Experimental and Numerical Investigation on the Regeneration Process of Passive Solar Shading and Dehumidifying System for Hot-humid Areas

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Abstract
This paper presents an idea of passive solar shading and dehumidifying system to improve the indoor thermal environment and energy conservation in hot-humid areas. Elementary investigation on the regeneration of this passive system is undertaken. First, the test apparatuses are constructed for solar shading dehumidifier and silica gel is chosen as the desiccant material; the effects of internal surface color and the orientation of the test apparatus on the regeneration process are experimentally investigated. Then a mathematical model and valid Fortran program made to calculate the regeneration process are checked by the experimental results, it is used to analyze the influences of airflow rate, glass layer, the thickness of desiccant material and insulation material. The distribution and variation of moisture content and air temperature at different point in the apparatus are also obtained by numerical calculation. Experimental results and numerical results show that: lower airflow rate is beneficial to the regeneration of this passive system, the airflow rate influences the regeneration process greatly; thinner desiccant material layer can be quickly and fully regenerated, but adsorbs moisture easily; single glass layer and black internal surface are more affective of using solar energy to regenerate the desiccant material; insulation material has almost no effect on the regeneration process. The numerical results also show that desiccant material is more dehydrated when it is far from the inlet of air.

Key words: passive solar shading and dehumidifying system; regeneration process; desiccant material; solar energy

1. Introduction
As well known, the indoor air velocity, internal surface temperature, air temperature and relative humidity are the main factors that influence the indoor thermal comfort of human body. In hot-humid areas, outdoor air temperature and relative humidity are always high in summer, and solar radiation is the main cause that makes indoor thermal environment hot by directly transmitting through windows or heating the external surface building. To lower the heat gain from solar radiation and resist the heat transferring through the building envelopes, many passive methods and technique have been developed and researched in the past years. Using shelter to shade or reflect the solar radiation is the traditional method for windows and insulation material is usually used for walls and roofs (Liu Xiaotu, 1997). Passive-cooling with water evaporation such as water storing roof (Sekhar N.Kondepudl, 1993), water spraying roof (Y.Urano et al, 1987), planting roof/wall (Feng ya and Chen Qigao, 1999) and water film wall (Meng Qinlin, 1997) are intensively investigated and analyzed by the former researchers. Long wave radiation cooling and convective cooling at night are also studied by researchers (Takeo S.Saitoh and Satoshi Marushima, 1998). All of those passive methods are based on the idea of hindering and wasting the solar radiation in the outside of the buildings. Obviously, the solar energy is not efficiently used to improve the indoor thermal environment.

In hot-humid areas, solar shading is very important for buildings, but traditional shelters are always connected with the envelopes and with high temperature; solar heat can also be transferred into room through thermal bridge or by long wave radiation. In fact, when the envelopes of a building are well shaded from solar radiation with shelters of low temperature, the external surface temperature of the envelopes are almost the same as the air dry bulb temperature of outdoors. Furthermore, when the shaded external surfaces are also wetted by water, the external surface temperature of the building

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would be lowered to the wet bulb temperature of outdoor air. In this case, the heat will transfer conversely from indoor to outdoor. However, indoor thermal environment can’t be well improved by just shading or passive cooling of external surface, because the indoor air relative humidity is also high in hot-humid areas; indoor air relative humidity should also be lowered at the same time, a dehumidifier should be needed. In addition, when air is cooled by buried pipe and introduced into buildings, the absolute humidity might be not adequately lowered, further dehumidifying is also needed. Although the air conditioner and electric dehumidifier may be used to lower the indoor air relative humidity, it is inconsistency for the energy conservation and there are some problems in managements.

