Possible application of solar steam regeneration method in absorption air-conditioning system

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Abstract. In recent years, solar absorption air-conditioning system have become an important directions of solar energy utilization. Improving solar energy utilization efficiency can effectively solve the problems of energy crisis. In traditional thermal method, low efficiency suffer from the heat loss and the cost is expensive. To improve solar energy utilization efficiency, a solar steam regeneration method was proposed: with corresponding material structure that can locate solar energy in the event of evaporation and minimize heat loss. The material structure has a high absorption in the solar spectrum, thermally insulating, hydrophilic surfaces and interconnected pores which allows the fluid flow to and from the structure. The solar steam regeneration method can be used in solar absorption air-conditioning system. Models have been developed and some important parameters have been investigated. The influence of concentration and absorbent variety has been analyzed in the experiments. Preliminary testing of the evaporation process has been carried out. It found the solar energy utilization efficiency with solar steam method has potential to further increase by 2 or 3 times. The solar energy utilization efficiency of the solar steam regeneration system approached 46%. That indicates it a promising choice for solar desalination and absorption system.

1. Introduction
In the conventional method, solar energy usually heats the bulk liquid to a quite high temperature to generate water steam [1]. Low efficiency and the requirement for high optical concentration limit the utilization of solar energy. Recently, Chen et al have proposed a solar steam method to improve the efficiency of solar energy utilization for steam generation [2]. The method uses photo-thermal materials to localize the solar heat in the evaporation surface and thus decreases the thermal loss to bulk water [3]. It can improve solar thermal efficiency at low optical concentration in open air while generating steam [4].

At present, researches on the solar steam method mainly focused on exploring materials with high absorption in the solar spectrum [5]. There are no studies on absorbent solutions. This paper presents propose a solar steam method based absorption air-conditioning system. We have analyzed and discussed the regeneration process of three common absorbents in theory. Experiments have been made to test the regeneration rate of water for different absorbent solutions. The results show solar steam method can greatly improve the thermal efficiency at lower optical concentration. The experimental solar energy utilization efficiency of solar steam method based absorption system increase exponentially.

2. Materials and methods
2.1. Principle of the solar steam method

The original idea about solar steam method was first proposed by a research group led by Chen in 2014 [2]. Its core is to achieve thermal heating localization. With photo-thermal materials, solar heat will gather on the evaporation surface, which can reduce the heat loss and improve the energy utilization efficiency. This photo-thermal structure demands four characteristics: high absorption in the solar spectrum, thermally insulating, hydrophilic surfaces and interconnected pores which allows the fluid flow to and from the structure. Figure 1 shows the schematic diagram [6]. The porous structure serves as the light absorber; the cellulose wrapped expanded polyethylene foam serves as the thermal insulation. When the structure is illuminated by sunlight, the upper surface will efficiently convert the absorbed light into localized heat. Then the surface water will evaporate and rapidly escape into the air. This method can bring high thermal efficiency and produce high temperature vapor under the same optical concentration.

![Figure 1. Schematic diagram [6].](image1)

![Figure 2. Experimental system.](image2)

2.2. Experimental system of the solar steam regeneration method

Figure 2 presents the configuration of the experimental platform. Three different absorbents are used in the experiment. We chose carbonized cunninghamia as the photo-thermal material. After treatment, the wood showed ultra-high absorptivity, low thermal conductivity, self-floating properties and high solar thermal efficiency [7]. Cunninghamia has good corrosion resistance and mechanical strength.

2.3. Performance estimation of the solar steam system

The solar energy utilization efficiency $\eta$ of the whole system is:

$$\eta = \frac{Q}{P} = \frac{lm}{PS}$$

where $l$ is the latent heat of water vaporization. $P$ is the power density of solar illumination. $S$ is the area of the material illuminated by sunlight.

By applying Eq. (1), we can analyze the utilization efficiency of the system.

2.4. Theoretical analysis of the solution regeneration

With the water vapor evaporating, the solution concentration becomes larger. It will inhibits the regeneration process. To maintain a same evaporation rate, it is necessary to consider increasing the solution temperature. One conception of the heating localization in the solar steam regeneration process is to reduce the liquid bulk to be heated. This measure can reduce the total energy provided to raise the liquid to a certain temperature. But actually, the less liquid leads to faster evaporation and faster concentration; so more energy must be provided to heat the solution to a higher temperature for maintaining the evaporation speed. Is the final result increased energy consumption or energy savings during the solar steam regeneration process?
Taking LiCl solution as an example, we first calculate the vapor pressure of LiCl solution of certain concentration, amount and temperature. The relative vapor pressure $\pi$ can be calculated as [8]:

$$\pi = \frac{p_{\text{sol}}(\xi, T)}{p_{\text{H}_2\text{O}}(T)}$$

(2)

$p$ is the vapor pressure, $\xi$ is the mass fraction of solute, $T$ is the absolute temperature.

$$c_{p,\text{sol}}(T, \xi) = c_{p,\text{H}_2\text{O}}(T) \times (1 - f_1(\xi) \times f_2(T))$$

(3)

c_{p,\text{H}_2\text{O}}$ is the specific thermal capacity of water, $c_{p,\text{sol}}$ is the specific thermal capacity of solution.

