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ORIGINAL PAPER

Estimation of dehumidifying performance of solid polymer electrolytic dehumidifier for practical application

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Abstract A two-layer model for a solid polymer electrolytic (SPE) dehumidifier is applied to a system in which the chamber to be dehumidified has some leakage area. By introducing this area, the attainable humidity in the chamber, which is the steady-state humidity to be attained after a long-time dehumidification, can be defined. Experimental results of dehumidification by an SPE dehumidifier are compared to the calculations based on the two-layer model for the SPE dehumidifier, which was presented in our previous paper. Equations for the two-layer model are simplified by making use of assumptions for the current characteristics and a constant environmental condition, and it is reduced to equations including a differential equation on the time variation of the humidity in the chamber. The differential equation to describe the attainable humidity in the chamber and time constant for the dehumidification is obtained. The current flowing in the dehumidifier under steady state conditions is also given as a function of the humidities in the spaces facing the anode and the cathode. A diagram to estimate the attainable humidity and the time required for dehumidification from the dehumidifying area and leakage area is also given.

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List of symbols

D	Diffusion coefficient of water in the dehumidifying element ($cm^2\ s^{-1}$)
e	Electron charge = 1.602×10^{-19} (C)
I	Current of the dehumidifying element (A)
κ_g	Coefficient relevant to the diffusion velocity of water from the air to the SPE membrane ($cm\ s^{-1}$)
κ_s	Coefficient relevant to the diffusion velocity of water from the membrane to the air ($cm\ s^{-1}$)
L	Thickness of the dehumidifying element (= 0.017 cm)
N_A	Avogadro's number = 6.02×10^{23} (mol^{-1})
RH	Relative humidity (%)
R_s	Electrical resistance of the dehumidifying element (Ω)
S	Area of the dehumidifying element (cm^2)
$S\ell$	Equivalent leakage area with the rate constant kg of water transfer (cm^2)
t	time (s)
T_g	Temperature of the gas space surrounding the dehumidifying element (K)
U_s	Voltage applied to the dehumidifying element (=3 V)
$V_{g,p}$, $V_{g,n}$	Volumes of the spaces facing the anode and the cathode (cm^3), respectively
α	The average number of water molecules carried by a proton moving to the cathode
ρ_g, ρ_s	Water density in the air surrounding the dehumidifying element and water content of the element ($g\ cm^{-3}$), respectively

$\rho_{g,p}$, $\rho_{g,n}$ Water density in the air facing the anode (positive electrode) and cathode (negative electrode) (g cm^{-3}), respectively

$\rho_{s,p}$, $\rho_{s,n}$ Water contents in the anode half and the cathode half of the dehumidifying element defined by two-layer model of the dehumidifier (g cm^{-3})

Subscripts

g Gas space

n Negative electrode or cathode

p Positive electrode or anode

s Solid polymer electrolytic dehumidifying element

1 Introduction

Ionic membranes have been increasingly used in many industrial areas such as fuel cell technology, chemical engineering for water improvement, etc. Several studies on the transport properties of water and ions through the membranes and a fuel cell model have been reported [1–3]. These studies are quite important for understanding the transport mechanism to predict the operating conditions adequate for industrial use. Zawodzinski et al. [1] investigated the transport properties through a Nafion 117 membrane and described the membrane conductivity as a function of the water content as well as the temperature dependence of the membrane conductivity. Anantaraman et al. [2] also reported the effect of humidity on the conductivity of Nafion [2]. However, these studies evaluated the conductivity of the electrolytic membrane itself. Although such conductivity is necessary for constructing a complete model, a combined element made from the electrolytic membrane and the electrodes on the membrane surfaces are used in practical applications. Therefore, the impedance or current characteristics of the entire element is necessary for practical applications.

The authors have developed a dehumidifying device using a solid polymer electrolytic (SPE) membrane as a protective measure against problems caused by high humidity. This device consists of a proton-conductive solid polymer electrolyte and porous electrodes with a catalytic layer composed of noble metal particles. This device can dehumidify the space facing the anode and humidify the space facing the cathode when a DC voltage is applied to the electrodes [4]. The dynamic characteristics of the SPE dehumidifier were numerically analyzed and found to be well explained by a two-layer model for the SPE dehumidifier [5]. The input parameters used in our model were obtained from our experiments. The relation of the water content and humidity obtained in our experiments were similar to that reported by Hinatsu et al. [6]. The dependence of the electrical conductance of the SPE dehumidifiers on the water content in our experiment is not as high as the dependence of the electrical conductance of the membrane itself (Nafion 117) reported by Anantaraman et al. [2], though a direct comparison could be difficult because of the difference in the components.

SPE dehumidifiers are used in containers for scientific instruments, outdoor type vessels containing electrical and electronic devices, etc. For these practical applications, it is very important to estimate how long it takes to reach the required humidity or what is the attainable humidity. The time to reach the required humidity and finally attainable humidity after a long dehumidification depends on the leakage area of the vessel.

