Fundamental Study on System Efficiency of Vacuum-based Membrane Dehumidification System

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Abstract. In recent years, the sensible heat load of buildings has been decreasing due to the promotion of energy conservation, and the sensible heat factor is expected to decrease. In response, the conventional dehumidification method using overcooled condensation is likely insufficient to handle latent heat, and an advanced dehumidification method is required. The authors have focused these issues and development on a dehumidification method using membranes. Membrane dehumidification systems (MDS) are relatively simple, then it is expected to be next-generation dehumidification system. Therefore, to evaluate the energy-saving performance of MDS, this study developed an energy consumption balance equation for a system that uses overcooled & reheating and MDS, and verified energy-saving performance under different conditions. The results of the study quantitatively showed the system efficiency (Specific energy consumption, vacuum pump consumption per unit of dehumidification) of MDS, which is the amount of energy saved by MDS compared to the conventional system under the specified COP of the cooled heat source equipment and reheating equipment. The system efficiency at which MDS is superior under different room sensible heat factors and membrane utilization methods are also clarified. This enables determining the required system efficiency when considering the introduction of a MDS, and understanding the conditions for introducing a system in which MDS is competitive.

1 Introduction

In recent years, the sensible heat load of buildings has been decreasing due to the promotion of energy conservation. The sensible heat factor is thus expected to decrease. Because the conventional dehumidification method, which is based on condensation, is likely to be insufficient to handle latent heat, a more advanced dehumidification method is required. In this study, a membrane dehumidification system is proposed, its application is demonstrated, and its feasibility is confirmed.

The Figure 1 shows that membrane dehumidify-cation systems use a membrane to separate water vapor from the conditioning air. The humid air undergoes a vapor transfer of adsorption, diffusion, and desorption to become dry air. Unlike desiccant-based systems, they do not require heat regeneration and are relatively simple. Such systems are expected to be next-generation dehumidification systems.

Bui et al. [1] conducted a theoretical analysis of the dehumidification performance of a membrane dehumidification system from the perspective of fundamental thermodynamics and discussed measures that can improve the system's performance.

Cheon et al. [2] developed a simplified numerical model of a membrane dehumidification system and confirmed the accuracy of the model by comparing it with experimental results.

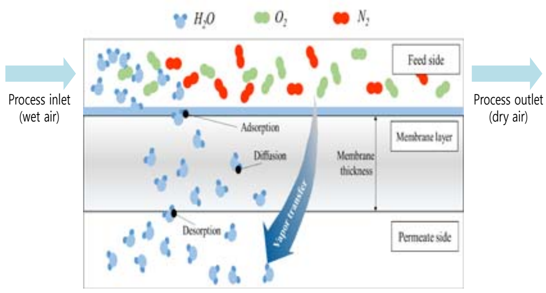

Fig. 1. Diagram of membrane dehumidification system

Cho et al. [3] showed that the energy efficiency of a membrane dehumidification system is higher than that of a conventional dehumidification system.

Membrane dehumidification technology is still under development. Research and development have begun to shift from basic theoretical research and laboratory-level feasibility verification to the cost evaluation and durability improvement of the system.[4]

Research on energy efficiency must be conducted to promote the system's development and generalization. The energy efficiency of the system depends on the energy efficiency of the cooling and reheating equipment of the conventional system, the indoor load characteristics, and the membrane installation method. A method for evaluating energy conservation performance considering these parameters is desirable.

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This study aims to clarify the energy conservation performance of a membrane dehumidification system and quantify the effects of various conditions on such performance.

2 Outline of Research

In this study, an energy balance equation based on changes in energy consumption for a dehumidification system with a membrane is derived. A dehumidification system with overcooling and reheating is used as the reference case. This equation can be used to evaluate energy conservation under various values of the coefficient of performance (COP) for the cooling and reheating equipment. Furthermore, the energy conservation effect of different placement locations of the membrane was confirmed under a low sensible heat load factor.

This study discusses two kinds of membrane applications: membrane installed before cooling coil (MBC) and membrane installed after cooling coil (MAC). MBC is a manner typically used in the previous study. MAC can be used to introduce a membrane into an existing HVAC system [5]. It is expected to reduce the number of membrane modules since it requires less water vapor to be removed by the membrane compared to that for MBC.

It assumes that a boiler and an electric heater are used as reheating equipment. The peak cooling load used in this study was calculated using TRNSYS ver.18 for a typical workspace in an office building in Japan based on standard data (2001-2010, Tokyo) from the Automated Meteorological Data Acquisition System (AMeDAS), which is run by the Japan Meteorological Agency.

