Effect of micro-encapsulated phase change materials on the performance of liquid desiccant dehumidification

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SUMMARY
A novel idea of auto internally-cooled liquid desiccant system was proposed in this paper, by adding micro-encapsulated phase change materials (MEPCMs) in the liquid desiccant solution, the isothermal heat absorption characteristics of phase change materials can be applied to achieve “auto internally-cooled” liquid desiccant dehumidification process, and the performance of the dehumidification process is expected to be improved. In this study, several factors influencing the dehumidification performance, such as the mass concentration of MEPCMs, the temperature and the flowrate of the micro-encapsulated phase change materials slurry (MPCMS), were investigated experimentally. Besides, the performances of liquid desiccant dehumidification with and without MEPCMs were compared. Under different conditions mixing proportions of liquid desiccant and varied moisture removal loads, the effect of MEPCMs on the performance of liquid desiccant dehumidification was obtained. A new empirical correlation was developed to predict the moisture effectiveness of MPCMS. The deviations between the calculated value and the experimental value are within 10%. Experimental results show that the temperature rise in the dehumidification process can be restrained considerably and the dehumidification performance can be improved by the MPCMS.

INTRODUCTION
Liquid desiccant dehumidification is an efficient air-condition technology and has been attracting more and more attention for its merit in environmental protecting and energy saving properties. However the temperature rise of the solution caused by the absorption of latent heat limits the dehumidification efficiency. Researchers (Niu et al. 2012; Niu et al. 2016) combined the liquid desiccant with heat pump, the liquid desiccant was cooled by the evaporative cooling capacity while the condensation heat was supplied to the regeneration process. The result showed that the COP of refrigeration system and dehumidification system had both been improved. Internally-cooled dehumidifier is another useful technique to improve the dehumidification effect. Researchers have proved that the internally-cooled dehumidifier is beneficial to the enhancement of dehumidification effect (Yin et al. 2009; Bansal et al. 2011). However, the application have been restricted due to the complex structure and inherent corrosive characteristics. Scholars have proposed some techniques to diminish the corrosive effect of liquid desiccants, such as coating the dehumidifier with epoxy (Turgut and Çoban 2016) or substituting thermally conductive plastic for metal materials in dehumidifier (Liu et al. 2015). However, the above studies didn’t fundamentally solve the problem of complex structure of the internally-cooled dehumidifier and as time passed by, dehumidification efficiency reduced due to the reoccurrence of corrosion. Researchers have ever attempted to use phase change materials (PCM) to suppress the desiccant temperature rise. Rady proposed a desiccant dehumidifying bed composed of silica gel particles and encapsulated phase change material (Rady et al. 2009). The PCM in above study were used in the dehumidifying bed and the diameter of particle is 2mm.

In this paper, the temperature rise in the dehumidification process is expected to be restrained by adding microencapsulated phase change materials (MicroPCMs). The latent heat will be absorbed by MicroPCMs, and the temperature of desiccant will be restrained, which enhance the dehumidification performance. By adding MicroPCMs into base fluid, the MPCMS were formulated. MPCMS has a large specific and can significantly enhance heat transfer. Wang found that the MPCMS can be significantly beneficial to the natural convection (Wang et al. 2016). Shabgard and Kong has respectively found that the MPCMS can enhance the heat transfer when flowing between parallel plates (Shabgard et al. 2016) or flowing in the helically coiled tube (Kong et al. 2016).

In the existed literature, there is no related research on the MPCMS based liquid desiccant system. In the paper, the effect of several factors on the dehumidification performance, such as the mass concentration of MEPCMs, the temperature and the flowrate of the MPCMS, were investigated experimentally.

