Performance Investigation of Liquid Desiccant Dehumidification System Integrated with Solar Thermal Energy and Shallow Geothermal Energy

Ching YI Tseng[1], Li Hao Yang [1], Jyun De Liang [1] and Sih-Li Chen [1]

[1] National Taiwan University, Taipei (Taiwan, ROC)

Abstract

This paper combines solar thermal energy and shallow geothermal energy with liquid desiccant dehumidification system in the Make-up Air Unit (MAU). The system uses Calcium chloride solution as its absorption solution and utilizes solar thermal energy as a regeneration heat source of the system, regenerating $CaCl_2$ solution. The study improves the dehumidification ability of the MAU with the energy efficient manner. Compared with the traditional dehumidification system, solar energy and shallow geothermal energy can reduce energy consumption. Increasing the air entrance mass rate, absorption solution entrance mass rate, air entrance absolute humidity and absorption entrance concentration improves water removal rate. Decreasing the air entrance mass rate and increasing absorption solution entrance mass rate can improve efficiency. According to the results, the study develops the MAU with an energy-efficient dehumidification manner.

Keywords: Solar Thermal Energy, Shallow Geothermal Energy, Liquid Desiccant Dehumidification.

1. Introduction

The study mainly combines solar thermal energy liquid desiccant dehumidification system with shallow geothermal energy liquid desiccant dehumidification system. Traditional air conditioners mainly produce cool water with chiller. Cooling and dehumidifying the air by coil tubes, then heating the cool air to a particular temperature lead to high electricity expense. In order to reduce the box energy consumption, the study improves the traditional dehumidification system, dehumidifying and regenerating by solar thermal energy preheat and shallow geothermal energy precool Calcium chloride solution which makes the air reach the moderate temperature and humidity. Calcium chloride solution dehumidification air conditioner is different from the traditional chiller (Bassuoni, 2011). Calcium chloride solution air conditioner has a higher dehumidification effect and is more environmentally-friendly and scalable in the system. Recently, the issue is extensively studied over the world (Zhang et al., 2017). The study simulates the operation of solar thermal energy liquid desiccant dehumidification system and shallow geothermal energy liquid desiccant dehumidification system with heat pump which has the cool side and hot side property, applied to the regeneration side and precool side of dehumidification, utilizing the results to lower the energy consumption of the box as well as improving the dehumidification effect.

2. Experimental processes and theoretical analysis

The study uses Calcium chloride solution as its absorption solution, simulating solar thermal energy and shallow geothermal energy with the cool side and the hot side of the heat pump, absorbing and regenerating in the dehumidification process. Removing the water in the air, which turns Calcium chloride solution to dilute concentration solution with pressure difference, and then recovering to thick concentration solution by regeneration. The method can recycle, which save more energy than the traditional air conditioner.

Figure 1 is the illustration of experiment system structure divided to air side and solution side. In the air side, the wet air enters the dehumidification part from point 1. The air then turns into the dry air after touching dehumidification solution, entering the indoor space from point 2. The dry air then enters the regeneration part from point 3, turning to the high temperature and high humidity air, emitting the air at point 4. In the solution side, low-temperature high concentration absorption solution enters dehumidification part from point a, lowering the concentration after touching the wet air, leaving the dehumidification part from point b, entering the regeneration part from point c through absorption solution preheat heat exchanger. Increasing temperature with solar thermal

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coil pipe, transmitting the solution water part to the air side, reaching the original concentration, leaving the regeneration part from point d. After the Calcium chloride solution is cool down by two-phase through absorption precool heat exchanger and absorption solution cool heat exchanger, entering the next stage cycle from point a.

The experiment contains three parameters at the air side, three parameters on the solution side. Parameters at the air entrance side include air mass rate, air dry ball temperature, air humidity; Parameters at the solution entrance side include solution mass rate, solution temperature, and solution concentration.