3 Evaluation of Membrane Installation Feasibility

3.1 Dehumidification methods

Figure 2 shows the state point of the designed outdoor air, indoor air, and supply air, respectively. The peak cooling load consists of a sensible heat load of 9.7 W/m^2 and a latent heat load of 4.8 W/m^2, giving a sensible heat factor of 0.67. Figure 2 also shows the air handling process for several cases. case-0 is a dehumidification method based on overcooling and reheating. Cooling with condensation is performed while air passes the cooling coil and reheating is performed to the set air supply designated point (supply air temperature: 15 °C). The amount of heat processed by the cooling coil in this case is Q_c and that processed by the reheating coil is Q_h. case-1 is a dehumidification method based on an MBC. The membrane removes water vapor from the coil inlet air before cooling is conducted by the cooling coil. The amount of latent heat processed by the membrane is $Q_{M,MBC}$ and that processed by the cooling coil is $Q_{c,MBC}$. Finally, case-2 is a dehumidification method based on a MAC. The membrane removes water vapor from the

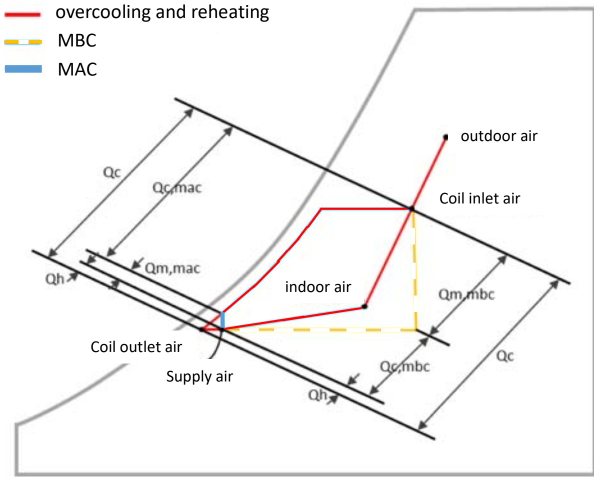

Fig. 2. Dehumidification method used in three cases

Table 1. Cooling, reheating and dehumidification heat rate for each case

Case-0	Q_c	10.6 Wh/kg'
	Q_h	0.8 Wh/kg'
Case-1	$Q_{M,MBC}$	5.6 Wh/kg'
	$Q_{c,MBC}$	4.2 Wh/kg'
Case-2	$Q_{M,MAC}$	0.6 Wh/kg'
	$Q_{c,MAC}$	9.2 Wh/kg'

coil outlet air after cooling is conducted by the cooling coil. The amount of heat processed by the cooling coil is $Q_{c,MAC}$ and that processed by the membrane is $Q_{M,MAC}$.

The required amount of process heat for the cooling and dehumidification process for each case is shown in Table 1. Comparing case-0 with case-1 and case-2 using the membrane, Q_c representing the overcooling in case-0 decreased to $Q_{c,MBC}$ and $Q_{c,MAC}$, by the introduction of the membrane respectively, and Q_h representing the reheating decreased to 0. The energy consumption of the vacuum pump to handle $Q_{M,MBC}$ and $Q_{M,MAC}$, increased compared to case-0, respectively. It can be estimated that the total amount of processing the latent heat is 11.4 Wh/kg' in case-0, while 9.8 Wh/kg' in case-1 and case-2 with the membrane method, which is about 14% smaller. The energy utilization efficiency of each case determines the energy performance of each case. From the next section, the energy balance equation for each case is derived, considering each device's energy utilization efficiency.

3.2 Derivation of Energy Balance Equation

In equation (1), W_{conv} is the energy consumption of the dehumidification method based on overcooling and reheating and $W_{M,MBC}$ is the energy consumption of the MBC in a membrane dehumidification system. Equation (1) is satisfied when W_{conv} for case-0 is greater than that for case-1. In other words, the membrane-based dehumidification method is more energy efficient than the conventional dehumidification method.

$$W_{\text{conv}} \geqq W_{M,MBC} \tag{1}$$

W_{conv} in equation (1) can be obtained from equation (2) and expressed as equation (5) using equations (3) and (4).

$$W_{\text{conv}} = W_{\text{conv},cooling} + W_{\text{conv},reheat} \quad (2)$$

$$W_{\text{conv},cooling} = \frac{Q_c}{COP_{cooling}} \quad (3)$$

$$W_{\text{conv},reheat} = \frac{Q_h}{\beta_{reheat}} \quad (4)$$

$$W_{\text{conv}} = \frac{Q_c}{COP_{cooling}} + \frac{Q_h}{\beta_{reheat}} \quad (5)$$

$W_{M,MBC}$ in equation (1) can be obtained from equation (6) and expressed as equation (9) using equations (7) and (8).

