

# Article

# Numerical Investigation of Small-Scale Adsorption Cooling System Performance Employing Activated Carbon-Ethanol Pair

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**Abstract:** Adsorber heat exchanger design has great importance in increasing the performance of the adsorption-based cooling system. In this study, a transient two-dimensional axisymmetric Computational Fluid Dynamics (CFD) model has been developed for the performance investigation of finned tube type adsorber using activated carbon and ethanol as the working pair. The operating conditions of the cooling system were 15, 20 and 80 for evaporation, cooling and heating temperatures, respectively. The simulated temperature profiles for different adsorbent thicknesses were validated with those from experimental data measured in our laboratory. Moreover, the error in mass and energy balance were 3% and 7.88%, respectively. Besides, the performance investigation has been performed for cycle time ranging from 600 s to 1400 s. The optimum cycle time was 800 s and the corresponding evaluated specific cooling power (SCP) and coefficient of performance (COP) were found to be 488 W/kg and 0.61, respectively. The developed CFD model will be used for fin height and fin pitch optimization and can be extended to other adsorbent-adsorbate based adsorption cooling system.

**Keywords:** CFD; activated carbon; ethanol; finned tube adsorber; adsorption cooling; performance investigation

# 1. Introduction

Refrigeration is an important sector for the growing and sustainable global economy. It contributes significantly to food and drug conservation, thermal comfort, etc. However, greenhouse gas (GHG) emissions from this sector represent 7.8% of total emissions. Conventional refrigeration system employs refrigerants with high global warming potential (GWP) such as Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) gases which produced 37% of the emissions and the remaining 63% was caused indirectly by the energy consumption of cooling and air conditioning systems [1].

In this context, adsorption cooling systems (ACS) are a feasible alternative to vapor compression cooling systems. In fact, they are driven by low-grade waste heat (below 100 °C) or solar thermal energy [2,3]. Moreover, they employ natural and environment-friendly refrigerants such as water [4,5], ethanol [6], methanol [7,8], ammonia [9], CO<sub>2</sub> [10], etc. Therefore, the widespread development



of adsorption cooling system will help to solve various energy and environment-related problems. Besides, in summer, when cooling demand goes to highest pick and gives stress to the electric grid, thermally driven sorption cooling systems will alleviate the electric grid pick [11].

Although ACS has several advantages, it is often impaired by low performance and bulkiness issues comparing to conventional vapor compression systems. Consequently, these issues hinder the widespread commercialization of thermally driven ACS [12]. Therefore, one of the big challenges for ACS is how to increase the system performance. The performance of ACS is commonly evaluated using two parameters, namely the coefficient of performance (COP) and specific cooling power (SCP) [13]. The higher the COP and SCP, the higher the system performance is. To improve the performance of the system, one of the key ways is to enhance the heat and mass transfer inside the adsorber bed, thus accelerating the adsorption and desorption process. Adsorber heat exchanger design improvement and thermal conductivity enhancement of adsorbent are two common techniques to ensure good heat transfer inside the bed [14].

Adsorber bed design optimization is very difficult to perform experimentally due to the high cost and huge time requirement. Several researchers [15–18] have performed simulations to investigate the performance of ACS for different adsorbent-adsorbate pairs with lump-sum modeling. Though these simulations provide more realistic performance comparing to ideal cooling cycle performance, however, the assumptions in that modeling such as the same temperature in the bed are not realistic.