In this paper, a passive system combined solar shading and dehumidifying is presented, it lowers the indoor temperature by solar shading and decreases the indoor relative humidity by using solar energy. Considering one airtight room of $3 \times 4 \times 3$ m$^3$ with indoor temperature $25^\circ$C and indoor relative humidity 60% in hot-humid area, assuming the outdoor vapor density as 24g/m$^3$ and the air change rate is 0.5, namely air flow rate is 0.005 m$^3$/s; 1.72kg water vapor should be dehumidified from this room during the night. If the dehumidifying capacity of this passive system is greater than or equals the moisture amount that requires to be moved away from this room, the system can be used to improve the thermal moisture environment without any artificial energy consumption. The dehumidifying capacity must be firstly surveyed for this passive system. Since the dehumidifying capacity during the night directly dependents on the regeneration capacity by solar radiation on daytime, this paper also presents the experimental and numerical investigation on the regeneration process of this passive system by choosing silica gel as the desiccant material. In our simulation investigation, when the airflow rate is 0.0055 m$^3$/s, the result shows that the moisture amount dehydrated from the desiccant material by solar energy on the daytime is greater than that required to be removed from the mentioned room during night (see Fig.6).

However, this investigation is just the first step to study on the passive solar shading and dehumidifying system, eventual performance and effectiveness in regulating indoor relative humidity and reduction of cooling energy should be more researched in the future studies. Since some drugs and foods must be dried by desiccant at low temperature, the results can also be referenced by the medicine and food industry when silica gel is dehydrated by solar energy.

2. Passive Solar Shading and Dehumidifying System

Figure 1 illustrated the example of the passive system using with external wall. An apparatus called “solar shading dehumidifier” is equipped in the outside of the wall; it acts not only as outside shading for the wall but also as dehumidifier for moist air. Between the wall and the apparatus, opened ventilation air layer is remained for outdoor airflow, which cools the external surface of the wall.

On the summer daytime, external wall is well shaded from solar radiation and cooled by outdoor ventilation; this greatly lowers the external surface temperature of the building. Meanwhile, solar radiation is absorbed by desiccant material and the temperature in the dehumidifier becomes high, this causes the air flowing into the apparatus from the opened inlet (inlet1 or inlet2) and flow out from the outlet2 when outlet1 is closed. The moisture contained by the desiccant material are desorbed and carried away by the flowing air. Therefore, desiccant material is regenerated by solar energy. In this case, when inlet1 is opened, regeneration process enhances the indoor ventilation. At the summer nights, inlet2 and outlet2 are closed, air flows into the apparatus from the inlet1 and out from the outlet1, dehumidified by the adsorption process of desiccant material making indoor air relative humidity lower. The problem of air temperature rise at the outlet due to the moisture adsorption process should be considered; this can be solved by indirect passive cooling before the air is introduced into the room.

In winter, this system would be used as a heat collecting or humidifying system. On the daytime, the inlet2 and outlet2 are closed, inlet1 and outlet1 are opened, solar shading dehumidifier apparatus acts as a Trombe wall to collect solar radiation, indoor air is heated and driven by solar energy, flowing into the apparatus from the inlet1 and out from the outlet1; in the case of acting as a humidifying system, the inlet2 and outlet2 should be opened during the night so that the desiccant material can adsorb moisture from outdoor and humidifies the indoor air on the daytime by just opening the inlet1 and outlet1. This makes it as a humidifying system in the winter.
3. The Test Apparatuses and Experiment Conditions

