R&D of Advanced Solar Dryers in Malaysia: (2) Water Based Solar Collectors

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Abstract: The design and performance of different types of commercial scale solar dryers with water based solar collectors are presented. The solar dryers presented in this paper are high efficiency, high power, long life and expensive drying systems. However, deciding factor for any solar dryers should be based on economics. Economic decisions are about choices among possible alternatives of action in the future. The approach is to minimize input (cost) for a give output (benefits), or to maximize the output (benefits) from a given input (cost). The simple solar will have lower output compared to the more sophisticated solar drying systems. Hence, the payback period for such higher efficiency and productivity solar dryers should be much lower that the simple solar dryers. In addition, the solar dryers presented in this paper have very stable output temperature and higher performance.

Keywords: Solar dryer, mechanical heat pump, chemical heat pump, PVT, dehumidification system, solid desiccant wheel

1. Introduction

Dou to the current trends towards scare and expensive of fossil fuel, also uncertainty regarding future cost and availability, use solar energy in drying of agricultural and marine products will probably increase and become more economically feasible in the near future. Open sun drying is traditional method to preserve agricultural products in tropical and subtropical countries. Considerable saving can be made with this type of drying since the source of energy is free and sustainable. However, open sun drying have many disadvantages such as degradation by rain, storm, wind-blown debris, dust, insect infestation, rodents, human and animal interference which will result in contamination of the product. Additionally, the drying time required for a given commodity can be quite long and result in post-harvest losses. The quality of the dried products may also be lowered significantly [1]. The resulting decrease in product quality causes do not fulfill the international quality standard and therefore cannot be sold on international markets. The quality of the products depends on many factors including the drying temperature and duration of drying time. Some product such as medicinal herbs requires low temperature to prevent the active volatile essential ingredient from being removed during conventional high temperature drying.

The objective of this paper is the design and performance of different types of solar dryers with water based solar collectors, which R&D in Solar Energy Research Institute, Universiti Kebangsaan Malaysia. It has developed four advanced solar dryers with air based solar collectors suitable for drying of various agricultural, marine products and medical herbs namely (a) the solar dryers with mechanical heat pump (b) solar dryer with hybrid PVT-mechanical heat pump (c) the solar dryer with the chemical heat pump (d) solar dryer with the dehumidification system and (e) solar dryer with solid desiccant wheel [2-4].

2. Solar Dryer with Mechanical Heat Pump

Fig. 1 and Fig. 2 show the schematics and photograph of the solar dryer with mechanical heat pump. The dryer consists of the multifunctional solar collector, the drying chamber, blower and mechanical heat pump. Fig.3 shows the schematics of the multifunctional solar collector. It consists of aluminum rods and fins that are covered by transparent plastic sheet on the top, and rubber foam on the bottom.

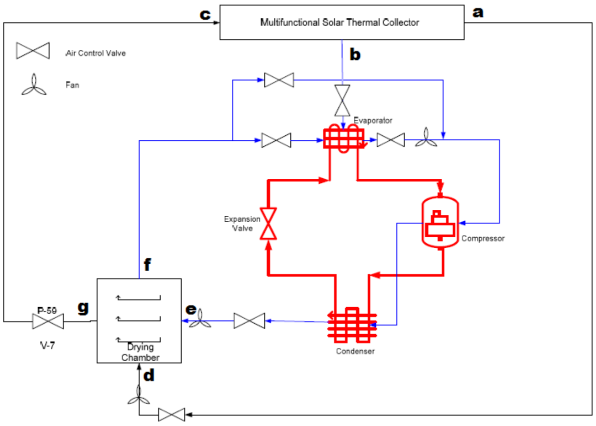

Fig. 1. The schematic of the solar dryer with mechanical heat pump

Fig. 2. The photograph of the solar dryer with mechanical heat pump

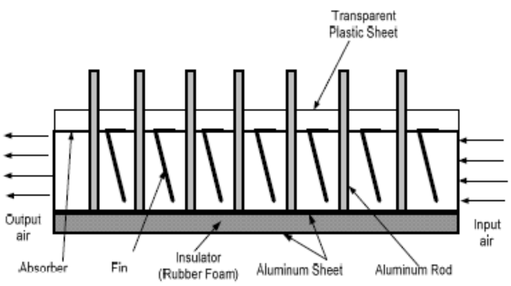

Fig. 3 The multifunctional solar collector

This dryer includes four operations such as heat pump without solar collector, heat pump with solar collector, solar collector as cooling system and solar thermal collector as an evaporator. In fact, by combining two heat sources (heat pump, and solar energy), drying efficiency will be increase. In this dryer, solar thermal collector has two outputs (a and b), and one input (c). The dryer chamber has two outputs (g, and f) and two inputs (e and d). The hot air from first thermal collector output (a) can be arriving to draying chamber (d) as direct by aluminum cannel. The air can be return back to input collector (c) from output draying chamber (g). Second output of solar thermal collector (b) acted as an evaporator to provide hot air for enters to heat pump evaporator. The compressor compressed working fluid of heat pump (R134a) that is superheated by evaporator of heat pump. The hot air for drying chamber (e) provides by releasing heat of working fluid with high temperature and pressure in condenser. Then, the high pressure R134a becomes liquid in super cool form by expansion valve. Output humid air from draying chamber (f) is passed though heats pump evaporator and becomes non-wet air. Experimental studies on the performance of this dryer on chilies, lemon grass and medical herbs have been conducted [5,6].