In contrast, CFD simulation can provide detailed heat and mass transfer distributions inside the adsorber bed. Moreover, CFD simulations can provide faster bed design at lower cost to realize higher SCP and COP. Due to the several advantages associated with CFD simulation, it has accrued a lot of interest recently. A transient two-dimensional simulation of combined heat and mass transfer in the adsorber bed of a silica gel-water adsorption cooler was presented by Niazmand and Dabzadeh [19]. The authors showed the effect of fin height, fin spacing and cycle time on COP and SCP for an annular fin adsorber. A three dimensional non-equilibrium model of combined heat and mass transfer employing water and composite sorbent SWS-1L has been developed by Mahdavikhah and Niazmand [20] to predict the dynamic performance of ACS. The authors examined the effects of plate fin heat exchanger configurations on the system performance and they mentioned that adsorber bed geometry has a great importance in designing ACS. Ramji et al. [21] presented three-dimensional modeling and CFD simulations of an activated carbon-methanol adsorber for mobile air-conditioning applications. A two-dimensional CFD simulation has been performed for silica-gel water pair by Caglar. The author showed the comparison of adsorbent bed with fin and finless tubes. Besides, the influences of various fin configurations on heat transfer inside the bed have studied by the author [22].

However, from the literature it is found that very few CFD simulation works have been done on the activated carbon and ethanol pair. Recently, Jribi et al. [23] showed the temperature change in the activated carbon packed heat exchanger during the adsorption process. Besides, the author showed the temperature profile with and without the heat of adsorption. Sourav et al. [24] reported the effects of heat exchanger aspect ratio and adsorbent particle size on the dynamic adsorption characteristics. However, in both cases, the authors did not show the simulation results for all cycle phases such as adsorption, pre-heating, desorption and pre-cooling process which is very important to investigate the adsorption system performance accurately. Moreover, the authors did not address the effect of cycle time in their study.

This study presents the mathematical model and transient CFD simulation of finned tube type adsorber/desorber bed employing activated carbon-ethanol pairs for adsorption cooling applications. Simulation results are compared with experimental data for all the adsorption cycle phases considering similar operating conditions. Good agreement is found between the experimental and simulated temperature and pressure profiles. Moreover, heat and mass balance are examined for the system. Finally, performance optimization is done based on cycle time ranging from 600 s to 1400 s. The optimum cycle time was reported 800 s and the corresponding evaluated SCP and COP were found to be 488 W/kg and 0.61, respectively. Besides cycle time, our developed CFD model can

be used to optimize the operating conditions and adsorber heat exchanger configurations such as fin pitch, fin height and fin thickness. Moreover, this developed model can be extended for other adsorbent-adsorbate pairs.

#### 2. Working Principle of Adsorption Cooling System

Figure 1 shows the schematic diagram of a one-bed adsorption cooling system. It generally consists of four components: a condenser, an evaporator, an adsorber/desorber bed filled with the activated carbon powder (ACP) and an expansion valve. An adsorption cycle comprises four processes, which are pre-heating, desorption, pre-cooling and adsorption. In the pre-heating process, the bed is disconnected from the evaporator and hot water is circulated in the adsorption bed to increase the bed pressure. When bed pressure becomes higher than that in the condenser, then it is connected to the condenser and desorption process starts. Ethanol vapor is desorbed from activated carbon bed to the bed because of additional heating and moves to the condenser where it condenses. After the desorption is finished, the bed is disconnected from the condenser and cooling water is circulated in the adsorber bed which is called pre-cooling process. Due to the cooling water supply, the pressure in the bed decreases and becomes lower than that in the evaporator. At this moment, the adsorber bed is connected to the evaporator and evaporated ethanol vapor comes out of the adsorber and is adsorbed in the activated carbon bed. During the adsorption process, cooling water is supplied to the bed continuously to remove the heat of adsorption.



Figure 1. Schematic of adsorption cooling system in desorption process.

## 3. CFD Modeling

Performance investigation of finned tube type adsorber employing activated carbon and ethanol pairs was carried out experimentally in our laboratory earlier [25,26]. The experimental apparatus consists of an adsorber, an evaporator and a condenser connected with stainless steel tubes. The temperatures and pressures in all components are measured by K-type thermocouples and pressure gages, respectively. Two copper finned tubes were incorporated inside the adsorber. The finned tube heat exchanger consists of 190 circular fins attached to an annular tube having a length of 700 mm. Fin height, fin pitch and fin thickness were 10, 3.7 and 0.53 mm, respectively. Porous activated carbon was

filled between two consecutive fins and sealed with a mesh sheet. The annular tube was 1.5 mm thick with an inner diameter of 26 mm. Ethanol was considered as refrigerant. Besides, water was used as a heat transfer fluid and passed through the annular tube. The adsorbent temperatures at 1 and 5 mm thicknesses were recorded experimentally by using K-type thermocouples shown as  $T_1$  and  $T_5$  in Figure 2.