To investigate the regeneration performance of this passive system and survey the effects of airflow rate, glass layer, internal surface color and the orientation on the regeneration process, test apparatuses for solar shading dehumidifier are designed and made. The construction and detail are shown in Figure 2. The frame of the test apparatus is made from wood panel with 10mm for bottom and 18mm for sides respectively. The test apparatus is 1421mm(length) × 830mm(width) × 200mm(height). Desiccant material layer is 1160mm(length) × 694mm(width) × 16mm(height) formed by iron meshes in the apparatus. The sides of the desiccant material layer are 32mm airflow layer. Two 4mm clear glasses are used as the upper glass and lower glass between them a 52 mm closed air layer is remained. 50mm foam polystyrene is used as insulation material for the bottom and the sides; it is stuck on the internal surface of the frame. Closed air layer between the glasses act as the insulation for the upper part. The two ends of the apparatus for the air flowing in and flowing out are not insulated, since they do not influence the flowing air temperature in the apparatus. Three fans are fixed as air blowers in the apparatus shown in Fig.2 (b), creating pressure and causing the air flow in the apparatus. All experimental investigations are taken by closing the inlet1 and outlet1, opening outlet2 with 20mm width. The width of the inlet2 is adjusted to control the airflow rate. When single glass is investigated, the upper glass is moved away. Before the desiccant material being packed, the weights of the dry desiccant and the empty apparatus (unpacked) are respectively measured by a balance with the resolution of 1g. The balance is also used to measure the total weight of the packed apparatus during the experiment investigation. The moisture weight in the desiccant material can be calculated by minus the weight of unpacked apparatus from the total weight. Since the total dry silica is about 10kg, the resolution of the balance is enough accuracy for the measuring. The total weight of the apparatus, outdoor air dry-bulb temperature and wet bulb temperature are recorded at the interval of one hour during the experimental investigation. The cumulated solar radiation is recorded at the interval of half hour. For the comparison of the investigation results, two same apparatuses marked B and C are used. The effects of the internal surface color and the orientation of the apparatus are respectively investigated on 9th and 18th of August in 2001.

4. Physical and Mathematical Model

In the regeneration process, air flows into the apparatus from one of the inlets and flow out from open outlet, the physical model can be made as Fig.2 shown. It is assumed that the distribution of air velocity in any section are uniform; the temperature and moisture content in the

| Test No. | Test date | Apparatus | Glass layer | Internal surface color | Orientation | Air flow rate( m³/s ) | Total Solar radiation (cal/cm²/day) |
|----------|-----------|-----------|-------------|------------------------|-------------|----------------------|-----------------------------------|
| 1        | 09th/08   | B         | Double      | White                  | Horizontal  | 0.0223               | 516                               |
|          |           | C         | Double      | Black                  | Horizontal  | 0.0211               |                                   |
| 2        | 18th/08   | B         | Double      | White                  | Vertical West| 0.01410              | 495                               |
|          |           | C         | Double      | Black                  | Vertical East| 0.01378              |                                   |
apparatus just changes with space variable x and time τ. Local thermal and moisture equilibrium state is also assumed to be valid in the desiccant material.

Fig.3. The Physical Model of Regeneration Process

The mass balance equation of moisture in the flow air is obtained by the analysis of the infinitesimal control volume; it is expressed as Eq. (1). Same procedure is used for the moisture balance in the desiccant material; it is expressed in Eq. (2) as follows.

\[
G_a \frac{\partial w}{\partial x} + 2h_r B \rho_m \frac{\partial w}{\partial \tau} = 2 \alpha_m B f (w_e - w) \tag{1}
\]

\[
h_2 B \rho_m \frac{\partial X}{\partial \tau} = 2 \alpha_m B f (w_e - w) \tag{2}
\]

Where, \( G_a \) is the dry air flow rate (m³/s); \( \omega \) and \( \omega_e \), the moisture ratio of flow air and equilibrium moisture ratio in desiccant material (kg/kg); \( h_r \) and \( h_s \), the thickness of flow air layer and desiccant material layer (m); \( B \) is the width of the desiccant material layer (m). \( f \) is the factor that is used to modify the contact surface area between flow air and desiccant materials. \( \alpha_m \) is the convective mass transfer coefficient based on the potential of moisture ratio (kg/(m²·s)); \( \rho_a \) and \( \rho_m \), the density of dry air and dry desiccant material (kg/m³); \( x \) and \( \tau \), space coordinate variable (m) and time variable (s). \( X \) is the moisture content of desiccant material (kg/kg).

