Effect of surface flatness on thermal conductivity measurements of rigid specimens

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Outline

- Introduction
- Modelling approaches
- Results of modelling
  - Effect of air layer thickness
  - Effect of heater plate surface emissivity
- Conclusions
Introduction

Thermal contact resistance (TCR)

• parasitic effect in thermal conductivity measurement using GPH method
• complex effect caused by imperfect contact between heater plates and specimen
  • specimen warping
  • non-ideal heater plate flatness
  • specimen and heater plate surfaces emissivities
  • gap filling (air or vapor?)
    • thermal conductivity
    • transparency to IR radiation
• currently no thermal conductive foils to minimize TCR at high-temperature region

 mAdapter
• influence of heater plate flatness on measurements with opaque rigid specimens
Modelling

Computational approaches

- ANSYS Fluent FVM calculations
- Simplified model and calculation algorithm implemented in Matlab

Computational setup and assumptions (simplifications)

- various specimen thermal conductivity (0.02, 0.2, 2) W·m$^{-1}$·K$^{-1}$
- gap filled with air (temperature dependent $\lambda$, transparent to IR radiation)
- different gap profiles, different mean thickness of air layer
- various specimen and heater surface emissivities
- rigid specimen opaque to IR radiation
- constant temperature gradient across the specimen (50 K)
- constant specimen thickness (50 mm)
Modelling

ANSYS Fluent calculations

- 2D geometry
- Radiation (DO model)
- Free convection
- Conduction
- Input parameters: heating power, material properties including $\lambda$ of specimen, cold plate temperature
- Output parameters: temperature distribution
Modelling

Simplified model

- horizontal heat flow neglected
- discretization in horizontal direction
- $T_0$: temperature of cold plate
- $T_2 - T_1$: temperature difference across air gap
- specimen and hot plate opaque to radiation
- natural convection neglected (thin air gap)
- algorithm solves $T_2$ and $T_1$ from $T_0$ and $T_3$ and material properties (thermal conductivity, emissivity of surface and lengths $L_i$)
- $T_0$ and $T_3$ are constant along the direction of discretization

- algorithm implemented in Matlab
- fast calculation even when extended to 3D

\[
R_{1,i} = \frac{L_{1,i}}{\lambda_1}
\]

\[
R_{2,i} = \left( \frac{\lambda_2}{L_{2,i}} + \sigma \varepsilon_r (T_{2,i}^3 + T_{2,i}^2 T_{1,i} + T_{1,i}^2 T_{2,i} + T_{1,i}^3) \right)^{-1}
\]

\[
R_{3,i} = \frac{L_{3,i}}{\lambda_3}
\]
Results

Comparison of Fluent results to analytical solution

• compared for equidistant air gap
• negligible effect of free convection for thin gap
• $t_1 = 800 \, ^\circ \text{C}, \, t_2 = 800.1 \, ^\circ \text{C}$

<table>
<thead>
<tr>
<th></th>
<th>Fluent results</th>
<th>Analytical solution</th>
<th>Relative difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{\text{rad}}$ (W)</td>
<td>1.401601</td>
<td>1.401799</td>
<td>-0.014</td>
</tr>
<tr>
<td>$\phi_{\text{cond}}$ (W)</td>
<td>3.574044</td>
<td>3.574845</td>
<td>-0.022</td>
</tr>
<tr>
<td>$\phi_{\text{tot}}$ (W)</td>
<td>4.975645</td>
<td>4.976644</td>
<td>-0.020</td>
</tr>
</tbody>
</table>

$\epsilon_1 = \epsilon_2 = 1$

$\epsilon_1 = 0.6, \, \epsilon_2 = 0.8$

$\phi_{\text{tot}} = \phi_{\text{rad}} + \phi_{\text{cond}}$

$\phi_{\text{rad}} = \sigma A \epsilon_r (T_2^4 - T_1^4)$

$\phi_{\text{cond}} = \lambda_{\text{air}} A (T_2 - T_1)/\delta$

➢ good agreement between ANSYS Fluent results and analytical solution
Results

Effect of parabolic gap profile

- gap thickness: $\delta(x) = kx^2 + q$

Characteristics of investigated profiles in mm

<table>
<thead>
<tr>
<th>No.</th>
<th>$\delta_{\text{max}}$</th>
<th>$\delta_{\text{min}}$</th>
<th>$\delta_{\text{mean,1}}$</th>
<th>$\delta_{\text{mean,2}}$</th>
<th>$\delta_{\text{mean,3}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
<td>0.038</td>
<td>0.044</td>
<td>0.046</td>
<td>0.044</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
<td>0.076</td>
<td>0.088</td>
<td>0.092</td>
<td>0.088</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>0.38</td>
<td>0.44</td>
<td>0.46</td>
<td>0.44</td>
</tr>
</tbody>
</table>