Under similar experimental conditions, the transient CFD simulation was performed using Ansys-Fluent software v.18.1 (ANSYS, Canonsburg, PA, USA). Geometry and meshing were created by using Ansys Design Modeler and Ansys Meshing, respectively. The details of the CFD modeling were presented as follows:

# 3.1. Assumptions

The assumptions used in the simulation are as follows:

- The adsorbent layer height is equal to the height of the fins.
- The porous media is considered as homogenous.
- Darcy model is adopted for flow through porous media.
- A thermal equilibrium model is assimilated for porous media i.e., the adsorbent and ethanol vapor are at same temperature.
- The variation of the heat of adsorption with the ethanol uptake is not considered, therefore, the average value of the heat of adsorption is used.

# 3.2. Geometry and Meshing

Figure 2 shows the finned tube geometry and computational domain. The finned tube heat exchanger has a symmetric axis; therefore, the geometry is reduced to 2D. Besides, the computational domain used in the simulation is the half space between the two fins as this geometry has several symmetry planes.



Figure 2. 2D-axisymmetric geometry of the finned tube adsorber showing computational domain.

To perform the simulation, we used fine meshing and divided the computational domain (11.5 mm  $\times$  1.85 mm) into 748 elements with 897 nodes. The following mesh quality is reported from Fluent:

- Minimum orthogonal quality = 0.9721 where orthogonal quality ranges from 0 to 1 and values close to 0 represents low quality.
- Maximum ortho skew = 0.0279 where ortho skew ranges from 0 to 1 and values close to 1 correspond to low quality.

#### 3.3. Materials and Porous Zone Properties

### 3.3.1. Materials

The materials used in the simulations were: (i) copper tubing for tubes and fins, (ii) ethanol as gas phase refrigerant, and (iii) activated carbon powder of type Maxsorb III packed between the fins. The properties of copper were taken from the Fluent database. Real gas properties of ethanol were imported into Fluent from NIST Refprop database (v.9.1, NIST, Gaithersburg, MD, USA). The properties of Maxsorb III were, the particle density  $\rho_p = 464.1 \text{ kg} \cdot \text{m}^{-3}$ , adsorbent-adsorbate thermal conductivity  $k_p = 0.2 \text{ W/(m} \cdot \text{K})$  [23] and specific heat capacity. The solid adsorbent heat capacity of Maxsorb III was investigated lately and the average value for temperatures ranging from 30 to 80 °C is 0.9 kJ/(kg·K) [27]. Therefore, the particle heat capacity for average instantaneous uptake of 0.7 g/g considering that the adsorbate is in the liquid phase [28] becomes 4.64 kJ/(kg·K).

#### 3.3.2. Porous Zone Properties

The permeability ( $\alpha$ ) and inertial loss coefficient (*C*) of porous media were calculated for the average particle diameter of Maxsorb III  $D_P = 70 \ \mu m$  and adsorbent porosity  $\gamma = 0.434$  [23] by the following equations [29]. The viscous flow resistance inside the porous media is the reciprocal of permeability of adsorbent:

$$\alpha = \frac{D_p^2}{150} \frac{\gamma^3}{(1-\gamma)^2}$$
(1)

$$C = \frac{3.5}{D_P} \frac{(1-\gamma)}{\gamma^3} \tag{2}$$

#### 3.4. Boundary Conditions

The boundary conditions applied in this simulation are shown in Figure 3 and the detailed boundary conditions are explained in Sections 3.4.1 and 3.4.2.

