International Journal of Smart Grid and Clean Energy

Analysis of a solar assisted $CaO/Ca(OH)_2$ chemical heat pump drying system

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Abstract

Toward the utilization of renewable energy for drying food and to reduce the environmental impact from using a fossil fuel energy, the solar assisted $CaO/Ca(OH)_2$ chemical heat pump drying system proposed to meet the demand in the drying field and for clean environment. In this paper the solar assisted $CaO/Ca(OH)_2$ chemical heat pump drying system designed and evaluated for tropical region. It consists of four main components: solar collector (evacuated tubes type), storage tank, solid-gas chemical heat pump and dryer chamber. The reaction used in the study is $CaO/Ca(OH)_2$. The predicted hourly efficiency of a solar evacuated tubes was recorded in the ranges of 79.65% to 46.33%, where the mean collector temperature and ambient temperature difference was 20^oC. The maximum of coefficient of performance achieved for the chemical heat pump (COP^h) was 2.87 for 0.6 m^2 solar collector area and 0.628 m^3 storage tank. The results show the predicted coefficient of performance for chemical heat pump by using calcium chloride with water vapor as working pair is more efficient than using metal chlorides/ammonia. Besides that, the use of water vapor for chemical heat pump is more suitable and safe when compared to ammonia gas.

Keywords: Solar collector, $CaO/Ca(OH)_2$ CHP, coefficient of performance (COP^h), drying

1. Introduction

Over the past three decades there has been nearly exponential growth in drying R&D on a global scale. After the energy crisis of the early 1970s, and although the price of oil did drop subsequently the awareness of the significance of improving the drying operation to save energy, improve product quality as well as reduce environmental effect remained and indeed has flourished over recent years [1]. Drying is the most energy-consuming industrial operation [2]. The increasing rate of fuel consumption in agriculture has made it necessary, not only to save energy; by intensifying the drying process, improving designs, etc., but also using renewable sources [3]. The idea of combining the heat pump and sources energy brings the mutual beneficial by improving COP of the heat pump and displace the fossil energy resource [4]. A number of investigations and studies have been conducted by several researchers in the design, modeling, and testing of solar assisted heat pump systems (SAHPS). The systems being studied can be categorized into several groups such as SAHPS in store drying, SAHPS for drying, SAHPS for heating, SAHPS for space heating, SAHPS with direct expansion for space heating and solar assisted ground source heat pump greenhouse heating system (SAGSHP) [5]. A chemical heat pump (CHP) is proposed as one of the potentially significant technologies for effective energy utilization in drying. Ogura and Mujumdar [6] studied the CHP and proposed a chemical heat pump dryer (CHPD) system for ecologically friendly effective utilization of thermal energy in drying. Fadhel *et al.* [7] have been studied the solar assisted chemical heat pump dryer using salt-ammonia chemical heat pump, and concluded that the coefficient of performance of CHP will decrease if the energy in condenser will decrease as well as the efficiency of drying will decrease, and the maximum coefficient of performance of a chemical heat

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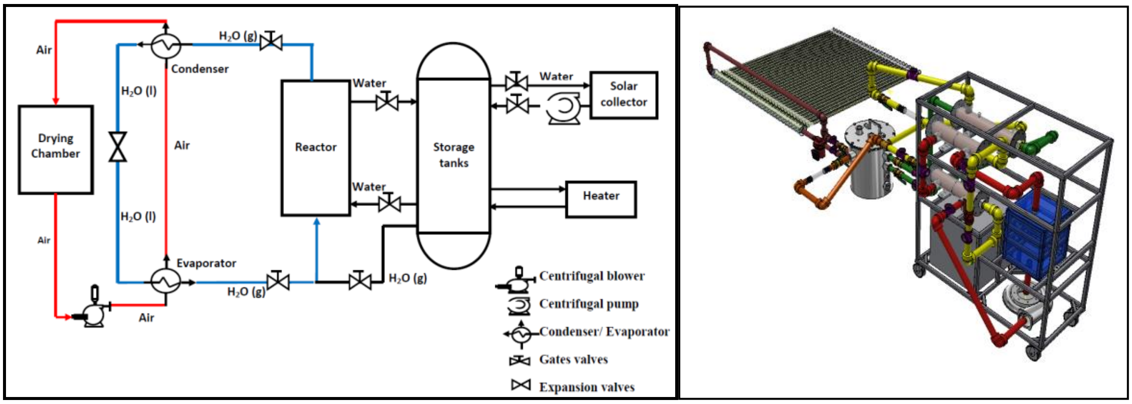
doi: 10.12720/sgce.4.4.311-315

pump, COP^h, was 2. The aim of this study to investigate the performance of solar assisted $CaO/Ca(OH)_2$ chemical heat pump drying system for tropical region.

2. System Description

The schematic and inventor drawing of solar assisted $CaO/Ca(OH)_2$ chemical heat pump drying system are shown in Fig. 1(a) and Fig. 1(b). The system consists of four main components which are solar evacuated tubes, storage tank, chemical heat pump unit, and drying chamber.



