Performance of Solid-Gas Chemical Heat Pump Subsystem of Solar Dryer

M. IBRAHIM, W.R.W. DAUD, KAMARUZAMAN IBRAHIM, AZAMI ZAHARIM, KAMARUZAMAN SOPIAN

Solar Energy Research Instiute,
National University of Malaysia,
43600 Bangi, Selangor,

mustafa@eng.ukm.my, azami.zaharim@gmail.com, ksopian@eng.ukm.my
Tel: + 60126862115, Fax: + 603-892 14593

Abstract: – In this paper the performance of solid-gas chemical heat pump subsystem of solar dryer has been investigated. A thermodynamic analysis is presented to upgrade solar energy with solid-gas chemical heat pump for agriculture drying purpose. A solar assisted chemical heat pump dryer has been designed, fabricated and tested 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 unit 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 value of the COP^h for the solid-gas chemical heat pump of 2.2 has been predicted against maximum experiment value of 2, whereas the maximum value of overall COPs of 1.741 has been predicted against maximum experiment value of 1.444. Any decreasing of coefficient of performance of solid-gas chemical heat pump as a result of a decrease in solar radiation will decrease the overall COPs which in the final decrease the efficiency of drying.

Keywords: – solar, solid gas chemical heats pump, drying, evacuated tubes, coefficient of performance (COP^h), overall COPs.

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. Ogura et. al. [2] studied the CHP and proposed a chemical heat pump dryer (CHPD) system for ecologically friendly effective utilization of thermal energy 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 [3]. 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 [4].Chemical Heat Pumps (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, suggests that CHP could be an option for energy upgrading of low temperature heat as well as storage. Chemical heat pumps are normally classified into two types: solid-gas and liquid-gas. Solid-gas chemical heat pumps consist of reactor (s) (or adsorbers), evaporator (s) and condenser (s). A thermodynamic analysis of chemical heat pumps has been performed previously by Sharonov and Aristov [5] to determine the coefficient of performance, COP, for various gas-solid systems. This paper presents the performance analysis of solid-gas chemical heat pump in solar chemical heat pump dryer system under the meteorological condition of Malaysia. This paper performs a Second Law analysis of solid-gas chemical heat pump particularly application to solar energy for dryer application.

2 Experimental Set Up

2.1 System Description

A solar-assisted chemical heat-pump dryer has been designed and built, as shown in Fig 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. The reactor and the evaporator/condenser are vacuumed to the appropriate pressures.

The general working of a chemical heat pump occurs in two stages: adsorption and desorption. The adsorption stage is the cold production stage, and this is followed by the regeneration stage, where decomposition takes place. During the production phase, the liquid-gas transformation of ammonia produces cold at low temperature in the evaporator. At the same time, chemical reaction between the gaseous ammonia and solid would release heat of reaction at higher temperature. The incoming air is heated by condensing refrigerant (ammonia) and enters the dryer inlet at the drying condition and performs drying. After the drying process, part of the moist air stream leaving the drying chamber is diverted through the evaporator, where it is cooled, and dehumidification takes place as heat is given up to the refrigerant (ammonia). The air is then passing through the condenser where it is reheated by the condensing refrigerant and then to the drying chamber.