#### 3.4.1. Pressure Inlet/Wall/Pressure Outlet Conditions

The interface between activated carbon and refrigerant is set as pressure inlet during adsorption process and the refrigerant inlet pressure was set to 3.85 kPa corresponding to evaporation temperature of 13.1 °C. Similarly, the interface is considered as pressure outlet during the desorption process. In addition, desorption is performed at a pressure of 10.35 kPa corresponding to the condensation temperature of 29.8 °C. Besides, at the time of preheating and precooling processes, the interface is considered as wall condition. The purpose of precooling is to reduce the bed pressure from condensation pressure to that of evaporation pressure. Therefore, when the bed pressure becomes lower than the evaporator's pressure, the precooling process was ended. Similarly, when the bed pressure becomes higher than that of condenser, the preheating process was terminated.

#### 3.4.2. Convection Boundary Conditions

We applied convection boundary condition at the tube inner surface. The water temperature was estimated from the average of inlet and outlet temperature of the tube as presented in Figure 4. The

free stream temperature profile was fitted to polynomial functions and implemented into fluent as a user-defined function (UDF). Moreover, Gnielinski correlation [30] is used to calculate the convection heat transfer coefficient for water flow rate of 3 L/min. Then, the heat transfer coefficient is incorporated into fluent as a UDF for the temperature range 20 °C to 80 °C. The heating and cooling processes were applied for 400 s each.



Figure 3. Domain boundary conditions.



Figure 4. Water source temperature profiles at the inlet (red) outlet (blue) and middle tube (green).

#### 3.5. Governing Equations

The main mathematical equations used in fluent are mass, momentum and energy conservation equations. To consider the adsorption phenomena, mass and energy source terms are added to these conservation equations through user-defined functions (UDFs).

#### 3.5.1. Mass Conservation Equation in Porous Media

The mass conservation equation for porous media is given by:

$$\frac{\partial(\gamma\rho_g)}{\partial t} + \nabla \cdot \left(\rho_g \vec{\upsilon}\right) = S_m \tag{3}$$

where the mass source term  $(S_m)$  denote the adsorbed ethanol gas inside the porous media and is specified as follows:

$$S_m = -(1-\gamma)\rho_p \frac{dq}{dt} \tag{4}$$

The term  $\frac{dq}{dt}$  represents the adsorption rate due to the diffusion of ethanol vapor through the Maxsorb III micro-pores which will be stated in Section 3.5.4.

#### 3.5.2. Momentum Conservation Equation

The momentum conservation equation for porous media is expressed by:

$$\frac{\partial}{\partial t} \left( \rho_g \overrightarrow{\upsilon} \right) + \nabla \cdot \left( \rho_g \overrightarrow{\upsilon} \overrightarrow{\upsilon} \right) = -\nabla p + \nabla \cdot \overline{\overline{\tau}} + \rho_g \overrightarrow{g} + \overrightarrow{F}$$
(5)

where the momentum source term (F) is estimated for the viscous and inertial losses in porous media.

$$F_i = -\frac{\mu}{\alpha} \upsilon_i - \frac{1}{2} \rho_g C \left| \stackrel{\rightarrow}{\upsilon} \right| \upsilon_i \tag{6}$$

The viscous resistance (inverse of permeability:  $1/\alpha$ ) and inertial losses coefficients were defined previously in Section 3.3.2:

#### 3.5.3. Energy Conservation Equation

The energy conservation equation for porous media considering thermal equilibrium condition is given by:

$$\frac{\partial}{\partial t} \left[ \gamma \rho_g E_g + (1 - \gamma) \rho_p E_s \right] + \nabla \cdot \left[ \overrightarrow{\upsilon} \left( \rho_g E_g + p \right) \right] = \nabla \cdot \left( k_{eff} \nabla T \right) - \nabla \cdot \sum_j h_j \overrightarrow{j}_j + \nabla \cdot \left( \overline{\overline{\tau}} \cdot \overrightarrow{\upsilon} \right) + S_h \tag{7}$$

 $S_h$  is the heat source term corresponding to the heat released by adsorption process and is given by:

$$S_h = (1 - \gamma)\rho_p Q_{st} \frac{dq}{dt}$$
(8)

Here,  $Q_{st} = 1002 \text{ kJ/kg}$  is the average heat of adsorption for Maxsorb III-ethanol pair [31].

