The Experimental Works And Some Parametric Investigations of Thermally Activated Desiccant Cooling System

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SUMMARY

This paper presents the study of the desiccant based cooling system in the laboratory. The main purpose of the study is to determine the performance of desiccant system components. Also, using some results from the experimental works, preliminary parametric investigation in TRNSYS had been done. The investigation is centered on the application of the system in different climatic conditions. The results showed the dependence of the desiccant system upon the performance of its components and the climatic conditions.

INTRODUCTION

Desiccant based dehumidification and cooling system is envisioned as an alternative to the refrigerant based cooling system. The main advantage of the desiccant based system is that it can be directly operated using renewable thermal energy sources compared to the refrigerant based which is electrically operated. Several studies are on-going for the application of desiccant system in actual situations. This paper presents the studies conducted in our laboratory regarding this technology. The study is focused on the performance evaluation of the system components including some preliminary modeling and parametric investigations.

EXPERIMENTAL FACILITY AND EVALUATION

Experimental Facility

The thermal conversion facility was constructed to simulate the outdoor and indoor air conditions. The main purpose of the said facility is to test and investigate the performance of the desiccant based system. The experimental facility has a physical set-up shown in Figure 1. It has two controlled chambers in which Chamber A is used to simulate the outdoor air condition and Chamber B for the indoor air condition. The first chamber (A) has temperature range from -10\degree C to 40\degree C with accuracy of 2\%. The humidity could be varied depending on the needed condition. The accuracy of maintaining the set-value of the air humidity content is within 10\%. For Chamber B, the operating temperature range is from 10\degree C to 40\degree C with
accuracy of within 1%. The air humidity content could be varied as in Chamber A. Its accuracy is within 1%.

The technical description of the facility as shown in Figure 2. The source of raw air for both controlled chambers is from ambient air. It is forced to flow into the chambers by fans. If the temperature set-value is lower than that of the ambient air, air cooling operates. On the other hand, if the set-value of the needed air temperature is higher than that of the ambient, air heater operates. Seemingly similar is the situation for maintaining the air humidity content. If the ambient air humidity is high, dehumidification process operates. And when the ambient air humidity content is lower compared to the set-value the humidifier operates. The conditioned air is mixed in the controlled chambers before supplying it to the testing chamber. The testing chamber is located between the two controlled chambers. The air is moved from the chambers into the testing chambers using fans attached to the ducting system. In the testing chamber any kind of air handling unit and heat exchanger can be tested and evaluated. For this study, the desiccant system was evaluated.

**Experimental Evaluation of Desiccant System**

The main components of the desiccant based system consist of desiccant dehumidifier, heat recovery wheel, desiccant heater and evaporative cooler. The performance of the whole desiccant cooling system is dependent on the performance of its components. To determine the performance of its components, the performance evaluations of the desiccant wheel and heat wheel were undertaken.
Desiccant Wheel Evaluation

The desiccant wheel subjected to evaluation is a Silica-Gel coated wheel. It has 300mm external diameter with 100mm depth. The parameters considered for the evaluation were the rate of volumetric flow, the regeneration temperature and the wheel rotational speed. The considered flow rates were 100m³/hr and 200m³/hr. The regeneration temperatures applied were 60°C, 70°C and 80°C. For 100m³/hr the wheel rotational speeds were 5, 10, 15, 20, 25, 30, 35, 40, 50 & 60 RPH and for 200m³/hr the rotational speeds were 5, 10, 20, 30, 40, 50, 60, 70, 80 & 90 RPH. The selection of different wheel speed for the different flow rates was based on the initial test run that as the flow rate increases the optimum speed of the wheel increases. Figure 3 shows the schematic diagram of the wheel and the governing performances were based on NREL testing manual [1]. Based on the manual, the dehumidification performance of the desiccant wheel is based on moisture removal capacity or MRC. It is expressed as,

$$MRC = m_{OA}(AH_{OA} - AH_{PA})$$  \hspace{1cm} (1)

The amount of moisture removal capacity or sorption rate is the same at the regeneration side moisture regeneration rate which is the moisture removal regeneration (MRR) expressed as,

$$MRR = m_{RA}(AH_{EA} - AH_{RA})$$  \hspace{1cm} (2)

To evaluate the characteristic and performance of the experiment, the moisture mass balance (MBB) determined the quality of gathered data and thus the MBB is a checking factor and expressed as,

$$MMB = \frac{MRC}{MRR}$$  \hspace{1cm} (3)

For acceptable accuracy of gathered data, the ratio of MMB should be within 0.5 to 1.5. To be within the limits of acceptable accuracy improvements of the experimental conditions and instrumentations are highly necessary. And the nomenclature, $m_{OA}$ and $m_{RA}$ are the mass flow rates (outside air and return air), kg/s. $AH$ is absolute humidity content of air, g/kg. $OA$, $PA$, $EA$ and $RA$ are the outside air, processed air, exit air and return air.

