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ABSTRACT
The objective of this paper is to present experimental results on distribution characteristics of solar irradiation absorbed by the narrow channel wall of desiccant rotor. Experiments are performed with the channel made by the silica gel and the poly propylene (PP). Energy absorption rate is measured in conditions of different channel lengths, incident irradiation angles, air temperatures, and humidity. The result of the present measurement for silica gel is equal to that of the previous study [J. Li, Y. Hamamoto, and H. Mori, Transactions of the Japan Society of Refrigerating and Air Conditioning Engineers 32(2), 149–154 (2015)], which is conducted using laser light as a source. It is confirmed the previous prediction model of laser light is suitable for this solar light system. Moreover, the previous model is improved, because the rate of laser for PP is larger than that of solar. These models are applicable to predict desorption rate of the water vapor in a desiccant rotor heated directly by the concentrated solar irradiation. The results show that the absorption rates of solar irradiation and red laser are equal to each other in the silica gel channel. The absorption rates of the laser irradiation are larger than that of the solar irradiation for PP materials. It is clear that the solar irradiation absorption rate cannot be influenced by the ambient humidity and temperature. The prediction model of the absorption efficiency based on the laser for silica gel channel can reproduce well the absorption efficiency of experiment based on solar irradiation. In the case of PP, the difference between the prediction and the measurement is observed.

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I. INTRODUCTION

With the rapid development of society, world energy consumption is projected to increase by 71% until 2030. Energy consumption in air conditioning is estimated to 45% of the whole civil and commercial buildings due to the bigger demand of people for comfortable living environments. Meanwhile, the air conditioning industries face huge challenges of energy shortage and threat of global warming. Therefore, it is imperative to develop new cooling technologies to substitute the conventional vapor compression systems.

Solid desiccant cooling system is one of the new cooling technologies in recent years. Compared with other cooling systems, solid desiccant cooling system has several advantages, such as adjusting ambient air not only temperature but also humidity, driving by low grade thermal energy, environmentally friendly.

Desiccant cooling system is mainly composed of the dehumidifier (desiccant material), the regenerative heat source, and the cooling unit. The desiccant materials are impregnated into the adsorbent bed. They adsorb water vapour from the humid air when the incoming air stream goes through the desiccant rotor. To make the system working continually, the adsorbed water vapor must be desorbed out of the desiccant material. Then adsorbent can be dried enough and regenerated to absorb water vapour in the next cycle. This is done by heating the desiccant material to its regeneration temperature.

Silica gel is used as desiccant materials due to its low cost and low regeneration temperature. The low regeneration temperature only around 60–80°C is demanded. This kind of desiccant cooling system is recognized as a method for reducing the environmental load.

The regeneration heat source supplies energy for desiccant rotor desorption. Variety kinds of heat source can be used for
regeneration, such as solar energy. Most of the researchers chose solar collector to ensure adequate energy supply due to the instability of solar energy. However, when people are using solar collector, it is difficult to provide thermal energy at high temperature for the regeneration process of rotor because of the energy loss of conversion process in the collector.

To overcome the problem of loss energy, an idea of the desiccant rotor heated by direct solar thermal energy using a non-imaging Fresnel lens was recommended. An experiment and numerical study was conducted to analysis the performance of desiccant rotor. The non-imaging Fresnel lens is used to concentrate solar irradiation and provide stronger solar heat flux to the desiccant rotor. By direct heating, the desiccant rotor can be heated and regenerated quickly and effectively. It is expected to improve the desiccant rotor performance. The image of the direct heating process in the desiccant cooling system by solar irradiation is shown in Figure 1.

Li et al. presented the absorbed energy distribution in the narrow channel. In that study, a red laser light was selected to irradiate the sample channel in order to understand the trend of irradiation energy distribution preliminarily. In the performance analysis of a desiccant rotor, the concentrate solar irradiation is treated as the driven energy of desorption process. Therefore, in this study, authors focus on performing some experiments and finding the distribution characteristics of absorbed solar irradiation on the narrow channel wall of desiccant rotor with direct heating. It is significant to compare the distribution result of solar irradiation with that of laser light. Moreover, prediction models of laser are examined to evaluate the solar irradiation distribution in the desiccant rotor. These models are useful to predict desorption rate of water vapor in a desiccant rotor in which concentrated solar irradiance is used to heat and desorb from the rotor wall.

