Experimental Performance of Solid-Gas Chemical Heat Pump in Solar Chemical Heat Pump Dryer

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Abstract**:** A solar assisted chemical heat pump dryer has been designed, fabricated and tested. The performance of the system has been studied under the meteorological conditions of Malaysia. The system consists of four mean components: solar collector (evacuated tubes type), storage tank, solid – gas chemical heat pump units and dryer chamber. A solid gas chemical heat pump unit consists of reactor, condenser and evaporator. The reaction used in this study ($CaCL_2$-NH_3). The maximum experimental value of the COP^h for the solid-gas chemical heat pump of 2 was found, and the total system energy output is 51 kWh over drying time about 9 hours. The results show that any reduction of energy at condenser as a result of a decrease in solar radiation which in the final decrease the coefficient of performance as well as decrease the efficiency of drying.

Keywords: evacuated tubes solar collector, solid gas chemical heat pump, reactor temperature, energy density, *coefficient of performance*, *drying*.

1. Introduction:

Solar-drying technology offers an alternative which can process the vegetables and fruits in clean, hygienic and sanitary conditions to national and international standards with zero energy costs. It saves energy, time, occupies less area, improves product quality, makes the process more efficient and protects the environment. [1]

Chemical heat pump (CHP) is proposed as one of the potentially significant technologies for effective energy utilization in drying. The CHP can store thermal energy such as the waste heat from dryer exhaust, solar energy, geothermal energy, etc. in the form of chemical energy, and release the energy at various temperature levels during the heat-demand period [2]. Benefits of chemical thermal energy storage are higher energy density compared with physical change - Compact storage, Long-term storage as reactants with small thermal loss, and Operation temperatures of storage and output are variable by choice of reaction conditions [3]. Chemical Heat Pump (CHP) are those systems that utilize the reversible chemical reaction to change the temperature level of the thermal energy which stored by chemical substances. These chemical substances play an important role in absorbing and releasing heat. The advantages of thermochemical energy storage, such as high storage capacity, long term storage of both reactants and products lower of heat loss, suggests that CHP could be an option for energy upgrading of low temperature heat as well as storage. The importance of chemical heat pump has increased due to the research on the development of a heat exchange system besides utilization of waste heat released from many industries [4]. Moreover, Chemical adsorption or chemisorption, a kind of reversible gas–solid reaction, is widely used in CHPs; it depends on many factors such as the thermophysical properties of the reacting bed, operating pressure, and temperature. [5]. This paper presents the experimental study of the performance of solid-gas chemical heat pump in solar chemical heat pump dryer system under the meteorological condition of Malaysia.

2. Experiment

2. 1 System description:

A solar-assisted chemical heat-pump dryer has been designed and built, as shown in Fig. 1 and 2 respectively. The system is located on the roof top of a three-storey building at the National University of Malaysia (Universiti Kebangsaan Malaysia). The system consists of four mean components solar collector (evacuated tubes type), storage tank, chemical heat pump unit and dryer chamber. In the solid-gas chemical heat pump a reactor coupled with a condenser or an evaporator. The reactor is shell-and-tube type include finned tubes. The salt is located between the fins of the heat exchanger. The salt has a uniform axial temperature distribution for all the reactions.

