International Sorption Heat Pump Conference

ISHPC 2017 INTERNATIONAL SORPTION HEAT PUMP CONFERENCE Tokyo

Effective thermal conductivity of adsorption packed beds

Mina Rouhani

Wendell Huttema and Majid Bahrami

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SFU SIMON FRASER UNIVERSITY ENGAGING THE WORLD

LAEC Laboratory for Alternative Energy Conversion

Greater Vancouver region, Canada

Simon Fraser University, Surrey Campus

- Transport phenomena in fuel cell catalyst layers
- Passive cooling systems for power electronics
- Thermal management of batteries
- Efficient HVAC-R
- Atmospheric water generation
- **Sorption chillers, thermal storage, dehumidification**

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Introduction: energy use and greenhouse gases

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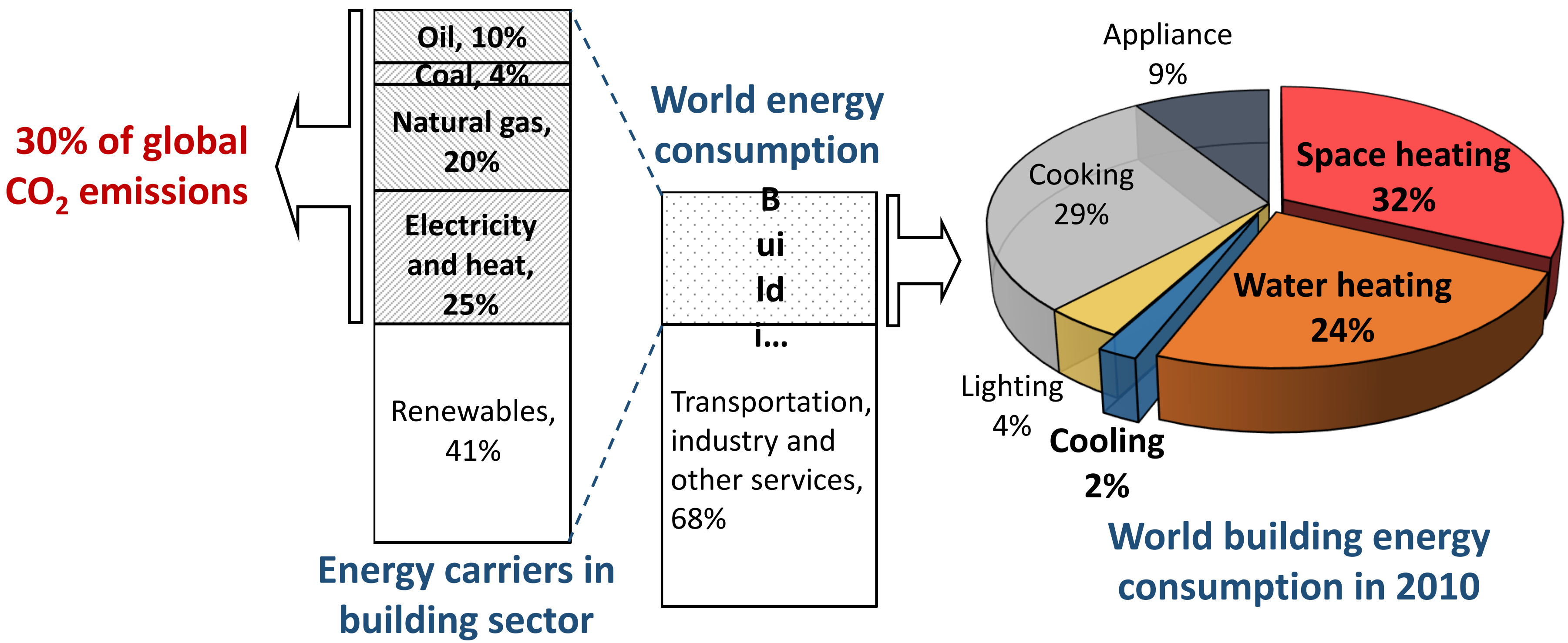
- **32% (115 EJ) of global energy demand** is used in **building sector**.
- Energy consumption for **heating** and **cooling** in building sector:
  32% space heating, 24% water heating and 2% cooling
- **60%** of the energy consumption in buildings is **non-renewables** and **CO_2 emission producers**.
- About **one-third of global CO_2 emissions** is produced by **buildings sector**.



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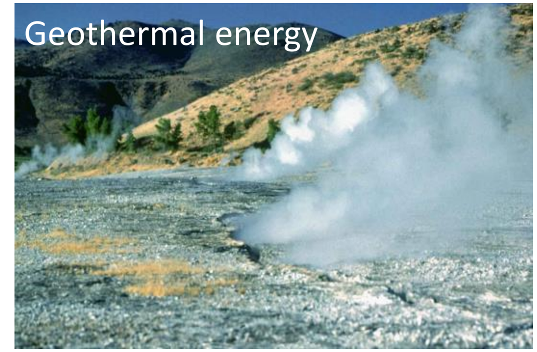
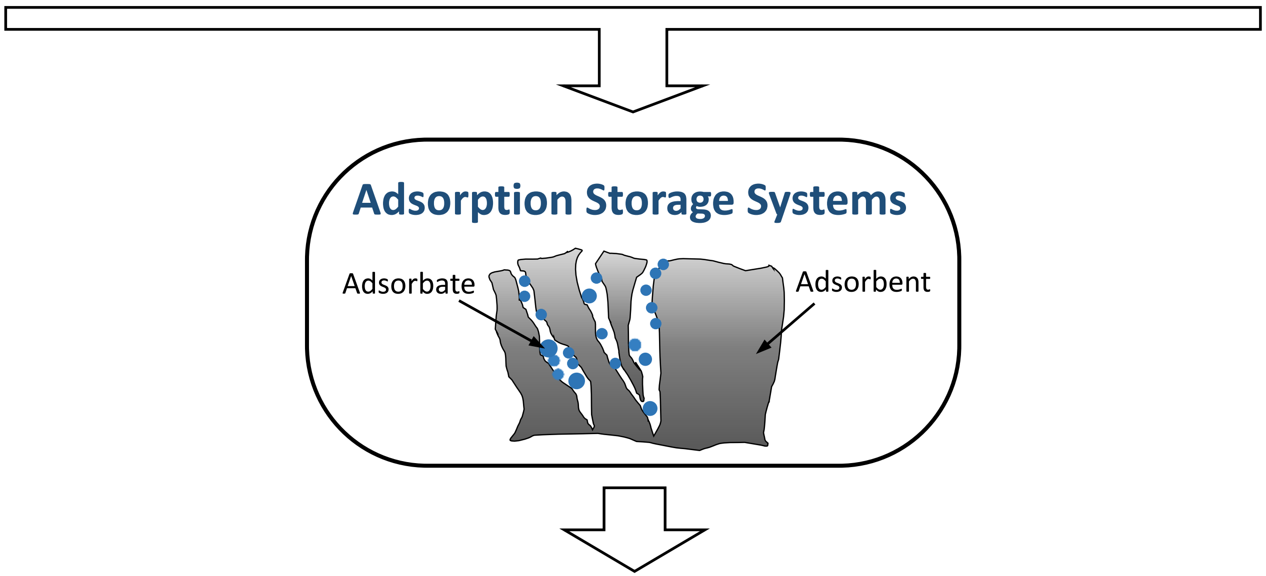
[1] International Energy Agency (IEA), available at https://www.iea.org/.
[2] Ürge-Vorsatz D., Cabeza L. F., Serranob S., Barreneche C., Petrichenko K., Renew. Sustainable Energy Rev. 41 (2015) 85–98.