$\delta_{\text{mean,1}} = (\delta_{\text{min}} + \delta_{\text{max}})/2$ ... arithmetic average

$\delta_{\text{mean,2}} = \frac{1}{r} \int_0^r \delta(x) \, dx$ ... integral mean value in 2D

$\delta_{\text{mean,3}} = \frac{2}{r^2} \int_0^r \delta(x) \, dx$ ... integral mean value in 3D and round specimen
Results

Average gap width 0.046 mm, $\varepsilon_1 = \varepsilon_2 = 1$, various specimen $\lambda$

The relative error increases with increasing thermal conductivity of specimen and diminishes with rising temperature of measurement.
Results

Effect of gap width, specimen $\lambda = 0.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, $\varepsilon_1 = \varepsilon_2 = 1$

- The relative error increases with increasing gap width and diminishes with rising temperature of measurement.
Results

Temperature difference across the air gap

specimen $\lambda = 0.2 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$, $\varepsilon_1 = \varepsilon_2 = 1$, hot plate temperature 850 °C, average gap width 0.092 mm

![Graph showing temperature difference across the air gap]
Results

Contribution of radiative heat transfer

- two parallel planes
  \[ \frac{\Phi_{\text{rad}}}{\Phi_{\text{cond}}} = \frac{\delta \sigma \varepsilon_r (T_2^3 + T_2^2 T_1 + T_1^2 T_2 + T_1^3)}{\lambda_{\text{air}}} \]

- \( \varepsilon_1 = \varepsilon_2 = 1 \) (most intensive radiation heat exchange)
- \( \Delta T = 0.1 \) K

- Gap width is a dominant factor
- Radiation becomes more significant for thicker gaps

Graph showing the contribution of radiative heat transfer over different gap widths and temperatures. The graph includes lines for gap widths of 0.05 mm, 0.1 mm, and 0.5 mm, with corresponding labels for each condition.
Results

Contribution of radiative heat transfer, influence of emissivity

- two parallel planes
  \[
  \frac{\Phi_{\text{rad}}}{\Phi_{\text{cond}}} = \frac{\delta \sigma \varepsilon_r (T_2^2 + T_1^2 T_2 + T_1^3)}{\lambda_{\text{air}}}
  \]
- \(\varepsilon_2 = 1\)
- \(\Delta T = 0.1 \text{ K}\)
- \(\delta = 0.1 \text{ mm}\)
Contribution of radiative heat transfer, influence of emissivity

Effect of heater plate surface emissivity on relative difference from the correct specimen thermal conductivity value (0.2 W·m⁻¹·K⁻¹) for parabolic air gap profile (average gap width 0.046 mm)

- Increasing emissivity of HP has the bigger effect for thick air gaps due to bigger relative contribution of radiative heat transfer
Results

Equivalent air-gap thickness calculated from results of Fluent simulations

- thickness of air layer between two parallel planes with the same thermal resistance $R_{\text{gap}}$
- $R_m = R_{\text{specimen}} + R_{\text{gap}}$
- $R_{\text{gap}} = \left( \frac{\lambda_{\text{air}}}{d_{\text{eq}}} + \sigma \varepsilon_r (T_2^3 + T_2^2 T_1 + T_1^2 T_2 + T_1^3) \right)^{-1}, \quad \varepsilon_r = \frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$