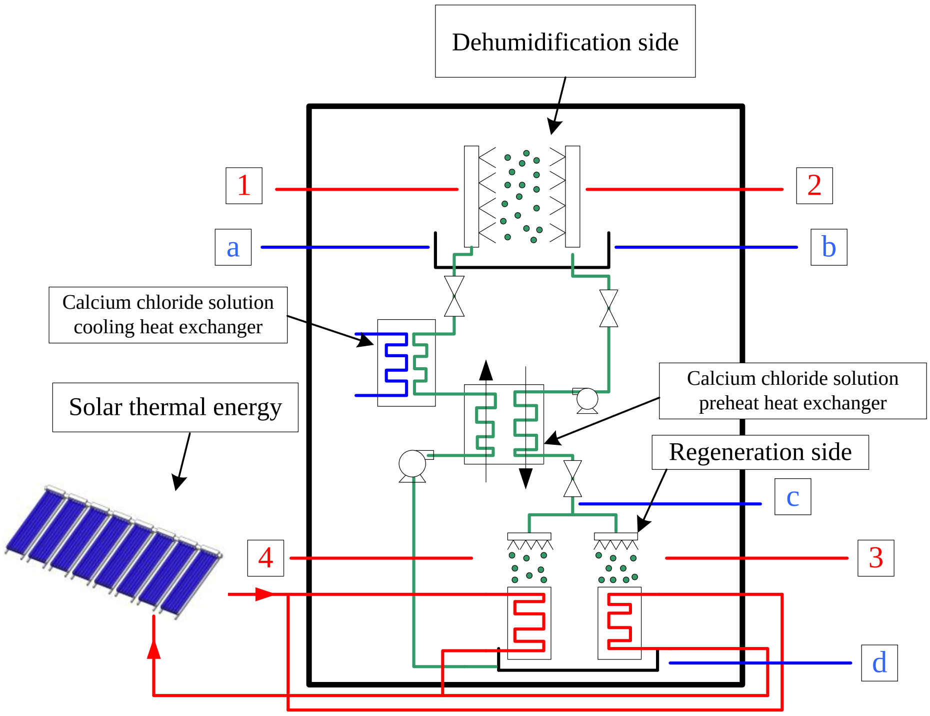

Fig 1. The experimental setup of the dehumidification system.

3. Mathematical models

The wet air is a mixture of dry air and water vapor. The humidity content in the wet air reaches saturation from zero, which is completely determined by the temperature and pressure of the environment at that time. The saturated state means a state in which a balance between the wet air and the condensed water phase is maintained.

The temperature and pressure of the air will change with the weather and altitude. The standard atmosphere is a standard that provides a reference for estimating the nature of air at various altitudes. On the horizon, the standard temperature is 15 °C; the standard atmospheric pressure is 101.325 kPa. The temperature is assumed to decrease linearly as the height of the troposphere increases, and is constant in the lower range of the stratosphere. The lower atmosphere is assumed to consist of dry air equivalent to the ideal gas. The gravity is also a standard fixed value –9.806 m/s^2. The following equations (1) and (2) are for pressure and temperature with altitude, and are accurate from 5,000m to 11,000 m.

$$P = 101.325\left(1 - 2.5577 \times 10^{-5} H\right)^{5.2559} \qquad \text{(eq. 1)}$$

$$T = 15 - 0.0065 \times H \qquad \text{(eq. 2)}$$

The dehumidification method of this experiment is chemical dehumidification, and the experiment will be carried out by selecting the reverse flow with the best dehumidification effect. The model of the mathematical theory is shown in Figure 2. The total length of gas-liquid contact in the dehumidification process is cut by the grid. After entering the inlet state, the export data and the status of various parameters of air and solution can be calculated in an iterative manner. In the heat and mass transfer process of gas-liquid contact in Figure 2, the air and solution ends must conform to energy conservation and mass conservation.

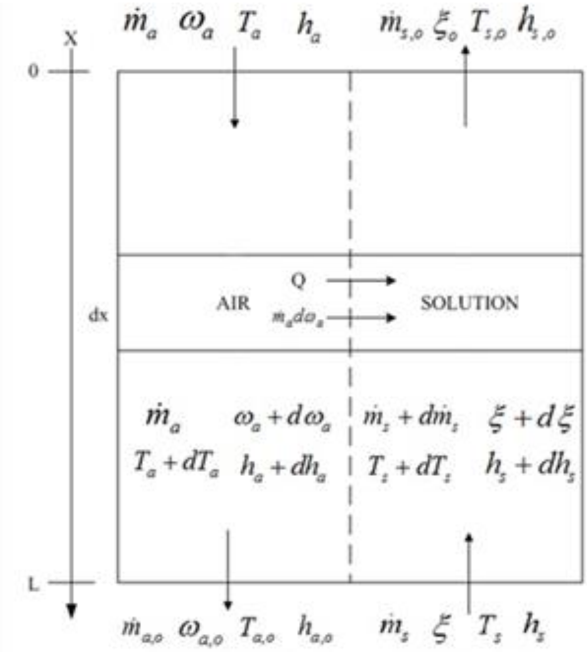

Fig 2. The absorption solution mathematical model architecture diagram.