$$W_{M,MBC} = W_{vp,MBC} + W_{M,MBC,cooling} \quad (6)$$

$$W_{vp,MBC} = Q_{M,MBC}\frac{\varepsilon}{\gamma}p \quad (7)$$

$$W_{M,MBC,cooling} = \frac{Q_{c,MBC}}{COP_{cooling}} \quad (8)$$

$$W_{M,MBC} = \frac{Q_{c,MBC}}{COP_{cooling}} + Q_{M,MBC}\frac{\varepsilon}{\gamma}p \quad (9)$$

Substituting equations (5) and (9) into equation (1) yields equation (10).

$$\frac{Q_c}{COP_{cooling}} + \frac{Q_h}{\beta_{reheat}} \geqq \frac{Q_{c,MBC}}{COP_{cooling}} + Q_{M,MBC}\frac{\varepsilon}{\gamma}p \quad (10)$$

From Figure 1, the processing heat rate for the cooling coil can be expressed as shown in equation (11).

$$Q_c = Q_{c,MBC} + Q_{M,MBC} + Q_h \quad (11)$$

Substituting equation (11) into equation (10) and rearranging yields equation (12).

$$\varepsilon \leqq \frac{\gamma}{p}\left[\left(\frac{1}{\beta_{reheat}} + \frac{1}{COP_{cooling}}\right)\frac{Q_h}{Q_{M,MBC}} + \frac{1}{COP_{cooling}}\right] \quad (12)$$

In the case of MAC case-2, the following energy balance equation is obtained in the same manner.

$$W_{\text{conv}} \geqq W_{M,MAC} \quad (13)$$

Equation (13) can be rearranged as done for case-1 to obtain equation (14).

$$\varepsilon \leqq \frac{\gamma}{p}\left[\left(\frac{1}{\beta_{reheat}} + \frac{1}{COP_{cooling}}\right)\frac{Q_h}{Q_{M,MAC}} + \frac{1}{COP_{cooling}}\right] \quad (14)$$

The conditions under which the energy consumption for case-1 and case-2 is less than that for case-0 can be obtained using equations (12) and (14), respectively.

In equations (12) and (14), the right-hand side is the sum of the energy reduction in the cooling equipment (refrigerator) and the energy reduction in the heating equipment (boiler or electric heater) required reheating, obtained by not performing overcooling and reheating due to membrane adoption. In other words, it represents the amount of energy reduction that can be expected with membrane adoption. The left-hand side, ε, is the energy consumption of the vacuum pump caused by the introduction of the membrane. The increase in fan power can be also included in this index.

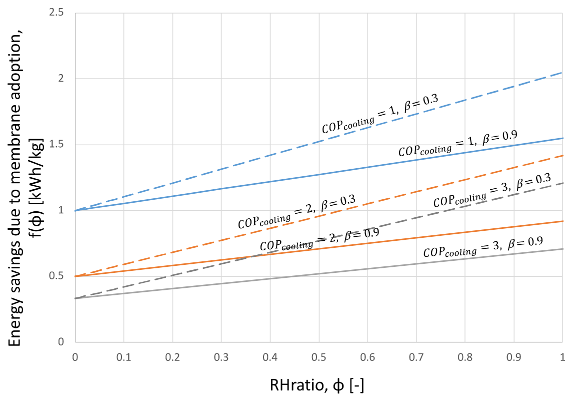

Fig. 3. Variation of f(φ) with respect to φ for various combinations of $COP_{cooling}$ and β values

Therefore, the amount of energy-saving by introducing the membrane equals to the sum of the energy reduction for heat source equipment and the energy increase by the vacuum pump. Also, the value of ε varies between the case-1 in equation (12) and the case-2 in equation (14).

$\frac{Q_h}{Q_{M,MBC}}$ and $\frac{Q_h}{Q_{M,MAC}}$ in equations (12) and (14) are defined as φ, and the right-hand side of the equation is defined as $f(\varphi)$. Here, φ is the ratio of the amount of heat treated for reheating to the required amount of latent heat treated by the membrane (hereinafter called RH ratio). It can be seen that $f(\varphi)$ is a linear function of φ. The intercept of this linear equation depends on the efficiency of the cooling equipment, and the slope depends on the efficiency of the cooling and reheating equipment. Also, when the amount of energy-saving by introducing membrane dehumidification without overcooling and reheating can be expressed as equation (15).

$$E = f(\varphi) - \varepsilon \quad (15)$$

3.3 Evaluation of Installation Feasibility using Energy Balance Equation

To achieve energy conservation by using the membrane system, ε must be smaller than the right-hand side of equation (12) or (14). In other words, energy is saved if the energy reduction from the adoption of the membrane on the right-hand side is larger than the energy increase from the adoption of the membrane on the left-hand side.

