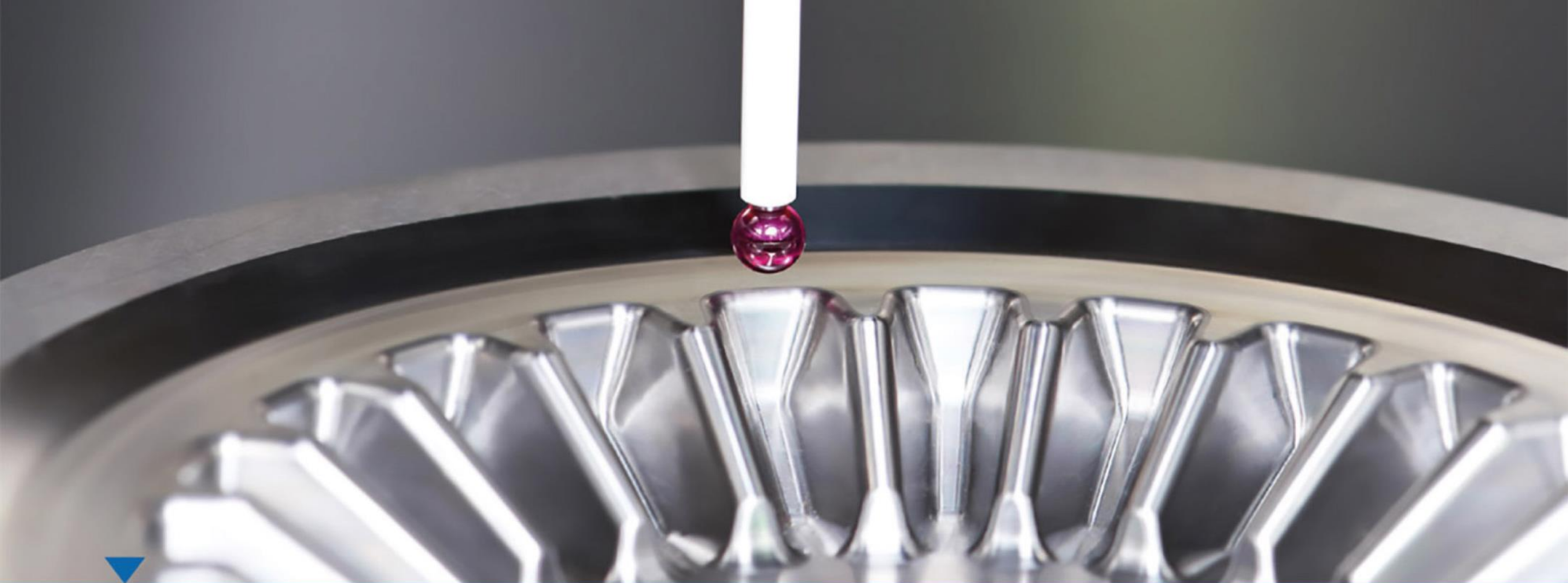


Effect of surface flatness on thermal conductivity measurements of rigid specimens

Aleš Blahut

EMRP SIB52 Thermo 36M Stakeholder Meeting, NPL, Teddington, 12. 5. 2016

CZECH METROLOGY INSTITUTE

EURAMET

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Outline

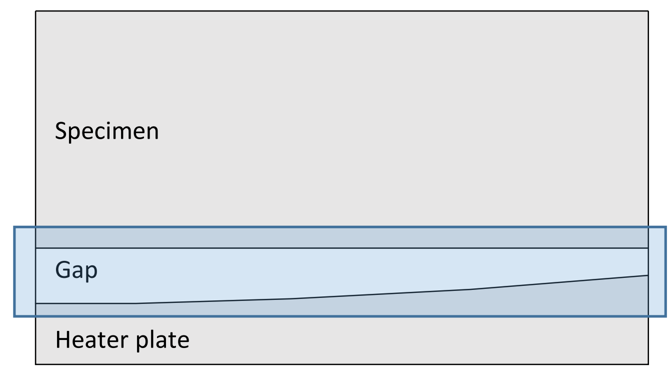
- Introduction
- Modelling approaches
- Results of modelling
  - Effect of air layer thickness
  - Effect of heater plate surface emissivity
- Conclusions

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

➢ influence of heater plate flatness on measurements with opaque rigid specimens



Modelling

Computational approaches

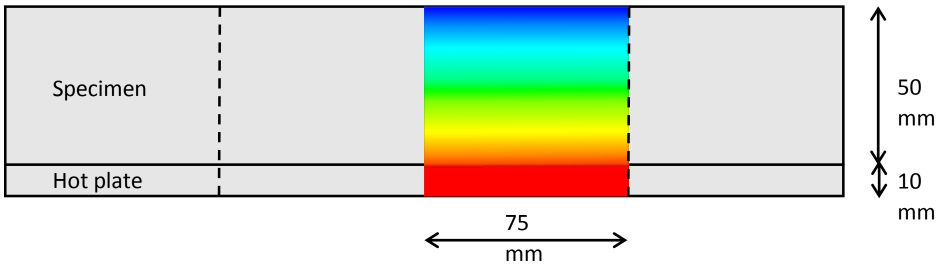
- ANSYS Fluent FVM calculations
- Simplified model and calculation algorithm implemented in Matlab