II. EXPERIMENT

A. Apparatus and samples

The schematic diagram of direct heating is shown in Figure 2. The desiccant rotor is irradiated directly by concentrated solar irradiation.

The measurement apparatus is composed of solar irradiation, basal plate, sample channels, laser power meter, nail, ruler, rotating holder, tracking device (nano.tracker equatorial) and tripod as shown in Figure 3 (a) and (b). Irradiation incident angle $\theta$ and sample channel length $l$ are set as variables.

Silica gel is widely used in the desiccant rotor of dehumidification air condition nowadays. Therefore, one of the sample channels is made by silica gel material, which is a part of the desiccant rotor and whose cross section is corrugate shape. This study also aims to find the influence factor of energy absorption in the narrow channel, so it is essential to select the materials of different roughness for comparison. Poly propylene plastic hollow board (hereinafter referred to as PP) is another sample choice. As compared to the silica gel channel wall, PP has smooth surface. Its cross section shows the shape of rectangular which is simpler than that of silica gel channel as shown in Figure 3 (c). Figure 3 (d) shows the schematics of the measuring apparatus for the solar irradiation energy absorption rate in side view and front view.

The sample parameters and ambient conditions are listed in Table 1. The hydraulic diameter $D_h$ of the channel is selected as the effective diameter for the following data calculation. In the measurement, changes in length are from 0.005 to 0.015m.

To measure the energy unabsorbed to the sample channel wall, the laser power meter is used as the energy receptor. It is a convenience and usual approach for the measurement. Its maximum measuring error is 5%. The diameter of sensor window of the laser power meter is 0.014 m less than the width and height of samples (0.016m×0.020m). Therefore, the sensor window can be covered by the desiccant sample.

In order to gain a better understanding of the distribution characteristics of absorbed energy in sample narrow channels, it is need to consider the influence of solar irradiation of different incident angles. The basal plate and samples should be rotated to different angles simultaneously due to the hard controlling of incidental solar rays. The rotated angle is changed in the range of 0 to $4\pi/9$, which is decided by the shuttle length of nail as shown in Figure 3 (b). The start incident angle is fitted when the solar ray is vertical to the cross section of sample. In the study, a tracking device (nano.tracker equatorial) is selected to decrease the error of measurement because of the earth rotation.

Additionally in order to understand the sample material property, authors measure the transmissivity of different layers of PP material with UV-VIS Spectrophotometer.

B. Data reduction

In Figure 3 (a), $I(0)$ denotes the detected energy before passing through the channel, that is, the amount of irradiation energy in
FIG. 3. (a) Side view of measuring apparatus (b) Front view of measuring apparatus (c) Cross section of samples (d) Schematics of measuring apparatus in side view and front view.

front of the sample at $x=0$. $I(x)$ expresses the detected energy after passing through the channel at the position $x=l$. Then, the irradiation energy absorption rate $g(x)$, that is, the rate of the absorbed energy between $x=0$ and $x=x$ to the inlet energy is calculated by the following eq. (1).

$$g(x) = 1 - \frac{I(x)}{I(0)} \quad (1)$$

C. Results and discussion

Measurements of energy absorption rate $g(x)$ for the sample silica gel and PP at temperature $12.1^\circ$C and relative humidity 42% are shown in Figure 4, plotted against the incident angle $\theta$. At $\theta=0$, there is expected no absorbed energy because the irradiated energy passes the channel from inlet to outlet directly. However, the small portion of the energy is actually absorbed at the edge of channel. Therefore,

| Energy source | Solar irradiation |
|---------------|-------------------|
| Adsorbent     | Silica gel [Equilibrium adsorption $q^* = 0.85\varphi/(1 + 4.5\varphi)$] |
| $l$ (m)       | 0.005, 0.010, 0.015 |
| $D_e$ (m)     | 0.0014 (Silica gel), 0.002(PP) |
| Roughness ($\mu$m) | 6.79 (Silica gel), 1.75(PP) [Thirteen points height roughness] |
| $\theta$ (rad) | 0 to $4\pi/9$ |
| $T$ ($^\circ$C) | 7, 12.1 |
| $RH$ (%)      | 42, 72 |
$g(x)$ at $\theta=0$ is not zero, although its amount is smaller than those at other incident angles. On the other hand, the absorption rate of irradiation energy reduces at $\theta=4\pi/9$ close to $\pi/2$ obviously where no incident ray reaches onto the channel inner wall.

