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Experimental Investigation of Relative Humidity Effect on the Thermal Conductivity of Desiccant Material

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ABSTRACT

Study on effective thermal conductivity (ETC) of desiccant materials is getting attention in the literature in order to optimize the operating parameters of close and open cycle adsorption cooling systems. In addition, it is an important parameter to enhance the performance of adsorption heat pump and adsorption cooling systems (AHP/ACS). Most of the desiccant materials are porous in nature, therefore, results in different ETC at different operating conditions i.e. temperature and humidity. In order to find the more precise performance expression, the combined effect of desiccant porosity, temperature and relative humidity (RH) should be considered. In this regard, many empirical and theoretical models have been presented for the estimation of ETC. Models developed in the literature are characterized by a single value at a particular temperature irrespective of humidity. Hence this study experimentally investigates the relative humidity effect on the thermal conductivity of the commercially available desiccant material i.e. AQSOA-Z05. The levels of RH were investigated in the range of 8% to 100%. The results showed that ETC of oven dry adsorbent material was $0.066 \text{ W m}^{-1} \text{ K}^{-1}$ whereas it increased from $0.067\text{-}0.089 \text{ W m}^{-1} \text{ K}^{-1}$ at RH of 8-100%, respectively. The ETC values increase due to the phenomena of pores filling by water vapor adsorption. It also showed that pore filling incorporate the change in the mean free path and it varied from $6.93\text{-}0.55 \mu\text{m}$ at RH range 8-100%, respectively.

Keywords: Thermal conductivity, humidity, adsorption, correlation

1. INTRODUCTION

In recent years, increase in energy demand as well as environmental issue created by existing energy source has promoted to strive for energy preservation. Nation and international policies have great affect to successfully execute and strengthen the efforts regarding the energy preservation. Increase in population and industrialization cause to increase in the world energy demand and its dependences on fossil fuels. The world energy outlook 2009 by IEA emphasis on change in policies regarding the efforts to strengthen the energy preservation, otherwise dependency on fossil fuel will lead energy scarcities. For a sustainable environment Kyoto protocol emphasis on utilization of renewable resources and energy saving technology i.e. re-use of exhaust and waste heat, storage of energy, etc.) (Aristov, 2007) . Mostly 60% of the total energy is consumed on heating and cooling of the residential

building (Urge-Vorsatz *et al.*, 2015) in this regard development in the field of refrigeration seek great importance. New development in this field focused on energy saving technology with the ability of utilizing various form of energy and high primary energy efficiencies. The motivation of adsorption cooling/heating system is attributed to use of various type of thermal energy i.e. low temperature waste heat from industries and power plant (Uyun *et al.*, 2009). In addition, adsorption refrigeration found quite safe for the environment as compared to conventional refrigeration system, as it employ nonpolluting refrigerants. Usually the coefficient of performance (COP) of the adsorption system is low though it is beneficial for environment. Many researcher work on adsorption system (Aristov, 2007; Umair *et al.*, 2014; Sultan *et al.*, 2018) aimed, improvement of system performance by investigating various adsorption cycle, adsorbent material and increasing the mass and heat transfer (Marlinda *et al.*, 2010). For high performance choice of the optimum absorbent and optimum working conditions are required.

Effective thermal conductivity of adsorbent material is one of the most promising research topics (Zhu *et al.*, 2010) to enhance the performance of the adsorption heat pump (AHP)/ adsorption cooling systems (ACs) (Teo *et al.*, 2017; Marlinda *et al.*, 2010; Miyazaki *et al.*, 2017). Thermal conductivity of adsorbent material describes its ability to transmit the heat. Low thermal conductivity and low mass diffusivity of the adsorbent material reduce the coefficient of performance (COP) and specific cooling power of the system. To overcome such limitations, many adsorbent materials have been developed (De Lange *et al.*, 2015). In the literature, most of research on AHP used the certain value of effective thermal conductivity for adsorbent materials. Whereas different working conditions e.g. temperature and relative pressure affect the total uptake by the adsorbent which also affect the effective thermal conductivity of packed bed (Tong *et al.*, 2009). Many researches on thermal conductivity of porous adsorbent material have shown that ETC is not a constant value (Ould-Abbas *et al.*, 2012; Rouhani and Bahrami, 2018; Rouhani *et al.*, 2018). It depends on the interfacial contact between different constituent phases in a packed bed. Due to coupling between fluid and solid particles ETC is considered as the function of porosity, pore structure of the media, water content, saturation degree, phase change of water and temperature (Tong *et al.*, 2009). In absorbent material, generally solid particles have higher thermal conductivity as compared to fluid (Calmidi and Mahajan, 1999). Heat transfer through porous material in packed bed is considered as combination of three mechanisms i.e. gas phase conductive and radioactive heat transfer, solid and gas phase conductive and radioactive heat transfer and within solid contact surface conductive heat transfer (Kunii and Smith, 1960).