Heat Wheel Evaluation

The evaluated heat wheel is coated with Silicone-Acrylic Compound. The physical appearance and dimension of the wheel is the same as the desiccant wheel. However, the
main purpose of the heat wheel is for sensible heat recovery only. In the evaluation, the moisture content of the air was not considered. To create temperature difference between the two counter flowing air streams in the wheel faces, air stream at cold side was maintained at 25°C and the air stream at hot side 50°C. For properly designed heat exchanger, variation of air streams temperature was found to have no effect on its performance. Therefore only these two temperatures were considered and the schematic diagram of the heat wheel is shown in Figure 3.

The other parameters used in the evaluation were the volumetric flow rates and the wheel rotational speed. The considered flow rates were 100 m³/hr and 200 m³/hr. The wheel rotational speeds were 2.5, 5, 10, 15 and 20 RPM. And, the performance evaluation of the heat wheel was based on its effectiveness in transferring sensible heat shown as [2],

$$\text{Eff}_{\text{Average}} = \frac{m_{CS}(T_{C(O)} - T_{C(I)}) + m_{HS}(T_{H(I)} - T_{H(O)})}{2m_{\text{Minimum}}(T_{H(I)} - T_{C(I)})}$$ \hspace{1cm} (4)

For the nomenclature, the $\text{Eff}_{\text{Average}}$ is the average effectiveness of the heat wheel. The $m_{CS}$ and $m_{HS}$ are the mass flow rates (hot and cold sides), kg/s. $T_{C(I)}$ and $T_{C(O)}$ are temperature of air in the cold side (inlet and outlet), °C. $T_{H(I)}$ and $T_{H(O)}$ are temperature of air in the hot side inlet and outlet, °C. And, $m_{\text{Minimum}}$ is the minimum flow rate of either cold or hot side, kg/s.

**EXPERIMENTAL RESULTS AND DISCUSSION**

**Desiccant Wheel**

Using equations 1, 2 and 3 in analyzing the gathered data and plotted below (Figure 4), the results show that the wheel performance is basically dependent upon its rotational speed. In the case of 100 m³/hr the optimum speed is 30RPH and for the 200 m³/hr flow rate the optimum speed is 50RPH. Meaning for the same type and dimension of wheel, increasing the flow rate will also increase the optimum wheel speed. The optimum speed is the same for different regeneration temperature. However, as the regeneration temperature increases, the moisture adsorption increases. At optimum speed, for the case of 100 m³/hr, the increase of moisture adsorption rate from 60°C to 70°C is 13% and from 70°C to 80°C the increase is 6 percent. In the case of 200 m³/hr flow rate the increase of adsorption rate from 60°C to 70°C is 14% and from 70°C to 80°C the increase is 5%. So, the amount of the regeneration temperature is another factor in the effectiveness of desiccant dehumidifier in moisture adsorption. However, the increase of moisture adsorption rate becomes lower as the regeneration temperature becomes higher. Based on the moisture mass balance presented in Figure 4 the gathered and analyzed data are within the range of 0.95 to 1.05. Thus experimental evaluation is within the accuracy imposed by NREL.

**Heat Wheel**

For the heat wheel the results of the experimental study are presented in Figure 5. For 100 m³/hr flow rate, the effectiveness approached 81% for wheel speed of 20RPM and for the 200 m³/hr the effectiveness approached 69% at 20RPM. Based on the results, the performance of the heat wheel is dependent on the wheel rotational speed and on the amount of flow rate. Results show that the wheel can be operated at 20 RPM as maximum rotational wheel speed.
MODELLING AND PARAMETRIC INVESTIGATION