$g(x)$ shows constant in the range of $\theta=\pi/9$ to $7\pi/18$ for the channel length 0.010 and 0.015m, while $g(x)$ gradually increases in that range of the short length 0.005m of silica gel channel. $g(x)$ of PP channel increases when the incident angle increases in the range of 0 to $\pi/3$.

In the previous study, a red laser was selected as an energy source to replace solar irradiation. In the present study, the result of silica gel channel indicates that the absorption rate trend of solar irradiation is similar to that of laser light as shown in Figure 4(a). Therefore the wavelengths of solar rays will influence $g(x)$ of the silica gel desiccant rotor weakly. However, the result of PP shows that $g(x)$ of laser is larger than that of solar as shown in Figure 4(b). Figure 5 shows the transmissivity of PP increases with the wavelength increases. The result indicates that long wavelength ray in solar irradiation is less absorbed to the wall. Therefore, $g(x)$ of solar irradiation in the PP channel is lower than that of laser light.

For the sample channels of silica gel and PP at different ambient humidity conditions, the changes of $g(x)$ at $\theta=0$, $\pi/18$, $\pi/3$, and $4\pi/9$ with the channel length are shown in Figure 6. The effects of humidity and temperature of surrounding air on $g(x)$ are seen little within the measurement accuracy. This result is same to that of the previous study which used laser light as the energy source. It means that there is no influence of the amount of adsorbed water on $g(x)$.

It is similar to the trend of the emissivity from the desiccant rotor material. PP is a suitable material to compare with silica gel on the diffused reflection which happens in the narrow channel due to its smooth surface. It shows that the energy absorption rate of silica gel channel is larger than that of PP as shown in Figure 6. This result is also as same as the result of laser. The authors believed that there is a diffused reflection in inner walls of the channel due to the different surface roughnesses. Therefore, the diffused reflection in the silica gel channel occurs strongly compared with the PP.

III. PREDICTION AND COMPARISON

In the previous study, two kinds of prediction models were presented to evaluate the energy absorption efficiency $f_a(x)$ which was calculated by the energy absorption rate $g(x)$. These models will play important roles in the analysis of desiccant rotor performance. However, authors proposed the models with laser irradiation. It is significant to compare the prediction $f_a(x)$ of laser with the experimental $f_a(x)$ of solar. In the above section, $g(x)$ of solar irradiation is presented. Here, $f_a(x)$ of solar is calculated from $g(x)$.
will examine the validity of the presented models for prediction the distribution of solar irradiation.

A. Comparison between energy absorption efficiency $f_a(x)$ of prediction based on laser and measurement based on solar in the silica gel channel

The prediction model of energy absorption efficiency $f_a(x)$ based on laser irradiation is expressed in eq. (2). The value of diffused reflection $\phi$ is assumed as 0.9. It means that the concentrated irradiation continues the reflection and diffusion in the desiccant rotor channel.

For $x \leq L_{di}$: $f_a(x) = a + \phi(1-a)$

For $x > L_{di}$: $f_a(x) = \{a + \phi(1-a)\} \times (1-\phi)^{\text{int}(x/L_{di})} (1-a)^{\text{int}(x/L_{di})}$

$$= E \exp(-Bx)$$

(2)

where $x$ is distance from the inlet along the channel [m], $L_{di}$ is direct radiation length of channel [m], $a$ is absorptivity of direct radiation [-], $\phi$ is diffused reflection ratio [-], $B$ is fitting parameter [m$^{-1}$], $E$ is fitting parameter [-].

Prediction method is as follows. Because $L_{di}$ is much shorter than the total length of the sample channel, the equation of $f_a(x)$ is written by the second equation of eq. (2) for $x>L_{di}$. As shown in Figure 7, energy absorption rate in the interval $\Delta x$ between $x-\Delta x$ and $x$ of narrow channel is expressed as eq. (3).

$$(I(x - \Delta x) - I(x)) \frac{\pi}{4} D^2 = I(0)f_a(x)\Delta x D_e$$

(3)

Combining eq. (3) with eq. (1), an equality equation $g(x)-g(x-\Delta x)$ and $f_a(x)$ is given as shown in eq. (4).

$$f_a(x) = \frac{D_e}{4} g(x) - \frac{g(x - \Delta x)}{\Delta x}$$

(4)