The humidity change in a chamber and current change flowing in the dehumidifying element were measured and compared to those calculated by a simulation based on a two-layer model. The formula for the current under steady state conditions is given as a function of the humidity of the spaces facing the anode and cathode. A differential equation, which gives the time constant and the humidity to be finally attained under steady state conditions, are derived from the two-layer model for the SPE dehumidifier. A diagram to give the relation of the dehumidifying capability of a SPE dehumidifier and attainable humidity in the chamber is derived. This diagram is very useful for practical use of the SPE dehumidifier.

2 Application of two-layer model of SPE dehumidifier to a system in which the chamber to be dehumidified has a leakage area

The basic equations for the two-layer model were proposed in our previous paper [5] and analysis by the two-layer model was made for a chamber with no leakage area. It was concluded that the model was valid for estimations of the current change and dehumidifying performance. In this paper, the model is applied to a system in which the chamber has some leakage area. Figure 1a and b shows the water flow of an SPE dehumidifier expressed by the two-layer model and the system of dehumidification by the dehumidifier in which a chamber has a leakage area ($S\ell$), respectively. The basic equations of the two-layer model can be modified as Eqs. 1–4. Equations 1 and 2 include the terms which express the leakage area ($S\ell$) between the inside and outside of the chamber. It is very difficult to determine the leakage area because the quantity of the actually leaked water may change depending on the shape and position of the area, etc. Hence, we define in this paper that the leakage area $S\ell$ is the equivalent area based on the assumption that the rate constant for water transfer is κ_g, which is the coefficient relevant to the diffusion velocity of water from the air to the SPE membrane defined in the previous paper [5]. Therefore, the leakage area must be determined from the humidity under steady state conditions which is realized after a long dehumidification time of the chamber.

Equations 5–7 define the current characteristics of the SPE dehumidifier, which were also obtained from our study shown in our previous paper [5]. It was found that the electrical resistance of the dehumidifier strongly depends on the water content $\rho_{s,p}$ of the anode side in the dehumidifying element [5].

$$V_{g,p}\frac{d\rho_{g,p}}{dt} = S\left(\kappa_s\rho_{s,p} - \kappa_g\rho_{g,p}\right) + S\ell\kappa_g\left(\rho_{g,n} - \rho_{g,p}\right) \tag{1}$$

$$V_{g,n}\frac{d\rho_{g,n}}{dt} = S\left(\kappa_s\rho_{s,n} - \kappa_g\rho_{g,n}\right) - S\ell\kappa_g\left(\rho_{g,n} - \rho_{g,p}\right) \tag{2}$$

$$\frac{LS}{2}\frac{d\rho_{s,p}}{dt} = -S\left(\kappa_s\rho_{s,p} - \kappa_g\rho_{g,p}\right) + \frac{DS\left(\rho_{s,n} - \rho_{s,p}\right)}{L} - \frac{18I(1+2\alpha)}{2eN_A} \tag{3}$$

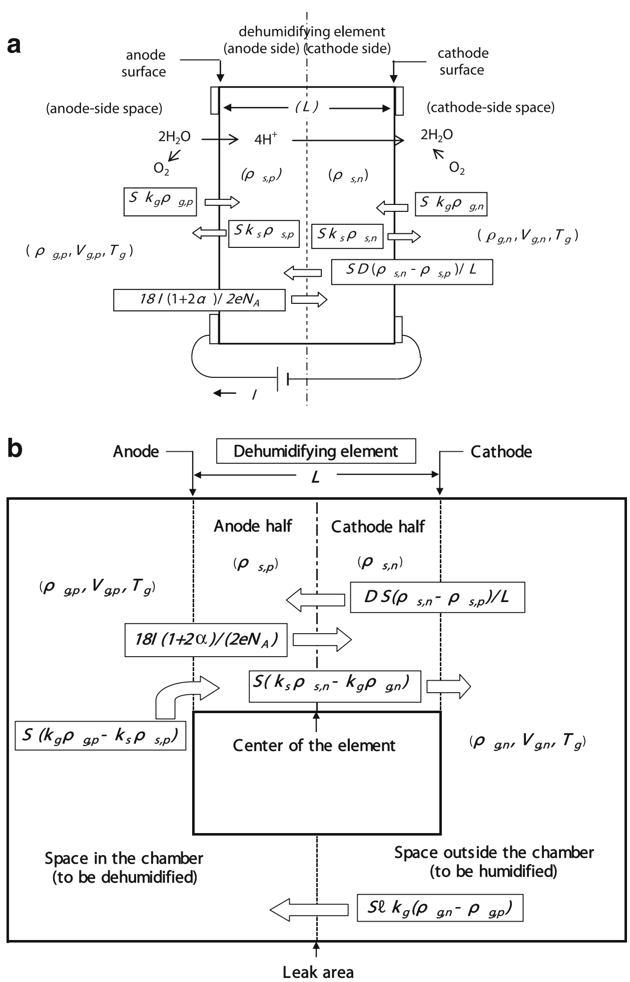

Fig. 1 Two-layer model for SPE dehumidifier and water transfer by SPE dehumidifier when the chamber has the leakage area $S\ell$. **a** Water flow expressed by two-layer model for SPE dehumidifier. **b** Water transfer by SPE dehumidifier when the chamber has a leakage area $S\ell$