<table>
<thead>
<tr>
<th>$t_{\text{cp}}$ (°C)</th>
<th>$t_{\text{hp}}$ (°C)</th>
<th>$t_{sb}$ (°C)</th>
<th>$R_m$ (K $\cdot$ m$^2$ $\cdot$ W$^{-1}$)</th>
<th>$R_{\text{gap}}$ (K $\cdot$ m$^2$ $\cdot$ W$^{-1}$)</th>
<th>$\lambda_{\text{air}}$ (W $\cdot$ m$^{-1}$ $\cdot$ K$^{-1}$)</th>
<th>$d_{\text{eq}}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>75.60</td>
<td>75</td>
<td>0.2530</td>
<td>0.0030</td>
<td>0.030</td>
<td>0.092</td>
</tr>
<tr>
<td>50</td>
<td>100.57</td>
<td>100</td>
<td>0.2528</td>
<td>0.0028</td>
<td>0.031</td>
<td>0.092</td>
</tr>
<tr>
<td>200</td>
<td>250.42</td>
<td>250</td>
<td>0.2521</td>
<td>0.0021</td>
<td>0.041</td>
<td>0.092</td>
</tr>
<tr>
<td>400</td>
<td>450.30</td>
<td>450</td>
<td>0.2515</td>
<td>0.0015</td>
<td>0.053</td>
<td>0.091</td>
</tr>
<tr>
<td>600</td>
<td>650.23</td>
<td>650</td>
<td>0.2511</td>
<td>0.0011</td>
<td>0.064</td>
<td>0.097</td>
</tr>
<tr>
<td>800</td>
<td>850.18</td>
<td>850</td>
<td>0.2509</td>
<td>0.0009</td>
<td>0.074</td>
<td>0.084</td>
</tr>
</tbody>
</table>

$R_{\text{specimen}} = 0.25$ K $\cdot$ m$^2$ $\cdot$ W$^{-1}$ ($\lambda = 0.2$ W $\cdot$ m$^{-1}$ $\cdot$ K$^{-1}$), gap mean thickness 0.092 mm, $\varepsilon_1 = \varepsilon_2 = 1$

- for parabolic gap profiles the contact resistance can be estimated from integral mean value of gap thickness
Results

Example of thermal contact resistance estimation

- Experimental parameters (taken from Fluent simulation on previous slide):
  - measured thermal resistance $R_m = 0.2521 \, \text{K} \cdot \text{m}^2 \cdot \text{W}^{-1}$
  - hot plate temperature $t_{HP} = 250.42 \, ^\circ\text{C}$
  - cold plate temperature $t_{CP} = 200.00 \, ^\circ\text{C}$
  - mean air gap thickness $d_{eq} = 0.092 \, \text{mm}$
  - temperature difference $\Delta t_{\text{gap}}$, unknown

Iteration procedure (starting with $\Delta t_{\text{gap},0} = 0.1 \, ^\circ\text{C}$)

- $T_2 = t_{HP} + 273.15 \, \text{K}$
- $T_{1,0} = T_2 - \Delta t_{\text{gap},0}$
- $R_{\text{gap},i} = \left(\frac{\lambda_{\text{air}}}{d_{eq}} + \sigma \epsilon_r (T_2^3 + T_2^2 T_{1,i-1} + T_{1,i-1}^2 T_2 + T_{1,i-1}^3)\right)^{-1}$
- $\Delta t_{\text{gap},i} = \frac{P}{A} R_{\text{gap},i}$
- $T_{1,i} = T_2 - \Delta t_{\text{gap},i}$
### Results

#### Example of thermal contact resistance estimation

- starting with $\Delta t_{\text{gap}} = 0.1 \, ^\circ\text{C}$

<table>
<thead>
<tr>
<th>$i$</th>
<th>$\Delta t_{\text{gap},i-1}$ ($^\circ\text{C}$)</th>
<th>$R_{\text{gap},i}$ (Km$^2$W$^{-1}$)</th>
<th>$\Delta t_{\text{gap},i}$ ($^\circ\text{C}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>0.002088</td>
<td>0.418</td>
</tr>
<tr>
<td>2</td>
<td>0.418</td>
<td>0.002089</td>
<td>0.418</td>
</tr>
<tr>
<td>3</td>
<td>0.418</td>
<td><strong>0.002089</strong></td>
<td>0.418</td>
</tr>
</tbody>
</table>

\[
R_{\text{specimen}} = 0.2521 \, - \, 0.0021 = 0.2500 \, \text{K} \cdot \text{m}^2 \cdot \text{W}^{-1}
\]
Conclusions

- Simplified numerical model and Fluent simulations provided similar results for parabolic air-gap profile in 2D, for more complicated profiles numerical model does not work well.

- With increasing temperature contact resistance and thus measurement error are decreasing (2 effects: higher air thermal conductivity, more intense radiative heat transfer contribution).

- For thin gaps between specimen and heater plate, heat conduction is dominant heat transfer mechanism (increasing emissivity of heater plates e.g. from 0.8 to 0.95 does not bring much effect).

- For wide gaps between specimen and heater plate, radiation is dominant heat transfer mechanism (increasing emissivity of heater plates has a considerable effect).

- Thermal contact resistance can be estimated on the basis of equivalent air-gap according to proposed algorithm.
Thank you for your attention