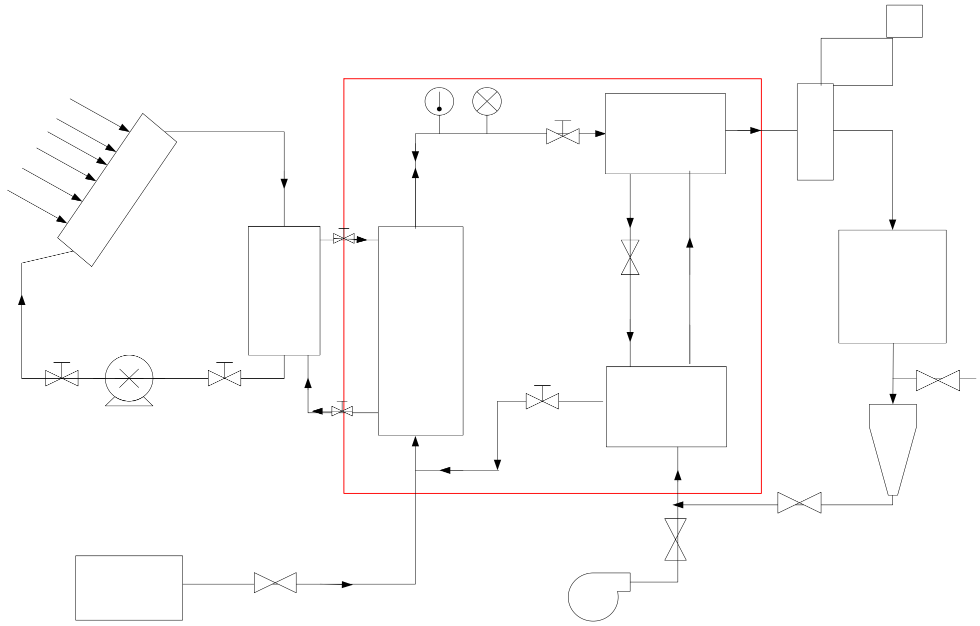


Fig.1 Schematic diagram of solar assisted chemical heat pump dryer

The reactor and the evaporator/condenser are vacuumed to the appropriate pressures. The joint valve connecting the reactor and the evaporator/condenser is opened for the absorption reaction or as a heat-releasing step. A set of condenser and evaporator to provide or absorb gas reacting with salt, which has been oversized to maintain the system at relatively constant pressure [6]. In the condenser component the inlet air enter at low temperature and exit in high temperature due to heat exchange with ammonia gas, the hot air which is exit from condenser is used for drying process. The absorber receives a low pressure of ammonia in mixture state (it comes from evaporator) so as to pump to the reactor as a strong solution at high pressure.

2.2 Basic Principle of Solid-Gas CHP Operation

In the solid-gas chemical heat pump, the reactor contains a salt which reacts with the gas. The ammonia-metal chloride systems are considered to be monovariant, only one variable (temperature or pressure) is normally specified to define the equilibrium state of the system. The overall reaction can be expressed as,

$$S.\ p\,G + q\,G \leftrightarrow S\,(p + q)\,G + q\,\Delta H_r \qquad (1)$$

Where S is metallic salt and G ammonia gas, the ΔH_r representing the Enthalpy change of reaction per mole of ammonia gas, and the *q* are represents change in stoichiometric coefficient of the metallic salt, it has range from 1 to 8 [7]. Besides, the vapor-liquid equilibrium in the evaporator/ condenser needs to be considered. Both the gas-solid reaction equilibrium and the vapor-liquid equilibrium monovariant, and are defined by the Clausius-Clapeyron equation:

Fig.2 Photograph of the experimental set-up

$$\ln(p) = \frac{-\Delta H_r}{RT} + \frac{\Delta S}{R} \qquad (2)$$

The CHP operates between three different temperature levels: low temperature Te, middle temperature Tc, and high temperature Tg., two different pressure: low pressure Pe and high pressure Pc, as illustrated in the Clausius-Clapeyron diagram in figure3.

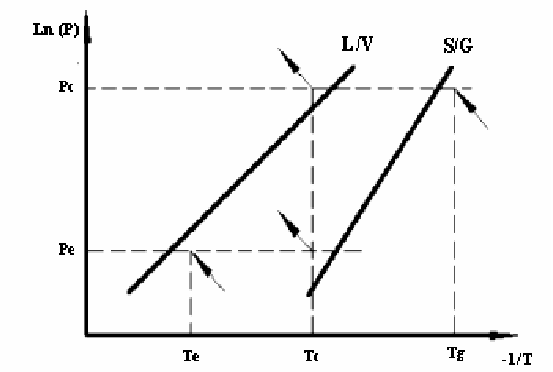
The reaction used in this study is:

$$CaCl_2.2NH_3 + 6NH_3 \rightleftarrows CaCl_2.8NH_3 + 6\Delta Hr \qquad (3)$$

2.3 Instrumentation

A well-equipped instrumentation system is deployed to measure various properties of the drying process, such as temperature, pressure, humidity and velocity. For the measurement of temperature at different locations of air, water and refrigerant path, K-type thermocouples are used, and for measurement of pressure at different locations of the system pressure gauges are used.

Fig. 3 Diagram of Clausius-Clapeyron



Vane type anemometer is used to measure the flow rate and velocity of the air, and the flow rate of refrigerant is measured with the help of a Hydorex flow meter. . A pyranometer is mounted near the collector to measure the instantaneous solar radiation. The relative humidity of the air entering and leaving the drying chamber is measured with the help of two humidity transmitters. The weight data of the drying material was recorded on personal computer at 30 second intervals using the data acquisition software. The power consumption of the system is measured by a Wattmeter. Finally, the data acquisition system, comprising of twenty channels.

