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Effect of mass transfer on heat transfer of microporous ceramic membranes for water recovery

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ABSTRACT

In this work, a theoretical study was carried out to investigate the heat and mass transfer of recycling water vapor from flue gas with using the microporous ceramic membrane. The mathematical model was also built to study the effect of mass transfer on heat transfer in the microporous ceramic membrane with the gas on one side and the liquid on the other side. Results showed that the heat transfer due to mass transfer increased with the increasing mass transfer flux, and gradually became the predominant part of the total heat transfer on the feed side. Inside the membrane, the heat conduction is the main heat transfer. In addition, the heat transfer due to mass transfer could be neglected on the permeate side. The modified heat and mass transfer model for calculating the wall temperatures of the membrane showed good agreement with the experimental results.

1. Introduction

As a kind of inorganic membrane, the ceramic membrane is frequently used in high-temperature and harsh environments because of its good thermal and chemical stability. The ceramic membrane also has great mechanical strength and possesses excellent acid and alkali resistance, especially the membrane with high Al_2O_3 content. Some new types of heat exchangers have used ceramic membranes to recycle the heat from the flue gas with high temperature (>1000 °C) to overcome the temperature limit of metal heat exchangers. The current research shows that hydrophilic micro-nano porous ceramic membranes can be used to recycle water vapor and waste heat from the tail flue gas. The research of Wang et al. [1] may be the first attempt on water and waste heat recovery from flue gas with using ceramic membranes. Wang [2] used the Dittus-Boelter formula in Transport Membrane Condenser, which was made from hydrophilic nanoporous membrane tube bundles, to study the heat transfer performance of the condenser. Convection Nusselt numbers on flue gas side of the ceramic membrane tube bundle were 50–80% higher than those of the stainless steel tube bundle. The condensation rate for the porous ceramic membrane tube bundle also increased by 60–80% compared with that of the stainless steel tube bundle. However, the model of mass and heat transfer in the process was not presented.

A thorough understanding of the mass transfer properties in the mass and heat transfer process of membranes is crucial for enhancing the transfer of water and heat. However, because of the complex coupled mass and heat transfer and the phase change of water vapor, the mechanism and the model in microporous ceramic membranes have not been fully studied.

So far, in industrial applications like the membrane distillation, the pervaporation, the membrane-based heat exchanger and the moisture exchange across a membrane, a lot of research on the mechanism of mass and heat transfer has been made, which can provide a reference for recycling water vapor and heat with using ceramic membranes.

For the direct contact membrane distillation (DCMD), a proposed heat transfer model showed that the effect of mass transfer on heat transfer on permeate side could be neglected under all conditions. Heat transfer due to the vapor transport was the major component of heat transfer inside the membrane [3]. Phattaranawik et al. [4] also studied the influence and experimental results showed that the effect of mass transfer on the heat transfer rate could be negligible. The heat transfer due to the vapor flowing in the membrane was equal to or greater than the heat conduction and increased with the feed temperature. In addition, the temperature distributions in membranes were closely linear. Wang et al. [5] used the non-equilibrium thermodynamic theory to study the coupled heat and mass transfer during the membrane osmotic distillation process. Lowering the membrane effective thermal conductivity and increasing the system average temperature could

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Nomenclature

$H\{T\}$	enthalpy at temperature T (kJ/kg)
T_0	reference temperature (K)
λ_m	effective thermal conductivity of membrane (W/m K)
λ_c	thermal conductivity of microporous ceramic membrane (W/m K)
q_f	convective heat transfer across the boundary layer of feed side (W/m^2)
q_f^m	heat transfer due to mass transfer across the thermal boundary layer of feed side (W/m^2)
h	heat transfer coefficient (W/m^2 K)
l	length of membrane (m)
γ	porosity
$\dot{m}_{rec}$	mass flux of recovered water (kg/s)
x	mass fraction of water vapor in feed gas
r_1	internal radius of membrane (m)
r_2	external radius of membrane (m)
f	Darcy resistance coefficient
P_r	Prandtl number
N_u	Nusselt number
J	mass transfer flux (kg/m^{2}s)
T_1	outer wall temperature of membrane (K)
T_2	inner wall temperature of membrane (K)
λ_w	thermal conductivity of water (W/m K)
q_l	heat transfer due to water flowing through the membrane (W/m^2)
q_p	convective heat transfer across the boundary layer of permeate side (W/m^2)
q_p^m	heat transfer due to mass transfer across the thermal boundary layer of permeate side (W/m^2)
C_p	specific heat at constant pressure (J/kg K)
q_c	heat transfer by conduction (W/m^2)
A	surface area (m^2)
d	internal diameter of membrane (m)