$$\frac{LS}{2}\frac{d\rho_{s,n}}{dt} = -S\left(\kappa_s\rho_{s,n} - \kappa_g\rho_{g,n}\right) - \frac{DS\left(\rho_{s,n} - \rho_{s,p}\right)}{L} + \frac{18I(1+2\alpha)}{2eN_A} \tag{4}$$

$$I = \frac{U_s}{R_s} = \frac{U_s S}{\frac{B(T_g)}{\rho_{s,p}} + r_{s0}} \cong \frac{U_s S\rho_{s,p}}{B(T_g)} \tag{5}$$

$$B(T) = 6.7\times 10^{-2}\times\exp\left(670/T_g\right) \quad \left(\Omega\,\mathrm{cm}^2\,\mathrm{g\,cm}^{-3}\right) \tag{6}$$

$$r_{s0} = 17.3 \quad \left(\Omega\,\mathrm{cm}^2\right) \tag{7}$$

If the time variation of the water content in the dehumidifying element is much lower than the other terms, then Eqs. 3 and 4 can be reduced to the following equations.

$$\frac{d\rho_{s,p}}{dt} = 0, \quad \frac{d\rho_{s,n}}{dt} = 0, \quad \text{then}$$

$$\rho_{s,p} = \frac{\kappa_g\left(\frac{D}{L} + \kappa_s\right)\rho_{g,p} + \kappa_g\frac{D}{L}\rho_{g,n} - \kappa_s\frac{18I(1+2\alpha)}{2eN_AS}}{\kappa_s\left(\frac{2D}{L} + \kappa_s\right)} \tag{8}$$

$$\rho_{s,n} = \frac{\kappa_g\frac{D}{L}\rho_{g,p} + \kappa_g\left(\frac{D}{L} + \kappa_s\right)\rho_{g,n} + \kappa_s\frac{18I(1+2\alpha)}{2eN_AS}}{\kappa_s\left(\frac{2D}{L} + \kappa_s\right)} \tag{9}$$

Substituting Eq. 8 into Eq. 1, Eq. 1 can also be reduced to the following form.

$$\frac{d\rho_{g,p}}{dt} + \frac{\kappa_g}{V_{g,p}}\left\{\frac{S\frac{D}{L} + S\ell\left(\frac{2D}{L} + \kappa_s\right)}{\frac{2D}{L} + \kappa_s}\right\}\rho_{g,p} = \frac{\kappa_g}{V_{g,p}}\left\{\frac{S\frac{D}{L} + S\ell\left(\frac{2D}{L} + \kappa_s\right)}{\frac{2D}{L} + \kappa_s}\right\}\rho_{g,n} - \frac{\kappa_s}{V_{g,p}}\left\{\frac{9(1+2\alpha)I}{\left(\frac{2D}{L} + \kappa_s\right)eN_A}\right\} \tag{10}$$

Equation 10 can be valid when the time variation in the water content in the element can be neglected. An equation similar to Eq. 10 could be derived by substituting Eq. 9 into Eq. 2.

Substituting Eq. 5 into Eq. 8, the following equations for the water content of the anode side of the dehumidifier and the current are obtained.

$$\rho_{s,p} = \frac{\kappa_g\left(\frac{D}{L} + \kappa_s\right)\rho_{g,p} + \kappa_g\frac{D}{L}\rho_{g,n}}{\kappa_s\left\{\frac{2D}{L} + \kappa_s + \frac{18(1+2\alpha)U_s}{2eN_AB(T_g)}\right\}} \tag{11}$$

$$I = \frac{U_sS}{B(T)}\frac{\kappa_g\left(\frac{D}{L} + \kappa_s\right)\rho_{g,p} + \kappa_g\frac{D}{L}\rho_{g,n}}{\kappa_s\left\{\frac{2D}{L} + \kappa_s + \frac{18(1+2\alpha)U_s}{2eN_AB(T_g)}\right\}} \tag{12}$$

Substituting (11) into (1), then the set of basic equations is reduced as follows.

$$\frac{d\rho_{g,p}}{dt}+\frac{\kappa_g S}{V_{g,p}}\left\{\frac{\frac{D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T)}}{\kappa_s+\frac{2D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T_g)}}+\frac{S\ell}{S}\right\}\rho_{g,p}=\frac{\kappa_g S}{V_{g,p}}\left\{\frac{\frac{D}{L}}{\kappa_s+\frac{2D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T_g)}}+\frac{S\ell}{S}\right\}\rho_{g,n} \quad (13)$$

$$\frac{d\rho_{g,n}}{dt}+\frac{\kappa_g S}{V_{g,n}}\left\{\frac{\frac{D}{L}}{\kappa_s+\frac{2D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T_g)}}+\frac{S\ell}{S}\right\}\rho_{g,n}=\frac{\kappa_g S}{V_{g,n}}\left\{\frac{\frac{D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T)}}{\kappa_s+\frac{2D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T_g)}}+\frac{S\ell}{S}\right\}\rho_{g,p} \quad (14)$$

