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FUNDAMENTAL STUDY ON SOLAR POWERED ADSORPTION COOLING SYSTEM

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Fundamental experiments on the solar-powered adsorption cooling system were carried out with small-scale apparatus simulating ideally a practical unit by employing a combination of silica-gel and water vapor as an example of the adsorbent-adsorbate combinations. A simple model which takes into account both adsorption properties and apparatus characteristics was proposed to interpret our experimental results quantitatively. Then the transitional behavior of heat and mass transfer in continuous adsorption-regeneration experiments was successfully interpreted by the model. The model proposed here is not a complete one and is to be considered as a first-step model for estimating operation with practical equipment. Also, the contribution of the level of regeneration temperature of adsorbents to the cooling performance was quantitatively clarified on the basis of the adsorption equilibrium relation, which is considered useful in choosing a favorable combination of adsorbent and adsorbate for the system.

1. Introduction

The adsorption cooling system has drawn attention since a demonstration unit using natural zeolites as adsorbents and water vapor as adsorbate was constructed and its performance was qualitatively reported by Tchernev.[5] Guilleminot *et al.*[4] suggested the feasibility of this system in comparison with the absorption cooling system from the viewpoint of thermodynamics. The principle of operation of this system is shown as a sketch in **Fig. 1**. The system is composed of a packed bed of adsorbents, a condenser and an evaporator. A combination of adsorbent and adsorbate is confined in the closed system. In the adsorption cycle shown in Fig. 1(a), while adsorption is taking place in the adsorbent bed, evaporation of adsorbate occurs in the evaporator, absorbing heat from outside the system. Cooling is carried out by making use of this heat absorption. In the regeneration cycle shown in Fig. 1(b), since the temperature of the adsorbent bed rises by receiving solar heat, desorption and condensation of adsorbate takes place in the adsorbent bed and the condenser respectively. The most significant merit of this system is the absence of moving parts in principle, which is a point

of difference from the absorption cooling system. As described above, the feasibility of the system is qualitatively suggested but quantitative studies for the design of practical equipment is not yet sufficient. In this work, from the standpoint of chemical engineering, a quantitative study of the system was made. Continuous adsorption–regeneration experiments were carried out with small-scale equipment simulating ideally a practical unit and the results obtained are interpreted by a simple model taking into account adsorption properties and apparatus characteristics.

2. Experimental

2.1 Apparatus

A schematic diagram of experimental apparatus is shown in **Fig. 2**. It consists of five T-type tubes used as packed beds of adsorbents, a condenser, an evaporator, an infrared lamp and a vacuum pumping system. T-type tubes are made of Pyrex and details of the one placed in the middle of the five are shown in **Fig.3**. A copper-constantan thermocouple is inserted into a narrow glass tube which is inserted into the bed to reach the center of it. The condenser is also made of Pyrex and has a heat transfer area of about $0.06\,\mathrm{m}^2$. The evaporator is a glass bottle of $0.025\,\mathrm{m}$ ID and $0.16\,\mathrm{m}$ height. To read from the outside the amount of adsorbate (working fluid) remaining in the evap-
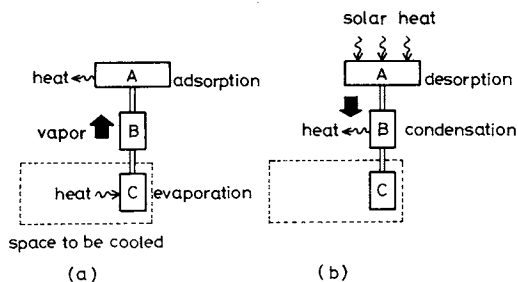
Fig. 1. Principle of operation of solar-powered adsorption cooling system.
(a) adsorption cycle; (b) regeneration cycle.
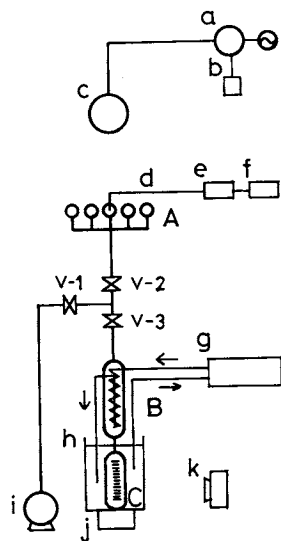A, packed bed of adsorbents; B, condenser; C, evaporator.