The energy balance equations for flow air and humid desiccant material can also be obtained by the analysis of the infinitesimal control volume. They are shown as Eqs. (3) and (4).

\[
G_a \rho_a \frac{\partial h}{\partial x} + 2h_r B \rho_m \frac{\partial h}{\partial \tau} = 2 B f \alpha_q (t_e - t) + 2 B f \alpha_m (w_e - w) r + K_1 B (t_f - t) + 4 h_1 K_3 (t_f - t) \tag{3}
\]

\[
h_2 B \rho_m \frac{\partial h_r}{\partial \tau} = 2 B f \alpha_q (t_e - t) + 2 B f \alpha_m (w_e - w) r + K_2 B (t_f - t) + 4 h_1 K_3 (t_f - t) \tag{4}
\]

Where, \( h \) and \( h_r \), the enthalpy of moist air and humid desiccant material (J/kg); \( t_e \) and \( t \), the temperatures of desiccant material and the flow air; \( t_f \), \( \alpha_q \) and \( \alpha_m \), outdoor air dry bulb temperature (°C), convective heat transfer coefficient between flow air and desiccant material (W/(m²·°C)) and intensity of solar radiation absorbed by desiccant material (W/m²); \( K_1 \), \( K_2 \) and \( K_3 \), the overall heat transfer coefficient of the part in bottom, upper and side of the test apparatus (W/(m²·°C)). \( r \) is the latent heat (J/kg).

Eqs. (1), (2), (3) and (4) are rewritten as Eqs. (5), (6), (7) and (8).

\[
\frac{\partial w}{\partial x} = \frac{2 \alpha_m B f (w_e - w) - 2 B h_r \frac{\partial w}{\partial \tau}}{G_a} \tag{5}
\]

\[
\frac{\partial X}{\partial \tau} = \frac{-2 \alpha_m f (w_e - w)}{h_2 \rho_m} \tag{6}
\]

\[
\frac{\partial h}{\partial x} = \frac{2 B f \alpha_q (t_e - t) + 2 B f \alpha_m (w_e - w) r}{G_a \rho_a} + \frac{K_1 B + K_2 B + 4 h_1 K_3}{G_a \rho_a} (t_f - t) - \frac{2 B h_r \frac{\partial h}{\partial \tau}}{G_a} \tag{7}
\]

\[
\frac{\partial h_r}{\partial \tau} = \frac{2 f \alpha_q (t_e - t) + 2 f \alpha_m (w_e - w) r}{h_2 \rho_m} + \frac{I}{h_2 \rho_m} + \frac{2 K_3}{B \rho_m} (t_f - t) \tag{8}
\]

The last term in the right-hand side of Eq. (5) and Eq. (7), is always very small than the other terms and can be neglected. Eqs. (5) and Eq. (7) are rewritten as follows:

\[
\frac{\partial w}{\partial x} = \frac{2 \alpha_m B f (w_e - w)}{G_a} \tag{9}
\]

\[
\frac{\partial h}{\partial x} = \frac{2 B f \alpha_q (t_e - t) + 2 B f \alpha_m (w_e - w) r}{G_a \rho_a} + \frac{K_1 B + K_2 B + 4 h_1 K_3}{G_a \rho_a} (t_f - t) \tag{10}
\]

In the numerical calculations of regeneration processes of desiccant material in solar shading dehumidifier, following relationships are necessary. The relationship between convective heat transfer coefficient \( \alpha_q \) and airflow rate \( G_a \) is expressed by Eq. (11) as follows (Yoshimi Urano and Hiroshi Nakamura, 2001).

\[
\alpha_q = 5.6 + \frac{3.9 G_a}{2 B h_r} \tag{11}
\]

The relationship between convective mass transfer coefficient \( \alpha_m \) and convective heat transfer coefficient \( \alpha_q \) is presented by using the Lewis relation as follows (Meng Qinlin et al, 1999).
\[ \alpha_m = \frac{\alpha_g}{\rho C_p L_e^{1/3}} \]  

(12)

where, \( \rho = \rho_g (1 + w) \) is the density of moist air (kg/m³); \( C_p = C_{pa} + C_{pw} \) is the specific heat of moist air at constant pressure \( [J/(kg \, ^{°}C)] \); \( C_{pa} \) and \( C_{pw} \), the specific heat of dry air and vapor moisture; \( L_e \) is the Lewis number, \( L_e^{1/3} = 0.953 \) for humid silica gel according to the document (C.E. Bullock and I.L. Threlkeld, 1986).