Modeling

Preliminary modeling of the desiccant based system was implemented in TRNSYS [3]. Standard components were used such as the desiccant dehumidifier, the heat wheel and evaporative coolers. In the TRNSYS, the model of the desiccant dehumidifier is based on the analogy between the heat transfer of the sensible heat exchanger and of the desiccant heat and mass transfer. The input parameters of the model are the two effectiveness values proposed by P.J. Banks which is discussed in TRNSYS Manual. In this study, experimental results of the performance of the desiccant wheel were available. However, it could not be used directly to the model of the desiccant wheel. Thus the comparison between the experimental performance of the desiccant wheel and the model in TRNSYS was done through series of trials in finding the two effectivenesses that can have almost similar result to the experimental works. In the future study, this limitation will be addressed later. The modeling of heat recovery wheel is based on the sensible heat transfer from two streams of air in different temperatures. The actual effectiveness from the experimental work was used in the model. For the evaporative cooler, the modeling was based on effectiveness in reducing the dry bulb temperature to the maximum of its web bulb temperature. Based on the study cited by Daou, et al. 2006 [4], the maximum effectiveness of direct evaporative cooler is 90% and of the indirect evaporative cooler 80%. These parameters were used in the modeling since the current experimental set-up did not include experimental investigations in these devices. In general, the above considerations were used in the modeling and parametric investigation. Thus some deviations occurred in the results when compared with the experimental works.

Figure 6 shows the schematic diagram of the experimental unit which was under experimental investigation. This set-up was also used for comparison with the modeling done in TRNSYS. As stated above, since the model of the desiccant wheel in TRNSYS has no provision for direct comparison with experimental results, series of trials had been done. The finest trials that can be reached are presented in Table 1. Based on the results, the comparisons are within 10 percent. However, some points such as of points 2, 3 and 7 of the relative humidity content, the results are more than 10 percent. These points are in the desiccant wheel. As stated above, since the TRNSYS desiccant model cannot have direct comparison with the experimental results, higher deviation in these states was expected. This is the limitation of TRNSYS and should be subject for more improvements to arrive at a good agreement between the experimental and the simulated results. Considering this limitation, some parametric investigations were done for testing the capability of the model when applied in different conditions.

Simulation

The parametric investigations for the application of the desiccant cooling system was implemented in different climatic conditions; for temperate climate - little bit warm and humid, for the Mediterranean - warm and humid and, of the tropical climate - relatively hot and humid for all-year-round. Table 2 shows the temperature and relative humidity for the countries representing the three different climatic conditions used in the study. Two models of the desiccant cooling system were used for the investigation: the standard desiccant cooling system shown in Figure 7 and, the desiccant cooling cycle with pre-cooling of outdoor air prior to the desiccant wheel shown in Figure 8.
PARAMETRIC INVESTIGATION RESULTS AND DISCUSSION

Using the performance data, stated above, regarding the comparison between the experimental results and modeling and, applied in different climatic conditions the results are presented in Table 3. Based on the presented results the standard desiccant cycle can operate effectively in temperate and Mediterranean climates. However, for the Mediterranean climate, the needed regeneration air temperature (RegA) is high, more than 100°C. For tropical climate, the standard cycle cannot operate and supply comfortable air condition since the sensible load of air is higher even though the air latent load is lower. On the other hand, the cycle with pre-cooling may attain the same capability in temperate and Mediterranean climates and comparable to standard cycle with lower supply air and regeneration temperature (only small difference). However, in the tropical areas, the system is still short of supplying comfortable air condition as shown in the condition of the supply air temperature. But, by using much more efficient pre-cooling devices such as borehole heat exchanger, absorption chiller and others, the system performance could be further improved as shown in graphical presentation, Figure 9.

Based on this presentation, the desiccant adsorption process increased when the air temperature entering the desiccant wheel decreased. Thus cooling the outdoor air to near saturation may increase the dehumidification performance of the desiccant wheel. However, further study should be done to determine the over-all performance of the system. Some research works conceptualized the pre-cooling effect intended for hybrid desiccant cooling system [5].