METHODS
An experimental test rig has been built to study the dehumidification performance of MPCMS. The schematic of the experimental test rig is shown in Figure 1. As shown in the Figure 1, the experimental test rig mainly consists of three parts: the air process facilities, the dehumidifier and the measurement facilities. The air inlet conditions are controlled by the air process facilities. The temperature and humidity ratio of the air can be maintained at the required condition by adjusted the electric heater and electrode humidifier with PID controllers. In the test rig, two 12cm×12cm×24cm solution tanks are used. MPCMS is adjusted to the required temperature condition in a constant temperature water bath and then is added into one tank from the injection hole. The other tank is used to stores the diluted MPCMS. The flow rate of MPCMS can be adjusted by valves. In the dehumidifier, structured packing with a specific area of 205m2/m3 is used. The packing is made of porous cellulose fibre paper which has a good wettability. The cross-sectional area of the packing is 0.04m2 and the height is 0.3m. The dehumidifier and tanks are made of Plexiglas with thickness of 10mm and the adiabatic condition of experiments can be ensured. During the experiment, MPCMS is pumped by a fluorine-lining magnetic pump from the strong desiccant storage tank into the dehumidifier. The solution pipes are...
made of CPVC, and all measurement instruments and mental joints are made of 316L stainless steel to prevent corrosion. MPCMS is sprayed evenly at the top of the dehumidifier. After heat and mass transfer process between MPCMS and air in the dehumidifier, the diluted desiccant solution leaves at the bottom of the dehumidifier and flow to the weak solution tank. Measurement facilities conclude measurement instruments and data collection instrument. The temperature of MPCMS is measure by PT100 RTDs (Resistance temperature detector) and the temperature of air is measured by T-Thermocouple. The humidity ratio of air is measured by humidity transducers. The flow rate of air and MPCMS are measured by an anemoscope and an electromagnetic flowmeter respectively. The concentration of MPCMS is measured by moisture tester. All the measuring data are collected by the data acquisition unit Agilent34972.

In this study, 110 groups of experiments were conducted to test the dehumidification performance of MPCMS in the counter flow packed-type dehumidifier. The concentration of lithium chloride (LiCl) aqueous solution is set at 35% and the mass concentration of MicroPCMs ranges from 0.5% to 2%. The air and MPCMS flow rate are set at relative small condition because of the small amount of MPCMS and prevention of desiccant carryover. The experimental conditions are listed in Table.2. In each experiment, the inlet condition can maintain stable for 10 minutes, which is long enough for reliable data collection. The energy balance analysis was conducted to examine the adiabatic condition of the experiments. In order to diminish the effect of the MicroPCMs, the lithium chloride aqueous solution is used in the energy balance analysis. The enthalpy variations of the air and the solution can be calculated by Eq.(1) – Eq.(3):

\[ Q_a = m_a(h_{a,in} - h_{a,out}) \] (1)

\[ Q = m_s(h_{s,out} - h_{s,in}) + m_d h_{d,out} \] (2)

\[ m_d = m_a(d_{a,in} - d_{a,out}) \] (3)

where \( m_a \) and \( m_s \) are the mass flow rate of air and solution respectively, kg/s. \( h_a \) and \( h_s \) are the enthalpy of air and solution respectively, KJ/kg. \( d_a \) is the humidity ratio of air, g/kg. The enthalpy of LiCl aqueous solution are be calculated by the fitting formulas reported in literature (Chaudhari and Patil 2002). Figure 2 shows the energy balance of experiment results between the air and LiCl aqueous solution. It can be seen that almost all the deviations are within ±15%. The results show that the adiabatic condition of the experiments are reliable. Figure 3 shows the moisture removal rate of LiCl solution in the experiments. The comparison between the experiment results and the predicted moisture removal rate from Chen’s model (Chen et al. 2006) are also shown in Figure 4. It can be seen that the maximum deviation between experiment results and predicted results is within 15%. It can be considered that the experimental test rig is reliable.