Computational setup and assumptions (simplifications)

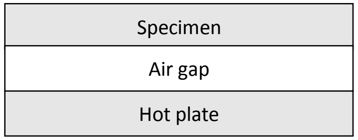
- various specimen thermal conductivity (0.02, 0.2, 2) $W \cdot m^{-1} \cdot K^{-1}$
- gap filled with air (temperature dependent λ, transparent to IR radiation)
- different gap profiles, different mean thickness of air layer
- various specimen and heater surface emissivities
- rigid specimen opaque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

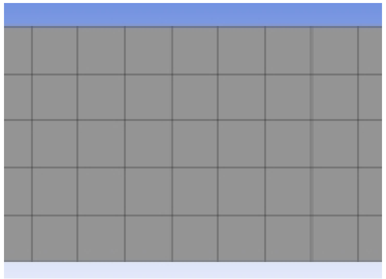
Modelling

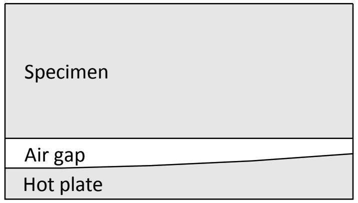
ANSYS Fluent calculations

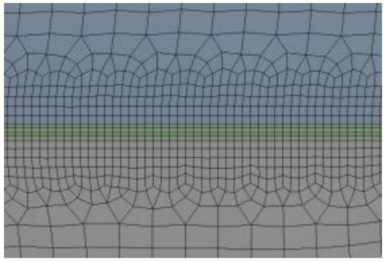


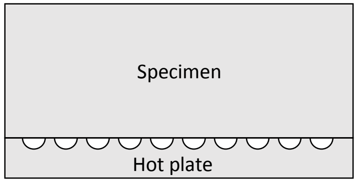
- 2D geometry
- raditaion (DO model)
- free convection
- conduction
- input paramters: heating power, material properties including λ of specimen, cold plate temperature
- output parameters: temperature distribution

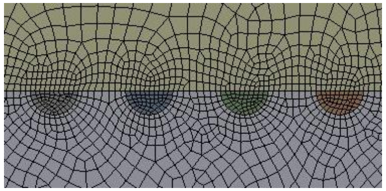






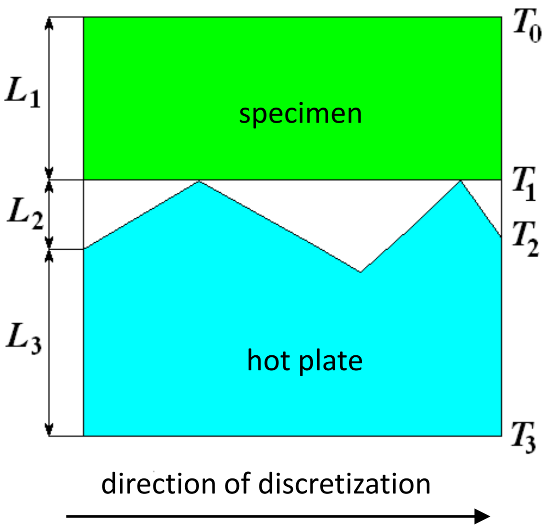






Modelling

Simplified model



$$R_{1,i} = \frac{L_{1,i}}{\lambda_1}$$

$$R_{2,i} = \left(\frac{\lambda_2}{L_{2,i}} + \sigma \epsilon_{\mathrm{r}} \left(T_{2,i}^3 + T_{2,i}^2 T_{1,i} + T_{1,i}^2 T_{2,i} + T_{1,i}^3 \right) \right)^{-1}$$

$$R_{3,i} = \frac{L_{3,i}}{\lambda_3}$$

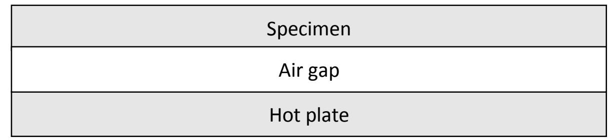
- horizontal heat flow neglected
- discretization in horizontal direction
- T_0: temperature of cold plate
- T_2 - T_1: temperature difference across air gap
- specimen and hot plate opaque to radiation
- natural convection neglected (thin air gap)
- algorithm solves T_2 and T_1 from T_0 and T_3 and 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 in when extended to 3D

Results

Comparison of Fluent results to analytical solution

- compared for equidistant air gap
- negligible effect of free convection for thin gap
- t_1 = 800 °C, t_2 = 800.1 °C



Comparison of resulting heat fluxes across the gap and their individual contributions

