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Study on the method for testing the water vapor diffusion resistance of membranes

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ABSTRACT

Water vapor diffusion resistance is an important property of porous membranes. In the paper, a new apparatus for specially measuring the water vapor diffusion resistance of porous membranes was developed. In the new apparatus, the humidity of circulating carrier air streams flowing over both sides of test membrane are controlled by different saturated salt solutions, which makes a variety of humidity conditions and improves the humidity stability. In order to decrease the error caused by the air boundary layer, the structure of the test chamber was optimized with the help of computational fluid dynamics technology. Seven types of porous membranes with stable moisture permeability were tested by the new apparatus at relative humidity gradients of 0.42, 0.45, 0.51, 0.55, 0.64, 0.69, 0.73 and 0.78 across the porous membranes at 25 °C. The results of the new apparatus were compared with the results of nitrogen carrier apparatus and ISO 2528. The maximum relative errors of the new apparatus and the nitrogen carrier apparatus compared to the ISO 2528 method are 22.3% and 19%, respectively. The test results of the three methods are in good agreement. The new apparatus is a simple, low-cost and time-saving alternative for measuring the water vapor diffusion resistance of porous membranes.

1. Introduction

Semi-permeable porous membranes have been used in a large variety of industrial and civilian production processes, including desalination [1–5], wastewater treatment [6–9] and air conditioning [10–14], etc. Water vapor diffusion resistance is one of the most important properties of porous membranes and has important effect on the performance of membrane-based equipment. Therefore, it is important for equipment optimization and membrane development to measure the water vapor diffusion resistance of porous membranes accurately.

Water vapor transmission rate is often used to characterize the moisture permeability of porous materials, and there have been standard methods for determining the water vapor transmission rate of materials (e.g. ISO 2528 [15], ASTM D6701 [16] and ISO 15106-3 [17]). ISO 2528, gravimetric (dish) method, is the most widely used method. A shallow dish containing distilled water or desiccant (silica gel or anhydrous calcium chloride ($CaCl_2$)) is covered with test material and weighed at set interval until weight change rate reaches constant. The ISO 2528 method ignores the resistance of still air layer below test material in the test dishes. The resistance of the still air layer increases with distilled water contained in the dish, which causes error in measuring the water vapor diffusion resistance. Moreover, several days or weeks are necessary for determining water vapor transmission rate, which is time-consuming [18]. For ASTM D6701, two test chambers are separated by the test materials. The upper chamber is filled with distilled water, and the dry nitrogen stream flows through the lower chamber. The water vapor transmission rate can be obtained with the humidity difference between the inlet and outlet of the lower chamber. Due to the complex velocity field in the test chamber of the ASTM D6701, the water vapor diffusion resistance calculated from ASTM D6701 is not accurate and generally significantly higher than the true result. Gaoming Ge et al. [19] tested two micro-porous membranes by ASDM D6701 and dynamic moisture permeation cell (DMPC) method. The comparison results of the ASDM D6701 are 54% and 56% higher than that of DMPC method, respectively. The structure of ISO 15106-3, also named electrolytic detection sensor method, is similar to the ASTM D6701. The upper chamber contains a glass-fibre plate impregnated with sulfuric acid solution to control humidity, and the dry nitrogen stream flows through the lower chamber. The water vapor transmission rate is calculated with the outlet humidity of the lower chamber. Due to the increasingly reduced concentration of the sulfuric acid solution in the glass-fibre plate, the humidity in the upper chamber decreases in the measurement process. Moreover, the resistance of the still air layer between the glass-fibre plate and test membrane is neglected. ASTM D1434 [20] is differential-pressure method. High-pressure and low-

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Nomenclature

A_c	Area of the cross section of rectangular tube (m^2)
A_m	Area of test membrane (m^2)
C	Water vapor concentration (kg/m^3)
C_p	Specific heat of air ($J/(kg{\cdot}K)$)
$\Delta\overline{C}$	Log mean water vapor concentration across membrane (kg/m^3)
D	Moisture diffusivity in air (m^2/s)
D_h	Hydraulic Diameter (m)
d_m	Thickness of membrane (m)
H	Heating power (W)
h	Heat transfer coefficient ($W/m^2{\cdot}K$)
h_m	Convective mass transfer coefficient of water vapor concentration difference (m/s)
k_m	Water vapor diffusion coefficient ($kg/m{\cdot}s$)
k_p	Water vapor permeation coefficient ($g\mu m/(m^2dPa)$)
L	Laminar developing length (m)
Le	Lewis number
m	Water vapor transmission rate ($kg/(m^2{\cdot}s)$)
M_w	Molecular weight of water (kg/mol)
N	The total number of nodes of the cross section
Nu	Nusselt number
P	Wetted perimeter (m)
p	Water vapor pressure of air (Pa)
p_{sat}	Saturated water vapor pressure in air (Pa)
Q	Volume flow rate of air (L/min)
R	Universal gas constant ($J/(mol{\cdot}K)$)
R_m	Water vapor diffusion resistance of membrane (s/m)
Re	Reynolds number
RH	Relative humidity
Sh	Sherwood number
T	Temperature (K)
t	Temperature (°C)
u	Air velocity (m/s)
X_i	Velocity of node (m/s)
$\overline{X}$	Average air velocity (m/s)
x_l, x_w	Length and width of membrane (m)