Equation 13 can be also written in the following form.

$$\frac{dRH_{g,p}}{dt}+\frac{\kappa_g S}{V_{g,p}}\left\{\frac{\frac{D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T)}}{\kappa_s+\frac{2D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T_g)}}+\frac{S\ell}{S}\right\}RH_{g,p}=\frac{\kappa_g S}{V_{g,p}}\left\{\frac{\frac{D}{L}}{\kappa_s+\frac{2D}{L}+\frac{18(1+2\alpha)U_s}{2eN_AB(T_g)}}+\frac{S\ell}{S}\right\}RH_{g,n} \quad (13a)$$

Equations 13 and 13a can be used for the estimation of the time variation of the humidity in the chamber under the conditions that the rate of water transmitted from the anode space to the cathode space through the dehumidifier is much higher than that of the water content change in the dehumidifier.

From Eqs. 13 and 13a, useful parameters of the time constant that is the time required for dehumidification and the steady state humidity to be attained after a long time dehumidification of the chamber can be obtained as follows.

$$\left.\frac{RH_{g,p}}{RH_{g,n}}\right|_{t=\infty}=\frac{\frac{D/L}{\kappa_s+2D/L+18(1+2\alpha)U_s/2eN_AB(T_g)}+\frac{S\ell}{S}}{\frac{D/L+18(1+2\alpha)U_s/2eN_AB(T_g)}{\kappa_s+2D/L+18(1+2\alpha)U_s/2eN_AB(T_g)}+\frac{S\ell}{S}} \quad (15)$$

$$\tau=\frac{V_{g,p}}{\kappa_g S}\frac{1}{\frac{D/L+18(1+2\alpha)U_s/2eN_AB(T_g)}{\kappa_s+2D/L+18(1+2\alpha)U_s/2eN_AB(T_g)}+\frac{S\ell}{S}} \quad (16)$$

By substituting the values for the SPE dehumidifying element estimated in the previous paper into Eq. 13 or 13a, the following equations are derived.

$$\frac{d\rho_{g,p}}{dt}+\frac{0.245}{V_{g,p}}(0.96\ S+S\ell)\rho_{g,p}=\frac{0.245}{V_{g,p}}(0.021\ S+S\ell)\rho_{g,n} \quad (17)$$

$$\frac{dRH_{g,p}}{dt}+\frac{0.245}{V_{g,p}}(0.96\ S+S\ell)RH_{g,p}=\frac{0.245}{V_{g,p}}(0.021\ S+S\ell)RH_{g,n} \quad (18)$$

$$\left.\frac{RH_{g,p}}{RH_{g,n}}\right|_{t=\infty}=\frac{0.021\ S+S\ell}{0.96\ S+S\ell} \quad (19)$$

$$\tau=\frac{V_{g,p}}{0.245(0.96\ S+S\ell)} \quad (20)$$

The coefficients included in these equations were calculated for the ambient temperature of 303 K. These coefficients of 0.96 and 0.021 are changed from 0.95 to 0.97 and 0.019 to 0.023, respectively, for the temperature range of 293–313 K. The dependence of these coefficients on the temperature is very small. Therefore, the estimation by Eqs. 19 and 20 would be approximately valid within this temperature range.

3 Experiments

(1) *Case 1*: $S\ell \cong 0$. The humidity change in a chamber with a volume of 51 L and with a leakage area as small as possible was measured under the conditions that the temperature and humidity surrounding the chamber remain constant. The time variation of the current was also measured. The measured humidity and current are compared to the calculations based on a two-layer model.

(2) *Case 2*: $S\ell \cong \infty$. The current of the dehumidifier located in the open air under the steady state conditions is measured and compared to the calculations based on a two-layer model.

The quantity of the actual water leakage is the rate coefficient of the water transferred through the leakage multiplied by the leakage area. The rate coefficient depends on the shape and position of the area as well as the area itself. Therefore, we define in this paper that the leakage area $S\ell$ is the equivalent area based on the assumption that the rate coefficient for water transfer is κ_g. It can be estimated by making use of Eq. 15 from the experiment of the attainable humidity. By introducing such equivalent leakage areas, the attainable humidity determined by Eq. 15 and/or 19 can be defined.

3.1 Experiment (1) and calculation using two-layer model

A chamber with a volume of 51 L and a dehumidifying element with an area of 100 cm^2 were used in this experiment (1).

