Investigation on the Performance of a Novel Dehumidifier for a Combined Solar Chimney and Liquid Desiccant Plant

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Abstract. A dehumidifier was one of the main component in the hybrid liquid desiccant system and solar chimney micro-plant. The performance of the hybrid liquid desiccant system and solar chimney micro-plant was strongly depended on the performance of it dehumidifier, but it is yet to be analyzed in any of the previous studies. Therefore, moisture removal rate (MRR) and dehumidification effectiveness ($\varepsilon$) were two parameters that had been chosen to evaluate the performance of the cross flow, cellulose panel structured bed dehumidifier in this study. Calcium Chloride (CaCl$_2$) desiccant solution was the only liquid desiccant solution used in this application. From the experiment, it was found that the highest effectiveness of the dehumidifier was about 22.78% and the highest moisture removal rate was about 0.22 ml/s. Besides that, parametric analysis had been conducted on five inlet parameters: desiccant inlet concentration, desiccant inlet temperature, inlet air humidity ratio, inlet air mass flow rate and inlet air temperature; the most influencing parameter was found to be the inlet air humidity ratio, $y_{a1}$. MRR increased by 52.68% and $\varepsilon$ of the dehumidifier increased by 48.59% when $y_{a1}$ increased from 0.0175-0.0200. Finally, three improvement strategies had been recommended: increasing the concentration of liquid desiccant, changing the type of liquid desiccant and increasing the thickness of the dehumidifier.

Keywords: solar chimney, fresh water, generator, water security, solar energy

1. Introduction

In human daily life, water and energy are two indispensable item for us to continue our living[1], as an example it is a natural resource that humans need in order to maintain the function of organ and regulate body temperature, while energy are needed for light. As the human population kept increasing globally, the dependence of fossils fuels and the scarcity of other non-renewable resources has force the scientist and researchers worldwide to find out alternative strategies for generating fresh water and electricity to fulfill the growing demand. Therefore, a technology of hybrid liquid desiccant and solar chimney system micro-plant has been applied in current study. This micro plant as shown in figure 1.1 is a combination of two green technologies which are liquid desiccant system and solar chimney, also known as solar updraft tower. The earliest application of solar chimney application is on 1982, the Manzanares power plant in Spain[2]-[4]. Since then, solar chimney or solar updraft tower has caught the attention of scientist and researchers worldwide and a research campaign on this new technology has been started. A review on the concept, history and operating features of the solar chimney application has been done. Besides that, the potential in combined solar chimney with liquid desiccant system for simultaneous production of electricity and fresh water through atmospheric humidity has also been discussed by the author.[5]
1.1. Literature review
As mentioned in the title, the investigation on the performance of a novel dehumidifier for a combined solar chimney and liquid desiccant plant, the main focus of this study is the novel dehumidifier used in this system. As a result, table 1.1 has list out all the similar previous studies related to the performance of liquid desiccant dehumidification system (dehumidifier). In this investigation, the flow configuration is cross-flow for the dehumidification systems of liquid desiccant apply in this combined micro plant. Therefore, heat and mass transfer process for cross-flow configuration and type of desiccant solution used has been study in order to formulate all the require equation for thermodynamic analysis. All the paper listed in the table is the main references for completing this literature review.

Table 1.1. Similar previous studies on the performance of liquid desiccant dehumidification system

| Author And Year     | Findings                                                                 | Desiccant Solution Used |
|---------------------|--------------------------------------------------------------------------|-------------------------|
| Bassuoni (2014)[6]  | A simple analytical method to estimate all exit parameters               | CaCl₂                   |
| Gao (2012)[7]       | Experiment investigation of heat and mass transfer                        | LiCl                    |
| Pineda & Diaz (2011)[8] | Performance of a small scale prototype                                 | CaCl₂                   |
| Babakhani (2010)[9] | Coupled mass and heat transfer process                                   | LiBr                    |
| Moon (2008)[10]     | New mass transfer performance data                                        | CaCl₂                   |
| Liu (2004)[11]      | Experimental study on mass transfer performance of cross flow dehumidifier using liquid desiccant | LiBr                    |
2. Methodology