Greek symbols

λ	Heat conductivity ($W/(m{\cdot}K)$)
μ	Average velocity of total nodes (m/s)
ω	Humidity ratio (kg/kg)
$\Delta\overline{\varpi}$	Log mean humidity difference across membrane (kg/kg)
ρ	Density (kg/m^3)
σ	Standard deviation
υ	Kinematic viscosity (m^2/s)
φ	Relative humidity
$\Delta\overline{\varphi}$	Log mean relative humidity difference across membrane

Subscripts

a	Air
i	Inlet
m	Membrane
n	Indicated value
o	Outlet
s	Actual value

pressure chambers are separated by test materials. By direct measurements of the changes in the volume and internal pressure, gas transmission rate can be calculated. The above-mentioned methods cause error due to the still air layer resistance and the humidity change in measurement process.

In Fig. 1, ISO 11092 [21] (sweating guarded hot plate test method) is a method for testing water vapor diffusion resistance of materials. A cellophane membrane, which is permeable to water vapor but prevent liquid water permeation is between porous plate filled with distilled water and test material. The dry bulb temperature, relative humidity (RH), pressure of air and the velocity above the top surface of the test material are 35 °C, 0.4, 101.3 kPa and 1 m/s, respectively. The water vapor partial pressure at the surface of the porous plate is equal to the saturated water vapor pressure in air. The water vapor transmission rate of material is determined with the heating power maintaining the set temperature of the porous plate. The water vapor diffusion resistance of material is calculated by the following equation.

$$R_m = \frac{(p_m - p_a)A_m}{H} \tag{1}$$

where R_m is the water vapor diffusion resistance of material, p_m and p_a are the water vapor pressure of the porous plate and the air, A_m is the test material area, and H is the heating power. It is difficult to prevent the heat loss from the porous plate to the air, which causes error for measuring the water vapor transmission rate. Moreover, the heating power needs to be regulated continually to keep the temperature of the porous plate equal to the air temperature, so the temperature matching process is always pseudo-equilibrium. Finally, due to the thermal inertia, the measurement is also time-consuming (usually more than 1 h) [22].

Dynamic moisture permeation cell (DMPC) for testing the water vapor diffusion resistance was first proposed by Gibson et al. [23]. As shown in Fig. 2, dry and saturated nitrogen streams are mixed before flowing over the top and bottom sides of the test material. The humidity of the mixed nitrogen streams is controlled by adjusting the proportion

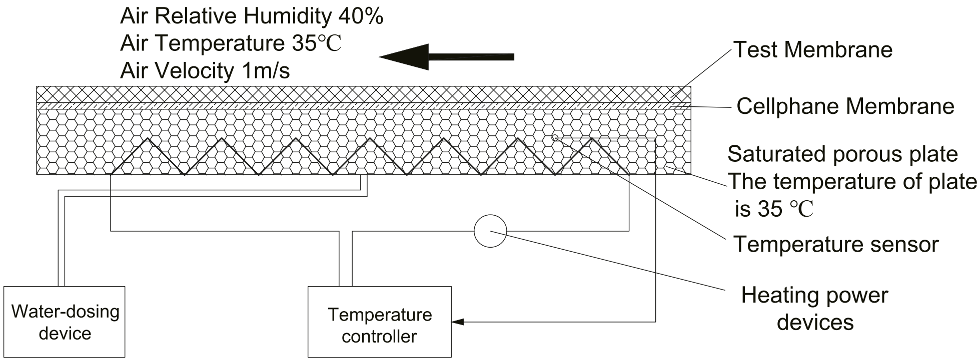

Fig. 1. Schematic diagram of ISO 11092 (sweating guarded hot plate test method).