Fig. 2. Experimental apparatus: A, packed bed of adsorbents; B, condenser; C, evaporator; a, transformer; b, voltmeter; c, infrared lamp; d, thermocouple; e, digital thermometer; f, recorder; g, circulator of constant-temperature water; h, constant-temperature water bath; i, rotary vacuum pump; j, magnetic stirrer; k, camera; v-1, 2, 3, valves 1, 2 and 3.

orator, the wall is calibrated in milliliters. The overall heat transfer coefficient between the outside and the inside of a packed bed of adsorbents on the basis of temperature difference between ambience and the center of the bed was determined in advance by measuring the temperature decrease rate from 373 K to the ambient temperature, and then the value of 7.2 W/(m²·K) was obtained. Also, the relationship between the electric power provided to the infrared lamp and the effective thermal energy penetrating into packed beds of adsorbents was checked prior to the experiments.

2.2 Materials

The choice of adsorbent-adsorbate combination is one of the significant problems in the investigation of this system. For the present aim of quantitative analyses of heat and mass transfer from the viewpoint of chemical engineering, a silica-gel–water vapor combination is employed for our experiments as an
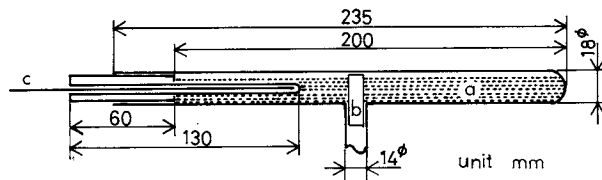

Fig. 3. Details of a packed bed of adsorbents: a, silica-gel; b, glass wool; c, CC thermocouple.

example of adsorbent-adsorbate combinations. Water is considered to be very promising as the working fluid in this system because of its large latent heat of vaporization, and silica-gel is commonly used as a desiccant.

Silica-gel used in our experiments is Fuji-A-type (Blue) manufactured by Fuji Davison Co. Ltd. This type of silica-gel changes its color from blue to pink when its moisture adsorption amount reaches about 10 weight percent. The size of packed particles of silica-gel is between 8 and 20 mesh, and the average radius, R_p, is 7.1×10^{-4} m. Adsorption properties of this silica-gel–water vapor combination were previously reported by Chihara et al.[1] as follows. Adsorption equilibrium is described by

$$q^* = k(P/P_s)^{1/n} \tag{1}$$

where q^* is the amount adsorbed in equilibrium with pressure P, P_s is the saturation vapor pressure, and both k and n are constants and are given respectively as $k = 0.346$ kg/kg and $n = 1.6$. Adsorption rate is controlled by surface diffusion inside a particle and the surface diffusivity, D_s, is given as a function of temperature by

$$D_s = D_{s0} \exp\left(-\frac{E_a}{RT}\right) \tag{2}$$

where D_{s0} is a pre-exponent constant, E_a is the activation energy of surface diffusion, R is the gas constant and T is temperature. The values of D_{s0} and E_a are given respectively as 2.54×10^{-4} m²/s and 4.20×10^4 J/mol. Then overall mass transfer coefficient for adsorption, $k_s a_p$, is given by[3]

$$k_s a_p = \frac{15 D_s}{R_p^2} \tag{3}$$

The isosteric heat of adsorption, Q_{st}, is reported as 2.8×10^6 J/kg.[2]

2.3 Procedure

About 0.1 kg of silica-gel was packed in the T-type tubes as shown in Fig. 3. As a pre-treatment, the adsorbent was degassed at a temperature of over 423 K and a pressure of under 0.1 Pa for over two hours. About 5×10^{-2} kg of pure water was set in the evaporator. Then air enclosed in the system or dissolved in water was sufficiently purged. While the experiments were carried out, room temperature was

not especially controlled but ranged only between 293 and 296 K. Temperature of walls of the condenser and the evaporator was kept constant at 283 K by circulating the constant-temperature water. Also, working fluid remaining in the evaporator was stirred by a magnetic stirrer to keep the temperature at the same level as the wall temperature even while evaporation was taking place.