	Fluent results	Analytical solution	Relative difference (%)
$\epsilon_1 = \epsilon_2 = 1$			
Φ_{rad} (W)	1.401601	1.401799	-0.014
Φ_{cond} (W)	3.574044	3.574845	-0.022
Φ_{tot} (W)	4.975645	4.976644	-0.020
$\epsilon_1 = 0.6,\ \epsilon_2 = 0.8$			
Φ_{rad} (W)	0.731270	0.731373	-0.014
Φ_{cond} (W)	3.574840	3.574845	0.000
Φ_{tot} (W)	4.306110	4.306218	-0.003

$$\Phi_{\mathrm{tot}} = \Phi_{\mathrm{rad}} + \Phi_{\mathrm{cond}}$$
$$\Phi_{\mathrm{rad}} = \sigma A \epsilon_{\mathrm{r}} (T_2^4 - T_1^4)$$
$$\Phi_{\mathrm{cond}} = \lambda_{\mathrm{air}} A (T_2 - T_1)/\delta$$

➢ good agreement between ANSYS Fluent results and analytical solution

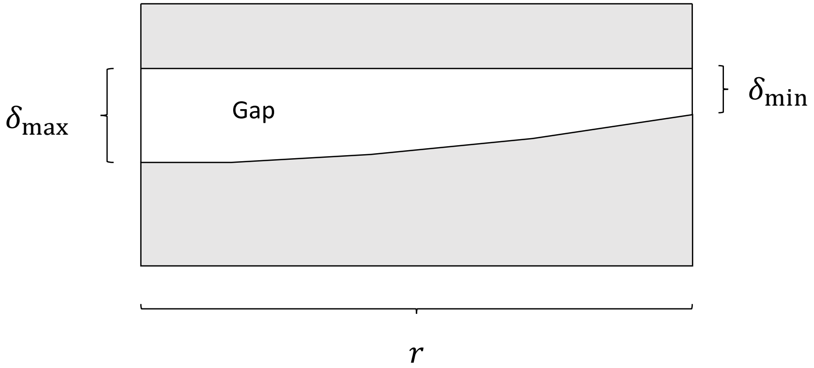
Results

Effect of parabolic gap profile

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

Characteristics of investigated profiles in mm

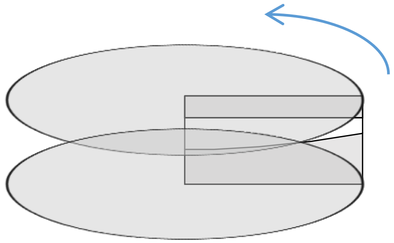
No.	$\delta_{\max}$	δ_{min}	$\delta_{\mathrm{mean},1}$	$\delta_{\mathrm{mean},2}$	$\delta_{\mathrm{mean},3}$
1	0.05	0.038	0.044	0.046	0.044
2	0.1	0.076	0.088	0.092	0.088
3	0.5	0.38	0.44	0.46	0.44



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

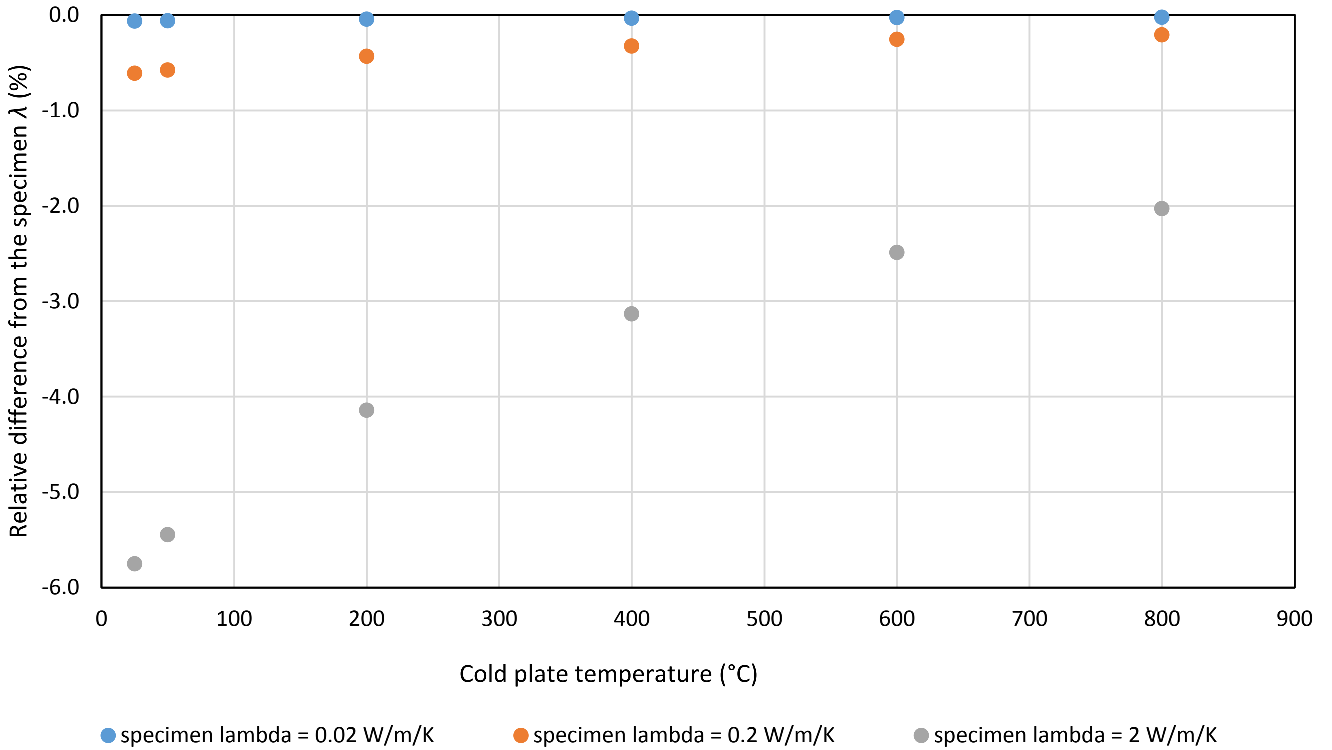
$\delta_{\mathrm{mean},2} = \frac{1}{r}\int_0^r \delta(x)\,\mathrm{d}x$ ... integral mean value in 2D