(a) (b)

Fig. 1. (a) Schematic of solar assisted $CaO/Ca(OH)_2$ chemical heat pump dryer (b) inverter drawing of solar assisted $CaO/Ca(OH)_2$ chemical heat pump dryer.

In the solid gas chemical heat pump, the reactor contains solid reactant, CaO which reacts with the working fluid, H_2O. The reactions used in this study are:

$$CaO(S) + H_2O(g) \rightarrow Ca(OH)_2(S) + \Delta H_{reaction} \tag{1}$$

In this study, the chemical heat pump operates in the heat pump mode, the heat is supplied to the reactor at high temperature to regenerate H_2O (g) which will then being condensed in the condenser at the medium temperature. The heat required at evaporator at low temperature is supplied to vaporize H_2O (l) to form H_2O (g) which will react with CaO (s) and releases heat at medium temperature. The charging process is defined as the endothermic process. The thermal energy is absorbed from an energy resource such as solar energy. This energy is used for dissociation of the $Ca(OH)_2$ (s). The energy is equivalent to the heat of reaction or enthalpy of formation, ΔH_r. After this process, the CaO (s) and H_2O (g) with different properties are formed that can be stored. In the storing process, the CaO (s) and H_2O (g) are separately stored energy with little or no energy losses during storing period. After storing process is then followed by discharging process, which is the exothermic reaction occurs. In this process, the the CaO (s) and H_2O (g) are combined and the released energy from the reaction which permits the stored energy to be recovered (Fig. 2(a)).

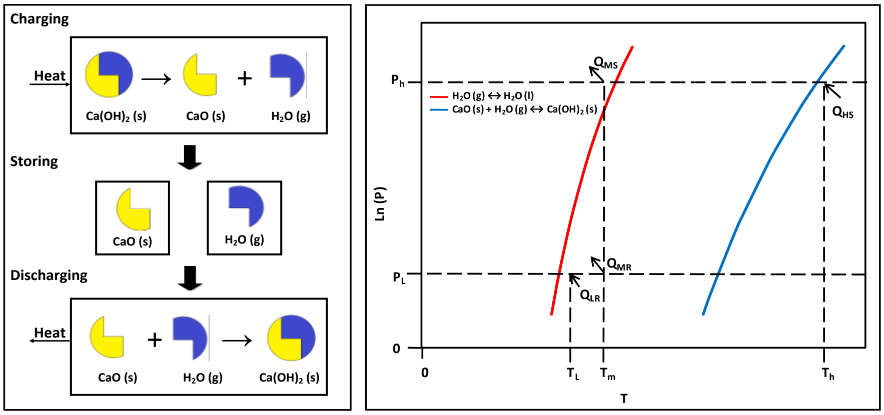
3. Analysis of Solid-Gas Chemical Heat Pump Operation

In this study the reaction is considered as monovariant, which is only temperature or pressure to be defined in the equilibrium state of the system. The Clausius Clapeyron equation for phase change of H_2O and chemical reaction for $CaO/Ca(OH)_2$ are respectively:

$$P_{H_2O} \cong 133.32^{18.305^{3816.433/(T-46.13)}} \tag{2}$$

$$P_{CaO} \cong 9\times10^{11-12531.5/T} \tag{3}$$

The chemical heat pump is operated at three different temperature which are low temperature, T_L, medium temperature, T_m, and high temperature, T_h as shown in Fig. 2(b).



(a) (b)

Fig. 2. (a) The thermochemical TES cycle (charging, storing and discharging) of chp, (b) clausius claypeyron diagram.

4. Mathematical Model

The development of the mathematical models for different components of the system is needed in order to evaluate the performance for the system. The thermal performance for evacuated heat pipe can be calculated by:

$$\eta_{eva} = 0.84 - \frac{2.02(T_m - T_a)}{I} - 0.0046\left(\frac{T_m - T_a}{I}\right)^2 \tag{4}$$

In this study, the cylindrical storage tank is used. The heat loss from the storage tank to environment temperature which is due to convection and conduction can be calculated as equation:

$$Q_{storage} = UA_{storage}\left(T_{water} - T_{enviroment}\right) \tag{5}$$

In the solid gas chemical heat pump, the heat is supplied to the reactor at the high temperature in order to generate H2O (g) which is condensed in the condenser at medium temperature. The heat supplied to the evaporator at low temperature is used to vaporize the H_2O (l) to form H_2O (g) which reacts with the calcium oxide and release heat at medium temperature. The heating performance of chemical heat pump is calculated by:

$$COP_h = \frac{Q_{condenser} + Q_{reaction}}{Q_{reaction}} = \frac{H_{condenser} + H_{reaction}}{H_{reaction}} \tag{6}$$

After integrated the chemical heat pump with the storage tank and solar collector, the coefficient of performance of a chemic is become:

$$COP_h = \frac{Q_{condenser} + Q_{reaction}}{(Q_{solarcollector} - Q_{storage}) + Q_{reaction}} \tag{7}$$

The heat reaction is defined as:

$$Q_{reaction} = \dot{m}_{\text{limitingreagent},H_2O} \times \Delta H_{reaction} \quad (8)$$