Figure 2 shows a comparison of the measured dehumidification characteristics(293 K) with the one calculated using the basic formulas (1)–(6) of a two-layer model. The calculation of the current change and humidity change in the chamber well agree with the measured one over the entire

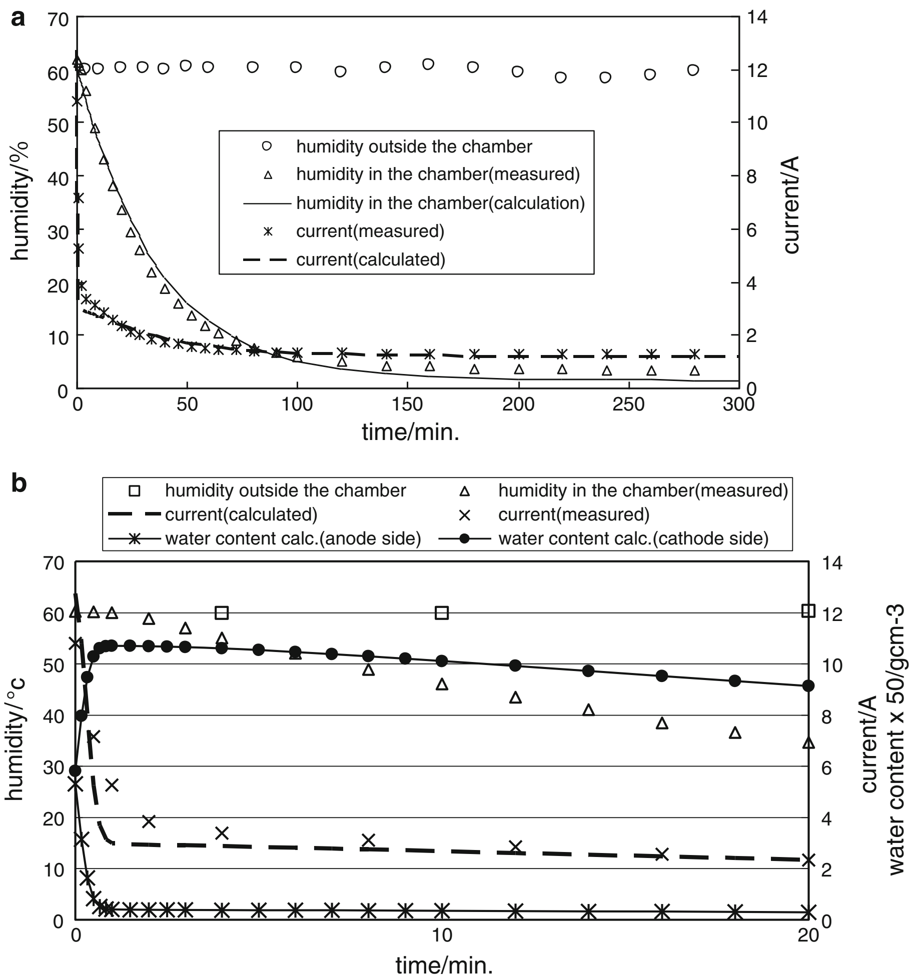

Fig. 2 Dehumidifying characteristics of the SPE dehumidifier (293 K, 60%), ($V_{g,p} = 51\ell$, $S = 100$ cm^2). **a** Long-time dehumidifying characteristics of the SPE dehumidifier. **b** Comparison of initial change in the current

processes. The dehumidification started at $t = 0$ by switching-on the DC supply in this experiment. A rapid reduction in the current is seen just after switching-on in the figure and it was explained in our previous paper that this is caused by the rapid decrease in the water content on the anode side in the element to form a gradient distribution of the water content in the element as shown in Fig. 2b. After the formation of a gradient shaped distribution, the current change mainly depends on the humidity change in both spaces facing the anode and the cathode. If the change of the humidity in the chamber is slow, the water content in the dehumidifying element would slowly change and be nearly the same as that under steady state conditions, depending on both the humidity inside and outside the chamber.

Figure 3a shows a comparison of the measured dehumidification process (293 K) of the same data as shown in Fig. 2 and the one calculated by Eq. 13, that is derived by using assumptions (8) and (9). As seen in Fig. 3a, the calculations well agree with the measured ones except for the period just after switching-on. From this observation, Eqs. 8 and 9 are assumed to be valid for almost the entire process except for a few minutes just after switching-on. Figure 3b traces the relation of the current and humidity in the chamber for the same data as shown in Fig. 3a. The current calculated by Eq. 12 is also shown in Fig. 3b. The measured current linearly changes with the humidity in the chamber and well agrees with the calculation except for the higher humidity range, which corresponds with the period just after switching-on. Figures 4 and 5 are other examples obtained for different temperatures (300 and 313 K). As the measured current in these figures agreed with the calculations assuming Eq. 12, the current for almost the entire period, except for the period just after switching-on, must be nearly the same under steady state conditions.