The governing equations of the dehumidification process will be written into the calculation form of the grid to obtain the export results of the air end and the solution end. In equations (3), (4), (5), (6), and (7), the subscript i is the state of a particular grid, and i+1 is the state of the next grid. The calculation is performed for each grid, and the grid is solved in an iterative method.

$$\dot{m}_a(h_{a,i} - h_{a,i+1}) = (\dot{m}_{s,i+1}h_{s,i+1} - \dot{m}_{s,i}h_{s,i}) \quad \text{(eq. 3)}$$

$$\dot{m}_a(\omega_{a,i} - \omega_{a,i+1}) = (\dot{m}_{s,i+1} - \dot{m}_{s,i}) \quad \text{(eq. 4)}$$

$$\dot{m}_{s,i}\xi_i = \dot{m}_{s,i+1}\xi_{i+1} \quad \text{(eq. 5)}$$

$$h_{a,i+1} - h_{a,i} = \frac{NTU}{N}(h_{e,i} - h_{a,i}) \quad \text{(eq. 6)}$$

$$\omega_{a,i+1} - \omega_{a,i} = \frac{NTU}{N}(\omega_{e,i} - \omega_{a,i}) \quad \text{(eq. 7)}$$

From equation (3), the mesh inlet humidity ratio ($\omega_{a,i}$) is known, and the air and solution phase equilibrium humidity ratio ($\omega_{e,i}$), The obtained method is the temperature and weight concentration of the known solution at this time, and the humidity ratio ($\omega_{e,i}$) at the time is obtained, and the humidity ratio ($\omega_{a,i+1}$) of the mesh outlet can be calculated. Calculate the enthalpy value of the outlet of the grid solution according to the eq. (3), calculate the mass flow rate of the outlet of the grid solution by using eq. (4), and calculate the concentration of the outlet of the grid solution by the eq. (5).

The process of numerical solution is to discretize these equations and solve them separately in each grid. The inlet state of air and solution is generally known in the calculation, and the absorption liquid is partially formed into a grid form. According to the above solution step, the outlet state of the grid N1 air and the solution can be obtained, and for the next grid N2, the N1 exit state can be regarded as the inlet state. So through the above solution step, the exit state of N2 can be obtained. By repeating the same method, you can find the state of each grid and know the exit status of the system.

4. Results and discussion

This article respectively focuses on the following three experiments to measure and examine the effect of dehumidification with calcium chloride solution and inlet temperature under various situations. The results of experiment and calculation will be discussed in this chapter, mainly as:

1. The influence on dehumidification system with varying mass flow rate and temperature of air inlet.
2. The influence on dehumidification system with varying humidity of air inlet.
3. The influence on dehumidification system with the solution inlet.

4.1 Testing the properties of calcium chloride

Before examining calcium chloride's capability of dehumidification, it is essential to make sure that the properties of calcium chloride used are congruent with the ones on Calcium Chloride Handbook, or there will exist deviations that affect the accuracy of this experiment.

Three different brands will be used in this testing. By contacting air with absorbent under long periods of time, moisture will then transfer from air with higher partial pressure to the solution with lower partial pressure. The solution will eventually be diluted, while the air will be dried. The testing will be comparing the dehumidification capability of the three calcium chloride solution brands under different weight percentages and using the best one to compare with the standard chart in Calcium Chloride Handbook.

This experiment is shown in Figure 4-1. The solution is placed in an iron bowl and placed in an airtight box to ensure that the wet air inside and outside the airtight box does not cause exchange effects to affect the experimental results, and then the instrument is inserted into the airtight box to start the experiment.

Fig 3. Calcium chloride performance test

The calcium chloride of the three manufacturers was tested at a constant temperature of 10% to 45% by weight at 30 °C, and allowed to stand for a long time until the temperature and humidity were no longer changed, and the relative humidity was recorded, as shown in Table 1.

After the various concentrations of the three manufacturers were tested, they were drawn into Figure 4. After comparison, it was found that the relative humidity of the calcium chloride of the manufacturer A was the lowest at each concentration, and the dehumidification effect of the calcium chloride solution representing the manufacturer A was the most, so choose manufacturer A for this experiment.

Tab. 1: Absorption performance of different manufacturers of calcium chloride solution at different weight percentages

weight percentage concentration (%)	(A)dew-point temperature after dehumidification (°C)	(B)dew-point temperature after dehumidification (°C)	(C)dew-point temperature after dehumidification (°C)
10	28.4	28.5	28.7
20	27.2	27.5	27.8
30	22.4	22.6	22.7
35	19.5	19.7	20.1
40	16.4	16.7	17.0
45	10.9	11.5	11.8