Introduction: pathway to clean, efficient heat and cold production





Useful Work

- ✓ Efficient use of energy (use of low-grade heat, below 100 ˚C)
- ✓ Effective climate protection through reduced CO_2 emissions

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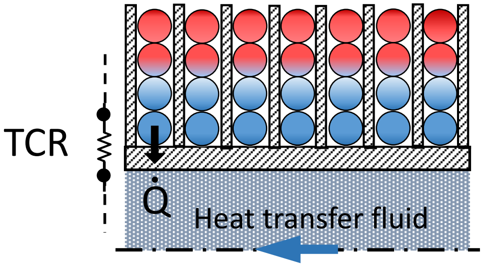
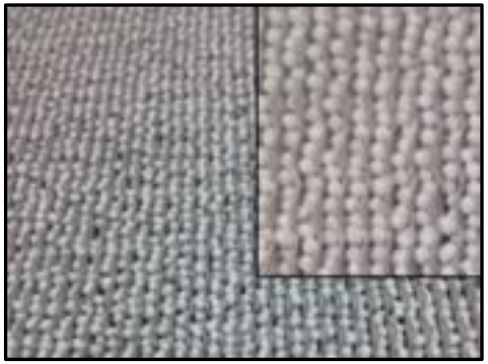
Storage of low-grade heat; challenges

Limiting factors against adoption of adsorption systems:

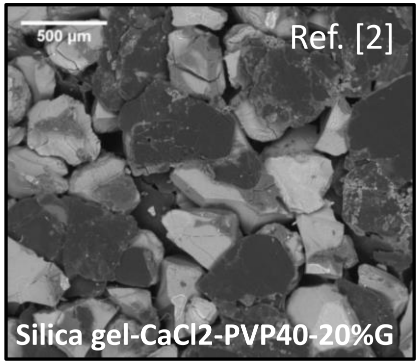
- ❑ Low mass transfer
- ❑ Low heat transfer
  - Low thermal conductivity of adsorbent materials (0.1-0.4 $W \cdot m^{-1} \cdot K^{-1}$)
  - High thermal contact resistance (TCR) between the adsorbent material and the heat exchanger (HEX) metal surface.



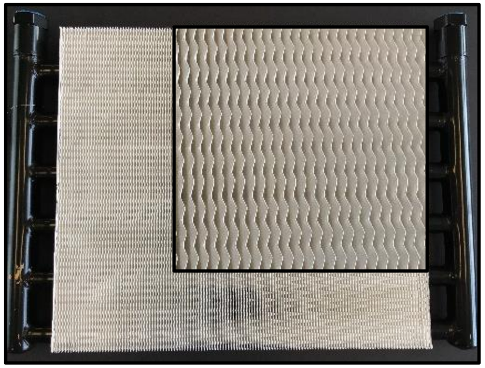
Contact types of adsorbent materials with HEX media:



Granular (loose grains)



Consolidated



Coated HEX

- ✓ Simple and cheap
- ✓ Higher volumetric power ($\frac{Q_{delivered}}{t \cdot V}$) [3] and higher energy storage density ($\frac{Q_{delivered}}{V}$)

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[2] K. Fayazmanesh, C. McCague, and M. Bahrami, *Appl. Therm. Eng.* (123) 753–760, 2017.
[3] A. Freni, L. Bonaccorsi, L. Calabrese, A. Caprì, A. Frazzica, and A. Sapienza, *Appl. Therm. Eng.* (82) 1–7, 2015.

Objectives

- **Measure** the **effective thermal conductivity** of a **AQSOA FAM-Z02** packed bed
- **Model** the **effective bed thermal conductivity** of packed bed adsorber
- Investigate the effects of **key parameters** on the thermal conductivity, including **temperature**, **uptake** and **numbers of adsorbent layers**
- Study the importance of **thermal contact resistance (TCR)** between the adsorbent medium and heat exchanger metal surface

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Thermal conductivity measurement of a packed bed adsorber

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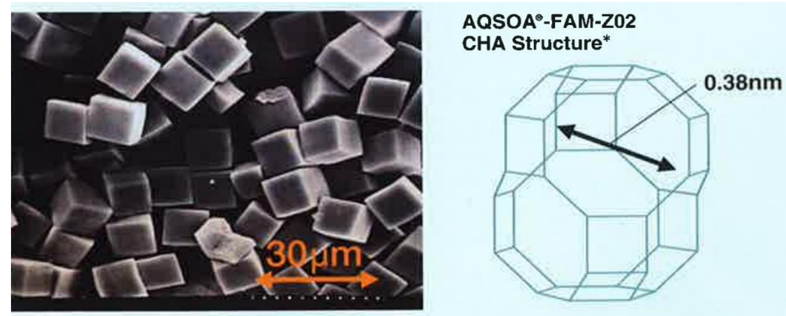
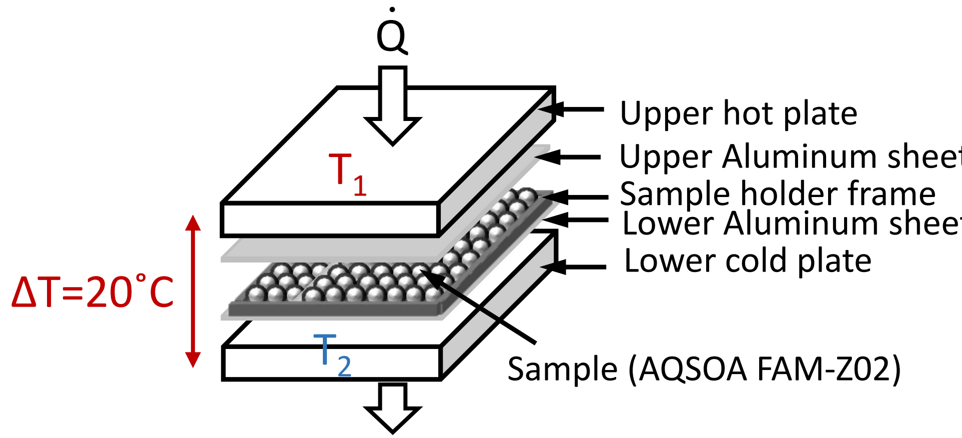
- **Adsorbent material: AQSOA FAM-Z02**

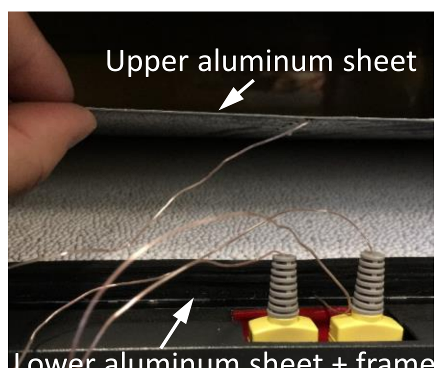
  (2 mm diameter beads, Mitsubishi Plastics)