3. Mathematical Module:

The two main criteria of performance of the thermochemical process are the energy density of the reactor (i.e. the quantity of stored energy relative to the volume of the reactor) De_R and the cooling or heating power ($Q_{e,c}$) which the evaporator or the condenser can deliver. The relationship between $Q_{e,c}$ and reaction power (Q_r) can be calculated by (8):

$$Q_{e,c} = \frac{\Delta h_g}{\Delta h_r} . Q_r \qquad (4)$$

Where Δh_g is the enthalpy of gas phase. The energy density for the reactor De_R can be conducted as:

$$De_R = Q_r / V_R \qquad (5)$$

Where the V_R is the volume of the reactor and Q_r is the heat storage capacity Q_r is the heat storage capacity for CHP only for the latent heat of the reaction and neglect sensible heats of the reagents.

For a given energy density of the reaction or reactive composite (De_r), can be express as:

$$De_r = De_R . \left(\frac{V_R}{V_{\Sigma M}} \right) . (1 + \frac{Z_e + 2Z_d}{2Z_r}) \qquad (6)$$

The values of thicknesses of the exchanger plates and the diffusers in this study as follows:

$Z_e = 1 \, x \, 10^{-3} \, m$ $\quad$ $Z_d = 2 \, x \, 10^{-3} \, m$

$V_R = 0.0135 \, m^3$

In the chemical heat pump a solid-gas reactor, coupled with condenser or an evaporator. The reactor contains a salt which reacts with the gas.

In the solid-gas chemical heat pump heat is supplied to the reactor at high temperature to regenerate ammonia which will then be condensed in the condenser at medium temperature, the heat required to evaporate at low temperatures supplied to vaporize ammonia, which reacts with salt and release heat at medium temperature.

The heating performance for chemical heat pump could be defined as:

$$COP^h = \frac{Q_C + Q_r}{Q_r} = \frac{\Delta H_C + \Delta H_r}{\Delta H_r} \qquad (7)$$

Where Q_C is the condenser hest rejection, and ΔH_c is the enthalpy of condensing.

And for the integrated heat pump with solar collector and storage tank the heating performance of chemical heat pump could be:

$$COP^h = \frac{Q_C + Q_r}{(Q_u - Q_S) + Q_r} \qquad (8)$$

4. Results and observations:

A series of experiments has been performed on the system to evaluate the performance. Figure 4 shows the hourly average values of meteorological data for a typical day in December for Malaysia. Figure 5 shows the relation between COP^h and the time while figure 6 shows the COP^h as function of solar radiation. As seen in figure 5 the maximum COP^h for chemical heat pump of 2 were found and The COP^h increase as solar radiation increasing as seen in figure 6. If there is a reduction in the energy available at the condenser as a result of a decrease in solar fraction as well as decrease in latent heat contribution from the drying material as the drying progress. Figure 7 shows the COP^h vs. generator temperatures (*Tg)*, at steady state constant temperature of condenser at *Tc*=50, and evaporator at *T*e =25. The COP^h values for this cycle increase with generator temperatures increasing. Figure 8 shows the air temperature changes at the inlet and the outlet of the heat exchanger in the condenser for hot air production. It is found that air temperature rises by condensation and hot air produced by condensation heat can be used for drying. Figure 9 shows the system energy output over about 9 hours drying time can, which found the total energy can produced over 9 hours is 51 kWh.