The efficiency of the reheating equipment was set to 0.9 for a boiler and 0.3 for an electric heater. $COP_{cooling}$ was set to 1-3. In this case, COP is set from 1 to 3 because a certain period of operation is assumed, whereas an efficiency of 3 or higher can be expected at the rated conditions. Equations (12) and (14) are plotted in Figure 3.

It can be seen that a larger $COP_{cooling}$ value leads to a smaller energy reduction obtained with membrane installation. Furthermore, the rate of increase of $f(\varphi)$ with φ increases with the lower efficiency of reheat equipment. From this, the amount of energy conserved can be quantitatively obtained under various $COP_{cooling}$ and β values.

In addition, it can be seen that $f(\varphi)$ increases with increasing φ. This means that the expected amount of energy reduction by the introduction of the membrane could be larger as larger φ. Under the assumption that ε is 0.5, $f(\varphi)$ is even or larger than 0.5 at the condition of a full range of φ in the case of $COP_{cooling}$ values of 1 and 2. However, in case of $COP_{cooling}$ values of 3, $f(\varphi)$ will be even or larger than 0.5 at the range of φ is over 0.43 (β=0.9) or 0.21 (β=0.3).

Under the conditions shown in Figure 2, for case-2, φ is 0.6 and $f(\varphi)$ is 1.33 kWh/kg, and for case-1, φ is 0.06 and $f(\varphi)$ is 1.03 kWh/kg. A previous study [6] showed that ε is 0.55 kWh/kg for case-2 and 0.59 kWh/kg for case-1. Therefore, the net energy savings will be 0.78 kWh/kg and 0.44 kWh/kg, respectively. It means that it can be expected that MAC is more likely to realize larger $f(\varphi)$ compared with the case of MBC, and it can be said that energy savings due to membrane adoption will be greater with MAC than with MBC.

4 Indoor Sensible Heat Factor and Effect of Membrane Installation

Figure 4 shows the relation between the sensible heat factor and the φ for each case. Calculating the sensible heat factor and φ, requires the design condition for the supply air temperature & humidity in the case of MAC, and the air condition of air introduced to the membrane which equals the mixing air in the case of MBC as well in the case of MBC.

A higher sensible heat factor thus leads to a lower φ, meaning that the lower the sensible heat factor, the larger energy reduction is expected with membrane utilization. Under the condition of the sensible heat factor is 0.5, φ for each case is 0.73, 0.26 respectively.

5 Conclusion

In this study, energy balance equations were derived to evaluate the energy conservation effect of a dehumidification system by membrane utilization compared with a conventional dehumidification system. Then, using the energy balance equation, it was possible to quantify the conditions under which a system using a membrane dehumidification mechanism saves energy compared to a conventional dehumidification method.

The study also examined the installation methods of different membrane dehumidification systems and showed that the installation method introducing membrane after cooling coil can be expected to have higher energy-saving performance compared to the installation shown in the previous study.

This study was conducted under design conditions only, and future evaluations will be taken into account the operating period performance of the system.

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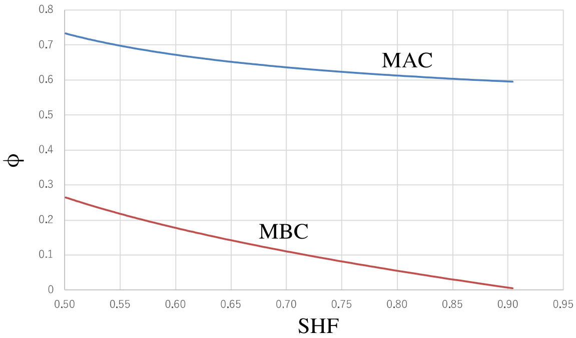

Fig. 4. The relation between the sensible heat factor and the φ for case-1 and case-2

Nomenclature

W: Energy consumption [kW], *Q*: Process heat [kJ] *COP*: COP based on primary energy [-], β: Energy efficiency based on primary energy [-], ε: Required vacuum pump power per unit of dehumidification of membrane [kWh/kg], p: Primary energy conversion factor [kJ/kWh] (9,760 kJ/kWh), γ: Latent heat of evaporation of water vapor [kJ/kg] (2,500 kJ/kg), E: Amount of energy saved by membrane dehumidification utilization [kWh/kg], φ: RH ratio [-]
conv: conventional dehumidification system, *MBC*: membrane before cooling coil system, *MAC*: membrane after cooling coil system, *M*: membrane system, *c*: cooling, *h*: reheating, *cooling*: cooling equipment, *reheat*: reheating equipment

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