#### 3.5.4. Adsorption Characteristics

The linear driving force (LDF) model [32] is used in this study to predict the adsorption kinetics  $\begin{pmatrix} dq \\ dt \end{pmatrix}$  and it is expressed by:

$$\frac{dq}{dt} = k(q^* - q) \tag{9}$$

where k and  $q^*$  are the diffusion time constant and equilibrium uptake, respectively. The diffusion time constant is defined by the Arrhenius equation (Equation (10)) and the equilibrium uptake was calculated by Dubinin-Astakhov (D-A) adsorption isotherm equation (Equation (11)):

$$k = Aexp\left(-\frac{E_a}{RT}\right) \tag{10}$$

$$q^* = q_s exp\left(-\left(\frac{RT}{E}ln\left(\frac{P_s}{P}\right)\right)^n\right)$$
(11)

 $A = 0.2415 \text{ s}^{-1}$ ,  $E_a = 225 \text{ kJ/kg}$ ,  $q_s = 1.2 \text{ kg/kg}$ , E = 139.5 kJ/kg and n = 1.8 denote the pre-exponential factor, activation energy, saturated uptake, characteristic energy and heterogeneity parameter, respectively [33].

In D-A equation,  $P_s$  denotes the saturated pressure (bar) calculated by the Antoine equation:

$$log_{10}P_s = A - \frac{B}{T+C} \tag{12}$$

where A = 5.247, B = 1598.673 and C = -46.424 are the constant parameters of Antoine equation for ethanol at the temperature range 292.77 to 366.63 K [34].

#### 3.5.5. Performance Investigation

The performance of adsorption cooling system was investigated using Equations (13) and (14) to calculate specific cooling power (SCP) and coefficient of performance (COP), respectively:

$$SCP = \frac{h_{fg} \cdot \int_{ads\_start}^{ads\_end} \dot{m}_{ads} dt}{t_{cycle} \cdot m_{ac}}$$
(13)

$$COP = \frac{Q_{chill}}{Q_{des}} \tag{14}$$

where:

$$Q_{chill} = h_{fg} \cdot \int_{ads\_start}^{ads\_end} \dot{m}_{ads} dt$$
(15)

#### 3.5.6. Mass and Energy Balance Equation

The mass balance in the adsorber/desorber bed implies that the mass of refrigerant adsorbed onto the adsorbent is equal to that desorbed from the bed as described in Equation (16):

$$\int_{ads\_start}^{ads\_end} \dot{m}_{ads} dt = \int_{des\_start}^{des\_end} \dot{m}_{des} dt$$
(16)

The energy balance in the adsorption cooling system indicates that the heat released by the condenser and adsorber bed is equal to that adsorbed by the evaporator and desorber bed as expressed by the following equation:

$$Q_{chill} + Q_{des} = Q_{cond} + Q_{ads} \tag{17}$$

#### 4. Results and Discussion

#### 4.1. Pressure Profile

Figure 5 shows the simulated pressure change vs. experimental pressure profile in the adsorber/desorber bed for two cycles. The experimental pressure was not constant during adsorption and desorption processes as it was affected by the temperature fluctuation in condenser and evaporator, respectively and this was not considered in this study. In the simulated pressure profile, adsorption and desorption occur at constant pressure condition as seen from Figure 5. Besides, the simulation can obtain the cyclic steady-state pressure within two cycles. Good agreement has been found between experimental and simulated pressure profiles at the beginning of pre-heating and pre-cooling processes.