![Schematic of experimental test rig](Image)

**Figure 1. Schematic of experimental test rig**

<table>
<thead>
<tr>
<th>Experimental inlet condition of air and MPCMS</th>
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</thead>
<tbody>
<tr>
<td><strong>Air</strong></td>
</tr>
<tr>
<td>m_a (kg/s)</td>
</tr>
<tr>
<td>29.8</td>
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<tr>
<td>-</td>
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<tr>
<td>-</td>
</tr>
<tr>
<td>16.9</td>
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<td>-</td>
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<tr>
<td>0.03</td>
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<td>-</td>
</tr>
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<td>0.03</td>
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</tbody>
</table>

![Enthalpy variation of air (kW)](Image)

**Figure 2. Enthalpy variation of air (kW)**

![Enthalpy variation of desiccant (kW)](Image)

**Figure 3. Comparison between predicted results by Chen’s model and experiment results**

![Predicted moisture rate (g/kg)](Image)

**Figure 4. Predicted moisture rate (g/kg)**
In the process of liquid desiccant dehumidification, the moisture transfer from the gas side to the solution side driven by the partial water vapor pressure difference between solution and air. The moisture removal rate and the moisture effectiveness are essential indices to determine the dehumidification performance of desiccant. The moisture removal rate is the difference between inlet and outlet air humidity. The moisture effectiveness is the ratio of the actual moisture removal rate to the maximum possible difference. These indices are defined by Eq. (3) and Eq. (4). The deviation between desiccant outlet temperature of MPCMS and LiCl solution has also been studied.

$$\Delta d = d_{a,\text{in}} - d_{a,\text{out}}$$  \hspace{1cm} (3)$$
$$\varepsilon_d = \frac{d_{a,\text{in}} - d_{a,\text{out}}}{d_{a,\text{in}} - d_{e,\text{in}}}$$  \hspace{1cm} (4)$$

Where $d_e$ is the equilibrium humidity ratio of air in equilibrium with desiccant surface.

RESULTS AND DISCUSSIONS

Influence of inlet parameters on the dehumidification performance

The influence of inlet parameters of the air and MPCMS on the dehumidification performance are investigated experimentally. The inlet parameters include air inlet humidity ratio, air inlet flow rate, air inlet temperature, desiccant inlet temperature, desiccant flow rate, as well as mass concentration of MicroPCMs. The influence of the inlet parameters on moisture removal rate and moisture effectiveness are shown in Figure 4 and Figure 5 respectively. It can be seen that the addition of MicroPCMs can significantly enhance the dehumidification performance. The moisture removal rate and effectiveness both improve with the increase of content of MicroPCMs. From Figure 5, it can be seen that the increase of air inlet humidity ratio and MPCMS flow rate can obviously enhance the moisture removal rate, while the air inlet flow rate, and the MPCMS inlet temperature will obviously reduce the moisture removal rate. The air inlet temperature has negative influence on the moisture removal rate, but the effect is not significant. As shown in Figure 6, the air inlet humidity ratio and the MPCMS flow rate have obvious positive influence on the moisture effectiveness, while the air inlet flow rate, air inlet temperature and the MPCMS inlet temperature have negative influence on the moisture effectiveness. Unlike LiCl solution, increasing the air inlet humidity significantly increases the moisture effectiveness of MPCMS. The reason for this phenomenon is that the addition of MicroPCMs reduce the partial water vapor of MPCMS and increase the specific heat of MPCMS, which increase the mass transfer potential. The moisture removal rate, as well as the effectiveness, reduces rapidly with the increase of MPCMS inlet temperature. The decline is more obvious with temperature rise. It is because the MicroPCMs has almost completed phase change at high temperature, which reduces the specific heat of MPCMS and raises the vapor pressure of MPCMS, and finally significantly reduced the mass transfer potential between the air and the MPCMS. The moisture removal rate and effectiveness increase with MPCMS flow rate. An approximately explanation is that the viscosity of MPCMS is relatively large, and increasing MPCMS flow rate can improve the contact between the air and MPCMS (Moon et al. 2009). However, the increase of air inlet flow rate

<table>
<thead>
<tr>
<th>Desiccant flow rate (kg/s)</th>
<th>Air inlet humidity ratio (g/kg)</th>
<th>Moisture removal rate (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>--</td>
<td>-</td>
<td>0.05</td>
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<td>24</td>
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</table>

**Figure 4. Influences of inlet parameters on the moisture removal rate**
reduces the moisture removal rate and effectiveness. The shorter contact time may account for that but the reason need further investigations.