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



Results

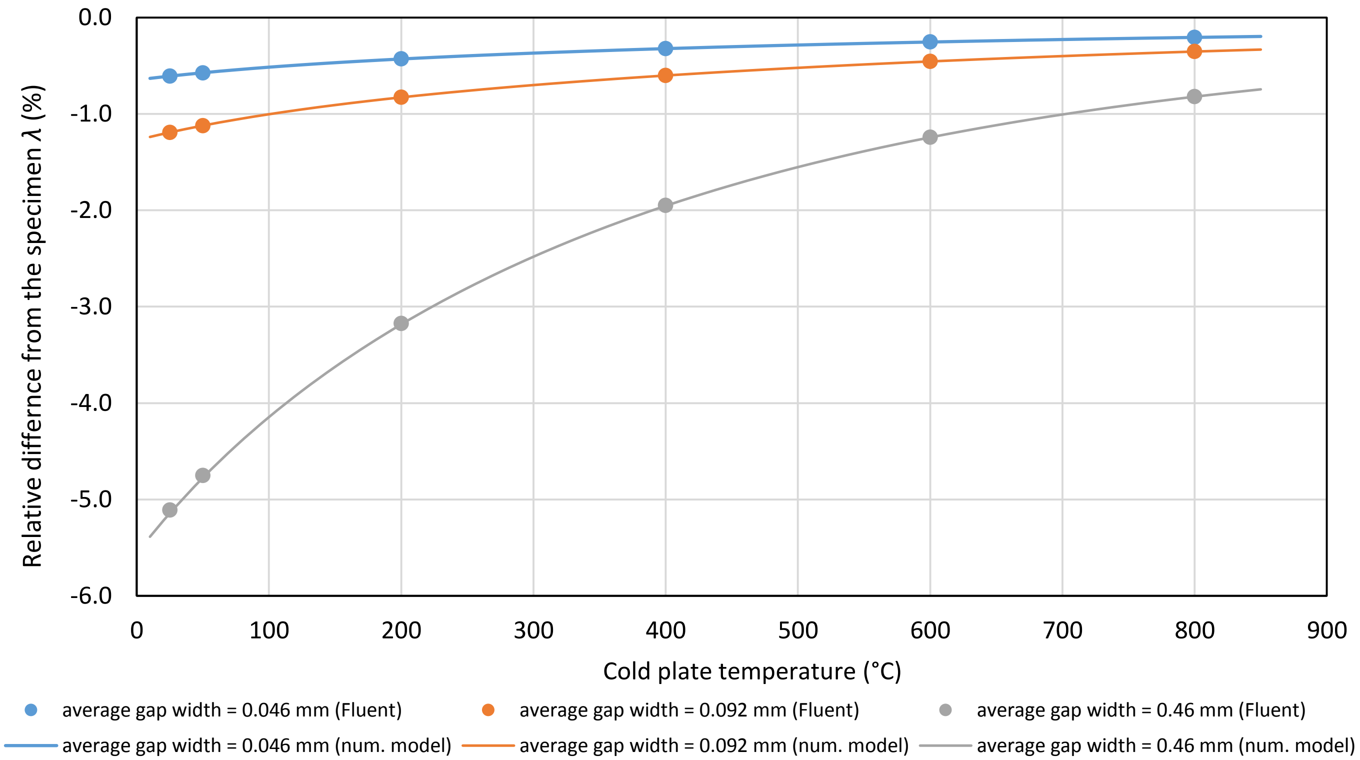
Average gap width 0.046 mm, $\varepsilon_1 = \varepsilon_2 = 1$, various specimen λ



- ➢ The relative error increases with increasing thermal conductivity of specimen and diminishes with rising temperature of measurement