**Figure 5.** Comparison of pressure change in the adsorber/desorber bed: experimental (red) and simulated (blue).

#### 4.2. Temperature Profiles

Experimental temperature change vs. simulated temperature profile at 1 and 5 mm adsorbent thicknesses ( $T_1$  and  $T_5$ ) were presented in Figure 6. Good agreement was found between the experimental data and the simulated results. From Figure 6, simulated temperature profile perfectly matched with that of experimental data at the end of desorption and in pre-cooling process. However, a little deviation is found during the adsorption process and at the starting of desorption. One possible reason for deviation at adsorption process is that Gnielinski correlation under-estimated the heat transfer coefficient from the adsorber bed to the heat transfer water.



**Figure 6.** Simulated (dashed line) vs. experimental (line) temperature profiles at 1 (blue) and 5 mm (red) adsorbent thicknesses.

Figure 7 provides the simulated temperature profile at different adsorbent thicknesses from the tube outer surface such as 0, 1, 5 and 8 mm. During pre-heating and pre-cooling processes, the change of temperature is almost same in all these points due to high heat transfer rate. However, during desorption and adsorption process, the change of temperature is noticeable at 0, 1 and 5 mm thickness.



Figure 7. Simulated temperature profiles at different adsorbent thickness.

#### 4.3. Adsorption Characteristics

The profiles of equilibrium uptake ( $q^*$ ) and instantaneous uptake (q) in the adsorber/desorber bed are displayed in Figure 8. The difference between maximum and minimum values of equilibrium uptake  $\Delta q^*$  is 0.51 kg/kg whereas the change in case of instant uptake  $\Delta q$  is 0.314 kg/kg. This means that ethanol adsorption onto activated carbon is only 61.6% of its capacity within the 400 s adsorption time.



**Figure 8.** Simulated average instantaneous (red) and equilibrium (blue) uptakes in the adsorber/desorber bed.

#### 4.4. Energy and Mass Balance

The total amount of heat removed from adsorber and that added to desorber were calculated by integrating the heat transfer profile as shown in Figure 9. The values of heat released from condenser and adsorber bed and those adsorbed by desorber and evaporator are used to check the energy balance as shown in Equation (17) and the error in energy balance is found to be 7.9%.

The simulated ethanol flow rate to/from the adsorber/desorber bed is presented in Figure 10. The error in mass balance was 3% which is estimated by Equation (16).

One of the main reasons for mass balance error is that the time for adsorption and desorption was not exactly same in the case of the experiment. The time difference during the experiment was around 12 s. This mass balance error also affects the energy balances. Besides, during adsorption at 20 °C temperature, the heat transfer coefficient was underestimated by Gnielinski correlation that is also visible in Figure 6. Therefore, heat input was higher than the heat removed from the bed.



Figure 9. Simulated heat transfer rate to and from the finned tube adsorber.



Figure 10. Simulated inlet/outlet mass flow rate to and from the adsorber for a volume between 2 fins.

## 4.5. Performance Investigation

The performance of adsorption cooling system (ACS) has been evaluated in terms of specific cooling power (SCP) and coefficient of performance (COP) by using Equations (13) and (14), correspondingly. The estimated SCP and COP for 800 s cycle time are found 488 W/kg<sub>ac</sub> and 0.61, respectively. This performance is also relevant to the reported performance for activated carbon-ethanol pair in other studies previously. The specific cooling capacity for activated-carbon ethanol pair considering two different particle size and three different domains has been reported between the range

of 424 and 710 W/kg<sub>ac</sub> by Sourav et al. [24]. Besides, the performance of activated carbon fiber-ethanol based adsorption cooling system was found 200 W/kg for SCP and 0.65 for COP previously [17].

Figure 11 shows the performance variation with cycle time. The COP increases with the increase of cycle time. However, the SCP reaches its maximum at a cycle time of 800 s. With adsorption time increase, the cooling effect increases as the total mass adsorbed increases. However, the flow rate of adsorbed mass increases sharply at starting of adsorption then decreases as shown previously in Figure 10. Therefore the cooling power increases with cycle time increase and reaches its maximum at optimum cycle time of 800 s. Then, for higher adsorption/desorption time, the cooling power decreases. The COP increases with adsorption/desorption time increase which as the increase in cooling effect generated is higher than the increase of heat consumed to desorb the refrigerant from activated carbon.



