c = 11.4$ mm
- $q = 2.5$ MW m$^{-2}$
- $h_w = 35$ kW m$^{-2}$ K$^{-1}$
Calculating $T_c$

\[ L^* = \frac{L_c}{d_m} \quad (1) \]

\[ T^* = \frac{k(T_c - T_{\text{water}})}{qL_{\text{eff}}} \quad (2) \]

\[ L_{\text{eff}} = \frac{k_m}{h_{\text{fin}}} + d_m \quad (3) \]

\[ T^* = 0.65L^* + 0.42 \quad (4) \]

\[ T_{\text{hot,cu}} = T_{\text{water}} + q_{\text{hot,cu}} \left( \frac{1}{h_{\text{fin}}} + \frac{d_m}{k_m} \right) \quad (5) \]

\[ T_c = \left( 0.65 \frac{L_c}{d_m} + 0.42 \right) (T_{\text{hot,cu}} - T_w) + T_w \quad (6) \]
Adding 3D accuracy to CON1D to interpret thermocouple temperatures
# Nomenclature

<table>
<thead>
<tr>
<th>Bolt holes</th>
<th>Deep end slot</th>
</tr>
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<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
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</table>

- $d$  
- $d_s$  
- $L_s$  
- $L_a$  
- $d_{th}$  
- radius = $r_{th}$

<table>
<thead>
<tr>
<th>Thermocouples</th>
<th>Angled slots</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram" /></td>
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</tr>
</tbody>
</table>

- $d_{th}$
- radius = $r_{th}$
- $L_e$  
- $L_a$  
- $w_a$
3D ANSYS Model Description

Hot Face

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

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

280

240

200

162

120

80

Cold Face

$q'' = h_w (T - T_w)$

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

$T_w = 35 \text{ °C}$

all temperatures [°C]

q''=0 where not specified

water slot

thermocouple

water slots

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

Thermocouple location:
Temp = 162 °C

4.5 mm offset

Position in Mold From Cold Side [mm]

Mold Temperature [°C]

ANSYS section t-t
CON1D at thermocouple
CON1D section w-w
ANSYS section w-w

Armco Wideface
ANSYS 3D model
q = 2.5 MW m⁻²
hw = 54 kW m⁻² K⁻¹
Tw = 35 °C
km = 315 W m⁻¹ K⁻¹

sect w-w
hot
cold
sect t-t
3D ANSYS Results

Armco Narrowface

$q, \text{ hot } cu = 2.5 \ \text{MW} \ \text{m}^{-2}$
$hw = 54 \ \text{kW} \ \text{m}^{-2} \ \text{K}^{-1}$
$Tw = 35 \ ^\circ \text{C}$
$km = 315 \ \text{W} \ \text{m}^{-1} \ \text{K}^{-1}$
$kth = 218 \ \text{W} \ \text{m}^{-1} \ \text{K}^{-1}$
Through-Thickness Mold Temperature Profiles
Comparing 3D and CON1D Predictions
Near the Water Slots and Near the Thermocouple

Thermocouple location, Temp = 162 °C

Position in Mold From Cold Side [mm]

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3D ANSYS Results
Columbus Narrowface

$q, \text{ hotcu} = 1.75 \text{ MW m}^{-2}$
$hw = 45 \text{ kW m}^{-2} \text{ K}^{-1}$
$T_w = 25 \degree \text{C}$
$km = 364 \text{ W m}^{-1} \text{ K}^{-1}$
Through-Thickness Mold Temperature Profiles
Comparing 3D and CON1D Predictions
Near the Water Slots and Near the Thermocouple

Mold Temperature [°C]

Position in Mold From Cold Side [mm]

Columbus Narrowface
- ANSYS 3D model
- q = 1.75 MW m⁻²
- h_w = 45 kW m⁻² K⁻¹
- T_w = 25 °C
- k_m = 364 W m⁻¹ K⁻¹

Thermocouple location, Temp = 99 °C
**3D ANSYS Results**

*Columbus Wideface*

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

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

$Tw = 25 \degree \text{C}$

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

<table>
<thead>
<tr>
<th>all [mm]</th>
<th>model</th>
<th>mold</th>
<th>channel</th>
<th>thermocouple</th>
<th>deep slot</th>
<th>bolt</th>
</tr>
</thead>
<tbody>
<tr>
<td>depth</td>
<td>dml</td>
<td>dm</td>
<td>dch</td>
<td>dth</td>
<td>dds</td>
<td>db</td>
</tr>
<tr>
<td>45</td>
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<td>18</td>
<td>5</td>
<td>21</td>
<td>18</td>
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</tr>
<tr>
<td>length</td>
<td>Lml</td>
<td>Lch</td>
<td>Lds</td>
<td>Lb</td>
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<tr>
<td>60.5</td>
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<td>14.5</td>
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</tr>
<tr>
<td>width (or radius)</td>
<td>wch</td>
<td>rth</td>
<td>wds</td>
<td>rb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.75</td>
<td>5</td>
<td>8</td>
<td></td>
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Through-Thickness Mold Temperature Profiles
Comparing 3D and CON1D Predictions
Near the Water Slots and Near the Thermocouple

Thermocouple location,
Temp = 102 °C

Columbus Wideface
ANSYS 3D model
q=1.75 MW m⁻²
hw= 45 kW m⁻² K⁻¹
Tw = 25 °C
km = 364 W m⁻¹ K⁻¹

4.2 mm offset
Effect of Mold Thickness on Offset

Temperature Profiles for Molds that were Machined Due to Wear
3D ANSYS Results

Mold Temperature [°C]

Position in Mold From Cold Side [mm]

Thermocouple location
Thermocouple Temperature = 162 °C

4.5 mm offset

3D ANSYS results
Armco Wide Face
New Mold Thickness = 35 mm

q=2.5 MW m⁻²
h_w= 54 kW m⁻² K⁻¹
T_w= 35 °C
Dependence of Offset on Boundary Conditions

Effect of Hot Face Heat Flux on Offset Distance for Two Water-Side Heat Transfer Coefficients

- Armco wide face
- 3D ANSYS results
- $T_w = 35 \, ^\circ C$

- Offset [mm] for $h_1 = 35 \, kW \cdot m^{-2} \cdot K^{-1}$
- Offset [mm] for $h_2 = 54 \, kW \cdot m^{-2} \cdot K^{-1}$

Effect of Water Temperature on Offset Distance

- Armco wide face
- 3D ANSYS results
- Hot face heat flux = 2.5 MW m$^{-2}$
Dependence of Offset on Boundary Conditions

Effect of Water-side Heat Transfer Coefficient on Offset distance for the Armco Wideface 3D Model

Offset Distance [mm] vs. $h_w$, Water-side Heat Transfer Coefficient [W m$^{-2}$ K$^{-1}$]

- Offset for Hot Face Heat Flux = 2.5 MW m$^{-2}$
- Offset for Hot Face Heat Flux = 1.0 MW m$^{-2}$
Calculate Offset Using CON1D Equations

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

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

\[ T_{\text{cold}} = T_{\text{water}} + \frac{q_{\text{cold}}}{h_{\text{fin}}} \]

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

\[ \text{offset} = d_{\text{thcpl}} - X_t \]

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

**CON1D Improvements**

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

\[ T_c = \left( 0.65 \frac{L_c}{d_m} + 0.42 \right) (T_{hot\_cu} - T_w) + T_w \]

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.