(1) Measurement of adsorption isobar

Pressure in the system is kept constant at the saturation vapor pressure of water at 283 K. The constancy of the pressure mentioned above was assured in the preparatory experiment with a mercury manometer, but after this assurance the manometer was removed from the system to prevent trace amounts of air leakage. Then the amounts adsorbed equilibrated to the pressure at adsorption temperatures of 293, 333, 353, 373 and 393 K were measured by the following method. By providing adequate electric power to the infrared lamp, the temperature of the adsorbent beds was kept at constant levels such as 293, 333, 353, 373 and 393 K. Then Valves 2 and 3 were opened. After adsorption equilibrium was attained, the decrease of water in the evaporator was measured. The equilibrium amount adsorbed, q^*, was determined by

$$q^* = \Delta W_w / W_s \qquad (4)$$

where ΔW_w is the decrease of water in the evaporator and W_s is the weight of adsorbent packed in the beds. In the above calculation, water in gas phase is ignored. Because dead volume of the system is so small that water in gas phase is considered to be negligible in comparison with that in liquid and adsorption phases.

(2) Adsorption and regeneration cycles

To examine experimentally the reproducibility of heat and mass transfer in long-term continuous operation and to analyze quantitatively the changes of temperature in the adsorbent beds and the amount adsorbed with passage of time in the operations, ten cycles of adsorption and regeneration were carried out. Adsorption cycles were carried out for 8 hours at an ambient temperature of about 293 K, and regeneration cycles were carried out for 4 hours with electric power provided to the infrared lamp so that the temperature in the adsorbent beds finally reached a scheduled regeneration temperature level of 373 K. The amount of water in the evaporator was recorded every one or two hours by taking photos with a camera controlled by a timer. Temperature in the adsorbent bed was continuously measured by a thermocouple and recorded on a recorder.

Continuous adsorption and regeneration cycles were carried out in the following two modes: (A) with time for cooling the adsorbent beds from regeneration
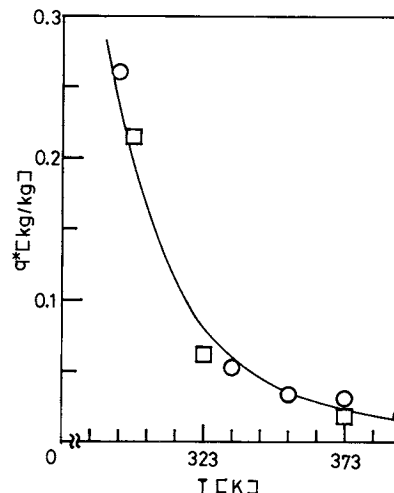

Fig. 4. Adsorption isobar of silica-gel and water vapor at $P = P_s$ (283): ○, obtained by the method in this work; □, obtained by the conventional gravimetric method; —, Eq. (1) with $P = P_s$ (283).

temperature to ambient temperature between regeneration and adsorption cycles with all valves closed, and (B) without such time between the two cycles.

3. Results and Discussion

3.1 Adsorption isobar

The amounts adsorbed in equilibrium with the saturation vapor pressure of water at 283 K obtained by the experiments are plotted in **Fig. 4** by circle symbols. Also in Fig. 4, experimental results obtained by a conventional gravimetric method using quartz balance equipment are plotted by square symbols. Agreement of the results from the two independent methods is sufficiently good. Then it is confirmed that the amounts adsorbed as determined by the method previously mentioned are reasonable. The solid line in Fig. 4 represents Eq. (1) with $P = P_s$ (283), which is the saturation vapor pressure at 283 K. Equation (1) successfully describes the adsorption equilibrium relation in the range of temperature below 393 K. Then the following discussion on a practical adsorption-regeneration cycle employing silica-gel–water vapor combination is developed on the basis of the adsorption equilibrium relation expressed by Eq. (1).

For the sake of quantitative considerations regarding a practical cycle, four levels of temperature in the cycle are defined in this work. Three of them are as follows. The atmospheric temperature, T_a, is 303 K; the evaporation temperature, T_{ev}, regarded as the cooling temperature, is 278 K; and the condensation temperature, T_{cond}, is 308 K on the assumption that condensation takes place in an air-cooled condenser. One more temperature level needing definition is the regeneration temperature, T_{reg}, which is to be obtained by receiving solar power. The level of T_{reg} is considered to depend not only on the solar power
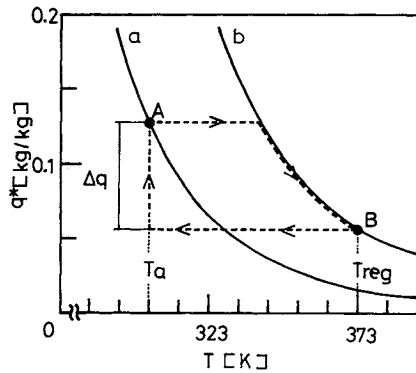
Fig. 5. Practical cycles of adsorption and regeneration on the assumption of $T_{reg} = 373$ K; line a, Eq. (1) with $P = P_s$ (278); line b, Eq. (1) with $P = P_s$ (308).
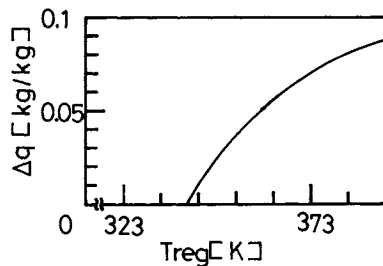