The solar fraction for solar assisted chemical heat pump can be calculated by:

$$SF = \frac{Q_{solarcollector} - Q_{storage}}{Q_{condenser}} \quad (9)$$

5. Results and Observations

The metallurgical weather conditions of Malaysia using in this study is recorded from the weather station at Melaka city, Malaysia, and the simulation is performed depends on the weather conditions on date 23-11-2013, from 8:00 am to 18:00 pm. The hourly average solar radiation on a horizontal surface and the hourly average outside air temperature of this location are shown in Fig. 3(a). Fig. 3(b) shows the maximum predicted hourly efficiency of evacuated tubes is 79.65% at 13:30 pm. However, the minimum predicted hourly efficiency of evacuated tubes is 46.33% in 18:00 pm. The collector efficiency is depending on the difference temperature between main collector and ambient temperature, and the collector efficiency decrease with the higher difference temperature. The Fig. 4(a) shows hourly solar fraction predicted curve as function of solar collector area which are 0.4m^2, 0.5m^2 and 0.6m^2, while Fig. 4(b) shows the predicted monthly coefficient of performance of chemical heat pump. It can be observed from Fig. 4(a), that the hourly solar fraction increases with the solar collector area but at a decreasing rate. It may due to the larger collector size give higher losses. Besides that, the higher collector size increases the difference value (T_m-T_a) then causes the decrease of collector efficiency. From Fig. 4(b), the maximum coefficient of performance can get 2.87 for 0.6m^2 solar collector and 0.628 m^3 storage tank. It can be observed that the decrease in energy available in condenser due to decrease in solar radiation will cause the decrease in coefficient of performance of chemical heat pump.

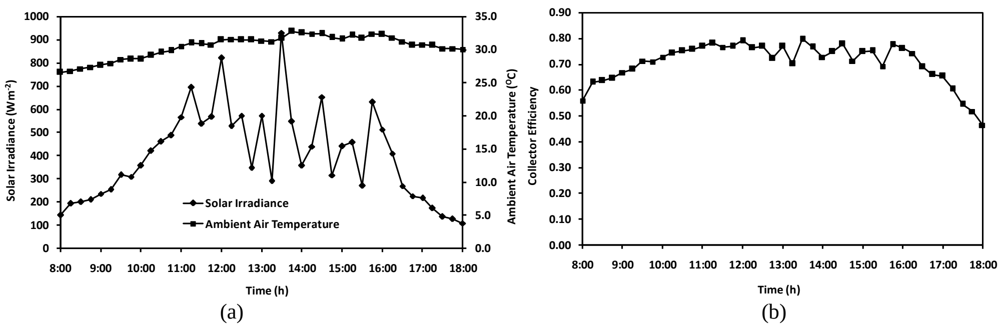


Fig. 3. (a) average hourly solar radiation and ambient temperature on date 23-11-2013 in Melaka, Malaysia, (b) hourly collector efficiency predicted curve of evacuated tube.

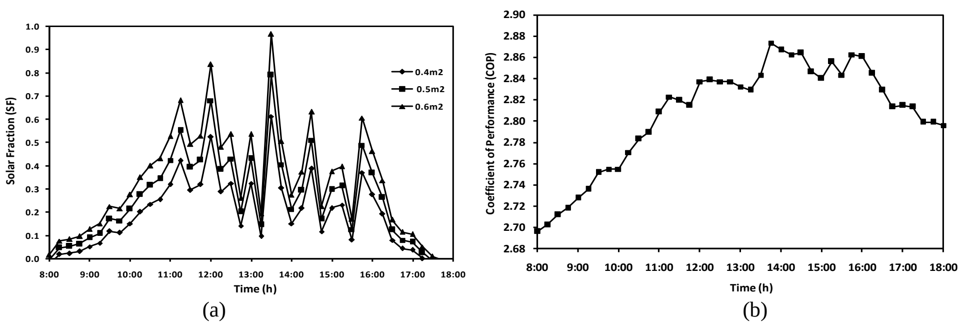


Fig. 4. (a) hourly solar fraction predicted curve as function of solar collector area (0.4m^2, 0.5m^2 and 0.6m^2), (b) hourly coefficient of performance predicted curve for 0.6m^2 solar collector area.

6. Conclusions

The performance of solar assisted $CaO/Ca(OH)_2$ chemical heat pump drying system under the meteorological conditions of Melaka, Malaysia is studied. The maximum value of SF is 0.97 as function of 0.6 m^2 solar collector and 0.628m^3 storage tank. And the maximum of COP^h is 2.87 as function of 0.6m^2 solar collector and 0.628m^3 storage tank. The results show the predicted coefficient of performance for chemical heat pump by using calcium chloride with water vapor as working pair is more efficient than using metal chlorides/ammonia. Besides that, the use of water vapor for chemical heat pump is more suitable and safe when compared to ammonia gas.

Acknowledgements

The authors would like to thank the Ministry of Higher Education, (FRGS), Malaysia for their sponsorship and supports.

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