Results

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

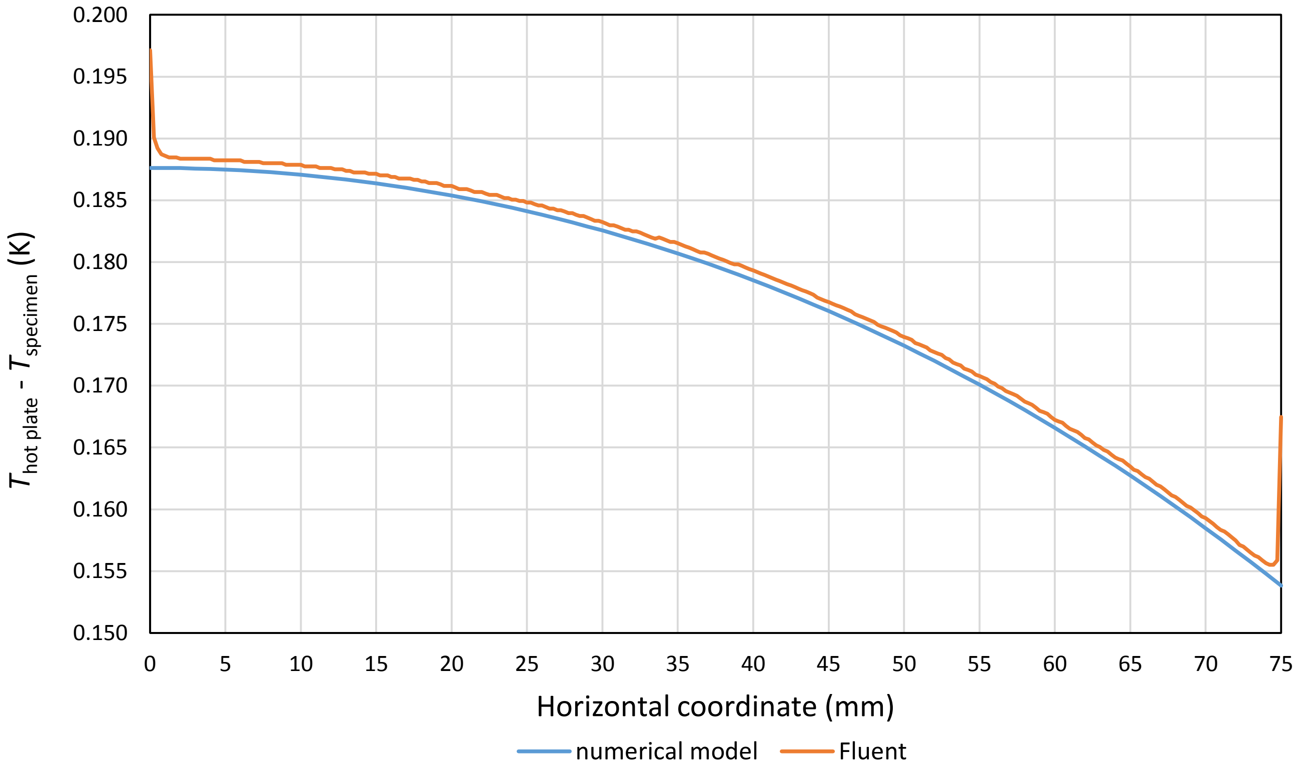


- The relative error increases with increasing gap width and diminishes with rising temperature of measurement