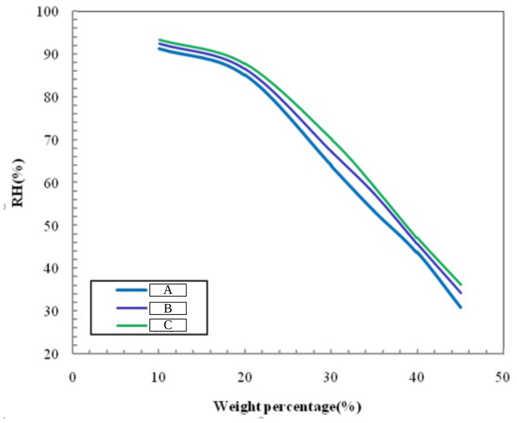

Fig 4. Comparison of dehumidification of calcium chloride solution at different weight percentages

4.2 Mass flow rate change of air inlet and temperature change affect dehumidification system

There are three parameters on the air side of the experiment, and three parameters on the solution side, for a total of six parameters. Air inlet side parameters include: air mass flow rate, air dry bulb temperature, air humidity; solution inlet side parameters include: solution mass flow rate, solution temperature, solution concentration. This section changes the inlet mass flow rate of air. The mass flow rate varies from 0.25 kg/s to 1.2 kg/s. Other parameters are controlled as much as possible to reduce the experimental error. The air side inlet dry bulb temperature range is 33.0 ºC ~ 34.3 ºC, the humidity ratio range is 17.2 g/kg ~ 17.7 g/kg; the solution side inlet mass flow rate is 0.69 kg/s, the temperature range is 25.0 ºC ~ 25.2 ºC, and the weight percentage is 38.5. %.

Humidity ratio is defined as the weight of water content per kilogram of air. Figure 5 shows relation between humidity ratio at air outlet and mass flow rate at air inlet. From the result, humidity ratio at air outlet increases gradually with the increasing mass flow rate at air inlet. At 0.25 kg/s inlet flow rate, minimum humidity ratio at outlet is 12.8 g/kg. Figure 6 shows the relation between humidity ratio difference and mass flow rate of the air. It can be found that as the air inlet mass flow rate increases, the humidity ratio difference will gradually decrease, and the maximum humidity ratio difference is 4.9 g/kg when the air inlet mass flow rate is 0.25 kg/s. The reasonable explanation of the phenomena in Figure 5 and Figure 6 is that when the air inlet mass flow rate is small, the contact time per unit volume of air and solution is more, and the water quality transfer ability is better. Therefore, the outlet humidity ratio is lower and the humidity ratio difference is higher. On the contrary, when the air inlet mass flow rate is large, the contact time per unit volume of air and the solution is small, and the water quality transfer ability is poor, so the outlet humidity ratio is high and the humidity ratio difference is low.

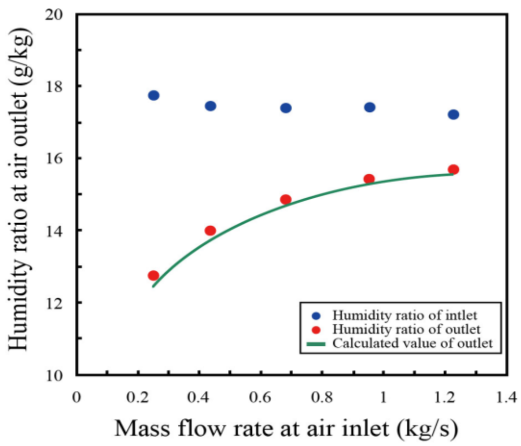

Fig. 5 Relation between humidity ratio at air outlet and mass flow rate at air inlet.

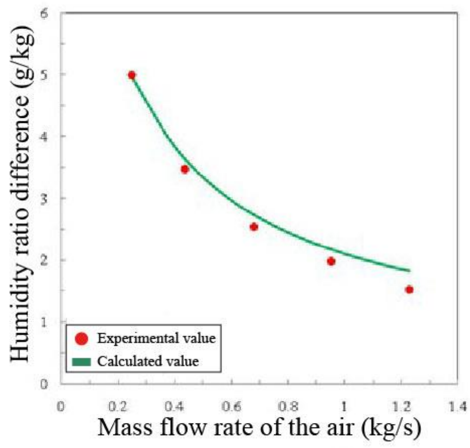

Fig. 6 Relation between humidity ratio difference and mass flow rate of the air.

The humidity removal rate is the product of the difference between the air mass flow rate and the inlet and outlet humidity ratio, which is the weight of water that the system can take away per second. As shown in Figure 7, as the mass flow rate of the air inlet increases, although the contact time per unit volume of air and the solution is less, However, due to the increase in air mass flow rate, the relationship between the pressure difference between gas and liquid increases. The humidity removal rate of the system shows an increasing trend.