2.1. System Description

Solar chimney usually consists of a circular greenhouse type collector and a tall tower at its center. This system application works when air flow radially inwards under the air collector and is heated by the collector floor and roof, and the hot air flow through a turbine to enters the chimney. The solar chimney in current study is applied and combined with the dehumidifier of the liquid desiccant system which generates water from the atmospheric humidity. As illustrated in figure 2.1, a typical schematic diagram of a technology for fresh water production from atmospheric humidity by using liquid desiccant system[12]. The main components in such system consist of dehumidifier, regenerator, heat exchanger, desiccant cooler, desiccant heater and also the circulating pumps. The application of solar chimney in current studies helps drawing in the wet atmospheric air from the surrounding into the dehumidifier of liquid desiccant system. As the wet atmospheric air flows into the dehumidifier, the liquid desiccant that flow through the top of the dehumidifier absorb the air moisture from the wet atmospheric air and bring the weak liquid desiccant solution (with air moisture) to the regenerator tank to produce fresh water. This kind of system usually applies near sea side, as the sea water can act as a natural sea water reservoir for cooling purpose. However, in current study this sea water reservoir has been replaced with a cooling water tank. The main focus of this study is about the cross flow, cellulose panel structured bed dehumidifier which surrounded the solar chimney and covered by transparent polyethylene sheet as shown in figure 2.2. The dimension of this dehumidifier used is 0.6m in height, 0.6m in width and 0.25m thick. The exact location of this micro plant is besides block G8 and behind the Tun Fatimah Residential Colleague of Universiti Tun Hussein Onn Malaysia (UTHM).

![Figure 2.1. Schematic diagram of a fresh water production technology from atmospheric humidity by liquid desiccant system.[12]](image-url)
Figure 2.2. Cellulose panel structured bed dehumidifier used in the combined solar chimney and liquid desiccant plant

2.2. Data Collection
To obtain all the operating parameter of the combined solar chimney and liquid desiccant micro plant in current study, a few instruments are needed as shown in table 2.1. The step and method to collect the parameters of solar chimney are shown in figure 2.3. A ladder will be used to climb over and the probe will be inserted to the chimney to obtain all the required operating parameters. A cloth will be put around the probe during measurement to prevent the hot air from flowing out from the cap. Air temperature, relative humidity and air velocity in the chimney are being measured at the designated cap of the solar chimney by using TSI VELOCICALC Plus Multi-Parameter Meters.

| Operating parameters                                      | Devices                                      |
|-----------------------------------------------------------|----------------------------------------------|
| Ambient air temperature and relative humidity (Surroundings) | BENETECH Digital Multi-purpose Anemometer    |
| Air Velocity, Air temperature and relative humidity in the chimney | TSI VELOCICALC Plus Multi-Parameter Meters |
| Concentration of Liquid Desiccant                         | Measuring Tube and Pocket Digital Scale      |
| Inlet Liquid Desiccant Temperature                         | AMS V-line Thermometer                       |
| Desiccant Flow Rate                                       | TT10 In-Line Digital Turbine Meter           |

Figure 2.3. Steps in collecting the data from the solar chimney
2.3. Thermodynamic Analysis
Thermodynamic analysis has been applied to this study as this system involves mass flow across the boundaries especially on the dehumidifier. Based on the conservation of mass principle, the net mass transfer, \( m_{\text{in}} - m_{\text{out}} \) is equal to the net change in the system, \( \Delta m_{\text{system}} \) during the process. Equation (1) shows the mass balance equation which is applicable to any kind of system with any kind of process. The conservation of mass equation can be referred as continuity equation in fluid mechanics.