Results

Temperature difference across the air gap

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



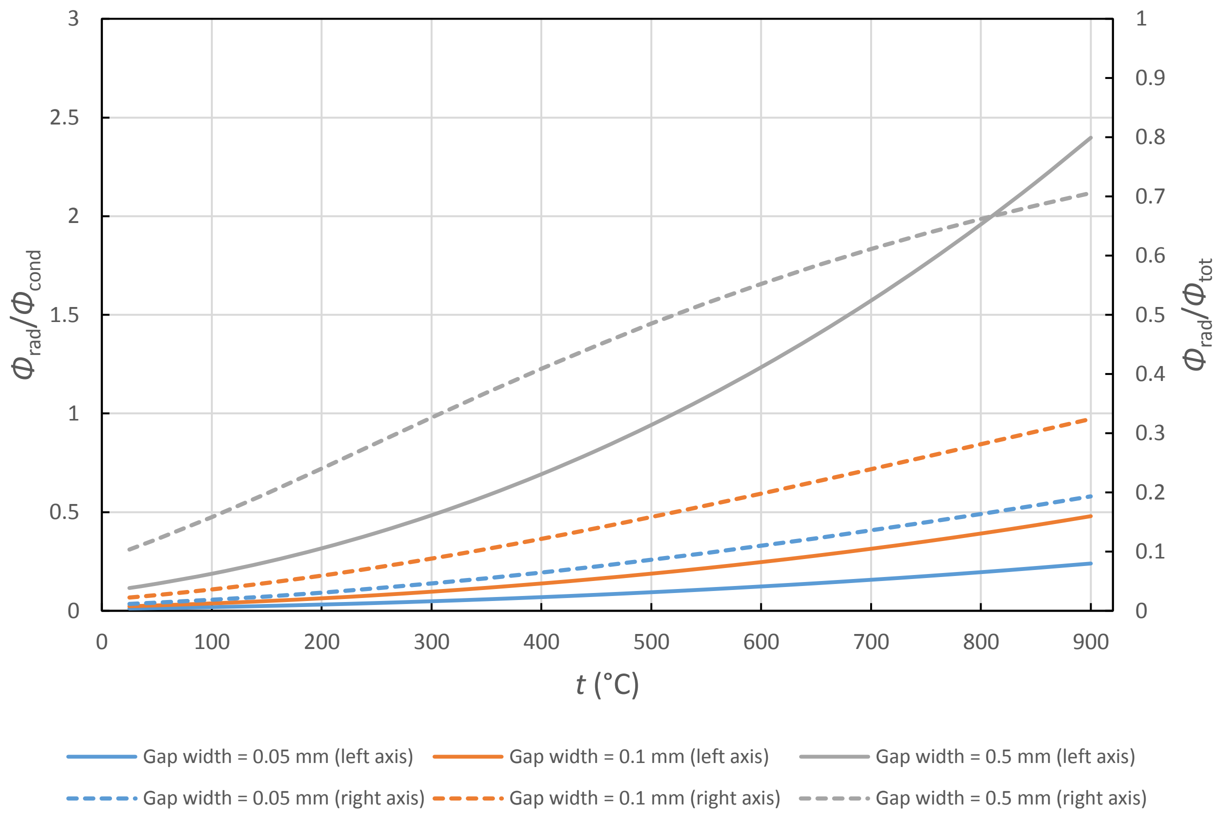
Results

Contribution of radiative heat transfer

- two parallel planes

$$\frac{\Phi_{\mathrm{rad}}}{\Phi_{\mathrm{cond}}} = \frac{\delta\sigma\epsilon_{\mathrm{r}}(T_2^3 + T_2^2 T_1 + T_1^2 T_2 + T_1^3)}{\lambda_{\mathrm{air}}}$$

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



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

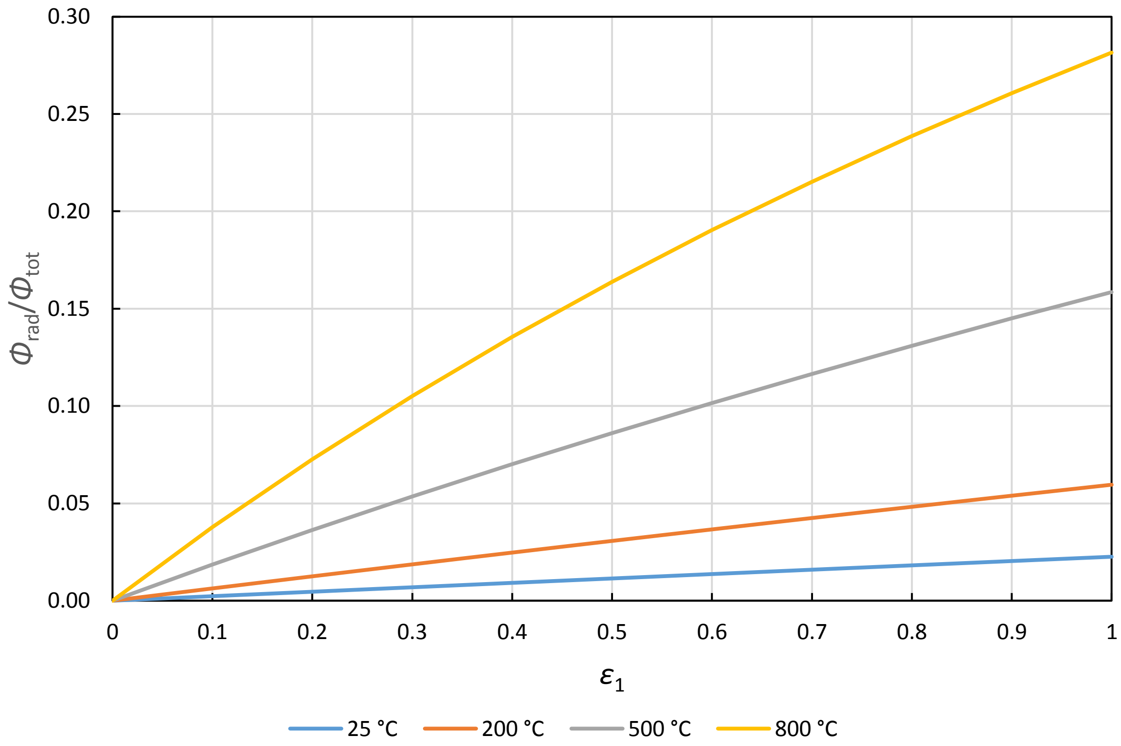
Results

Contribution of radiative heat transfer, influence of emissivity

- two parallel planes

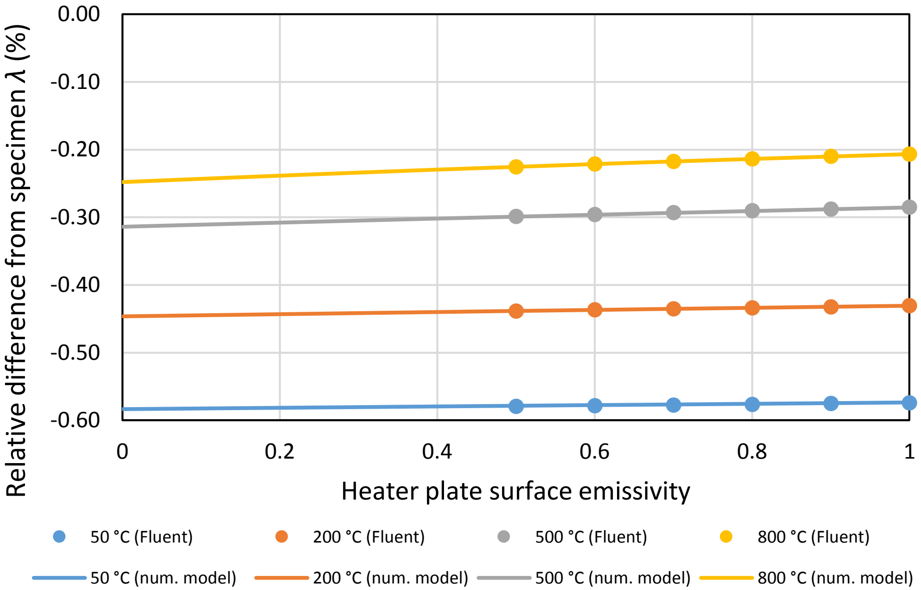
$$\frac{\Phi_{\mathrm{rad}}}{\Phi_{\mathrm{cond}}} = \frac{\delta\sigma\epsilon_{\mathrm{r}}(T_2^3 + T_2^2 T_1 + T_1^2 T_2 + T_1^3)}{\lambda_{\mathrm{air}}}$$