The energy consumed $Q$ by heating the absorbent solution is:

$$Q = c_{p,\text{sol}} m_{\text{sol}} \Delta T$$

(4)

$m_{\text{sol}}$ is the amount of the solution. $\Delta T$ denotes the temperature increase of the solution.

3. Results and discussion

3.1. Theoretical results of solution regeneration

Taking 500g of LiCl solution as an example. The initial solution temperature is 25℃ and heat it to 70℃. Here we take different percentages of the solution to calculate the concentration and vapor pressure. The vapor pressure of LiCl solution in 70℃ are displayed in Figure 3 (a). As it shows: the vapor pressure in 70℃ increases from 6.4898KPa to 16.7419KPa; $\text{Con}_{\text{LiCl}}$ decreases from 41.7% to 28.5%. With the increases of concentration, the energy consumed $Q_1$ by heating the solution decreases from 5.6512KJ to 5.0814 KJ.
To maintain the same regeneration speed, the solution must be heated to a higher temperature. Suppose the vapor pressure of different concentrations of LiCl solution is 16.7419KPa. Figure 3 (c) shows the temperature rises from 70°C to 90.9°C as Con_{LiCl} increases from 27.2% to 41.7%. The energy consumed Q_1 increases from 5.6512KJ to 7.6162KJ. Figure 3 (d) shows Q_1 is less than Q_2 for the same concentration. The difference between Q_1 and Q_2 enlarges as Con_{LiCl} increases. That indicates heating LiCl solution with smaller liquid body increased the total energy consumption. Similarly, the results of LiBr solution are shown in Figure 3. When heating LiBr and CaCl_2 solution with smaller liquid body achieve a final energy saving effect.

3.2. Experimental results

Figure 4 (a) shows the evaporation rate of LiCl solution. The evaporation rate based on the solar steam method rapidly increased in the first ten minutes, then it tended towards smoothly. Comparatively, the evaporation rate without the solar steam method had no distinct change. The evaporation rate based on the solar steam method is greater. Compared with the rate without the method, it had been raised by 260 percent. Figure 4 presents the evaporation rate with different concentrations. The evaporation rate of water kept on decreasing as Con_{LiCl} increased from 20% to 35%. The comparison between the theoretical and experimental results are shown in Figure 5. Figure 5 (a) reveals the experimental evaporation rates. Figure 5 b presents the change law of the theoretical vapor pressure. The solution vapor pressure determines the evaporation rate. The trend of the change of the evaporation rate is correspondent with that of the theoretical vapor pressure. That indicates the theoretical analysis results are in good agreement with the experimental results.

Figure 4. The evaporation rate of LiCl solution with different concentrations.
3.3. Solar energy utilization efficiency of the absorption system based on the solar steam method

Figure 6 shows the solar energy utilization efficiency of LiCl solution. It can be found the solar energy utilization efficiency keeps increasing at the beginning. The solar energy utilization efficiency decreases with the increasing concentration. The maximum value reaches 30.1% and the average is 24.9%. The average value of the solar energy utilization efficiency is only 9.8% when $\text{Con}_{\text{LiCl}}$ is 35%.

3.4. Discussion
The solar steam based system uses photo-thermal materials to achieve thermal heating localization. This manner can decrease the thermal loss to bulk water and achieve high efficiency steam generation. Cost is another advantage of the solar steam based system. The core of the absorption system is fabricated by a low-cost and ordinary materials. Solar energy utilization efficiency will decrease as the increases of the concentration.

4. Conclusions
The solar steam method based absorption system has many good features of the traditional solar absorption system. Moreover, the use of photo-thermal materials reduces the initial investment and maintenance cost. Primary experimental researches have exposed the new method can greatly increase the evaporation rate of solution at lower optical concentration. The solar energy utilization efficiency of LiCl solution reaches 30.1%. The experimental solar energy utilization efficiency is between 10%
and 40% under different solution concentrations. The solar energy utilization efficiency with the solar steam method increases by 2 or 3 times. The solar energy utilization efficiency is higher with lower absorbent solution concentration.

5. References
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