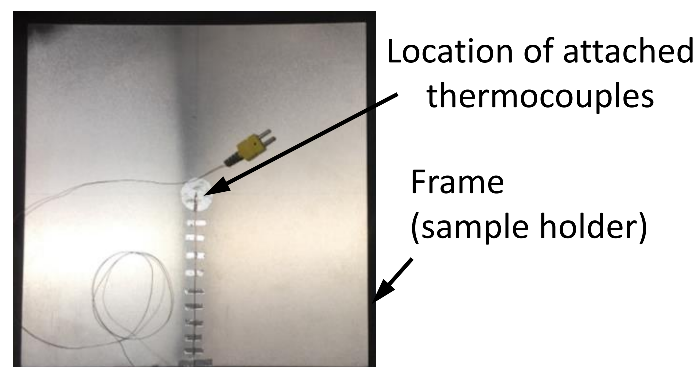
- **Apparatus:**
  - Heat flow meter (HFM 436/3/1E, Netzsch)
  - Suitable for low conductivity materials **(0.002 to 2.0 W·m^{-1}·K^{-1})**
  - Accuracy of ± **1-3%**
  - ASTM C518 standard



Mitsubishi Plastics



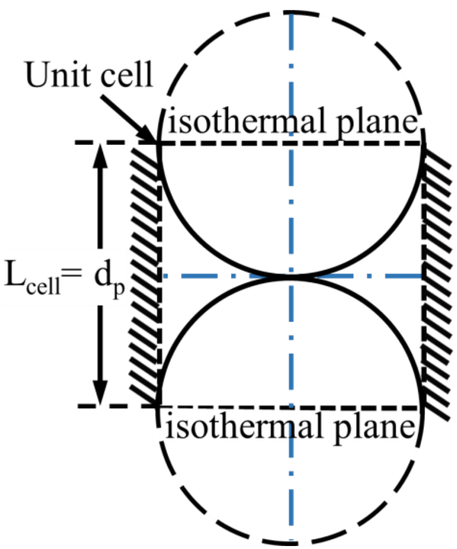


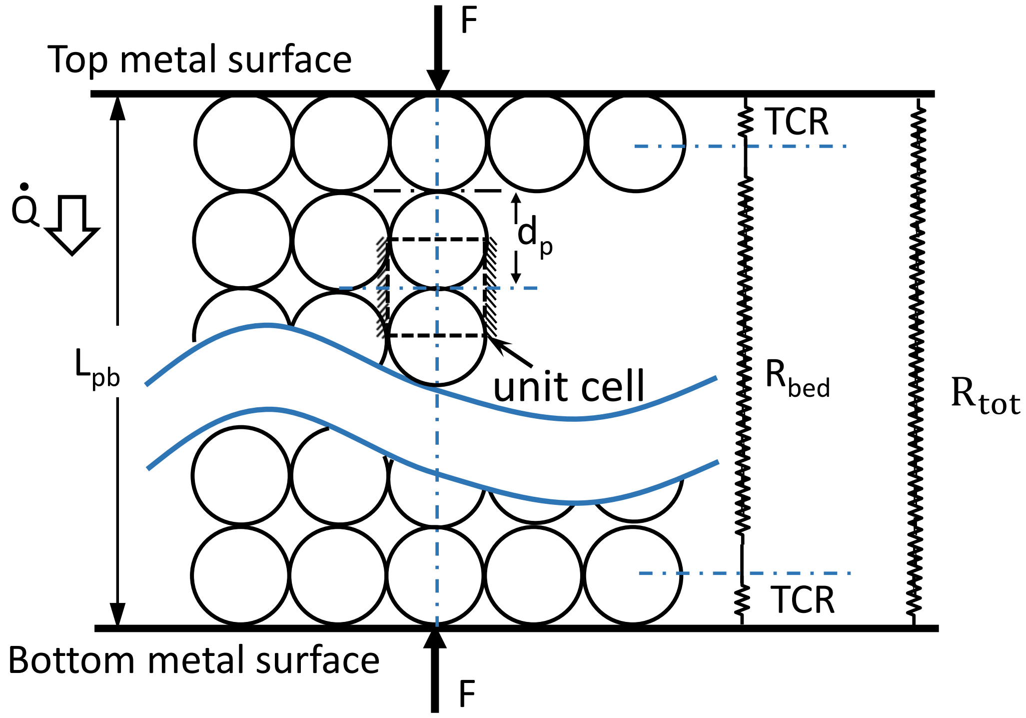


Calculating thermal conductivity of an adsorbent packed bed

Predicting effective thermal conductivity of an adsorption packed bed as a function of:

- Temperature
- Contact pressure
- Particle size
- Gas pressure
- <u>**Packed bed arrangement**</u>
- <u>**Water uptake**</u>



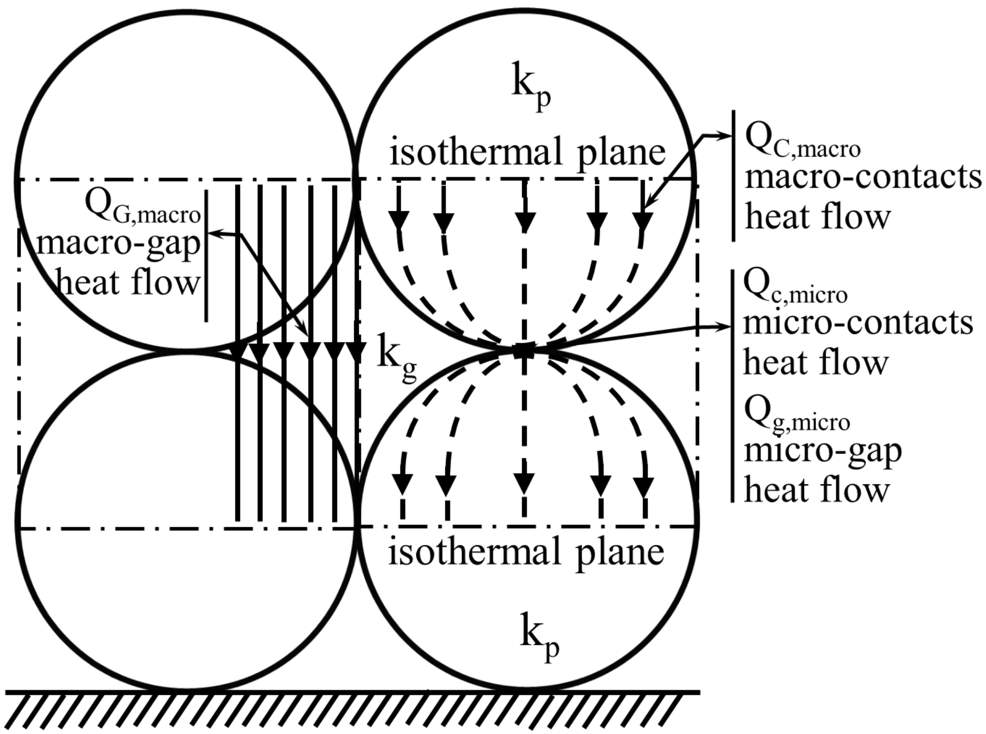


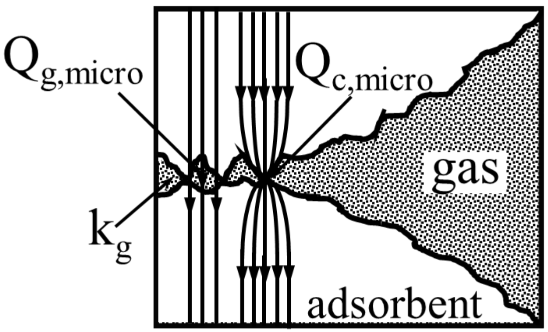
[2] M. Bahrami, M. M. Yovanovich, and J. R. Culham, *Int. J. Heat Mass Transf.*, vol. 49, no. 19–20, pp. 3691–3701, 2006.