There are many techniques applied for measuring the thermal conductivity of the materials for both bulk and thin film solid-state included transient plane source, transient hot-wire method, laser flash diffusivity method and steady-state method (Zhao *et al.*, 2016). In current experiment C-term TCi analyzer is used for measuring the thermal conductivity of material which uses the transient plane source method (Pal *et al.*, 2017; El-Sharkawy *et al.*, 2016).

Many researches on thermal conductivity of porous adsorbent material have shown that ETC is not a constant value (Ould-Abbas *et al.*, 2012; Rouhani and Bahrami, 2018; Rouhani *et al.*, 2018). Many empirical and theoretical models specific to a certain material have been presented to estimate the effective thermal conductivity. Whereas for fully saturated or dry adsorbent materials these models characterized by a single value as the effect of temperature, moisture and porosity are not considered (Tang *et al.*, 2008). Mostly in all open and close adsorption cooling system operating conditions changes which also affect the COP of the system. In order to find the more precise expression of COP of the system, the effect of change in ETC due to change RH should consider. The importance of considering this parameter is proven from the sorption isotherm of adsorbent material, as the amount of moisture uptake is different at different relative pressure (Goldsworthy, 2014; Sultan *et al.*, 2016). The main objective of this research is to develop an experimental setup to measure the ETC at different RH levels. Adsorbent material AQSOA-Z05 is used for conducting the experiment. The change in ETC also induces change in thermal conductivity of pore (k_{pore}) and thermal conductivity of solid (k_s) which also determined in this study.

2. EXPERIMENTAL SECTION

2.1 Material

In present experiment zeolite based adsorbent material used is AQSOA-Z05 (Shimooka *et al.*, 2007) (Goldsworthy, 2014). It has AFI structure type and synthesized from aluminophosphate gel with pore size of 7.4 Å (Shimooka *et al.*, 2007) and crystal density of 1.75g m L⁻¹ determined from crystallographic structure (Abuserwal *et al.*, 2017) (“Structure Commission of the International Zeolite Association-Database of Zeolite Structures” 2017). Adsorbent enable S-shaped water vapor adsorption isotherm. The details of the adsorption isotherm can be found from Ref.(Shimooka *et al.*, 2007).

2.2 Description of experimental setup

Effective thermal conductivity of the adsorbent AQSOA-Z05 has been measured at different levels of RH by using the experimental setup. Figure 1 shows the schematic diagram of the experimental setup.