\[
m_{\text{in}} - m_{\text{out}} = \Delta m_{\text{system}} \tag{1}
\]

2.4. Moisture Removal Rate
The moisture removal rate (MRR) can be defined as equation (2), where \( m_{\text{cond}} \), is the rate of water vapor condensed by the dehumidifier kg/s.

\[
m_{\text{cond}} = MRR = m_a(\Delta y) \tag{2}
\]

2.5. Dehumidification Effectiveness
Dehumidification effectiveness is one of the common performance measures for investigating the dehumidifier potential to dehumidified air. From the research paper of Moon et al.\[10\], equation (3) an empirical correlation of the humidity effectiveness \( \epsilon \) which is valid for cross-flow liquid desiccant dehumidifiers have been developed.

\[
\epsilon = \frac{y_{a1} - y_{a2}}{y_{a1} - y_{eq}} \tag{3}
\]

Where, \( y_{eq} \) the humidity ratio of air in equilibrium with desiccant (CaCl\(_2\)) solution at the interfacial area is calculated as shown in equation (4):

\[
y_{eq} = \frac{0.622p_{\text{vap}}}{1.013\times10^{5} - p_{\text{vap}}} \tag{4}
\]

As \( p_{\text{vap}} \), partial vapor pressure on the desiccant solution surface in Pa. By using equation (5) the correlations introduced by Gad et al.\[13\], the partial vapor pressure on CaCl\(_2\) will be calculated with this formula below

\[
ln(p_{\text{vap}}) = (a_0 + a_1X) - \frac{(b_0+b_1X)}{T_s+C} \tag{5}
\]

Where:
- \( a_0, a_1, b_0, b_1 \) and \( C \) are all constant value
- \( X \) desiccant (CaCl\(_2\)) solution concentration, \( kg_d/kg_s \)
- \( T_s \) desiccant (CaCl\(_2\)) temperature in °C
3. Results And Discussion

3.1. Experimental Results

Five testing days in between 19th October 2018 to 4th November 2018 has been choose to conduct experiment study on the hybrid liquid desiccant system and solar chimney micro plant, from 9 am to 6 pm on a full day basis. All the results obtained have been analyzed in the next section.

3.2. Performance Parameters

As illustrated in figure 3.1 below, an hourly average line has been plotted and only 3 days have exceeded the average line during the peak hour at 1 pm. The highest MRR obtain is on the 28 October. Based on the data obtained, 28 October is one of the humid day experienced during the testing as most of the ambient humidity ratio is above 0.02. Another factor that leads to high MRR believes to be the ambient temperature on 28 October, an ambient temperature as high as 36°C is registered at the noon (about 1pm). On the other hand, the hourly effectiveness of the dehumidifier also give some similar results to the MRR, as there are only 3 days that exceed the average line at the peak time as shown in figure 3.2. These 3 days that exceed the average line of MRR and hourly effectiveness of dehumidifier are the same which are 24 Oct, 28 Oct and also 4 Nov. The highest effectiveness of 22.78% has been registered on the 24 October. Referring to the data recorded, 24 October is assumed to be a humid day because the humidity ratio registered at 1 pm is about 0.0221, which was the highest among the five testing days. Besides humidity ratio, the difference in humidity ratio, Δy during 24 October is 0.005, which is the highest when compared to all the data registered among five testing days. This explains why the dehumidification effectiveness is the highest during 24 October. As a results, good MRR will need a combination of high outdoor humidity ratio and high air mass flow rate, while good effectiveness need a combination of high outdoor humidity ratio and a good difference in humidity ratio, Δy.