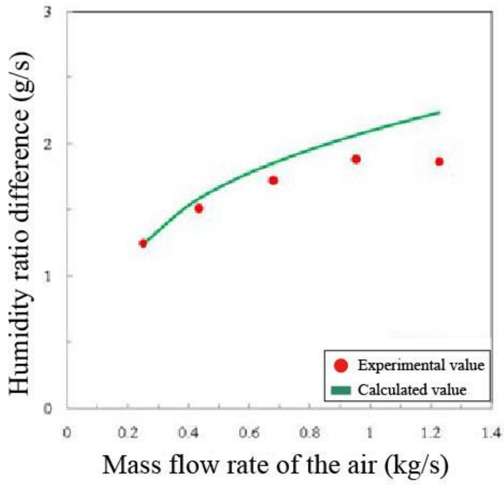

Fig. 7 Relation between humidity removal rate and mass flow rate of the air.

As shown in Figure 8, the air inlet dry bulb temperature condition is controlled between 33 ^oC and 34 ^oC, the solution inlet temperature condition is controlled at about 25 ^oC, and air inlet dry bulb temperature is higher than the solution inlet temperature. The dry bulb temperature of air outlet gradually increases as the mass flow rate of air inlet increases. The main reason is that as air mass flow rate increases, the contact time between the unit air and the solution decreases. The solution outlet temperature gradually increases as the air inlet mass flow rate changes. The main reason is that as the air mass flow rate increases, the humidity removal rate of the system increases and the heat of melting of calcium chloride increases. The temperature difference between the outlet of the air and the solution gradually increases as the mass flow rate of the air inlet increases, and it is precisely because the contact time of the unit air and the solution decreases as the air mass flow rate increases.

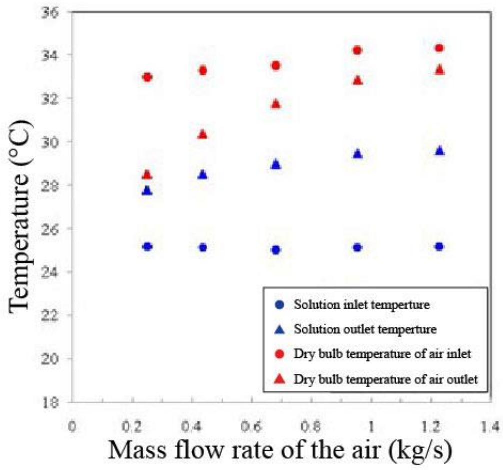

Fig. 8 Relation between temperature and mass flow rate of the air.

The dehumidification efficiency is defined as the experimental value of the difference between the air inlet and outlet humidity ratio and the ratio of the air inlet to the gas-liquid equilibrium humidity content difference. Figure 9 shows the dehumidification efficiency as a function of the air inlet mass flow rate. It can be seen that the dehumidification efficiency decreases as the air inlet mass flow rate increases. Because when the air mass flow rate increases, the moisture exchange time between gas and liquid is shortened, and the water that can be removed per unit volume of air is reduced, resulting in a decrease in dehumidification efficiency. As the air inlet mass flow rate increases from 0.25 kg/s to 1.23 kg/s, the dehumidification efficiency will decrease from 68% to 55%.

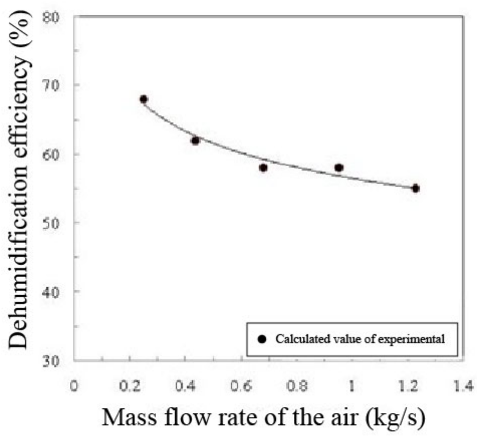

Fig. 9 Relation between dehumidification efficiency and mass flow rate of the air

4.3 Air inlet humidity changes affect the absorption system

Figure 10 shows the humidity of the air inlet increases; the humidity ratio of the air outlet will gradually increase. When the air inlet humidity is 12.3 g/kg, the lowest outlet humidity ratio is 11.5 g/kg. Figure 11 shows the change in the humidity ratio of the outlet with the humidity of the air inlet. It can be found that as the humidity of the air inlet increases, the humidity ratio will gradually increase. When the air inlet humidity is 18.8 kg/s, the maximum humidity ratio difference of 3.0 g/kg will be obtained. It is reasonably explained by the phenomena in Figures 10 and 11 that when the air inlet humidity is small, the vapor pressure difference between the air end and the solution end is low. The ability to transfer humidity from the air end to the solution end is weak, so the humidity ratio difference is low. Conversely, when the humidity of the air inlet is relatively large, the difference in vapor pressure between the air end and the solution end is large, so that the air transfer capacity of the air end to the solution end is strong, so the humidity ratio difference is high.