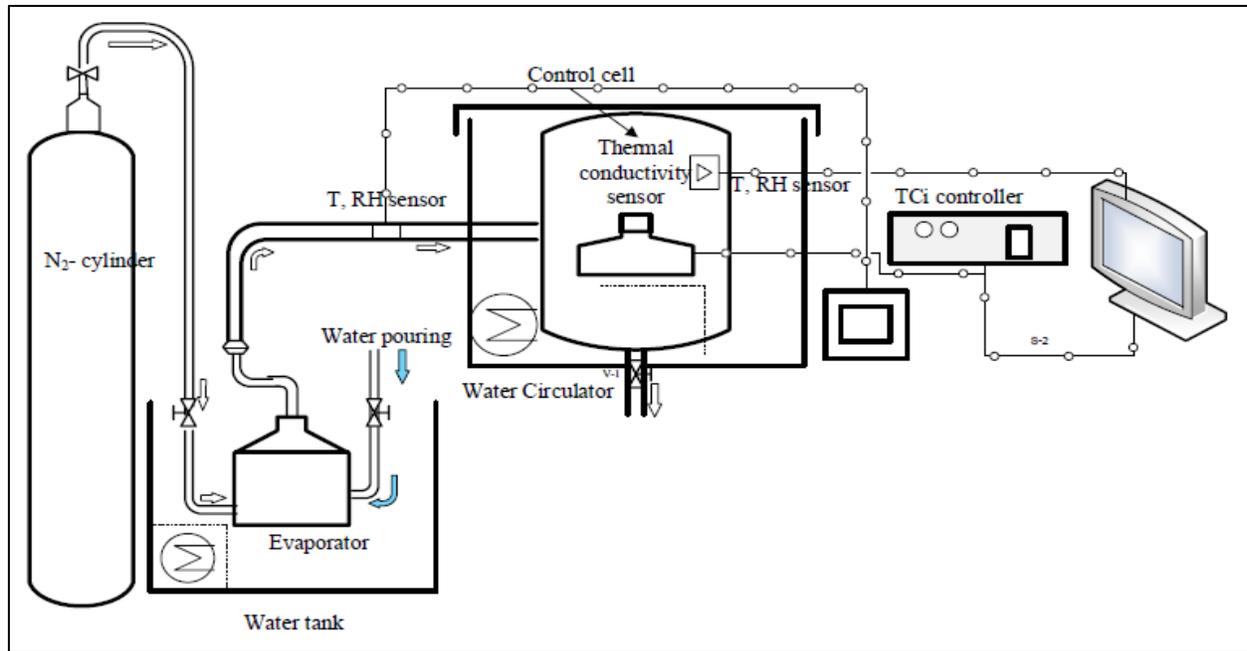


Figure: 1 Schematic diagram of thermal conductivity measurement setup.

It mainly include C-Therm TCi sensor; C-Therm TCi controller connected with the TCi sensor via computer; control cell for maintaining the required experimental conditions; evaporator with precise temperature control system to maintained the humidity level; water circulator for maintaining the temperature of control cell; temperature and relative humidity sensors inside and outside of the control cell. Humidity is maintained by passing the 99.9% N₂ gas via evaporator and temperature of the control cell is set at 25±1 °C for all different levels of RH. Hygroclip type sensor is used just before the entrance to control cell and wireless type sensor having accuracy RH± 2, temperature ±0.3 % is used inside the control cell.

Figure 2 represents the C-Therm TCi sensor. It consists on spiral shape central heater/sensor to produce and sense the heat, guard ring to support the heat flow in one dimension and glass coating with silicon sealant to protect the internal components of sensor. Equation (1) (C-Therms Technologies Ltd. 2013) represents the heat flow in one dimension.

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + G' \quad (1)$$

where ρ , C_p , k , T , t and x are the density (kg m⁻³), specific heat capacity of sample material (kJ kg⁻¹ K⁻¹), thermal conductivity of the sample material (W m⁻¹ K⁻¹), temperature (K), time (s) and length flow parameter by heat (m), respectively. G' is the heat per unit volume (W m⁻³).

3. DATA REDUCTION

Initially adsorbent material is dried in an oven at safe temperature 80°C for 24 hours. Afterward adsorbent material is poured into test cell on the C-Therm TCi sensor which itself is attached with C-Therm TCi controller and computer. Required experimental conditions are maintained in the control cell by passing N₂ gas through the evaporator. Once the required experimental conditions achieved, C-Therm TCi controller is turned on for reading. For each experimental conditions reading were taken at the intervals of 3 hr for two days to make assure the

development of equilibrium between the adsorbent sample and control cell. The average of the reading is used as ETC of material.

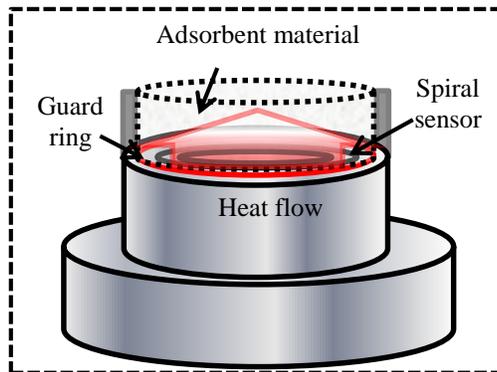


Figure: 2 C-Therm TCi sensor.