Fig. 6. Dependency of Δq on T_{reg} in a combination of silica-gel and water vapor.

itself at a place where the equipment is located, but also on the structure of packed beds of adsorbents or the method of solar power collection. So it is difficult to define T_{reg} as a certain level. The effect of T_{reg} on the cycle is described below. Adsorption isobars for the saturation vapor pressures of water at 278 K, which is the level of T_{ev}, and at 308 K, which is the level of T_{cond}, are shown in **Fig. 5**. In Fig. 5, Point A represents the state at the end of the adsorption cycle and Point B represents that of the regeneration cycle in the case of $T_{reg} = 373$ K as an example. The adsorption-regeneration cycle is represented by dashed lines. In this example case, the difference of the amount adsorbed between Points A and B shown in Fig. 5 as Δq is about 0.07 kg/kg. The dependency of Δq on T_{reg} derived from Fig. 5 is shown in **Fig. 6**. The absolute quantity of heat removal of this cooling system, Q_r, is given by using Δq as

$$Q_r = L W_s \Delta q \qquad (5)$$

where L is the latent heat of vaporization of adsorbate and W_s is the weight of adsorbents employed in the system. The cooling of 3.5 kW for 8 hours, which is considered as a typical case of practical air conditioning, requires 570 kg of adsorbents in a condition of $\Delta q = 0.07$ kg/kg.

3.2 Continuous operation

(1) Analysis model

For the purpose of designing practical equipment

or determining the optimal operating condition, it is necessary to establish an adequate theoretical model useful in describing the transitional behavior of heat and mass transfer in the system. No interpretation of experimental results of the adsorption cooling system by using a model on the basis of chemical engineering has been found in past investigations. A model is proposed here for the quantitative interpretation of our experimental results obtained by using a small-scale idealized apparatus simulating a practical unit. For the design of practical equipment, the model must take into account adsorption properties, equipment characteristics and environmental conditions. In this sense the model proposed here is not a complete one and is to be considered as a first-step model for estimating numerically the operation of the system.

Mass balance of the adsorbate (working fluid), which is water in our experiments, is expressed by neglecting the mass in gas phase as

$$W_s \frac{dq}{dt} + \frac{dW_w}{dt} = 0 \qquad (6)$$

where W_s is the weight of adsorbents employed in the system, q is the amount adsorbed, W_w is the weight of adsorbate in liquid phase and t is time.

Heat balance in the packed beds of adsorbents, which is silica-gel in our experiments, is expressed as

$$W_s C_{ps} \frac{dT_s}{dt} = W_s Q_{st} \frac{dq}{dt} - A_s h_s (T_s - T_a) + A_s Q \qquad (7)$$

where C_{ps} is the heat capacity of the adsorbent, T_s is the temperature in the beds, Q_{st} is the heat of adsorption, A_s is the heat transfer area of the beds, h_s is the overall heat transfer coefficient of the beds, T_a is the atmospheric temperature and Q is the effective heat influx into the beds by radiation by considering the receiving area as A_s.

Heat and mass balance described above are based on the following assumption. Both the temperature in the beds and the amount adsorbed, T_s and q, are uniform in the beds since the packed beds used in our experiments are considered to be small enough to neglect their distribution.

For the silica-gel–water vapor combination employed in this work, the adsorption equilibrium relation is given by Eq. (1) above and is expressed as a function of T_w and T_s as

$$q^* = k(P_s(T_w)/P_s(T_s))^{1/n} \qquad (8)$$

where $P_s(T_w)$ and $P_s(T_s)$ are the saturation vapor pressures at the temperature of T_w and T_s, respectively, and are calculated by using Antoine's equation.

Adsorption rate is expressed as

$$\frac{dq}{dt} = k_s a_p (q^* - q) \qquad (9)$$

where $k_s a_p$ is the overall mass transfer coefficient, which is evaluated by using Eqs. (2) and (3).