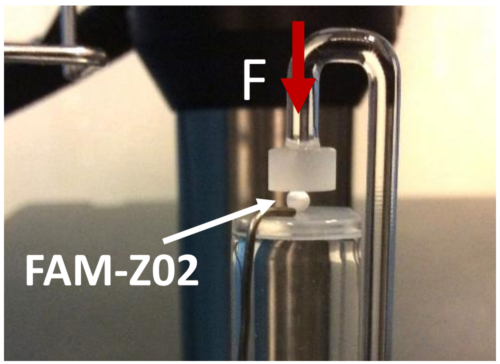
Heat transfer mechanisms in a packed bed adsorber

Two main paths for heat transfer in the packed bed:

- Conduction through solid adsorbent, i.e., a) macro-contact, b) micro-contact heat transfer
- Conduction through interstitial gas, i.e., a) macro-gap, b) micro-gap gas heat transfer



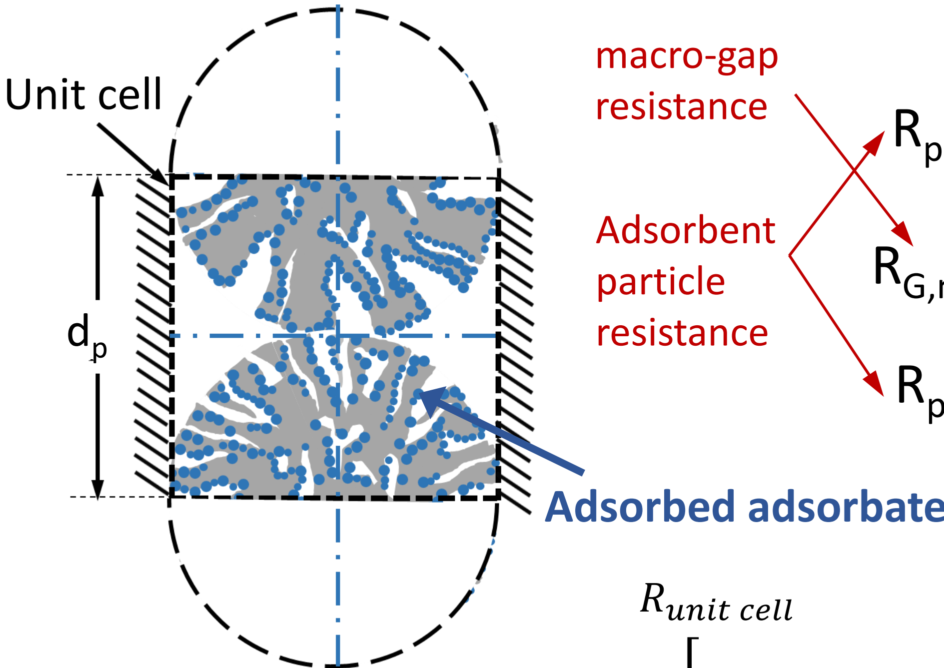


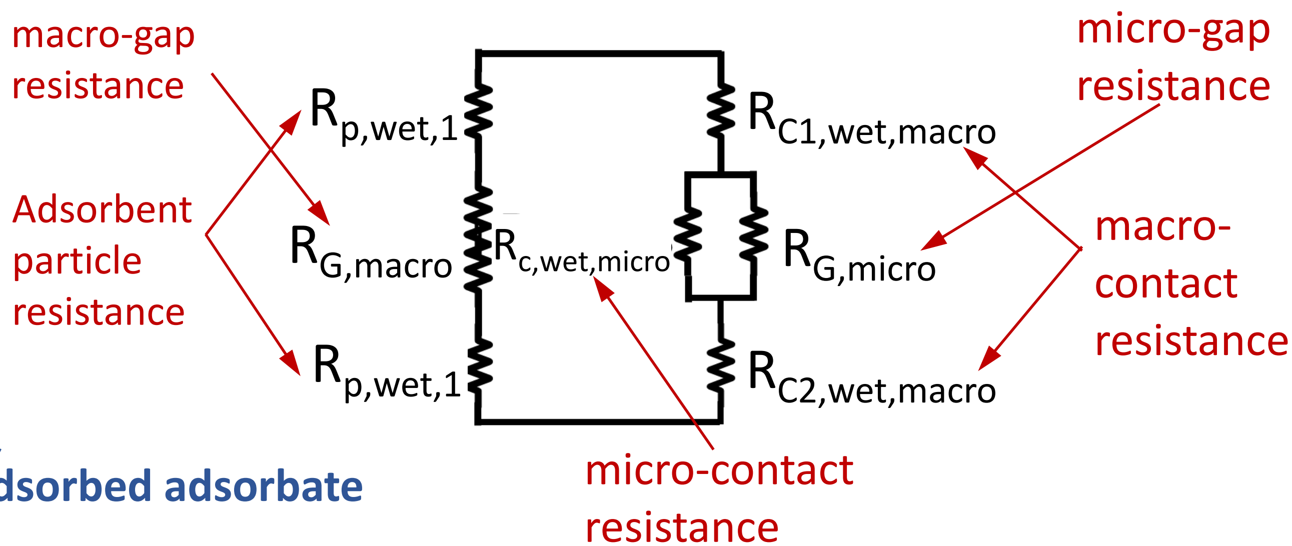


Thermomechanical analyzer (TMA Q400EM, TA Instruments)

[2] M. Bahrami, M. M. Yovanovich, and J. R. Culham, *Int. J. Heat Mass Transf.*, vol. 49, no. 19–20, pp. 3691–3701, 2006.