In the experiment, the difference in the length of the sample channels is 0.005m. This length interval is sufficiently small compared with general rotor dimension. Therefore, the length interval 0.005m is treated as $\Delta x$ in the prediction. $f_a(x)$ of experiment are calculated from data of the adsorption rate $g(x)$ shown in Figures 4 and Figure 6. The comparison between $f_a(x)$ of prediction and $f_a(x)$ of this experiment is shown in Figure 8. The values of variable parameters $B$ and $E$ in eq. (2) are shown in Table II. The results indicate that the trends of $f_a(x)$ from the prediction and $f_a(x)$ from the measurement are consistent. Therefore, the prediction model of laser can reproduce $f_a(x)$ data of solar experiment well. We examine that the prediction model of laser irradiation is valid for prediction of distribution of solar irradiation in the silica gel channel.

B. Improvement of the prediction model based on laser for PP

Because there are differences between energy distribution of laser and that of solar in the PP channel, so it means that the prediction model for PP must be improved.

Figure 9 shows the comparison between experiment process and view factors. The prediction method is as follows. The radiation energy has the similar absorption situation in interval length $\Delta x$ as

| $\pi/36 \leq \theta \leq \pi/6$ | $\pi/6 \leq \theta \leq 4\pi/9$ |
|-----------------|-----------------|
| $B$             | 573$\theta + 100$ | 400 |
| $E$             | $-1.43\theta + 1.12$ | 1.55exp(-2.55$\theta$) |

**Table II. Values of parameters $B$ and $E$ in eq. (2).**

**Figure 8.** Comparison of $f_a(x)$ between experiment and prediction model of silica gel channel.

**Figure 9.** Comparison between experiment process and view factors.
shown in eq. (3). The relationship between the absorption efficiency \( f_a(x) \) and the view factor \( F_{13} \) is written as eq. (5). Eq. (5) is rewritten as eq. (6). \( dF_{13}/dx \) is given by eq. (7). The cylindrical channel is selected to calculate the value of view factors. \( S \) is cross-sectional circumference of the sample channel.

Path 4: The B mass block was moved first, after a period of time, the A mass block was moved, then, the two mass blocks would reach predetermined position at the same time. Rational calculation formula is as follows:

\[
I(0) \times f_a(x) \times \Delta x \times S \approx F_{13}(x) - F_{13}(x - \Delta x)
\]

(5)

\[
f_a(x) \approx \frac{F_{13}(x) - F_{13}(x - \Delta x)}{\Delta x} = \frac{dF_{13}}{dx}
\]

(6)

\[
dF_{13} = -\frac{4}{D_e} x^2 + \frac{2}{D_e} \left( \frac{1 + x^2}{\Delta x} \right) x^2 + \frac{1}{\Delta x} \left( 1 + x^2 \right)^{-1}
\]

(7)

In the prediction, the absorption efficiency \( f_a(x) \) was given by eq. (8). \( \beta(x) \) was a fitting equation and determined by experimental data of laser irradiation as shown in eq. (9). But eq. (9) is not suitable for \( f_a(x) \) of solar irradiation. Therefore, authors improve eq. (9) for solar as shown in eq. (10).

\[
f_a(x) = \beta(x) \frac{dF_{13}}{dx} = g(x) - g(x - \Delta x)
\]

(8)

\[
\beta(x)_{\text{Laser}} = 1650x + 0.67
\]

(9)

\[
\beta(x)_{\text{Solar}} = 2840x + 1.75
\]

(10)

IV. CONCLUSIONS

This study presents experimental results of distribution characteristics of absorbed solar irradiation in the narrow channel of a regenerated desiccant rotor. Moreover, presented model is examined to predict the solar radiation distribution accurately. The main findings are summarized as follows.

1. The absorption rates of the solar irradiation and the red laser are equal to each other in the silica gel channel in the measurement error range.

2. The absorption rates of laser irradiation are larger than that of solar irradiation for PP.

3. Solar irradiation energy absorption rate does not depend on humidity and temperature. It means there is no influence of the amount of absorbed water on the rate. This result is observed not only the solar but also the laser.

4. The prediction model of absorption efficiency based on laser for silica gel channel can reproduce well the absorption efficiency of experiment based on solar irradiation.

5. For the case of PP, there is a difference between the prediction and measurement. Authors improve the fitting parameter of prediction model.

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