As the principal object of our experiments is the observation of heat and mass transfer followed by adsorption/desorption caused in the packed beds of adsorbents by thermal swings, the temperature of adsorbate in the liquid phase, T_w, was controlled at a constant level by the method described earlier. Then, in the analysis of our experimental results, T_w is fixed at a constant value. However, in practical cases, the change of T_w should be taken into account by expressing the heat balance in the evaporator as Eq. (10) for example.

$$\frac{d}{dt}(W_w C_{pw}(T_w - T_a)) = L\frac{dW_w}{dt} - A_w h_w(T_w - T_a) \quad (10)$$

where C_{pw} is the heat capacity of adsorbate, T_w is the temperature of adsorbate in liquid phase, L is the latent heat of vaporization, A_w is the heat transfer area of the evaporator and h_w is the overall heat transfer coefficient of the evaporator.

(2) Interpretation of experimental results

The changes of T_s and q with the passage of time are calculated by numerical integration using Eqs. (6) to (9) and are compared with experimental results. Plots in **Figs. 7** and **8** show the average values obtained in ten repetitions. The reproducibility of the behavior of heat and mass transfer in repeated adsorption-regeneration cycles was sufficient. Solid lines in Figs. 7 and 8 represent the results described by the calculation. The agreement of the results calculated and experimentally obtained is sufficiently good, as shown in both Figs. 7 and 8. It is confirmed that the heat and mass transfer in the idealized system on a small scale can be estimated by the simple model proposed here.

3.3 Favorable combination of adsorbent–adsorbate

The performance of this system depends on the relationship between Δq and T_{reg} as shown in Fig. 6 for our experimental case. Generally it is desirable to obtain a larger amount of Δq at a lower level of T_{reg}. The relations among Δq, T_{reg} and adsorption properties are discussed on the basis of the following conditions. (1) Temperature levels of T_{ev}, T_a and T_{cond} are the same as those previously defined in this paper. (2) The adsorption equilibrium relation which should be examined is that in the range of $P/P_s < 0.2$, since the value of $P_s(T_{ev})/P_s(T_a)$ is about 0.2. In that range, the adsorption equilibrium relation is successfully expressed in the form of Eq. (1). (3) The parameter k in Eq. (1) means the limiting amount adsorbed at $P/P_s = 1$. Then k is assumed to be approximately given as

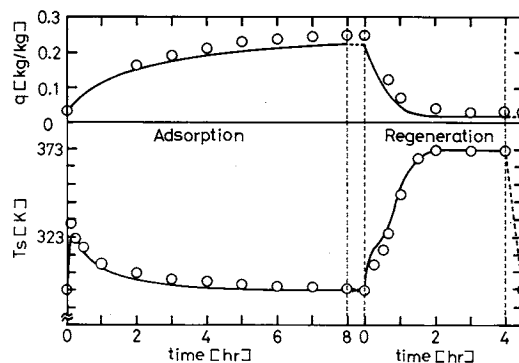$$k = \frac{\rho^* \varepsilon_p}{\rho_p} \quad (11)$$

Fig. 7. Continuous cycles of adsorption and regeneration in mode (A): $\bigcirc$, experimental; —, calculated.
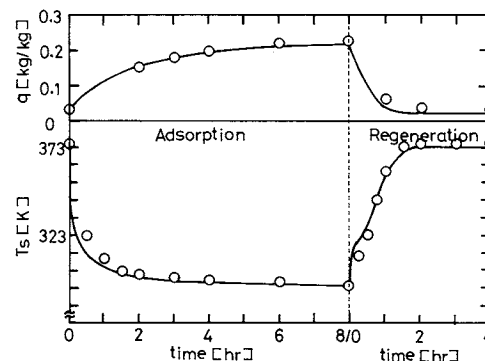
Fig. 8. Continuous cycles of adsorption and regeneration in mode (B): $\bigcirc$, experimental; —, calculated.