Predictive model for thermal conductivity of a packed bed of uniform spheres





$$R_{unit\ cell} = \left[\frac{1}{\left(1/R_{c,wet,micro} + 1/R_{g,micro}\right)^{-1} + R_{C,wet,macro}} + \frac{1}{R_{G,macro}}\right]^{-1}$$

- **Bruggeman's method** based on the assumption of **effective homogeneous medium**:

$$\sum_{i=1}^{3} \beta_i \frac{k_i - k_{p,wet}}{k_i + 2k_{p,wet}} = 0, \quad \text{where} \ \sum_{i=1}^{3} \beta_i = 1$$

$$\begin{cases} \beta_s = 1 - \varepsilon & \text{Solid particle} \\ \beta_w = \omega \dfrac{\rho_s}{\rho_w}(1 - \varepsilon) & \text{Adsorbed water} \\ \beta_g = \varepsilon - \omega \dfrac{\rho_s}{\rho_w}(1 - \varepsilon) & \text{Filling gas} \end{cases}$$

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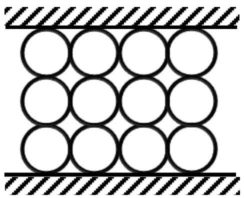
Predictive model: packed bed adsorber arrangement

- **The model is applicable to the following packed bed arrangements:**

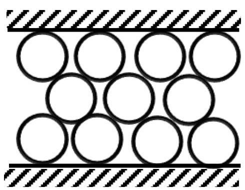
I. Simple cubic (SC)



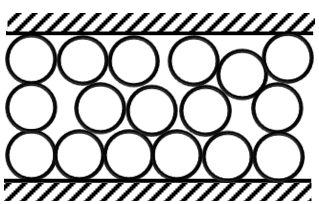
Packing	Solid fraction, ψ	Bed length, L_{bed}	Cell length, L_{cell}
SC	0.524	$n \times d_p$	d_p
FCC	0.740	$\left((n-1)\sqrt{2}/2+1\right)d_p$	$\sqrt{2}d_p/2$

* n: number of layers

II. Face-centered cubic (FCC)



III. Randomly packed bed adsorber



$$\psi_{FCC} < \psi_{bed} < \psi_{SC}$$

$$k_{FCC} < k_{bed} < k_{SC}$$

linear asymptotic solution:

$$\frac{\boldsymbol{\psi_{bed}} - \psi_{SC}}{\psi_{FCC} - \psi_{SC}} = \frac{\boldsymbol{k_{bed}} - k_{SC}}{k_{FCC} - k_{SC}}$$

Asymptotic solution for intermediate solid fraction (randomly packed)

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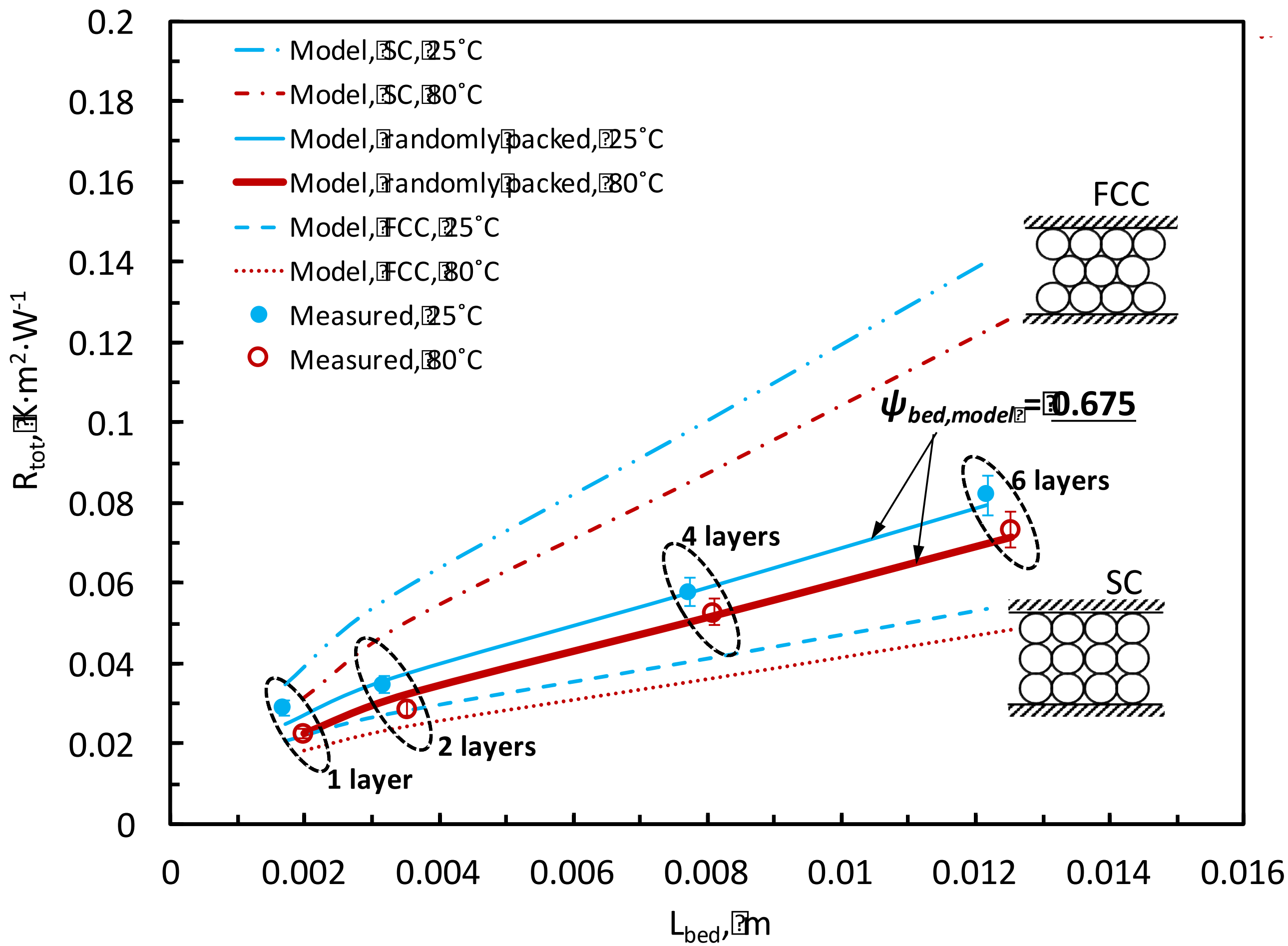

d_p = 2 mm
$P_{contact}$ = 0.7 kPa
ω = 0.3 kg·kg^{-1}

- **SC** is the **lower limit** of **thermal resistance** of the packed bed. **FCC** is the **upper limit** of **thermal resistance** of the packed bed.
- **Solid fraction** of the bed is **0.675**.
- **Thermal resistance** at **25℃** is higher than **80℃**, due to lower thermal conductivity of adsorbent and gas at lower temperatures.