SUMMARY AND CONCLUSIONS

Experimental works and some parametric investigations were conducted. Based on the results, the performance of the desiccant cooling system is dependent on the intrinsic and
**Table 1. Results of the experimental works and of the simulation (100m$^3$/hr).**

<table>
<thead>
<tr>
<th>STATE POINT</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation (T) [°C]</td>
<td>30.0</td>
<td>55.3</td>
<td>31.7</td>
<td>26.0</td>
<td>49.4</td>
<td>82.3</td>
<td>56.8</td>
</tr>
<tr>
<td>Experimental (T) [°C]</td>
<td>30.8</td>
<td>59.2</td>
<td>33.5</td>
<td>26.1</td>
<td>52.6</td>
<td>80.0</td>
<td>51.9</td>
</tr>
<tr>
<td>% Difference</td>
<td>2.5</td>
<td>6.6</td>
<td>5.4</td>
<td>0.4</td>
<td>6.1</td>
<td>2.8</td>
<td>8.7</td>
</tr>
<tr>
<td>Simulation (RH) [%]</td>
<td>60.0</td>
<td>7.1</td>
<td>24.1</td>
<td>55.0</td>
<td>15.4</td>
<td>3.6</td>
<td>18.9</td>
</tr>
<tr>
<td>Experimental (RH) [%]</td>
<td>58.5</td>
<td>9.1</td>
<td>35.3</td>
<td>55.5</td>
<td>13.3</td>
<td>3.9</td>
<td>20.1</td>
</tr>
<tr>
<td>% Difference</td>
<td>2.5</td>
<td>22.5</td>
<td>31.7</td>
<td>0.9</td>
<td>13.6</td>
<td>8.7</td>
<td>6.0</td>
</tr>
</tbody>
</table>

**Table 2. The different climatic conditions for parametric investigation.**

<table>
<thead>
<tr>
<th>CLIMATE</th>
<th>COUNTRY</th>
<th>DBT (T) [°C]</th>
<th>RH [%]</th>
<th>AH [g/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMPERATE (Warm and Less Humid)</td>
<td>JAPAN (Tokyo)</td>
<td>30</td>
<td>60</td>
<td>16</td>
</tr>
<tr>
<td>MEDITERRANEAN (Warm and Humid)</td>
<td>ITALY (Palermo)</td>
<td>30</td>
<td>70</td>
<td>19</td>
</tr>
<tr>
<td>TROPICAL (Hot and Very Humid)</td>
<td>PHILIPPINES (Manila)</td>
<td>35</td>
<td>75</td>
<td>27</td>
</tr>
</tbody>
</table>

**Figure 5. The Heat Wheel Effectiveness.**

**Figure 6. Schematic diagram of the first unit desiccant cooling system.**

**Figure 7. Standard and common desiccant cooling system.**

**Figure 8. The standard desiccant cooling system with pre-cooling.**
Table 3. The simulation results between the standard desiccant cycle (Figure 7) and with pre-cooling of outdoor air prior desiccant wheel (Figure 8).

<table>
<thead>
<tr>
<th>DESICCANT COOLING SYSTEM</th>
<th>CLIMATE</th>
<th>OA(T) [°C]</th>
<th>OA(RH) [%]</th>
<th>SA(T) [°C]</th>
<th>SA(RH) [%]</th>
<th>SA(AH) [g/kg]</th>
<th>RegA(T) [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1 (Standard Cycle)</td>
<td>Temperate</td>
<td>30</td>
<td>60</td>
<td>21.60</td>
<td>57.30</td>
<td>9.20</td>
<td>85.50</td>
</tr>
<tr>
<td>Model 2 (With Pre-Cooling Cycle)</td>
<td>21.20</td>
<td>58.20</td>
<td>9.12</td>
<td>82.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1 (Standard Cycle)</td>
<td>Mediterranean</td>
<td>30</td>
<td>70</td>
<td>22.70</td>
<td>54.90</td>
<td>9.44</td>
<td>98.60</td>
</tr>
<tr>
<td>Model 2 (With Pre-Cooling Cycle)</td>
<td>22.40</td>
<td>55.50</td>
<td>9.37</td>
<td>96.40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 1 (Standard Cycle)</td>
<td>Tropical</td>
<td>35</td>
<td>75</td>
<td>27.10</td>
<td>46.10</td>
<td>10.32</td>
<td>149.00</td>
</tr>
<tr>
<td>Model 2 (With Pre-Cooling Cycle)</td>
<td>26.70</td>
<td>46.80</td>
<td>10.23</td>
<td>146.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The Return Air (RA) condition was maintained at 26°C and 55%.

Figure 9. Effect of increasing the performance of pre-cooling prior desiccant wheel.

extrinsic parameters such as effectiveness of its components and outdoor air condition. For practical application of the system in real conditions, further investigation and analyses are imperative and thus additional and thorough research is important. Further investigation of the desiccant cooling system will be the next direction of this research works.

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