The specific enthalpy of moist air \( h \) is the function of temperature \( t \) and moisture content \( w \), the relation is given by Eq. (13)

\[ h = (C_{pa} + C_{pw} w) t + rw \]  

(13)

The specific enthalpy of humid desiccant material \( h_m \) is the function of temperature \( t_e \) and moisture content \( X \), the relation is written in Eq.(14)

\[ h_m = (C_{pa} + \beta + C_{pw} X) t_e + \Delta L_X \]  

(14)

Where, \( C_{pa} \), \( C_{pw} \) and \( C_{pw} \), the specific heat of iron meshes, dry desiccant material and liquid water in desiccant material. \( \beta \) is the mass ratio of iron meshes to dry desiccant material. \( \Delta L \) is the adsorption heat, it is a function of moisture content \( X \), and can be expressed with Eq.(15) by regressing as following.

\[ \Delta L_X = a_1 X + a_2 X^2 + \cdots + a_n X^n + \cdots \]  

(15)

The equilibrium moisture content \( w_e \) is the function of the temperature \( t_e \) and the moisture content \( X \) in the desiccant material, it can be calculated from the isothermal adsorption or desorption curves of the desiccant material. The relation between \( w_e \) and \( t_e \) is the experiment apparatus. Therefore, the parameters \( w \) and \( h \) of the second cell from the parameters of first cell by Euler numerical method. The \( w \) and \( h \) in the other cells are calculated by the same way. Therefore, the distributions of \( w \) and \( h \) in the flow air layer are firstly obtained. Parameter \( t \) is then also obtained by Eq. (13).

3) Using the above calculated \( w \), \( h \) and \( t \), the parameters of \( X \) and \( h_m \) in the desiccant material are calculated with Eqs.(6) and (8) by Euler numerical method. Therefore, after the first step of time, the distribution of \( X \) and \( h_m \) are obtained, also related \( t \) and \( w \) are obtained by Eq.(14) and (16).

When the values of \( w \) and \( t \) are achieved, next \( w \) and \( h \) are calculated by the same procedure mentioned in above 2), and then the \( X \) and \( h_m \) are also calculated in the next step of time. Step by step, the distributions of parameters in the solar shading dehumidifier at any step are achieved.

6. Experimental Results and Numerical Results

The experimental results and numerical results for the test No.1 are shown in Fig.4 (b). Empty marks indicate the experimental results of apparatus B and C, solid dots indicate the numerical result of apparatus B. It shows that the numerical result agree well with the experimental result. Fig. 4a shows the changes of cumulated solar radiation, outdoor air dry bulb temperature and wet bulb temperature during the experimental investigation. The effects of the internal surface colors on the regeneration process are also showed in Fig. 4(b) by experimental results. It shows that black internal surface is better than white internal surface in the regeneration. This can be explained as following reason, the black surface absorbs more solar radiation than the white surface in the apparatuses, and makes the temperature of desiccant material higher; therefore, it is more affective than white surface in using solar energy to regenerate the silica gel. However, the thickness of silica gel layer in the test apparatuses is sufficient that most of the solar radiations are absorbed by desiccant material; the difference between black surface and white surface becomes small.