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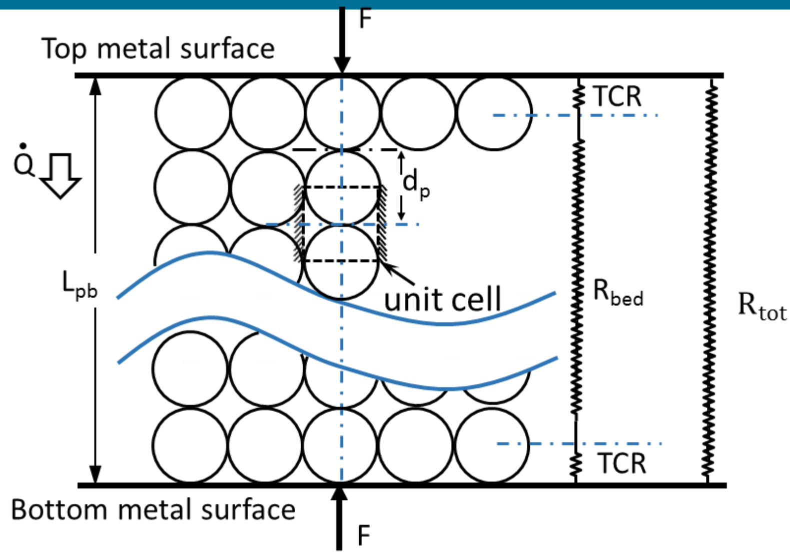
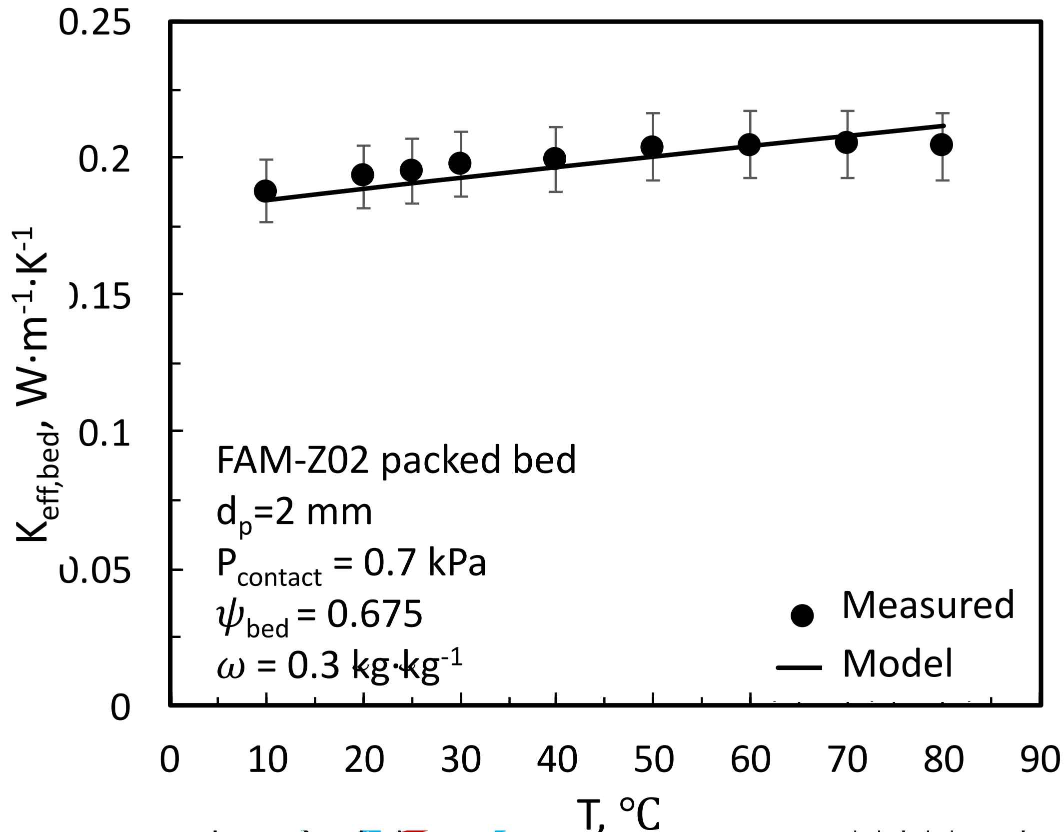
Results: Effective bed thermal conductivity

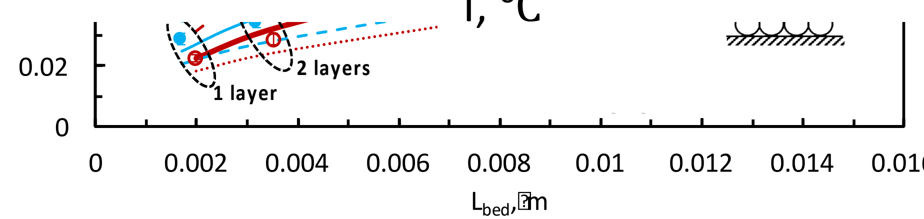


$$R_{tot,1} = \frac{L_{bed,1}}{k_{eff,bed}\,A} + TCR$$

$$R_{tot,2} = \frac{L_{bed,2}}{k_{eff,bed}\,A} + TCR$$

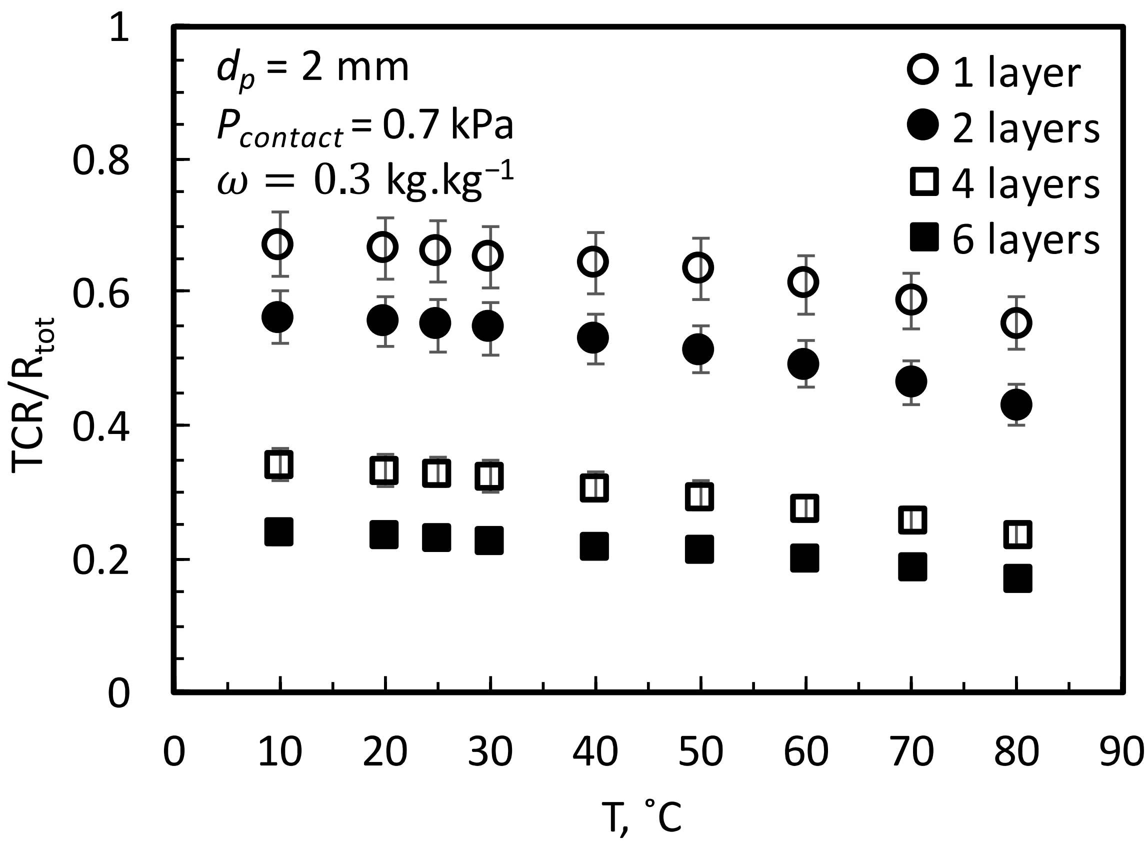
$$k_{eff,bed} = \frac{A\left(R_{tot,2} - R_{tot,1}\right)}{\left(L_2 - L_1\right)}$$

