Available online at www.sciencedirect.com

SCIENCE DIRECT®

International Journal of Heat and Mass Transfer 49 (2006) 1176–1184

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Investigation of moisture transfer effectiveness through a hydrophilic polymer membrane with a field and laboratory emission cell

Li-Zhi Zhang *

Key Laboratory of Enhanced Heat Transfer and Energy Conservation of Education Ministry, School of Chemical and Energy Engineering, South China University of Technology, Wushan Road, Guangzhou 510640, China

Received 1 March 2005; received in revised form 22 July 2005
Available online 25 October 2005

Abstract

This research focuses studies of water permeation potential through a polymer membrane with the help of a standard field and laboratory emission cell. Special efforts are devoted to finding a correlation governing the relations between the number of transfer units (NTU) and the moisture exchange effectiveness. As a first step, moisture diffusivity in the hydrophilic polymer membrane is experimentally measured. In combination with mathematical modeling, the moisture concentration distributions in the cell, the water uptake gradients in the membrane, as well as the local vapor emission rate on membrane surface, are investigated. The results are that the emission rates show a non-uniform character and a polynomial equation governing the moisture exchange effectiveness and the dimensionless number of transfer units, could be used to inversely estimate the diffusivity of water vapor in hydrophilic membranes. The form and the value of constants in the equation are obtained.

Keywords: Moisture transfer; Diffusion; Hydrophilic membranes; Air dehumidification

1. Introduction

Recently, membrane dehumidification processes attracted the attention of the public instead of the other dehumidification processes, such as adsorption, absorption, and refrigeration cycles and so on. From the viewpoint of low cost and low energy requirements, the separation of water vapor from air by membrane separation processes has been studied by many workers [1–5]. Some other workers also studied the membrane systems for total energy recovery [6–8], which has similar mechanisms to air dehumidification.

It is well known that hydrophilic polymer membranes, say, polycellulose acetate, polyvinylidene fluoride, polyethersulfone, Nafion, and polyvinyl alcohol, are useful for the separation of water vapor from other gases in air mixture, because the water molecule is easily incorporated into the hydrophilic polymer membranes, due to the strong affinity between the water molecule and the hydrophilic polymers, which facilitates the transport of water, while impeding the permeation of other gases through the membranes.

Moisture transport properties in such hydrophilic polymer membranes are the most important parameters affecting the system performance and the proper design of the units. Traditionally, the measurements of water vapor diffusivity in membranes are conducted by two ways: transient drying experiments [9–11], and permeation tests [2–4,12]. In the transient drying experiments, transient losses of membrane weight are recorded to calculate the effective moisture diffusivity, with the analytical solution of Fick's second law of diffusion. Though popular and extensively used, this technique has inherent problems: the assumptions and the operating conditions for the analytical solution of Fick's law are very rigorous and any deviation from this would lead to substantial errors [11]. On the other hand, the permeation tests, though directly measure the moisture

* Tel./fax: +86 20 87114268.
E-mail address: Lzzhang@scut.edu.cn

0017-9310/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2005.08.029

Nomenclature

C	shape fact or for the isotherm
D_{va}	vapor diffusivity in air (m^2/s)
D_{vm}	moisture diffusivity in membrane (m^2/s)
E_v	local emission rate ($kg\ m^{-2}\ s^{-1}$)
H_d	duct height of air stream (m)
k	convective mass transfer coefficient (m/s)
k_p	partition coefficient (kg air/kg membrane)
N	air exchange rate (s^{-1})
NTU	number of transfer units
r	radius coordinate (m)
Re	Reynolds number
RH	air relative humidity
S	transfer area (m^2)
Sc	Schmidt number
Sh	Sherwood number
T	temperature (K)
t	time (s)
t_r	time to reach steady state (s)
u_a	air bulk velocity (m/s) along radius
V	volume of the cell (m^3)
W_{max}	maximum water uptake of membrane material (kg/kg)
z	coordinates in membrane thickness (m)

Greek symbols

ν	kinematic viscosity of air (m^2/s)
τ	dimensionless time
ω	humidity ratio (kg moisture/kg air)
ε	moisture exchange effectiveness
θ	moisture uptake in membrane (kg moisture/kg dry membrane)
λ	total moisture transfer coefficient ($kg\ m^{-2}\ s^{-1}$)
ρ_a	density of dry air (kg/m^3)
ρ_m	density of membrane (kg/m^3)
δ	membrane thickness (m)

Superscript

*	dimensionless

Subscripts

i	inlet
L	lower chamber
o	outlet
s	surface

transport through membranes at steady state, are rather complicated in the set-up. Most importantly, the obtained data are case-specific, since the convective resistance on both sides of the membrane usually plays an important role in the moisture transport performance, but was always neglected, which would make the results less accurate.

In recent years, field and laboratory emission cell (FLEC) has become the standard equipment for emission test of volatile organic compounds in Europe [13] and some other parts of the world, due to its compactness, high sensitivity, and ease in operation. The author and co-workers have investigated the convective mass transfer characteristics in the cell [14] and measured the emissions of VOCs from dry and wet building materials using the system [15,16]. The fluid dynamics conditions are clear from the previous researches. Studies will be extended to measure the moisture diffusivity through hydrophilic polymer membranes with the system in this work. The NTU-effectiveness relations are also the interests of study, which will provide a guidance in future.

2. Experimental test equipment and procedures

2.1. The FLEC cell

The flow geometry of the FLEC is shown in Fig. 1. It is composed of two parts as shown in Fig. 2: cap (Fig. 2a) and lower chamber (Fig. 2b). When testing, the planar specimen of the emission material is placed in the lower chamber and becomes an integral part of the emission cell. The upper surface of the specimen (the emission surface) and the inner surface of the FLEC cap form a cone-shaped cavity. The air is supplied through the air slits in the cap. It is introduced through two diametrically positioned inlets (symmetrically placed) into a circular-shaped channel at the perimeter, from where the air is distributed over the emission surface through the circular air slit. The air flows inward radially, until it exits the FLEC outlet in the center.

2.2. The whole set-up

In this test, saturated NaCl solution is poured into the lower chamber of the FLEC cell. Then a hydrophilic polymer membrane is covered on the lower chamber. Following this step, the cap of the FLEC is placed on the membrane to form a sandwiched structure. The membrane holding module is shown in Fig. 3. A 1 mm gap between the sodium chloride solution and the membrane tested is kept. The saturated solution in the lower chamber supplies a constant humidity ratio below the membrane lower surface. When the humidity ratio between the two sides of the membrane is different, moisture will diffusive through the membrane. Humid air is supplied from the inlets of the cap, which will exchange moisture with the membrane and the humidity ratio will change along the path. During the test, the temperature is kept constant. The relative humidity of the inlet and the outlet air streams are measured, and the moisture exchange effectiveness can be calculated.