- ε_2 =1
- ΔT = 0.1 K
- δ = 0.1 mm

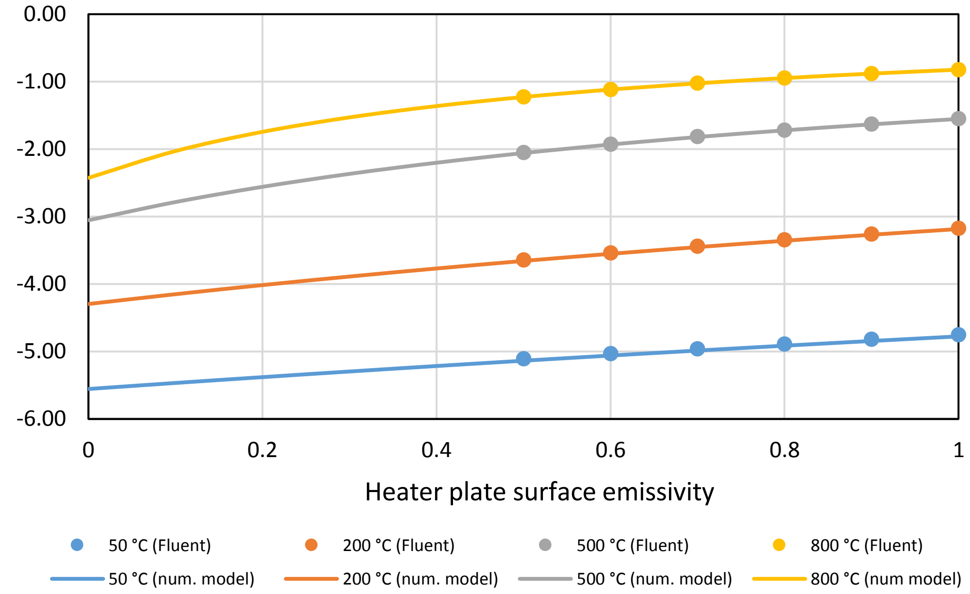


Results

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)



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 0.46 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_{gap}
- $R_{\mathrm{m}} = R_{\mathrm{specimen}} + R_{\mathrm{gap}}$
- $R_{\mathrm{gap}} = \left(\frac{\lambda_{\mathrm{air}}}{\boldsymbol{d}_{\mathbf{eq}}} + \sigma\epsilon_{\mathrm{r}}(T_2^3 + T_2^2 T_1 + T_1^2 T_2 + T_1^3)\right)^{-1}$, $\epsilon_{\mathrm{r}} = \frac{1}{1/\epsilon_1 + 1/\epsilon_2 - 1}$

t_{CP} (°C)	t_{HP} (°C)	t_{sb} (°C)	R_{m} (K · m^2 · W^{-1})	R_{gap} (K · m^2 · W^{-1})	λ_{air} (W · m^{-1} · K^{-1})	**d_{eq} (mm)**
25	75.60	75	0.2530	0.0030	0.030	**0.092**
50	100.57	100	0.2528	0.0028	0.031	**0.092**
200	250.42	250	0.2521	0.0021	0.041	**0.092**
400	450.30	450	0.2515	0.0015	0.053	**0.091**
600	650.23	650	0.2511	0.0011	0.064	**0.097**
800	850.18	850	0.2509	0.0009	0.074	**0.084**

R_{specimen} = 0.25 K · m^2 · W^{-1} (λ = 0.2 W · m^{-1} · 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

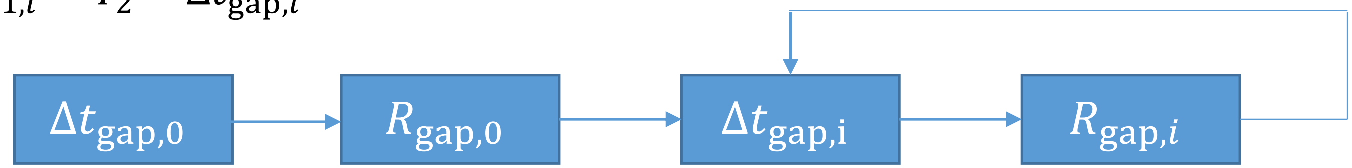
Results

Example of thermal contact resistance estimation

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

Iteration procedure (starting with $\Delta t_{\mathrm{gap},0} = 0.1\ °\mathrm{C}$)