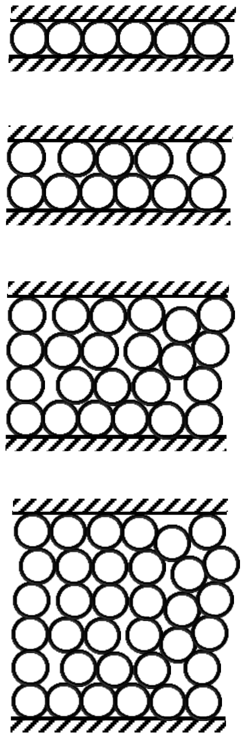




- **$1/(k_{eff,bed}\cdot A)$** is the **slope** of the plot of R_{tot} versus L_{bed}.
- **TCR** is the **intercept** of the plot of R_{tot} versus L_{bed}.

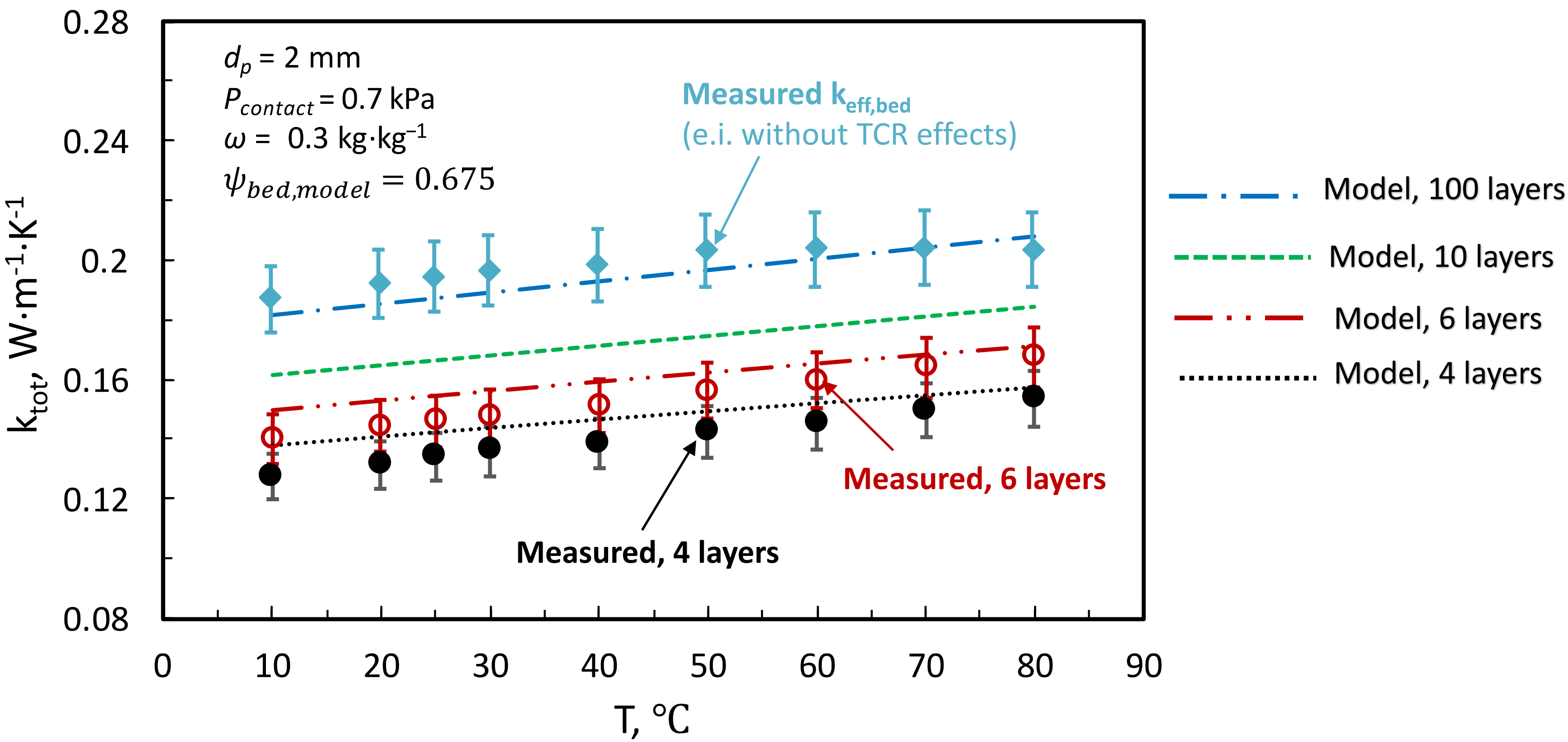
Results: Relative importance of TCR to the total resistance





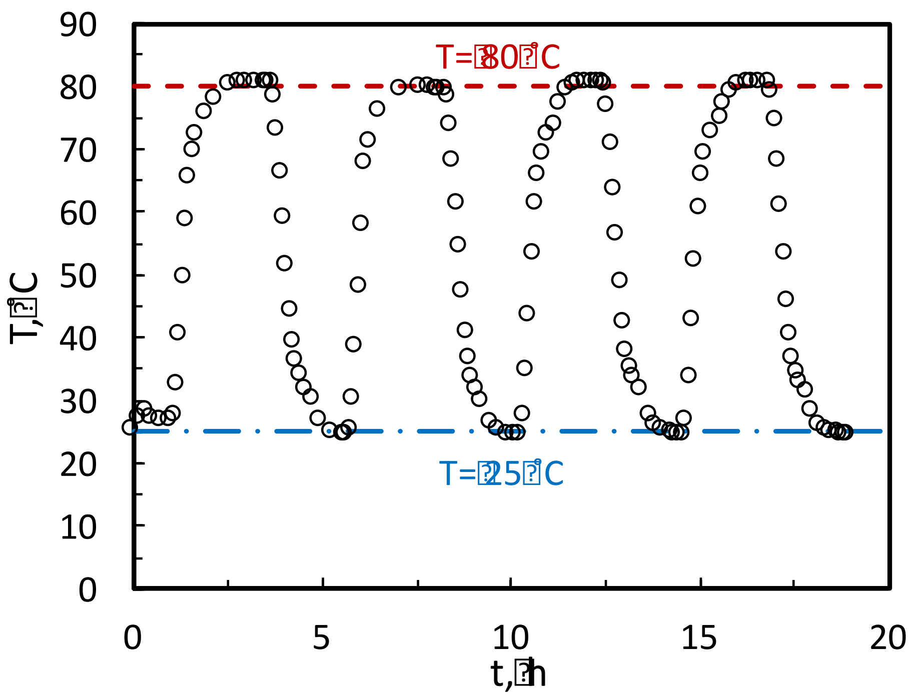
- **TCR/R_{tot}** is greater for **lower number of adsorbent layers** and **lower temperatures**.
- At **higher temperatures**, **TCR** decreases due to
  - **i)** **higher thermal conductivity** of adsorbent and filling gas;
  - **ii)** **better contact** at the interface due to **the thermal expansion**