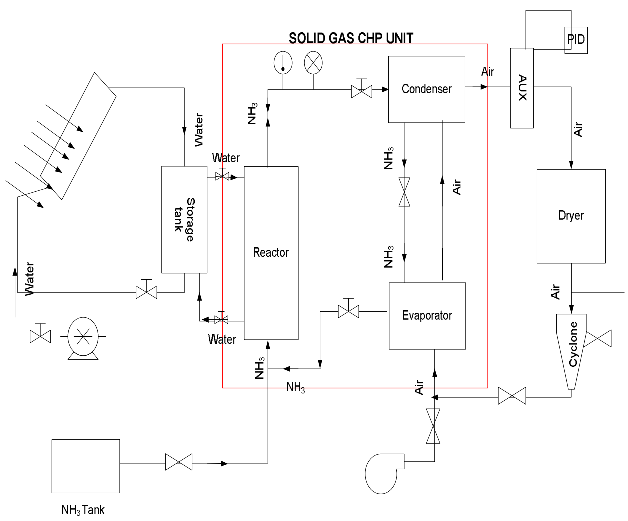
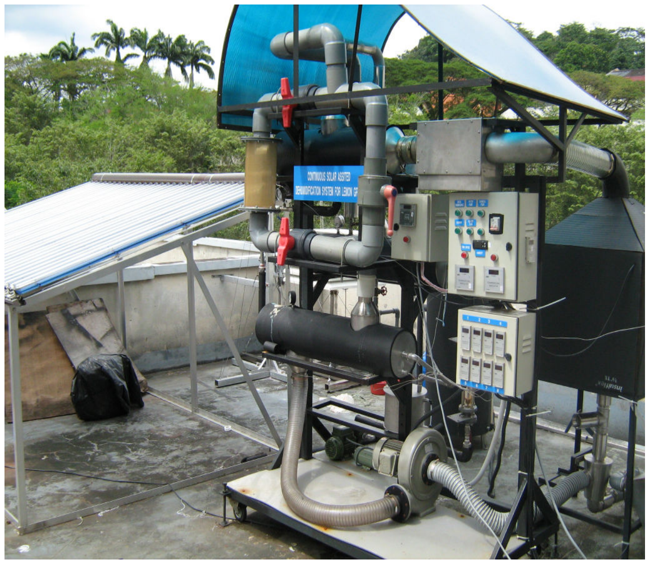


Fig.1: Schematic diagram of solar assisted chemical heat pump dryer



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. 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:

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

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 Fig. 3.

Fig. 3: Diagram of Clausius-Clapeyron

The reaction used in this study is:
$CaCl_2.2NH_3 + 6NH_3 \rightleftarrows CaCl_2.8NH_3 + 6\Delta Hr$
(3)

3 Thermodynamic Analyses of Chp and Overall Cops

In this section, a Second Law analysis will be performed to examine the overall thermodynamic feasibility of upgrading solar heat from low to higher temperatures. The maximum theoretical coefficient of performance (COP) for a chemical heat pump is the Carnot COP [5]. In this study the thermodynamic analysis of heating cycle will be performed and heating values will be calculated. For an ideal 3T system (with zero thermal masses) the energy balance (the first law) [5]:

$$Q_c - Q_e - Q_r + Q_a = 0 \quad (4)$$

And the entropy balance (the second law)

$$-\frac{Q_c}{T_c} + \frac{Q_e}{T_e} + \frac{Q_r}{T_g} - \frac{Q_a}{T_a} = \Delta S \geq 0 \quad (5)$$

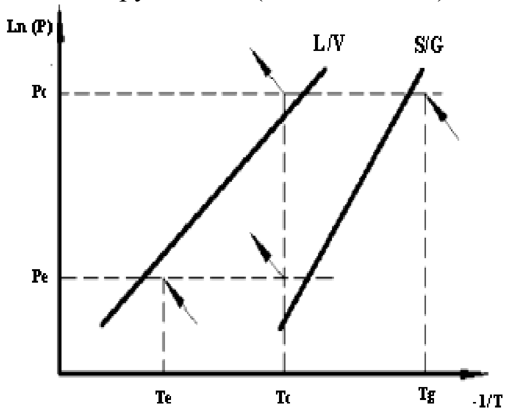
If all processes within the chemical heat pump are reversible, the entropy generation is equal to zero. In this case the Carnot COP for heating is:

$$COP_c^h = \frac{Q_c + Q_r}{Q_r} \quad (6)$$

And for the integrated heat pump with solar collector and storage tank the energy balance (the first law) could be:

$$Q_c - Q_e - Q_r - (Q_u - Q_s) + Q_a = 0 \quad (7)$$

And the entropy balance (the second law)



$$\frac{Q_c}{T_c} + \frac{Q_e}{T_e} + \frac{Q_r}{T_g} + \frac{(Q_u - Q_s)}{T_g} - \frac{Q_a}{T_a} = \Delta S \geq 0 \quad (8)$$