Effective thermal conductivity of the porous material is a function of various parameters i.e.

$$k_e = f(k_s, k_g, E, T, D_p) \quad (2a)$$

where k_s and k_g are the thermal conductivity of the solid particle and fluid, respectively. E is the void fraction of packed adsorbent bed and D_p is the average particle diameter. Model of (Hayashi *et al.*, 1987) is used to estimate the k_e numerically.

$$k_e = \frac{1}{2}(3E - 1)k_{g1} + \frac{3\beta'(1-E)(1-\delta)}{2\left(\frac{\phi + 2\beta\lambda}{D_p}\right) + \frac{(1-\phi)}{k_s}} + \frac{3}{2}(1 - E)\delta k_s \quad (2b)$$

where k_g , k_{g1} , k_s , δ , λ , β' , D_p and ϕ are the thermal conductivity of fluid ($\text{W m}^{-1} \text{K}^{-1}$), thermal conductivity of fluid in void space ($\text{W m}^{-1} \text{K}^{-1}$), thermal conductivity of solid ($\text{W m}^{-1} \text{K}^{-1}$), one contact point fractional area for heat flow, free path for fluid molecule (m), factor related to angle between the actual heat flow and parallel to the axis of solid particles (1.0 for loose packing, 0.9 for close packing), average particle diameter (m) and measure of the effective thickness of fluid between the solid particle (m), respectively. β is calculated from (Hayashi *et al.*, 1987) and its value found 0.7.

Mean free path (λ) is calculated by using equation (3) (Zhao and Shen, 2012).

$$\lambda = \frac{RT}{\sqrt{2} \pi d_a^2 N_A P} \quad (3)$$

where R , N_A , P and d_a are the universal gas constant [$8.314510 \text{ J K}^{-1} \text{ mole}^{-1}$], Avogadro's number [$6.0221367 \times 10^{23} \text{ mole}^{-1}$], pressure [Pa] and pore size [m], respectively.

As adsorbent material's solid particles are itself porous in nature and cubical in shape as compared to the model assumption, therefore, thermal conductivity of solid particle (k_s) also changes at different amount of moisture uptake at particular RH. So it is required to determine the change in thermal conductivity of solid particle (k_s) at different RH. Equation (4) is used to determine the thermal conductivity of the pore filling (k_{pore}).

$$k_s = \varepsilon k_{pore} + (1 - \varepsilon)k_p \quad (4)$$

where k_p is the thermal conductivity of particle and assumed $0.113 \text{ W m}^{-1} \text{K}^{-1}$ and porosity (ε) of AQSOA-Z05 is 0.14. The increase in % ETC at different levels of RH was determined by using Equation (5)

$$\% ETC = \frac{k_{RH_i} - k_0}{k_0} \cdot 100 \quad (5)$$

Where k_0 is effective thermal conductivity of oven dry material ($\text{W m}^{-1} \text{K}^{-1}$) and k_{RH_i} is the effective thermal conductivity of material at particular level of RH ($\text{W m}^{-1} \text{K}^{-1}$).

4. RESULTS AND DISCUSSION

The measured ETC of the adsorbent material AQSOA-Z05 is shown in Figure 2 at different levels of RH and temperature 25 °C. It is shown that by increasing the RH, ETC of the materials also increased.

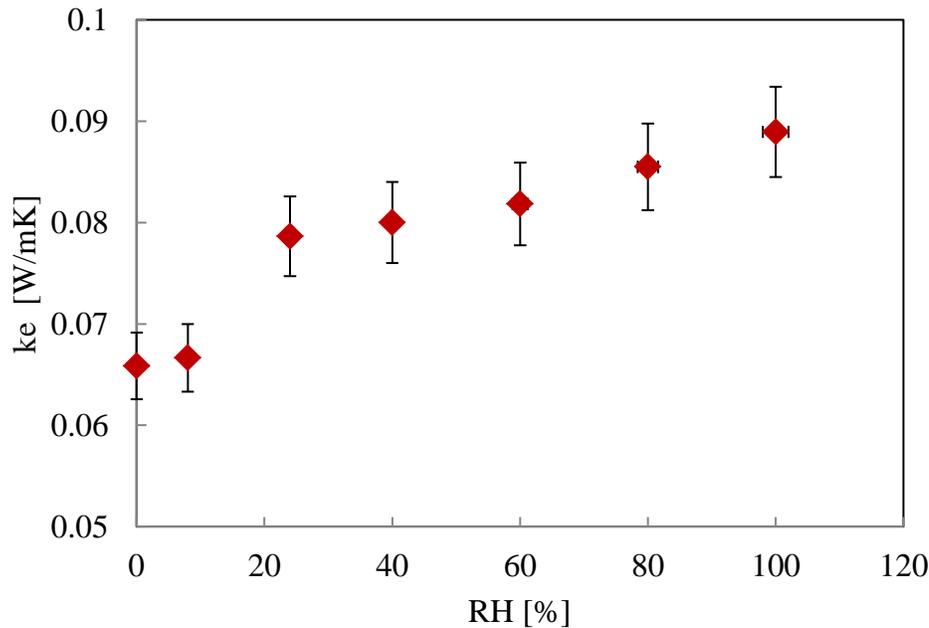


Figure 3. Experimental observed effective thermal conductivity of adsorbent material AQSOA-Z05 at different levels of RH