3.2 Experiment (2) and calculation by the two-layer model

Figure 6 shows a comparison of the calculation and measurement for the relation of the current and humidity surrounding the element. This figure is quoted from our paper [5]. The measurement was made under the condition that the tested dehumidifying element was located in open air. The calculation of the current was made using Eq. 12. It

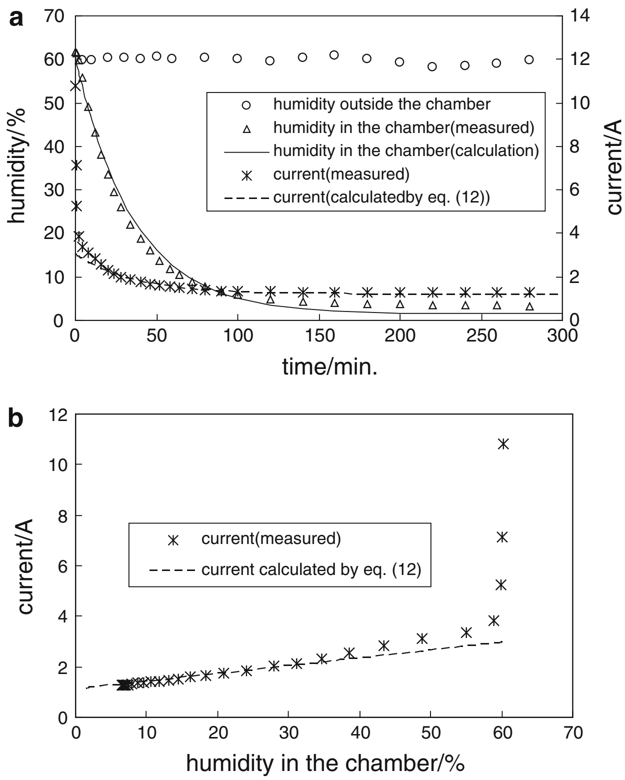

Fig. 3 Dehumidifying characteristics of SPE dehumidifier under the conditions that the temperature and humidity outside the chamber are maintained at 293 K and 60%, respectively. **a** Comparison of measured dehumidifying process and the calculated values. **b** Comparison of measured current and the calculated values using Eq. 12

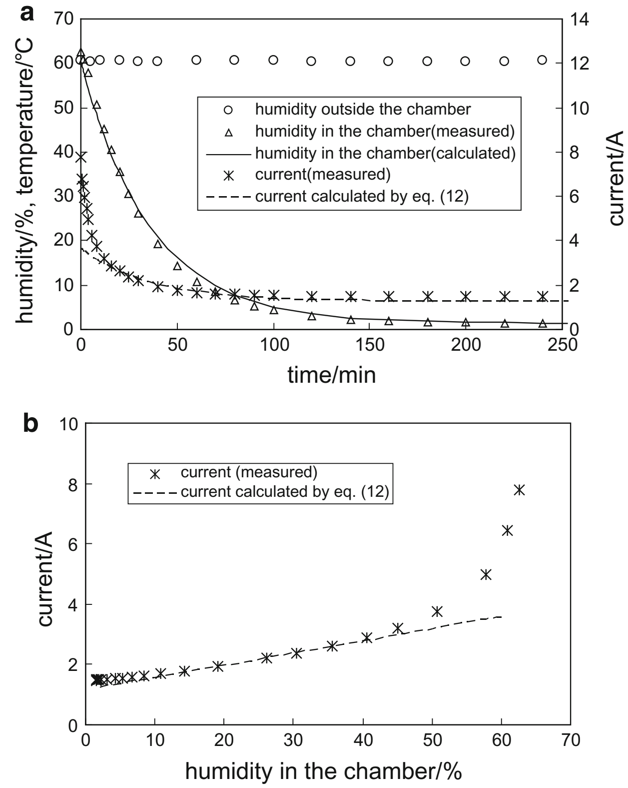

Fig. 4 Dehumidifying characteristics of SPE dehumidifier under the conditions that the temperature and humidity outside the chamber are maintained at 303 K and 60%, respectively. **a** Comparison of measured dehumidifying process and the calculated values. **b** Comparison of measured current and the calculated values using Eq. 12

was found in Fig. 6 that the calculation well agrees with the measurement. Therefore, Eq. 12 can determine the steady-state current even for an open air condition.

From the results shown in Figs. 3, 4, 5 and 6, the current under a steady-state condition can be expressed by Eq. 12 and then the water content in the anode side of the element can also be expressed by Eq. 11.

When Eq. 12 is valid, Eq. 1 can be reduced to the simplified form as expressed by Eqs. 13 or 13a, and then the attainable humidity and the time constant to change the humidity in the chamber can be given by Eqs. 15 and 16, respectively. Equations 15 and 16 indicate the relation of the attainable humidity versus (*S*, *Sl*) and the time constant versus (*S*, *Sl*). Therefore, these equations can be expressed in a diagram as shown by Fig. 7. This diagram gives a set of variables (*RHg,p*/*RHg,n*, τ) corresponding to another set of variables (*S*, *Sl*). This diagram would be useful to estimate the performance of a dehumidifier required for a specific application.