Influence of inlet parameters on the MPCMS outlet temperature

As shown in Figure 6, the addition of MicroPCMs can obviously reduce the desiccant outlet temperature and the outlet temperature reduces obviously with the increasing content of MicroPCMs. Increasing desiccant flow rate can obviously reduce the desiccant outlet temperature, while the left four parameters all contribute to the desiccant outlet temperature.
temperature rise. The temperature decline between MPCMS and LiCl solution reduce with the increase of air inlet humidity ratio. An explanation is that with the increase of air humidity, more moisture transfer to the MPCMS and more latent heat is absorbed, which leads to the temperature rise. The air temperature rise increases the heat transfer potential between air and MPCMS, which also leads to the desiccant temperature rise. The temperature decline between MPCMS and LiCl also reduce with the increasing desiccant inlet temperature. This may be because the MicroPCMs keep absorbing heat and changing phase with the increasing temperature, which lead to the reduce of specific heat of MPCMS. The increase of air inlet flow rate reduces the temperature decline between MPCMS and LiCl solution, but the effect is no significant. This is due to the ineffective utilization of contact area and short contact time.

**Empirical correlation of moisture effectiveness**

Based on the experimental results, a new empirical correlation of the moisture effectiveness is developed. The correlation is given in Eq(5). The limitation of this correlation is that it does not take the packing size into account. The validity range is also limited due to the relative small range of air inlet flow rate and desiccant flow rate.

$$
\varepsilon = 2.01555m_n^{-0.0873667}L_n^{-0.11205}d_{in}^{0.144984} 
\times m_s^{0.159902}a^{-0.269545}w_{MPCMS}^{0.082}
$$

In the correlation, the parameters with positive power exponent has positive influence on the dehumidification effectiveness, while the parameters with negative power exponent has negative influence on the effectiveness. The absolute value of the power exponent reflect the incidence of the parameters. The deviation of the predicted effectiveness and experimental effectiveness is shown in Figure 8. The discrepancies between the predicted values and the experimental values are within ±10% and the average absolute difference is 5.1%. The results above indicate that the new empirical correlation can be used to predict the dehumidification performance of MPCMS.

**ACKNOWLEDGEMENT**

This work was supported by the National Natural Science Foundation of China [grant number 51406076]; the Natural Science Foundation of Jiangsu Province [grant number BK20140942]; and the Research Innovation Program for College Graduates of Jiangsu Province [grant number SJCX17_0283]. The support is gratefully acknowledged.

**REFERENCES**


**CONCLUSIONS**

In the study, an experimental test rig has been built to investigate the dehumidification performance of MPCMS. MPCMS works as a novel liquid desiccant in the counter flow packed-type dehumidifier. The dehumidification performance is evaluated by the moisture removal rate and the moisture effectiveness. A empirical correlation is developed depend on the experiment results to predict the moisture effectiveness of MPCMS. The predicted results are compared with the experimental results. The deviations between predicted values and experimental vales are within 10% and the ADD is 5.1%. The correlation can be used to predict the dehumidification performance of MPCMS.

The experimental results shows that the addition of MicroPCMs can significantly enhance the dehumidification performance. At the same condition, the MPCMS has much higher moisture removal rate and moisture effectiveness than LiCl solution. The enhancement can increase with the increase of content of MicroPCMs. The air inlet humidity and the MPCMS flow rate can have obvious positive influence on the moisture removal rate while the air inlet temperature, air inlet flow rate and the MPCMS inlet temperature have negative influence on the moisture removal rate. The increasing air humidity ratio can also enhance the moisture effectiveness, as well as the MPCMS flow rate. The temperature rise can be obviously restrained by adding MicroPCMs. Increasing desiccant flow rate can obviously reduce the desiccant outlet temperature, while the left four parameters all contribute to the desiccant temperature rise. The desiccant outlet temperature of MPCMS is lower than that of LiCl solution when the inlet condition are the same. The temperature decline will increase with the increase of content of MicroPCMs.