- $T_2 = t_{\mathrm{HP}} + 273.15\ \mathrm{K}$
- $T_{1,0} = T_2 - \Delta t_{\mathrm{gap},0}$
- $R_{\mathrm{gap},i} = \left(\frac{\lambda_{\mathrm{air}}}{\boldsymbol{d}_{\mathbf{eq}}} + \sigma \epsilon_{\mathrm{r}} \left(T_2^3 + T_2^2 T_{1,i-1} + T_{1,i-1}^2 T_2 + T_{1,i-1}^3 \right) \right)^{-1}$
- $\Delta t_{\mathrm{gap},i} = \frac{P}{A} R_{\mathrm{gap},i}$
- $T_{1,i} = T_2 - \Delta t_{\mathrm{gap},i}$



Results

Example of thermal contact resistance estimation

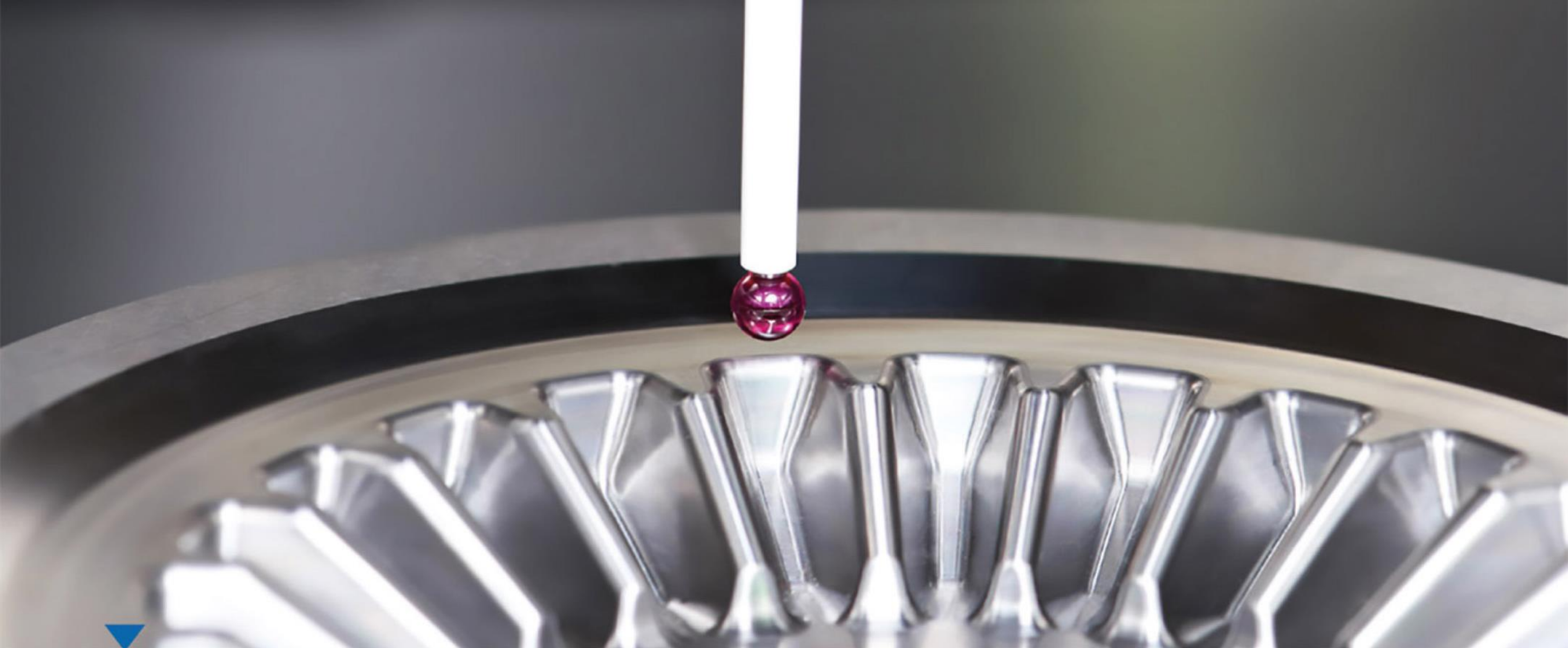
- starting with $\Delta t_{\mathrm{gap}} = 0.1\ °\mathrm{C}$

i	$\Delta t_{\mathrm{gap},i-1}$ (°C)	$R_{\mathrm{gap},i}$ $(\mathrm{Km^2W^{-1}})$	$\Delta t_{\mathrm{gap},i}$(°C)
1	0.1	0.002088	0.418
2	0.418	0.002089	0.418
3	0.418	0.002089	0.418

$$R_{\mathrm{specimen}} = 0.2521 - 0.0021 = 0.2500\ \mathrm{K \cdot m^2 \cdot W^{-1}}$$

Conslusions

- 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

CZECH
METROLOGY
INSTITUTE