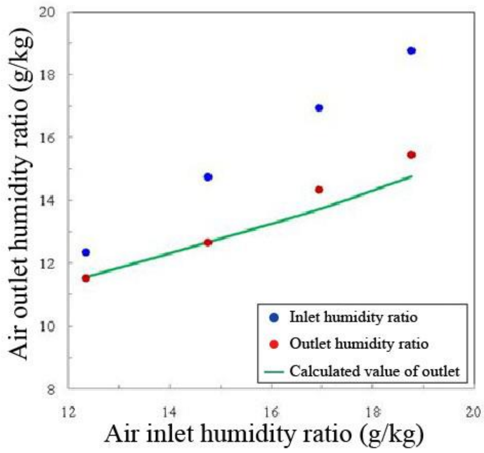

Fig. 10 Relation between Air outlet humidity ratio and air inlet humidity ratio.

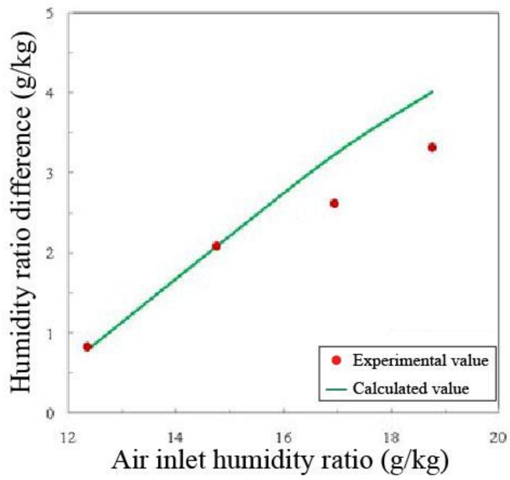

Fig. 11 Relation between humidity ratio difference and air inlet humidity ratio.

Figure 12 shows the relation between system humidity removal rate and air inlet humidity ratio. It can be seen from the figure that as the humidity of the air inlet increases, the vapor pressure of the air increases, so the pressure difference between the air end and the solution end is increased, so that the mass transfer capability of the water is increased. Therefore, the humidity removal rate of the system is increasing.

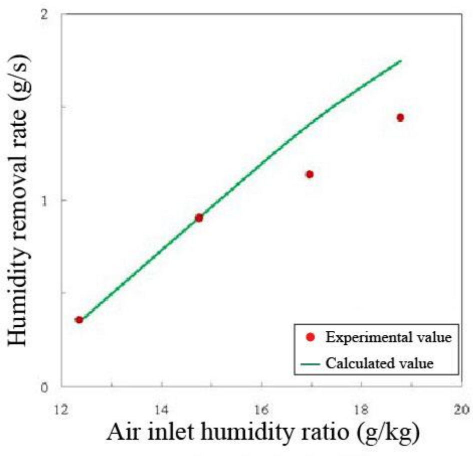

Fig. 12 Relation between humidity removal rate and air inlet humidity ratio.

Figure 13 shows the change in air side, solution side inlet and outlet temperatures with air inlet humidity. Figure 13 shows that air inlet dry bulb temperature condition is controlled at about 34℃, the solution inlet temperature condition is controlled at about 25℃, and air inlet dry bulb temperature is higher than the solution inlet temperature. The outlet temperature of air and solution gradually increases as the humidity of air inlet becomes larger. The main reason is that as the humidity of air inlet increases, the increase in air humidity transfer is accompanied by more heat of dissolution of calcium chloride solution.

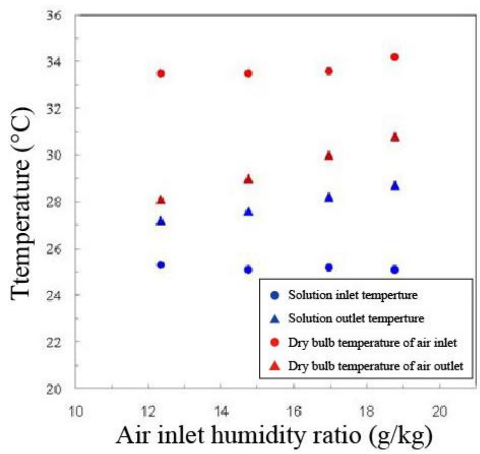

Fig. 13 Relation between change in air side, solution side inlet and outlet temperatures and air inlet humidity ratio.

Figure 14 shows the change in dehumidification efficiency and air inlet humidity. As the air inlet humidity rises from 12.3 g/kg to 18.8 g/kg, the dehumidification efficiency hardly changes with the air inlet humidity.