where ρ^* is the density of adsorbate in the adsorption phase, ε_p is the pore fraction in a particle and ρ_p is the particle density. On the above assumption k is determined by physical properties of adsorbent and adsorbate. In our experimental case, the values of ε_p and ρ_p are respectively 0.44 and $1.3 \times 10^3 \text{ kg/m}^3$,[6] and the value of ρ^* is about $1 \times 10^3 \text{ kg/m}^3$ since ρ^* is reasonably considered as the same as the density in liquid phase. Then k is evaluated by using Eq. (11) as 0.34 kg/kg, which is sufficiently close to 0.346 kg/kg cited earlier. On the above conditions, Δq is given as

$$\Delta q = \left(\frac{\rho^* \varepsilon_p}{\rho_p}\right)\left[\left(\frac{P_s(T_{ev})}{P_s(T_a)}\right)^{1/n} - \left(\frac{P_s(T_{cond})}{P_s(T_{reg})}\right)^{1/n}\right] \quad (12)$$

The dependency of T_{reg} on n was derived from Eq. (12) and is shown in **Fig. 9** in an example case of $\rho^* \varepsilon_p/\rho_p = 0.34 \text{ kg/kg}$. It is found in Fig. 9 that T_{reg} takes the minimum value in every case of $\Delta q = 0.02$ to 0.1 kg/kg when n is around 2. The tendency above mentioned is found regardless of the value of $\rho^* \varepsilon_p/\rho_p$. Then it becomes clear that the combination of adsorbent-adsorbate which takes the adsorption equilibrium expressed by Eq. (1) with $n = 2$ is favorable for the adsorption cooling system.

4. Conclusions

(1) Fundamental experiments on the solar-powered adsorption cooling system were carried out
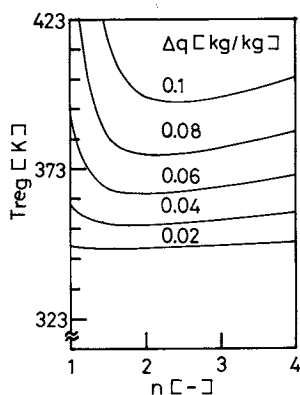
Fig. 9. Relation among T_{reg}, n and Δq in the case of $k = 0.34$ kg/kg.

with a small-scale apparatus simulating ideally practical equipment by employing silica-gel–water vapor combination as an example of the absorbent–adsorbate combinations.

(2) A simple model taking into account both the adsorption properties and apparatus characteristics was proposed and the experimental results were successfully interpreted by the model.

(3) The contribution of the level of regeneration temperature on the performance of the system was quantitatively clarified.

Nomenclature

A_s	= heat transfer area of adsorbent bed		[m^2]
A_w	= heat transfer area of evaporator		[m^2]
C_{ps}	= heat capacity of adsorbent		[J/(kg·K)]
C_{pw}	= heat capacity of adsorbate		[J/(kg·K)]
D_s	= surface diffusivity		[m^2/s]
D_{s0}	= pre-exponent constant in Eq. (2)		[m^2/s]
E_a	= activation energy of surface diffusion		[J/mol]
h_s	= overall heat transfer coefficient of adsorbent bed		[W/(m^2·K)]
h_w	= overall heat transfer coefficient of evaporator		[W/(m^2·K)]
k	= constant in Eq. (1)		[kg/kg]
$k_s a_p$	= overall mass transfer coefficient		[s^{-1}]
L	= latent heat of vaporization		[J/kg]
n	= constant in Eq. (1)		[—]
P	= pressure		[Pa]
P_s	= saturation vapor pressure		[Pa]
$P_s(T)$	= saturation vapor pressure at the temperature of T		[Pa]
q	= amount adsorbed		[kg/kg]
q^*	= equilibrium amount adsorbed		[kg/kg]
Δq	= difference of amount adsorbed between before and after regeneration		[kg/kg]
Q	= effective heat influx into adsorbent bed by radiation		[W/m^2]
Q_r	= absolute quantity of heat removal		[J]
Q_{st}	= isosteric heat of adsorption		[J/kg]
R	= gas constant		[J/(mol·K)]
R_p	= average radius of a particle		[m]
t	= time		[s]
T	= temperature		[K]
T_a	= atmospheric temperature		[K]
T_{cond}	= condensation temperature		[K]
T_{ev}	= evaporation temperature		[K]
T_{reg}	= regeneration temperature		[K]
T_s	= temperature of adsorbent		[K]
T_w	= temperature of adsorbate in liquid phase		[K]
W_s	= weight of adsorbent		[kg]
W_w	= weight of adsorbate in liquid phase		[kg]
ΔW_w	= decrease of water in evaporator		[kg]
ε_p	= pore fraction in a particle		[—]
ρ^*	= density of adsorbate in adsorption phase		[kg/m^2]
ρ_p	= particle density		[kg/m^3]

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