Figure 11. The variation of coefficient of performance (COP) and specific cooling power (SCP) with cycle time.

#### 5. Conclusions

CFD modeling of a finned tube adsorber employing activated carbon-ethanol as the adsorbent-adsorbate pair has been performed. The simulated pressure and temperature profiles were compared with experimental data of an adsorption cooling system tested in our laboratory for evaporation temperature of 15 °C, cooling temperature of 20 °C, the heating temperature of 80 °C and total cycle time of 800 s. Good agreement was found between experimental and simulation results. The performance of the system was investigated numerically for different adsorption/desorption phase times ranging from 300 to 700 s. The optimal cycle time for pre-heating and adsorption phases as well as pre-cooling and adsorption phases corresponded to 400 s. At this condition, the cooling power reached 488 W per kilogram of adsorbent and the COP was 0.61. This CFD model will allow performance optimization of the system by optimizing the operating conditions as well as fin dimensions.

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# Nomenclature

| Α                                  | pre-exponential factor ( $s^{-1}$ )  |
|------------------------------------|--|
| С                                  | inertial loss coefficient ( $m^{-1}$ )   |
| D                                  | diameter (m)   |
| Ε                                  | energy (kJ)  |
| $\overrightarrow{F}$               | force vector (N)   |
| $\overrightarrow{q}$               | gravitational acceleration ( $m \cdot s^{-2}$ )                                  |
| o<br>hco                           | heat of evaporation $(I \cdot kg^{-1})$  |
| k                                  | diffusion time constant ( $s^{-1}$ )   |
| n                                  | heterogeneity parameter (-)  |
| m                                  | mass flow rate $(kg \cdot s^{-1})$   |
| m                                  | mass (kg)  |
| р                                  | pressure (Pa)  |
| R                                  | gas constant (kJ·kmol <sup><math>-1</math></sup> ·K <sup><math>-1</math></sup> ) |
| $S_m$                              | mass source term (kg·m <sup>-3</sup> ·s <sup>-1</sup> )                          |
| q                                  | uptake (kg·kg <sup>-1</sup> )  |
| 0                                  | thermal energy (J)   |
| Q <sub>st</sub>                    | heat of adsorption (kJ·kg <sup><math>-1</math></sup> )                           |
| t                                  | time (s)   |
| Т                                  | temperature (K)  |
| υ                                  | velocity magnitude ( $m \cdot s^{-1}$ )  |
| $\stackrel{\rightarrow}{\upsilon}$ | overall velocity vector ( $m \cdot s^{-2}$ )                                     |
| Greek                              | , , , , , , , , , , , , , , , , , , ,  |
| α                                  | permeability (m <sup>2</sup> )   |
| $\gamma$                           | porosity (-)   |
| $ u_{\mu}$                         | adsorbent' micropore volume ( $cm^3 \cdot g^{-1}$ )                              |
| ρ                                  | density (kg⋅m <sup>-3</sup> )  |
| μ                                  | dynamic viscosity (Pa·s)   |
| $\nabla$                           | gradient   |
| $\overline{\overline{\tau}}$       | stress tensor (Pa)   |
| Superscripts                       |  |
| *                                  | equilibrium  |
| Subscripts                         |  |
| а                                  | apparent, activation   |
| ас                                 | activated carbon   |
| ads                                | adsorption   |
| chill                              | chill  |
| cond                               | condenser  |
| des                                | desorption   |
| eff                                | effective  |
| g                                  | gas phase  |
| р                                  | particle   |
| s                                  | solid, saturated   |
| Acronyms                           |  |
| ACS                                | adsorption cooling system  |
| CFD                                | computational fluid dynamics   |
| NIST                               | National Institute of Standards and Technology                                   |
| SCP                                | specific cooling power   |
| COP                                | coefficient of performance   |
|                                    |  |

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