Fig.5 (b) shows the experimental results and numerical results for the test No.2. It indicates that vertical east facing apparatus C is just regenerated before noon, and
keeps at constant weight in the afternoon. Vertical west facing apparatus B is little dehydrated before noon, and dehydrated obviously in the afternoon. Comparing the total amounts of moisture that are dehydrated from 7:30 to 17:30, the moisture desorbed in apparatus B is more than that in apparatus C. This can be explained as following, the air temperature and solar radiation are always lower in the morning. Empty marks also indicate the experimental results; solid marks indicate the numerical results. It also shows that the numerical result agree well with the experimental result. Fig.5a shows outdoor conditions during the experimental investigation, which is also used for the numerical calculation.

It is necessary to investigate the effects of many other factors on the regeneration process of the solar shading dehumidifier; this can be done by numerical analysis with the program which is prove to be valid by the experiment results. In the numerical analysis, the properties of silica gel and the outdoor conditions shown in Fig.4 (a) are used; parameters of apparatus B listed in table1 are used as the basic reference parameters. In other words, when one of the factors is investigated, other factors for numerical calculation are same as that of apparatus B on 9th of August in 2001. For example, when the effect of airflow rate is investigated, double glass layer, white internal surface, horizontal orientation and 16mm desiccant material are reconsidered.

Fig.6 (a) shows the numerical results for airflow rate. It shows that airflow rate influences the regeneration process greatly; low airflow rate can improve the moisture desorption and week the moisture adsorption during the regeneration process. When the airflow rate is 0.00575 m³/s, the regeneration capacity is about 2.0
kg on the daytime. This means that the apparatus is effective to dehumidify the moisture during night for the room mentioned in the introduction. When the effect of desiccant material thickness is numerically investigated, moisture content of desiccant material would be used for comparison. Fig.6 (b) shows the numerical results of average moisture content in silica gel material. It shows that thinner desiccant material layer can be quickly and fully regenerated, but adsorbs moisture easily.

The numerical analysis results for the glass layer and insulation material are showed in Fig.7 (a) and Fig.7 (b) respectively. It shows that single glass layer is more affective than double glass layer in using solar energy to regenerate the desiccant material. Double glasses can form a closed air space to reduce the heat loss, but the total thickness of the glasses is twice of that of single layer and causes low transmittance of solar radiation. Fig.7 (b) suggests that the insulation material has almost no effect on the regeneration process of desiccant material. Therefore, the insulation material in solar shading dehumidifier should not be used in the practice. It should be noted that, this is the numerical result just for the regeneration process of desiccant material. When the apparatus is used as Trombe wall to collect the solar radiation in winter, the insulation material would be considered.

The distribution of moisture content and air temperature in the apparatus are also obtained by numerical calculation. The results are showed in Fig.8 (a) and Fig.8 (b). It indicates that the distributions of moisture content and air temperature are almost linear with x coordinate at any moment. The changes of moisture content in desiccant material and temperature in flow air at typical positions are showed in Fig.9 (a), and Fig. 9(b). When the position is far away from the inlet, the humid desiccant is more dehydrated.
7. Conclusions
A passive system combined solar shading and dehumidifying is presented for hot-humid areas. The passive regeneration processes of this system are experimentally and numerically investigated in this paper. Main conclusions are made as follows for the design and performance valuation of the passive solar shading and dehumidifying system.
(1) Single glass layer and black internal surface can enhance the regeneration of silica gel;
(2) Airflow rate influences the regeneration process greatly. In the range of our numerical investigation, low flow rate is affective of using solar energy to regenerate the desiccant material.
(3) Thinner desiccant material layer can be quickly and fully regenerated, but adsorbs moisture easily;
(4) Insulation material has almost no effect on the regeneration process of desiccant material;
(5) The distributions of moisture content and air temperature in the space of the solar shading dehumidifier are almost linear;
(6) Vertical west facing apparatus dehydrated more moisture than vertical east facing apparatus in a daily regeneration.
(7) Desiccant material is desorbed when solar radiation intensity becomes higher, and adsorbs moisture from the humid air when the intensity of solar radiation becomes lower. The regeneration process should be stopped before the adsorption occurring in practice.

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