And for reversible chemical heat pump, the coefficient of performance of chemical heat pump could be:

$$COP^h = \frac{Q_c + Q_r}{(Q_u - Q_s) + Q_r} \quad (9)$$

The overall COPs of the solar Chemical heat pump is equal to product of the efficiency of the solar collector and the COP^h given by [6]:

$$COPs = \eta \, COP^h \quad (10)$$

Where η is the collector efficiency. The collector efficiency for the evacuated tube collector is given by [7]:

$$\eta_{eva} = 0.84 - 2.02(T_m - T_a)/I - 0.0046[(T_m - T_a)/I]^2 \quad (11)$$

4 Results and Observations

In this section, the predicted results of COP^h and Overall COPs are compared with those obtained from experiments under meteorological condition of Malaysia. 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.

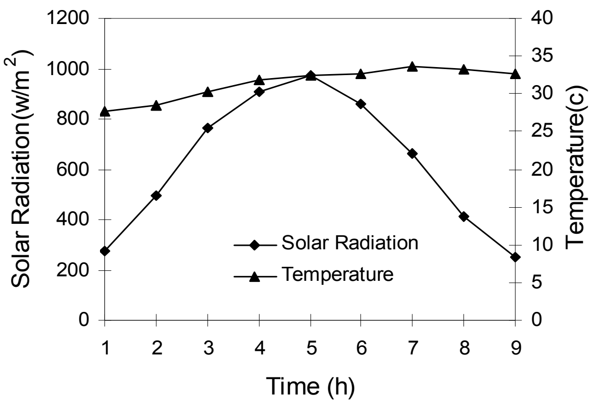


Fig. 4: Average hourly radiation and ambient temperature in Malaysia in December

Figure 5 shows predicted and experimental values of coefficient of performance of chemical heat pump (COP^h). As seen in the figure a maximum value COP^h of 2.2 is predicted against maximum experimental COP^h of 2 and the COP^h increase as solar radiation increasing. If there is a reduction in the energy available at the condenser as a result of a decrease in solar radiation as well as decrease in latent heat contribution from the drying material as the drying progress. Figure 6 shows predicted and experimental values of overall COPs. A maximum overall COPs of 1.741 as seen from the figure is predicted against the maximum experimental overall COPs of 1.444. The slight decreasing in the values of overall COPs can be attributed to the system's loss to the ambient. condensation and hot air produced by condensation heat can be used for drying.

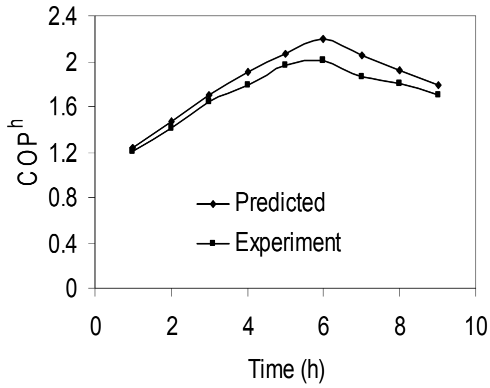


Fig.5: Coefficient of performance curve against time

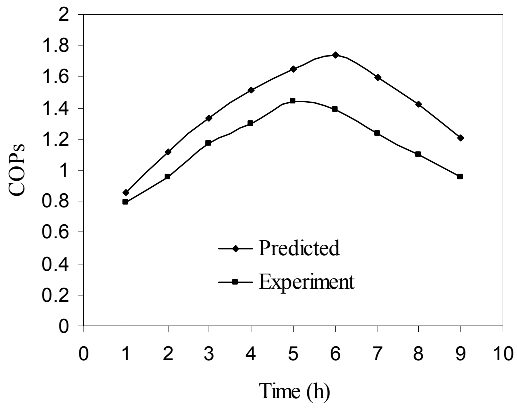


Fig.6: Overall COPs curve against time

Figure 7 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.