4 Results and discussion

The current was expressed as a function of the water content on the anode side in the element as shown in Eq. 5. The water content of the anode side, assuming steady state conditions, was expressed by Eq. 11 as a function of the humidities of the spaces facing both the anode and the cathode. The water content of the anode side can be interpreted as the one in the vicinity of the anode because the water contents in the element defined by the two-layer model are the water contents represented at the electrode surfaces in the element. Therefore, Eq. 5 can be assumed to be the current represented as a function of the water content in the vicinity of the anode. Equation 11 can also be assumed to be the water content in the vicinity of the anode under a steady state condition when the humidity of both spaces facing the anode and the cathode is given. When a steady state condition is attained under the surrounding condition of 303 K and 60%, the water content $\rho_{s,p}$ calculated by Eq. 11 is about 8 mg cm^{-3}. The value of $\lambda(N_{H_2O}/N_{SO_3H})$ corresponding to the $\rho_{s,p}$ is about $\lambda = 0.3$. This is very low and there was no information about the impedance for such a low λ, but the current calculated by the method mentioned in the previous section well agrees with the measured current within the measured ranges.

Anantaraman et al. [2] reported the effect of humidity on the conductivity of Nafion 117. They measured the

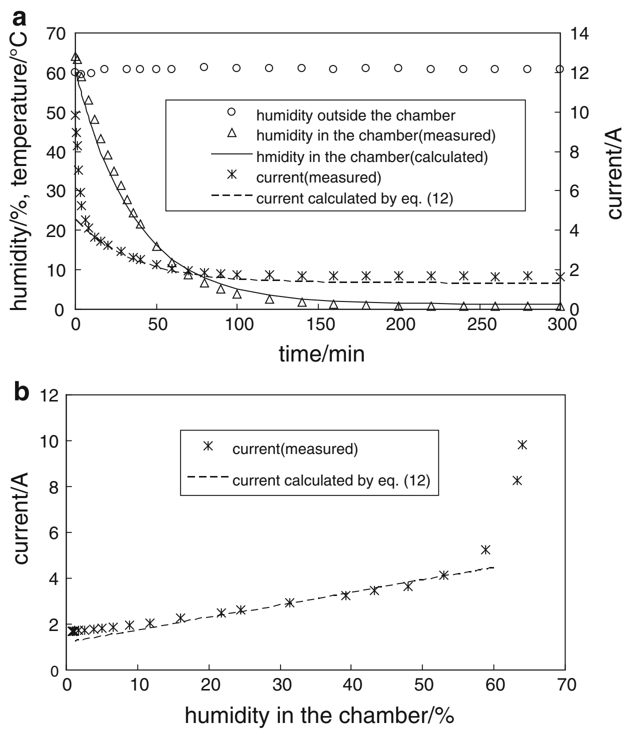

Fig. 5 Dehumidifying characteristics of SPE dehumidifier under the conditions that the temperature and humidity outside the chamber are maintained at 313 K and 60%, respectively. **a** Comparison of measured dehumidifying process and the calculated values. **b** Comparison of measured current and the calculated values using Eq. 12

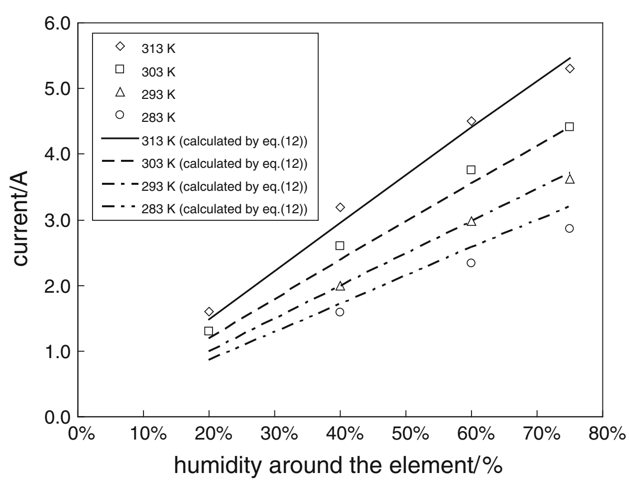

Fig. 6 Steady-state current flowing in the dehumidifying element exposed to the open air ($S = 100\ \mathrm{cm}^2$, under the condition $\rho_{g,p} = \rho_{g,n}$)

conductance by a high frequency impedance method. The electrical conductivity of Nafion 117 for $\lambda = 1.18$–18 measured by them depends much more on the relative humidity in the surrounding air than that of our results presented in our previous paper. They also measured the conductivity of Nafion 117 with a humidity gradient and the results showed the strong dependence of the

