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Coupled heat and mass transfer during moisture exchange across a membrane

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ABSTRACT

Coupled heat and moisture transfer through a membrane was modeled and analyzed. Two air fluids flow on each side of the membrane, with one fluid having a higher temperature and a higher humidity ratio than the other, causing a simultaneous heat and moisture transfer across the membrane. The model considers the effects of the adsorption heat which is treated as adsorption capacity and temperature dependent. Analyses were carried out for two air states and for a variety of membrane parameters, which included the membrane moisture and thermal resistances. The membrane moisture resistance ranges 10–10,000 $\mathrm{kg^{-1}\,m^2 s}$ while the membrane thermal resistance ranges 0.2–$2.0\times 10^{-3}\,\mathrm{W^{-1}\,m^2\,K}$. The results show that with increasing membrane moisture resistance, the adsorption capacity at the membrane surface on the feed side increases while that on the permeating side decreases, correspondingly, the adsorption heat at the membrane surface on the feed side decreases while that on the permeating side increases. The membrane thermal resistance has only a small influence on the adsorption capacity and adsorption heat. The moisture flux decreases with increasing membrane moisture or thermal resistance, with the maximum moisture flux having an order of $10^{-3}\,\mathrm{kgm^{-2}\,s^{-1}}$. The total heat flux, which is the sum of the adsorptive and convective heat fluxes, shows a variation similar to that of the moisture flux.

1. Introduction

When gas transports through a dense membrane, it first adsorbs at one side of the membrane, then diffuses through the membrane, and finally desorbs from the other side of the membrane, the adsorption releases heat while the desorption absorbs heat, which influences the transmembrane heat and mass transfer characteristics.

Physical adsorption is the primary adsorption phenomenon during membrane transport. Gas adsorption on a solid surface is a gas molecule agglomeration process with heat generation. The heat of adsorption comprises two parts: the heat of condensation caused by the interaction among the adsorptive molecules, and the surface energy caused by the interaction between the adsorptive and adsorbent molecules. So, the adsorption heat can be considered as the sum of the condensation heat and the surface energy, it is affected by not only the adsorption capacity but also the system temperature.

Some researchers investigated the water vapor permeation through various membranes, in which they ignored the effects of the adsorption heat when analyzing the transmembrane mass transfer process [1–7]. There would be no problem with this ignorance if the adsorption heat induced temperature difference between the two sides of the membrane was small. For fixed membrane transport property and thickness, such a temperature difference is determined only by the transmembrane mass flux, with a larger mass flux yielding a larger temperature difference. Some researchers took into account the effects of the adsorption heat when they modeled the heat and moisture transfer across membranes, but they treated such heat as a constant [8–14]. With this situation as a background, we have recently studied the effects of the adsorption heat on the transmembrane heat transfer characteristics with consideration of the dependence of the adsorption heat on the adsorption capacity [15]. The results show that when the adsorption heat is treated as constant, the membrane surface temperatures and the transmembrane convective and adsorptive heat fluxes all vary linearly with the mass flux; when the adsorption heat is treated as adsorption capacity dependent, more complicated variations are observed for all those temperatures and heat fluxes.

Our previous research [15] used the water vapor as the adsorbate, this can be recognized from the model and calculations for the adsorption capacity and adsorption heat. Further, our previous research used the mass flux as an argument to analyze

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the membrane surface temperature and transmembrane heat flux, no analysis was done for the convective moisture transfer between the bulk fluid and membrane. The advantage of pursuing analysis in this way was that it could simplify the problem and highlight the effects of the mass transfer on the heat transfer. However, the mass flux is not a variable that can be directly altered in practice, it can only be controlled by the adsorbate concentration difference between the bulk fluids on the two sides of the membrane as well as the membrane parameters. Also, when the mass flux was specified, the adsorption capacities at the membrane surfaces could actually be calculated using the Fick's law instead of the adsorption capacity equation, as a result of this, the adsorption capacity was not really coupled with the membrane surface temperature on analysis of the heat and mass transfer in our previous research. In view of these, the present research has been designed as follows:

1. it uses the water vapor in moist air as the adsorbate, further, it uses the air state (humidity and temperature) instead of the mass flux to model and analyze the heat and mass transfer.
2. It considers not only the dependence of the adsorption heat on the adsorption capacity and temperature but also that of the adsorption capacity on the temperature when analyzing the heat and mass transfer.
3. It takes the air state and membrane parameter as variables to show the heat and mass transfer characteristics.

Our previous research focused on the comparison of the result generated by the variable heat of adsorption with that by the constant heat of adsorption, it used the mass flux as an independent variable to show how the former differed from the latter. The present research adopts the variable heat of adsorption model to investigate the effects of the air state and membrane parameter on the heat and moisture transfer process. In this paper, equations for the adsorption capacity and adsorption heat as well as the coupled heat and mass transfer across membrane are first summarized and the calculation results are then presented and discussed.