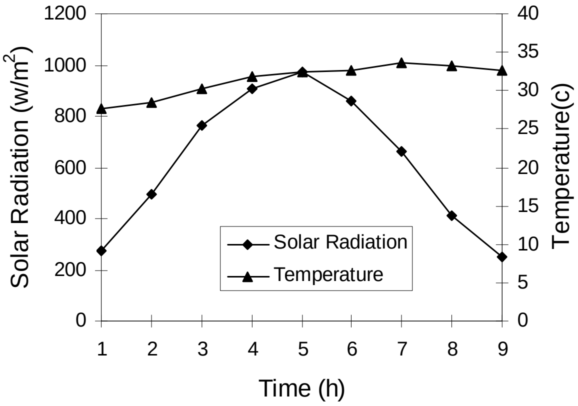


Fig. 4 Average hourly radiation and ambient temperature in Malaysia in December

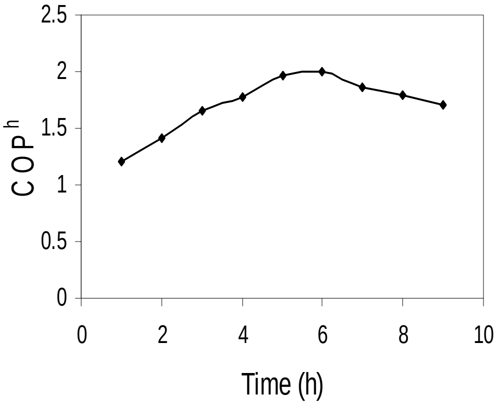


Fig.5 Coefficient of performance experimental curve against time

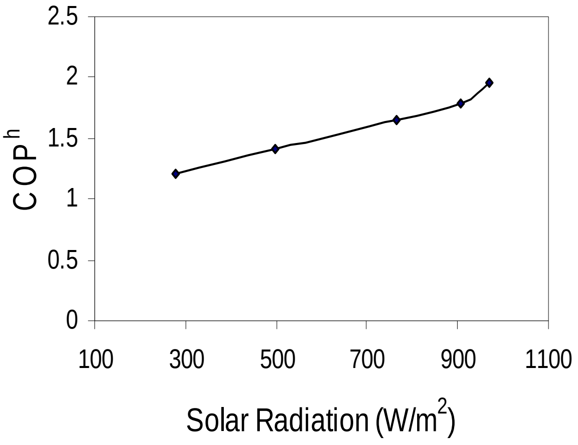


Fig.6 Coefficient of performance experimental curve as function of solar radiation

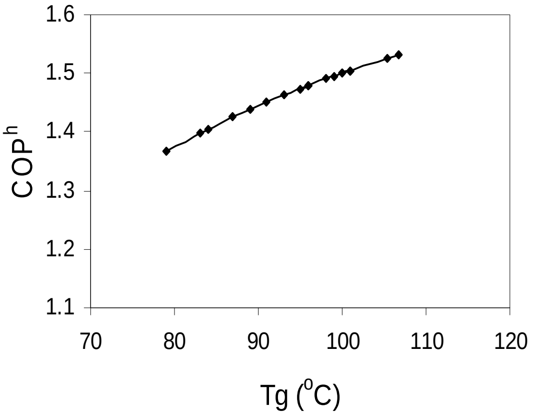


Fig.7 Coefficient of performance experimental curve as function of generator temperature.

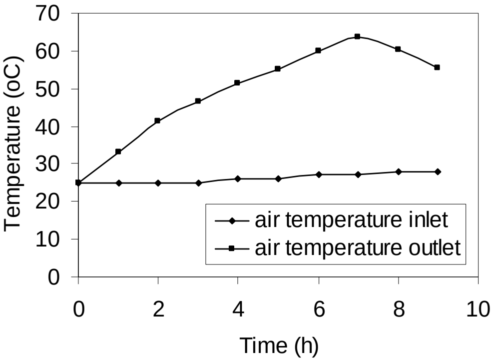


Fig.8 Air temperature changes at inlet and outlet of heat exchanger in condenser

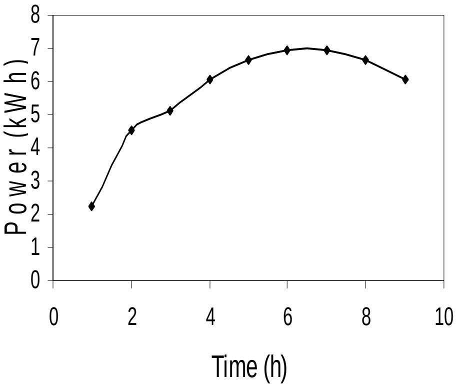


Fig.9 System energy output

5. Conclusion:

The performance of solid-gas of solid-gas chemical heat pump in solar chemical heat pump dryer has been investigated under the metrological conditions of Malaysia. A series of experiments has been performed on the system to evaluate the performance. The value of the COP^h of the solid-gas chemical heat pump as high as 2, and the total system energy output is 51 kWh. The results show that any reduction of energy at condenser as a result of a decrease in solar radiation which in the final decrease the coefficient of performance as well as decrease the efficiency of drying.

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