The first values for each curve represented the ETC of the oven dry sample on thermal conductivity axis. Thereafter, RH increases correspondingly ETC also increases but follow a particular pattern which has resemblance with the adsorption uptake isotherm. At lower levels of RH there is no significant change observed. However thereafter it start increasing and reached maximum level for a small range of RH which is due to isotherm type IV or V behavior (Sing, 1985) followed AQSOA-Z05. This lead to sharp increase in the amount of adsorbate uptake for a small range of RH changes (Goldsworthy, 2014).

Figure 4 represents the percentage increase in ETC at different levels of RH. It showed that ETC of the material increased only 1.22% from the ETC of oven dried material by increasing the RH up to 8%. It indicated that AQSOA-Z05 showed hydrophobic behavior at low relative pressure (Wei-Benjamin-Teo *et al.*, 2017). Whereas increase in ETC value was 19.41% 21.49%, 24.28%, 29.24% and 35.064% at RH 24%, 40%, 60%, 80% and 100% respectively. It also showed that within small range of RH 8 % to RH 24 %, there is maximum increase in ETC value i.e. 18%.

Thermal conductivity of solid (k_s) and pore (k_{pore}) was calculated by using equations (2)-(4). Figure 5 represents the thermal conductivity of solid particle (k_s) and thermal conductivity of pore (k_{pore}) at different levels of RH. It is shown that initially up to 24% RH, increase in thermal conductivity of pore and solid was very fast, later increasing trend decreased. This fact is due to S shaped isotherm both materials exhibit monolayer adsorption at low partial pressure to multilayer adsorption at higher partial pressure (Sing, 1985).

However more variation was found in the value of thermal conductivity of pore (k_{pore}) as compared to thermal conductivity of solid (k_s) due to the phenomena of pores filling by adsorption. Equation (3) is used to calculate the mean free path and it is found that its value varied from 6.93-0.55 μ m. at RH 8-100%. It showed inverse behavior than the thermal conductivity of solid particle (k_s) and pore (k_{pore}), as increase in RH causes to pore filling by adsorption.

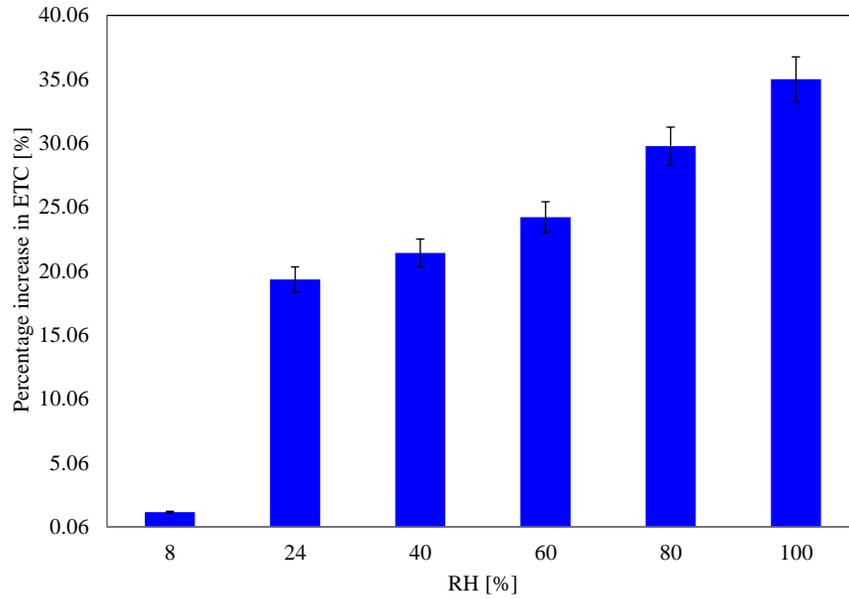


Figure: 4 Percentage increase in ETC at different level of RH.