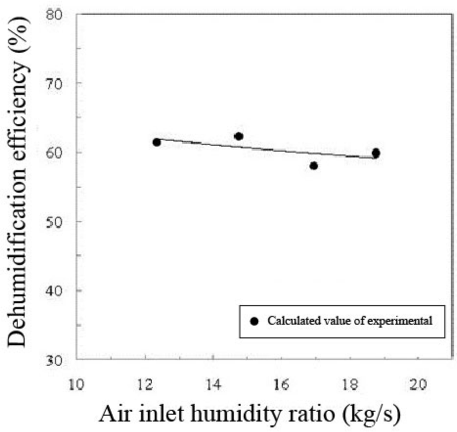

Fig. 14 Relation between dehumidification efficiency and air inlet humidity ratio.

4.4 Effect of solution inlet on absorption system

From figure 15, as the mass flow rate of the solution inlet increases, the humidity ratio of the air outlet will gradually decrease. When the mass flow rate of the inlet of the solution is 0.69 kg/s, the lowest outlet humidity ratio is 14.3 g/kg. Figure 16 shows the difference between the inlet and outlet humidity ratios as the mass flow rate of the inlet of the solution changes. As the mass flow rate of the solution inlet increases, the humidity ratio difference will increase. The effect of figure 15 and 16 can be reasonably explained as when the mass flow rate at the inlet is low, the contact surface area of air per volume and the solution is small, weakening its capability to transfer mass, which results in higher humidity at the outlet with lower humidity ratio difference. On the contrary, when the mass flow rate at the inlet is high, the contact surface area of air per volume and the solution is big, improving its mass transfer capability, which results in lower outlet humidity with higher humidity ratio difference.

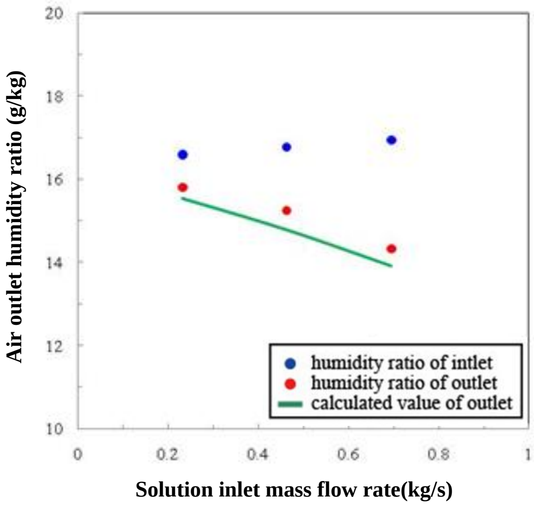

Fig. 15 Relation between air outlet humidity ratio and solution inlet mass flow rate.

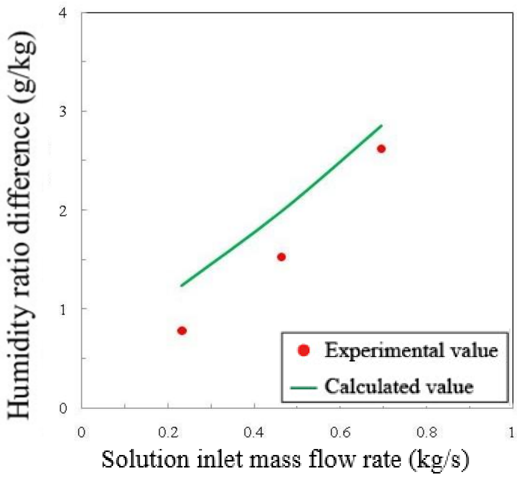

Fig. 16 Relation between humidity ratio and solution inlet mass flow rate.

Figure 17 shows the change in humidity removal rate and solution inlet mass flow rate. As shown in Figure 17, as the mass flow rate of the solution inlet increases, the contact surface area of the unit volume of air and the solution increases, improving its mass transfer capability for more moisture to be removed from the solution, making the system's humidity removal rates a tendency to increase.

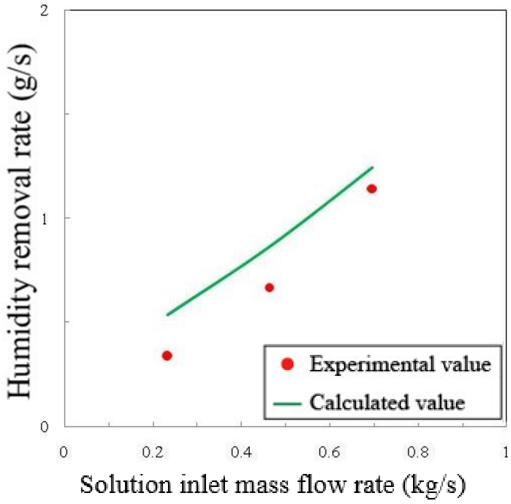

Fig. 17 Relation between humidity removal rate and solution inlet mass flow rate.