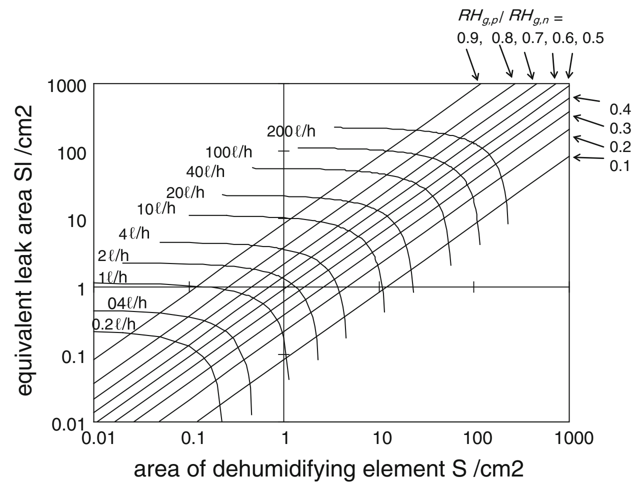

Fig. 7 Diagram to estimate attainable humidity and time constant for dehumidification from S and $S\ell$

conductivity on the humidity. Zawodzinski et al. [1] reported the conductance of Nafion 117 as a function of the water content in the membrane. They showed that the conductance decreases roughly linear with decreases in the water content of the membrane. Although these reports are on the conductance of the membrane itself and direct comparison with our results with them is not possible, the conductance of the dehumidifying element in the present paper strongly depends on the water content of the element. There are no other references found about the electrical conductance for such a low water content of $\lambda = 0.3$. As a major part of the voltage drop would mainly be concentrated in the vicinity of the anode, it seems to be valid that the current characteristics are strongly influenced by the water content near the anode.

Assuming that the values of $S\ell$ and I in Eq. 10 are zero, the equation can determine some useful parameters like the water vapor transmission rate (WVTR) as follows.

$$\mathrm{WVTR} \equiv \frac{V_{g,p}}{S}\frac{d\rho_{g,p}}{dt} = \frac{D}{L}\left(\frac{\kappa_g}{2D/L + \kappa_s}\right)\left(\rho_{g,n} - \rho_{g,p}\right) \tag{21}$$

The WVTR rate is defined [7] using the parameters of the permeability P as follows.

$$WVTR = \frac{P}{L}\left(p_{g,n} - p_{g,p}\right) \tag{22}$$

By comparing Eqs. 21 and 22, the permeability P can be expressed by the parameters used in the two-layer model.

$$\begin{aligned} P &= \frac{D\kappa_g}{2D/L + \kappa_s}\,\frac{18 \times 10^{-6}}{RT_g} \\ &= 9.8 \times 10^{-12} \quad \left[\mathrm{g\ cm^{-1}\ s^{-1}\ Pa^{-1}}\right] \\ &\quad \left(\text{at } T_g = 303\ \mathrm{K}\right) \end{aligned} \tag{23}$$

The typical value of WVTR at the temperature of 303 K and humidity difference of 100% is calculated to be

2.4×10^{-6} (g cm^{-2} s^{-1}) using Eqs. 22 and 23. This value is on the same order as the water transmitted just by the current during the operation of the dehumidifier.

The time variations in the current and chamber humidity calculated using the two-layer model well agree with those of the measured characteristics. The current rapidly decreased for a few minutes just after switching-on the SPE dehumidifier. Thereafter, the current and humidity of the chamber were more slowly reduced toward the steady state. These characteristics can be explained by the two-layer model. The time to form the gradient distribution would at least take a few minutes and the time constant for the dehumidification would be from several tens of minutes to several hours for most practical applications. Therefore, Eqs. 12 and 13 are valid for most practical applications.

Equation 12 gives the steady state current as a function of the humidity surrounding the element. The measured current well agrees with the one calculated using Eq. 12. Therefore, the measured current for almost the entire period except for the period just after switching-on must be nearly the same as that under the steady state conditions. Equation 11 must also be valid under the steady state conditions.

As Eq. 12 is valid, the two-layer model expressed by the set of equations (1–4) can be reduced to the simplified form as Eq. 13 or 13a.

5 Conclusions

The analysis of the current characteristics of a SPE dehumidifier was made using the two-layer model of the SPE dehumidifier. Calculations of the current and humidity changes of the dehumidification process by the two-layer model well agree with the measured ones.

Current flowing in the element was approximated to be proportional to the water content in the vicinity of the anode as expressed by Eq. 5.

The current flowing in the element under steady state conditions can be expressed by Eq. 12 as a function of its surrounding humidity. The water content in the vicinity of the anode can also be expressed by Eq. 11 as a function of the humidity.

The dehumidification performance by the SPE dehumidifier for practical applications can be approximately estimated by Eq. 13 or 13a. These equations produce a diagram which describes the relation between a set of parameters (the attainable humidity, time constant for dehumidification) and a set of parameters (the dehumidifying area, equivalent leakage area of the chamber). The diagram seems to be practically useful for selecting the dehumidifier performance required for specific application conditions.

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