Figure 3.1. Hourly Moisture Removal Rate, MRR of the dehumidifier
3.3. Parametric Analysis

There are five inlet parameters which are desiccant inlet concentration, desiccant inlet temperature, air inlet humidity ratio, air inlet mass flow rate and air inlet temperature in this study which will surely affect the performance, moisture removal rate (MRR) and effectiveness ($\varepsilon$) of the novel dehumidifier of a combined solar chimney and liquid desiccant plant. Parametric analysis has been conducted with the operating conditions as table 3.1 below to determine the most influencing parameters for these systems.

| Case                                | Value of the inlet parameters |
|-------------------------------------|-------------------------------|
|                                     | $T_{a1}$ °C | $m_a$ kg/s | $y_{a1}$ kg$_{sw}$/kg$_a$ | $T_{x1}$ °C | $X_1$ kg$_d$/kg$_s$ |
| Desiccant Inlet Concentration ($X_1$) | 33       | 0.037     | 0.0221               | 32       | 0.302-0.400          |
| Desiccant Inlet Temperature ($T_{x1}$) | 33       | 0.037     | 0.0221               | 28-38    | 0.302                |
| Inlet Air Humidity Ratio ($y_{a1}$) | 33       | 0.037     | 0.0175-0.020       | 32       | 0.302                |
| Inlet Air Mass Flow Rate ($m_a$)    | 33       | 0.037-0.047| 0.0221             | 32       | 0.302                |
| Inlet Air Temperature ($T_{a1}$)    | 28-34    | 0.037     | 0.0221             | 32       | 0.302                |

![Figure 3.2. Hourly Effectiveness, $\varepsilon$ of the dehumidifier](image)
3.4. Effect Of Inlet Parameters To Performance Parameters
After completing all parametric analysis on the previous section, one can observe that inlet humidity ratio is the most influencing parameter for moisture removal rate, MRR (52.68%) and dehumidification effectiveness (48.59%). The second goes to inlet air temperature, which caused 30.17% increment in average, while 22.68% increment on the dehumidification effectiveness. Other inlet parameters such as the concentration of inlet liquid desiccant, desiccant inlet temperature and inlet air mass flow rate did increase or decrease the performance parameters but only in a less significant ways, in average less than 5%. However, both inlet humidity ratio and inlet air temperature depending on the outdoor climate condition and it is uncontrollable. Therefore, this combined solar chimney and liquid desiccant plant can perform well in place with high humidity ratio and high ambient temperature.

3.5. Improvement Strategies
A summary of the strategies suggested has been tabulated as shown in table 3.2 below:

| Opportunities                          | How                                                                                                                                 |
|----------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| The concentration of Liquid Desiccant  | Increase the Concentration from 30.2% to 40%. As proven in the parametric in the previous section, increase the concentration may results in increment in the moisture removal rate, MRR.  |
| Type of Liquid Desiccant               | In this study, Calcium Chloride is used as the liquid desiccant solution. Lithium Bromide (LiBr), Lithium Chloride (LiCl) and even mixture of CaCl$_2$ and LiCl can be used as liquid desiccant for combined solar chimney and liquid desiccant plant.[14] |
| Size of the dehumidifier               | Increase the size of the dehumidifier by increasing it thickness[7]. However, the equilibrium point between pressure loss and moisture removal rate should be found to obtain the best results. |

4. Conclusion
The conclusions of this study are as below:
- A combined solar chimney and liquid desiccant plant micro-plant has potential to be developed into a new technology for simultaneous production of fresh water and electricity in the near future.
- The highest dehumidification achieved is around 22.78% (24Oct) as shown in figure 3.1, while the highest moisture removal rate (MRR) registered among the five testing days are 0.22ml/s (28Oct) as shown in figure 3.2. It can be conclude that the highest MRR does not result in the highest effectiveness of the dehumidifier. Dehumidification effectiveness and MRR does not depend on the same parameters but a combination of a few parameters, such as ambient temperature, relative humidity and even the climate condition.
- After completing the parametric analysis (refer to table 3.1), it is found that the most influencing parameter is the inlet air humidity ratio although it is uncontrollable and fully depends on the outdoor conditions.
- Several improvement strategies had been suggested for future studies. (refer to table 3.2)

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