Figure 18 shows the change in the inlet and outlet temperatures of the air side and the solution side with the mass flow rate of the solution inlet. As shown in Figure 18, the air inlet dry bulb temperature condition is controlled at about 34 ℃, the solution inlet temperature condition is controlled at about 25 ℃, and the air inlet dry bulb temperature is higher than the solution inlet temperature. The dry bulb temperature at the air outlet gradually decreases as the mass flow rate of the solution inlet increases, mainly because the contact surface area per unit volume of air and solution increases as the mass flow rate of the solution increases. While the air outlet dry bulb temperature and the solution outlet temperature gradually decrease as the solution inlet mass flow rate increases, which is also due to the increasing contact surface area of air per volume and the solution as solution mass flow rate increases.

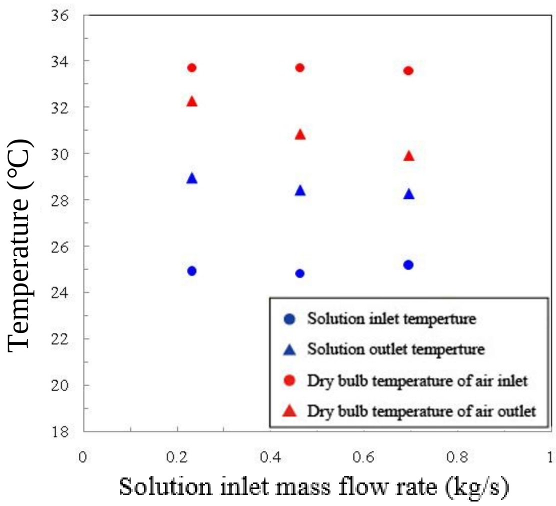

Fig. 18 Relation between change in air side, solution side inlet and outlet temperatures and inlet mass flow rate.

Figure 19 shows the dehumidification efficiency with varying solution inlet mass flow rate. It can be found that dehumidification efficiency increases as solution inlet mass flow rate increases, which is because when solution mass flow rate increases, the rising temperature after solution dehumidification is diminished, which results in greater pressure difference between gas and liquid while improving its mass transfer capability, the dehumidification efficiency is then promoted. As solution inlet mass flow rate rises from 0.23 kg/s to 0.69 kg/s, dehumidification efficiency will rise from 38 % to 61 %.

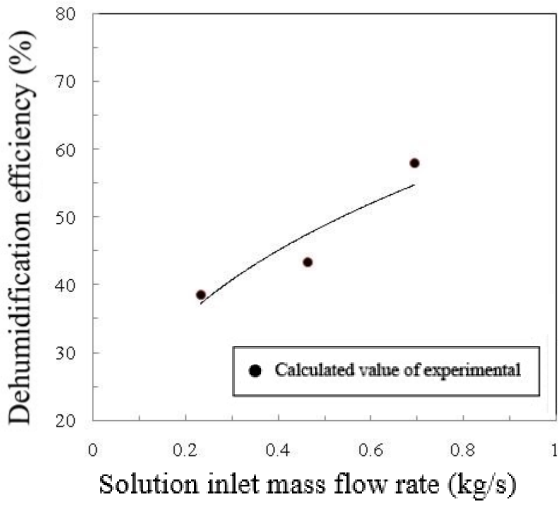

Fig. 19 Relation between dehumidification efficiency and solution inlet mass flow rate.

5. Conclusions

The dehumidification system of this paper uses Calcium chloride solution as its absorption solution. This paper discusses the influence inflicted by dehumidification toward air side and solution side.

(1) Utilizing the technique of solar thermal energy and shallow geothermal energy can not only reduce the energy consumption of the compressor but also assist the usage of heat pump, achieving the aim of energy-saving.

(2) The air mass rate has the best dehumidification efficiency of 68% at 0.25 kg/s. Dehumidification efficiency remains around 60% for the parameters of air temperature and air humidity.

(3) The solution mass rate has the best dehumidification efficiency of 61% at 0.69 kg/s. Dehumidification efficiency of remains around 60% for the parameters of air temperature and air humidity.

(4) According to the results of the experiment, the best dehumidification efficiency of 68% happens when air mass rate is 0.25 kg/s, air dry bulb temperature is 33.0 ºC, air humidity ratio is 17.7 g/kg, solution mass rate is 0.69 kg/s, solution temperature is 25 ºC, solution weight percentage of 38.5%, system atmosphere ratio is 17.7 g/kg, relative humidity is 60%, which is the most comfortable humidity for human body.

6. References

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