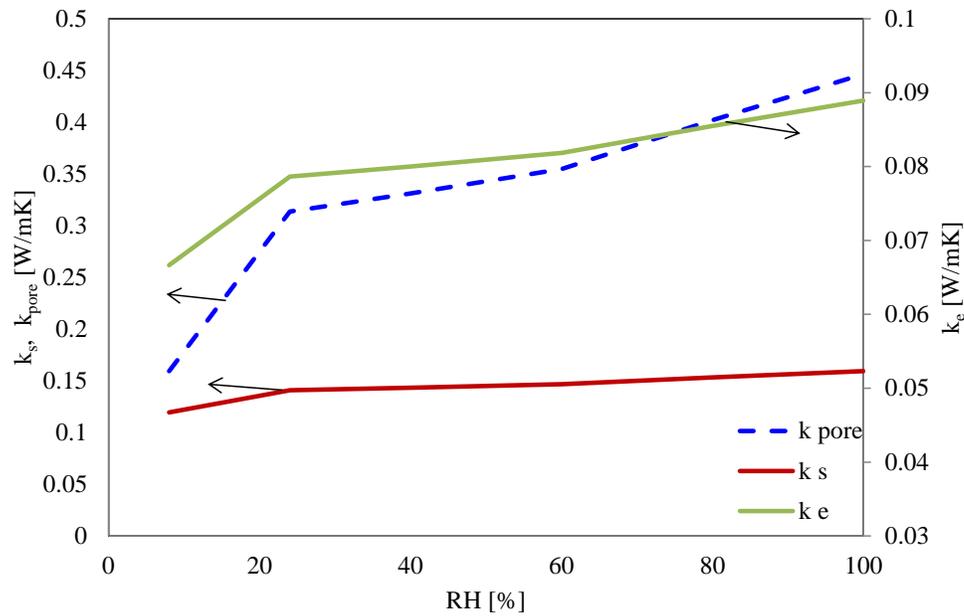


Figure: 5 Variation in thermal conductivity of pores (k_{pore}) and thermal conductivity of solid particle (k_s).

5. CONCLUSIONS

Present study investigates the effect of RH on effective thermal conductivity of adsorbent AQSOA-Z05 at temperature 25 °C. Effective thermal conductivity (k_e) of oven dry AQSOA-Z05 was $0.066 \text{ W m}^{-1} \text{ K}^{-1}$ and it increased up to $0.089 \text{ W m}^{-1} \text{ K}^{-1}$ which is 35% increase in value at RH 100%. Most of the change in ETC value occurs in the range of lower RH i.e. 24%. It also showed the, thermal conductivity of solid particle (k_s) and thermal conductivity of pores (k_{pore}) varies at different levels of RH. due to change in RH. Thermal conductivity of pore (k_{pore}) varied

from $0.152 \text{ W m}^{-1}\text{K}^{-1}$ to $0.446 \text{ W m}^{-1}\text{K}^{-1}$ and solid particle (k_s) varied from $0.118 \text{ W m}^{-1}\text{K}^{-1}$ to $0.159 \text{ W m}^{-1}\text{K}^{-1}$. It also showed the mean free path (λ) decreases by increasing the RH due to the phenomena of pore filling by adsorption.

NOMENCLATURE

C_p	Specific heat capacity ($\text{kJ kg}^{-1}\text{K}^{-1}$)
D_p	Average particle diameter (m)
E	Void fraction (-)
G'	Heat source per unit volume (W m^{-3})
k_0	Effective thermal conductivity of oven dry material ($\text{W m}^{-1}\text{K}^{-1}$)
k	Thermal conductivity ($\text{W m}^{-1}\text{K}^{-1}$)
k_e	Effective thermal conductivity ($\text{W m}^{-1}\text{K}^{-1}$)
k_g	Thermal conductivity of fluid ($\text{W m}^{-1}\text{K}^{-1}$)
k_{g1}	Thermal conductivity of fluid in void space ($\text{W m}^{-1}\text{K}^{-1}$)
k_p	Thermal conductivity of particle ($\text{W m}^{-1}\text{K}^{-1}$)
k_{RH_i}	Effective thermal conductivity of material at particular RH level ($\text{W m}^{-1}\text{K}^{-1}$)
k_s	Thermal conductivity of solid ($\text{W m}^{-1}\text{K}^{-1}$)
T	Dry bulb temperature ($^{\circ}\text{C}$)
t	Time (s)
β	Constant used in equation (3b) (0.7)
δ	Fractional area corresponding to one contact point heat flow ()
λ	Mean free path (m)
ρ	Density (kg m^{-3})
ϕ	Effective thickness of fluid between the solid particles (m)

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