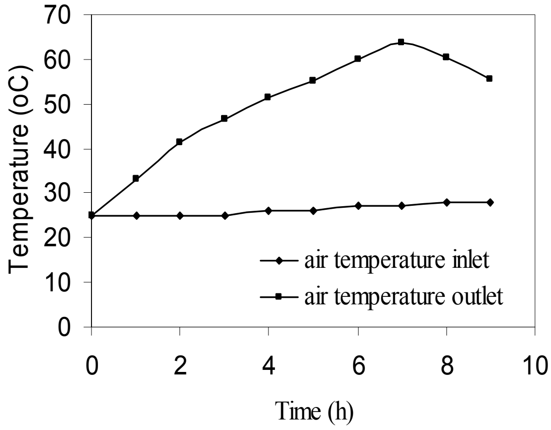


Fig.7: Air temperature changes at inlet and outlet of heat exchanger in condenser

5 Conclusion

This paper has presented the thermodynamic analysis of combined solid-gas chemical heat pump with solar collector for drying purpose. The performance of solid-gas chemical heat pump subsystem of solar 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 maximum value of COP^h of 2.2 has been predicted against the maximum experiment value of 2, whereas the maximum overall COPs value of 1.741 has been predicted against maximum experiment value of 1.444. 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 and overall COPs as well as decrease the efficiency of drying.

Units and Measurements

A_c collector area, m^2
A_s exposed area of storage tank, m^2
COP^h coefficient of performance of chemical heat pump
COPs overall coefficient of performance of solar chemical heat pump
G gas
I solar radiation, MJ/m^2
P preassure, bar
Pc condenser pressure, bar
Pe evaporator pressure, bar
q stoichiometric coefficient of the gas in the reaction, mol_G/mol_s
Q_c condenser heat rejection, J
Q_r reaction heat, J

Q_s storage tank heat loss, J
Q_u useful energy gain of collector, W
S metallic salt
T_a ambient air temperature, K
Tc condenser temperature, K
T_{col} collector temperature, K
Te evaporator temperature, K
Tg reactor temperature at regeneration stage, K
T_m mean collector temperature, K
ΔHc enthalpy of condensing, J/mol
ΔH_r enthalpy of chemical reaction, J/mol
ΔS change of entropy, K
η collector efficiency
η_{eva} evacuated tube collector efficiency

References:

[1] Sharma A., Chen C. and Nguyen Vu Lan. Solar-energy drying systems: A review. Renewable and Sustainable Energy Reviews. 13 (2009) 1185–1210.

[2] Ogura H., Yamamoto T., Kage H., Matsuno Y., and Mujumadar A. S. Effects of heat exchanger condition on hot air production by a chemical heat pump dryer using $CaO/H_2O/Ca(OH)_2$ reaction. *Chemical Engineering Journal*, 86, 2002, 3-10.

[3] Kawasaki, T. Watanabe and A. Kanzawa. Proposal of a Chemical Heat Pump with Paraldehyde Depolymerization for Cooling System, Applied Thermal Engineering, 19, 1999, 133-143.

[4] K. Yukitaka. Transportation of energy by utilization of Thermal Energy Storage Technology, Kick-Off Workshop of Annex 18, Germany, 15 November, 2005.

[5] Sharonov VE., Aristory YI. Chemical and adsorption heat pumps: comments on the Second Law efficiency. Chemical Engineering Journal, 136, 2008, 419-424.

[6] Fathi R., and Ouaskit S. Performance of a solar LiBr-Water absorption refrigerating system. Rev. Energ. Ren: Journees de Thermique, 2001, pp. 73-78.

[7] Ucar A., and Inalli M. Thermal and economic comparisons of solar heating systems with seasonal storage used in building heating, *Renewable Energy,* 33(12), 2008, 2532-2539.