2. Theoretical model

2.1. Adsorption capacity and adsorption heat

Same as in our previous research [15], the Dubinin–Astakhov (D–A) adsorption equation is used to calculate the adsorption capacity of water vapor in moist air at the membrane surface:

$$x = x_0 \exp\left[-F\left(T \ln\left(\frac{p_s}{p}\right)\right)^n\right] \tag{1}$$

where x is the adsorption mass of water vapor per unit mass of membrane at adsorption temperature and pressure of T and p, p_s is the saturated vapor pressure of water at T, F and n are the adsorption characteristic constants, with n reflecting the size distribution characteristics of membrane micropores and F the interactive strength of the water and membrane, and x_0 is the saturation adsorption mass of water per unit mass of membrane. We note that the D–A equation is based on the Polanyi adsorption potential theory, which has a wide scope of application and liberal application conditions. Qi [16] points out that the advantage offered by the D–A model over other adsorption models such as Langmuir and Freundlich equations is that the parameters included in it are independent of temperature. Linders et al. [17] state that the D–A equation is capable of describing the adsorption isotherm of water, while the adsorption equations like the Langmuir or the Dubinin–Radushkevich (D–R) equation are not capable of doing that. When Eq. (1) is used to evaluate the adsorption capacity of water vapor in moist air at the membrane surface as in the present case, it can be expressed as

$$x = x_0 \exp\left[-F(-T \ln \phi)^n\right] \tag{2}$$

where ϕ is the air relative humidity.

Equation for the heat of adsorption or desorption can be obtained based on the D–A equation, the result is as follows. The derivation process can be found in our previous paper [15].

$$q_{st} = \Delta H_V + R_g T \left[-\frac{1}{F} \ln\left(\frac{x}{x_0}\right)\right]^{\frac{1}{n}} \left[\frac{1}{T} + \frac{1}{n x_0 \ln(x/x_0)} \frac{\partial x_0}{\partial T}\right] \tag{3}$$

where q_{st} is the heat of adsorption or desorption and ΔH_V is the latent heat of condensation or vaporization. Eq. (3) supports that the adsorption heat consists of two parts: the latent heat of condensation and the surface energy which relates to the adsorption capacity and temperature.

Water is one of the most common substances, the dependence of water density on temperature under the standard atmospheric pressure can be represented by [18]

$$\rho = \frac{1}{AT + B/T} \tag{4}$$

where A and B are constants with $A = 1.8105 \times 10^{-6}\ \mathrm{m^3\ kg^{-1}\ K^{-1}}$ and $B = 138.08 \times 10^{-3}\ \mathrm{m^3\ kg^{-1}\ K}$. The saturation adsorption capacity can thus be expressed as [19,20]

$$x_0 = \rho(T) v_0 = \frac{v_0}{AT + B/T} \tag{5}$$

where v_0 is the micropore volume per unit mass of membrane. Differentiating Eq. (5) in regard to temperature yields

$$\frac{dx_0}{dT} = \frac{d\rho(T) v_0}{dT} = \frac{\left(B/T^2 - A\right) v_0}{(AT + B/T)^2} \tag{6}$$

Substitution of Eq. (5) into Eq. (2) provides equation for the water vapor adsorption capacity while substitution of Eqs. (5) and (6) into Eq. (3) gives equation for the water vapor adsorption heat.

2.2. Coupled heat and mass transfer across membrane

Consider the coupled heat and moisture transfer across a membrane as shown in Fig. 1, where the bulk air temperatures on the two sides of the membrane are T_{10} and T_{20}, the humidity ratios are w_{10} and w_{20}, and with $T_{10} > T_{20}$ and $w_{10} > w_{20}$, while the air temperatures at the two surfaces of the membrane are T_1 and T_2, the humidity ratios are w_1 and w_2, and the adsorption capacities at the two membrane surfaces are x_1 and x_2. According to the solution-diffusion theory, when water vapor transfers through a membrane, it first adsorbs at the membrane surface on the feed side, then diffuses through the membrane due to the water concentration difference between the two sides of the membrane, and finally desorbs from the membrane surface on the permeating side. During this process, the adsorption liberates heat while the desorption absorbs heat, which affects the heat and mass transfer characteristics, so the total heat transferred between the bulk air fluid and membrane is the sum of the convective heat and adsorptive heat, as shown in Fig. 1, that is

$$q_{C1} + q_{A1} = q_{C2} + q_{A2} = q_T \tag{7}$$

where

$$\begin{aligned} q_{C1} &= h_1(T_{10} - T_1) \\ q_{C2} &= h_2(T_2 - T_{20}) \end{aligned} \tag{8}$$

$$\begin{aligned} q_{A1} &= J q_{st1} \\ q_{A2} &= J q_{st2} \end{aligned} \tag{9}$$