Subscripts

f	feed gas side
p	permeate side
w	tube wall
m	membrane
c	conduction
L	liquid

be proved to reduce the total entropy generation rate. Vacuum membrane distillation has been experimentally studied in a capillary membrane module and the heat transfer coefficients have been evaluated [6]. In the pervaporation process, the heat transfer has been shown to affect the mass transfer. It has also been shown that the heat transfer in the liquid boundary layer would cause a temperature drop across the liquid boundary layer, which in turn reduced the mass transfer [7]. Alves et al. [8] calculated the temperature profile with using a model, which combined the heat and mass transfer equations. The model was also used to calculate the water flux and the overall mass transfer coefficient during the pervaporation process.

The fundamental dimensionless group for coupled heat and moisture transfer in membrane-based heat exchanger was derived and validated with experimental data. Studies showed that the sensible effectiveness was determined mainly by the number of transfer units, while the latent effectiveness was influenced by both the material and the operating conditions [9,10]. Moreover, it was a good method to analyze the heat and mass transfer in terms of the thermal and moisture resistances [11].

Min [12] thought that the numerical method with consideration of the adsorption heat could give the best results for evaluating the performance of a membrane-type total heat exchanger. Adsorption heat was an important factor affecting the heat transfer characteristics during the heat and mass transfer across a membrane [13]. For the moisture exchange across a membrane, Hu et al. presented a dimensionless parameter to evaluate the influence of mass transfer on heat transfer. Results showed that the effect of mass transfer on the total heat flow increased with the increasing mass transfer flux when the mass and heat transfer in the same direction. It was also found that the adsorption heat of membrane affected the total heat transfer in the process [14,15]. Wang et al. [16] thought a larger concentration difference, a smaller temperature difference and a higher membrane average temperature would lead to a higher mass flux. The moisture flux decreased with increasing membrane moisture or thermal resistance [17].

In summary, there have been many research results on mass and heat transfer of the membrane technology. The water vapor and waste heat recovery with using microporous ceramic membranes, however, has many differences with these technologies. Transmembrane mass transfer can affect the performance of ceramic membranes, and it is necessary to conduct the theoretical analysis and establish the mathematical model for studying the effect of the parameters on heat transfer. Our research group has done some research on the performance of the ceramic membrane in experiments. This paper is attempt to present a model to describe the mass and transfer in the process, which can be validated by experimental data. The external pore size of the hydrophilic ceramic membrane is about 1–2 μm, the porosity of which is 28%. Theoretically, there is no capillary condensation for the membrane and the surface condensation is the main mode of condensation for water vapor. It can be used to promote the recovery of water and waste heat from flue gas in gas-fired power plants and the clean flue gas in coal-fired power plants.

2. Theory

For the mass and heat transfer process, the simulated flue gas (nitrogen and water vapor) flows outside the membrane, the gas (water vapor) to be separated will permeate through the membrane in the form of liquid or vapor (liquid in this work) and the cooling water flows in the membrane tube. It is essential to analyze the interaction effect of mass transfer and heat transfer simultaneously.

(1) Mass transfer:

The process can be divided into three parts: the convective mass transfer on the feed gas, the liquid water transporting through the membrane and the convective mass transfer on the cooling water side. On the feed gas side, the driving force is the water vapor concentration difference between the bulk gas and the wetted membrane surface, while the main driving force is the pressure difference between the two sides of the membrane to make the condensed water permeate through the membrane.

(2) Heat transfer:

For the heat transfer, it also has three parts corresponding to the mass transfer: the convection heat transfer on the feed gas side, the heat conduction inside the membrane and the convection heat transfer on the cooling water side.