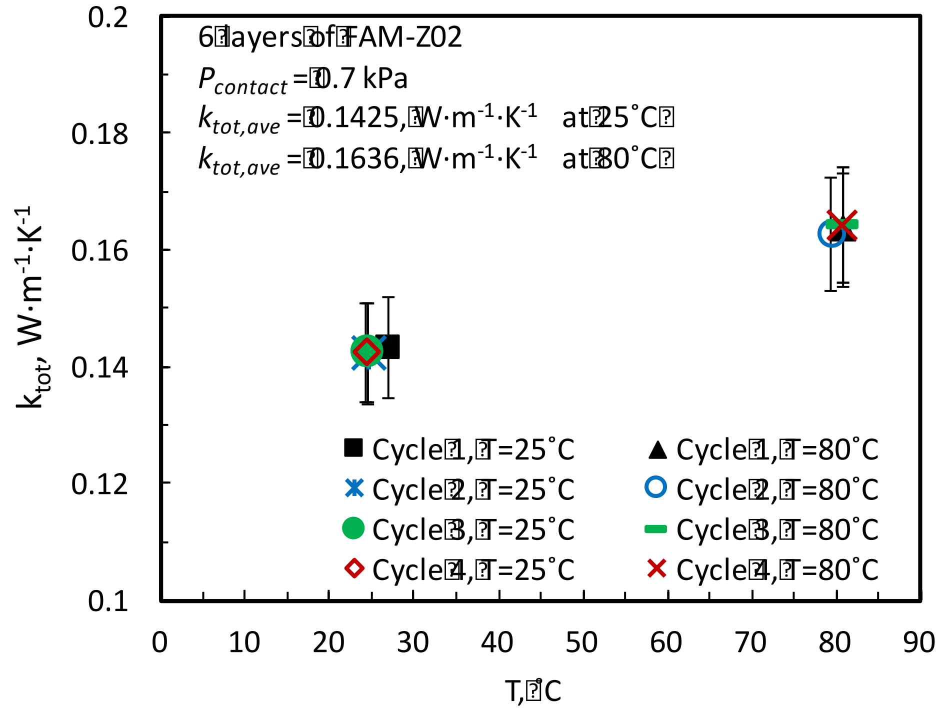
Total bed thermal conductivity and effective thermal conductivity



- Total bed thermal conductivity **increases** as **temperature increases** due to the **lower TCR**.
- For **multi-layer adsorbent,** the thermal behavior approaches the **"effective" or continuum medium** thermal conductivity.

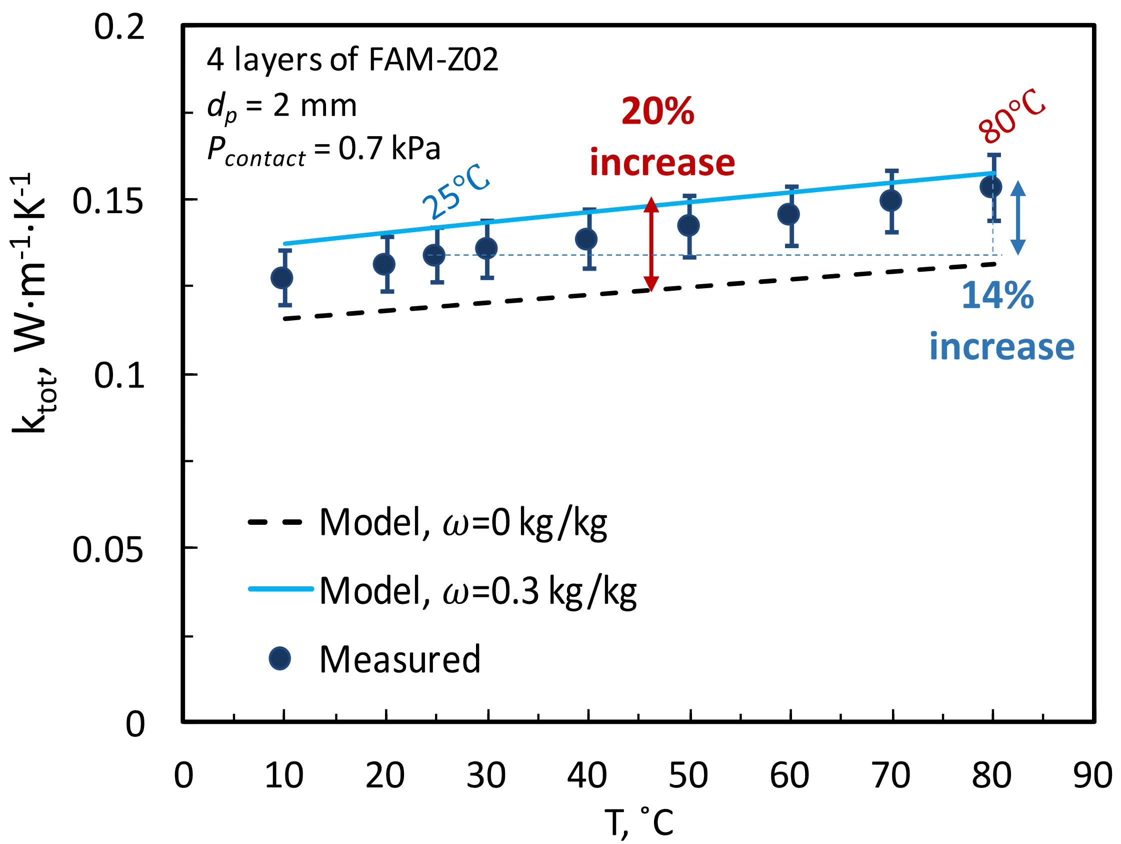
Results: hysteresis analysis of thermal conductivity under the adsorption/desorption cyclic temperature change





- Negligible hysteresis in thermal conductivity for the cyclic temperature changes between 25°C (adsorption) and 80°C (desorption).
- Maximum relative difference is 1%, for both adsorption and desorption, for cyclic temperature changes between 25 to 80 ˚C.

Results: effect of water uptake on thermal conductivity



- **20% increase** in the total thermal conductivity by increase in the **uptake from 0 to 0.3 kg·kg^{-1}**.
- **14% increase** in the total thermal conductivity by increase in the **temperature from 25°C to 80°C**.

Summary

- Effective thermal conductivity of FAM-Z02 packed bed adsorber is measured.
- TCR is deconvoluted from the total bed thermal resistance.
- Importance of thermal contact resistance to the total resistance is calculated.
- Thermal conductivity and TCR of packed bed adsorber are modeled as a function of temperature, bed arrangement, gas pressure and number of adsorbent layers.
- Young's modulus of FAM-Z02 is measured.

Thank you for your attention!