3. Solar Dryer with Hybrid PVT-Mechanical Heat Pump

Normally, solar collectors and photovoltaic panels are used separately. These two systems can be combined together in a hybrid photovoltaic thermal (PVT) energy system. The term PVT refers to solar thermal collectors that use PV cells as an integral part of the absorber plate. The system generates both thermal and electrical energy simultaneously. The number of the photovoltaic cells in the system can be adjusted according to the local load demands. In conventional solar thermal system, external electrical energy is required to circulate the working fluid through the system. The need for an external electrical source can be eliminated by using this hybrid system. With a suitable design, one can produce a self-sufficient solar collector system that required no external electrical energy to run the system [7]. Photovoltaic (PV) modules convert a part of solar radiation energy directly into electricity, while, the unconverted part of the solar radiation into electricity is absorbed in a PV module resulting in very high temperatures.

Fig. 3 and Fig. 4 show the schematics and photograph of a solar dryer with hybrid PVT-

ISBN: 978-1-61804-175-3

mechanical heat pump. The main components are the direct integration of PV panels, thermal absorbers, drying chamber and heat pump. The mechanical heat pump consists of a compressor, one air cooled condenser, a water cooled condenser, one evaporator as dehumidifier, one evaporator as air conditioner, expansion valves which are interconnected in a closed-loop system, one auxiliary heater, storage tank, water pump and one water-refrigerant heat exchanger. This system was consists of three distinct flow paths: water, refrigerant and air. The performance of the system has been investigated theoretically and experimentally under the meteorological conditions of Malaysia. In order to test short term performance, high and low irradiance days in August and March were chosen, individually and water heating, drying and air conditioner modes have been tested within these days. Furthermore, the PV/T module performance was studied experimentally and theoretically. The findings of the experimental study were in good agreement with the theoretical predictions on the system for each individual mode. Guava, a tropical fruits was dried using the dryer.

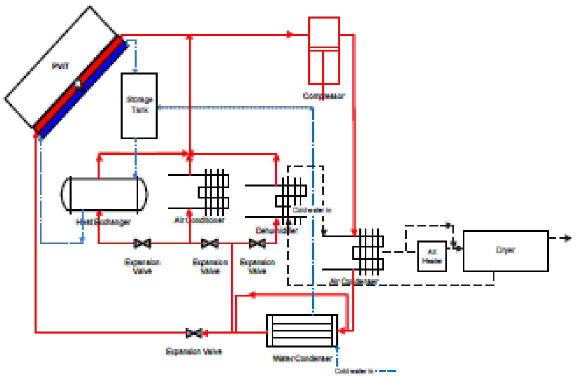

Fig. 4. The schematic of the solar dryer with hybrid PVT-mechanical heat pump

Fig. 5. The photograph of the solar dryer with hybrid PVT-mechanical heat pump

The highest average indoor temperature range during the high radiance days in air conditioner mode was measured between 27-28.8 ◦C and the lowest indoor temperature between 22.8-24 ◦C, while the highest average indoor temperature range for low irradiance days was shown as 24.6-27.1 ◦C and also lowest indoor temperature as 22.8-23.7 ◦C. The COP for all the modes is shown in Figs 6 to Figs. 8.

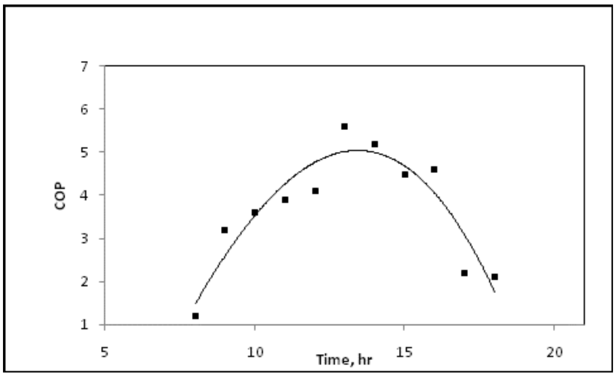

Fig. 6. COP of water heating mode

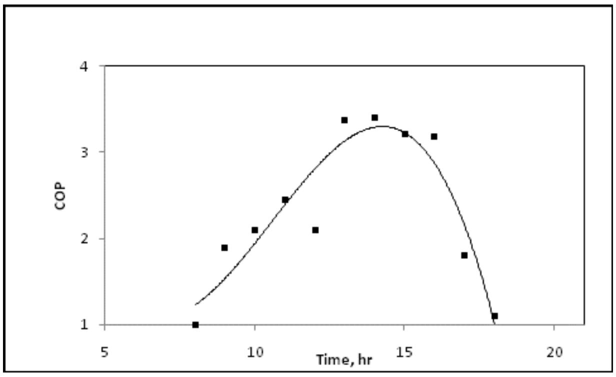

Fig.7. COP of air conditioner mode

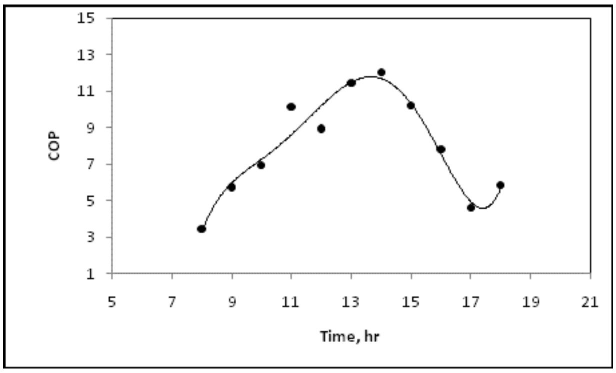

Fig. 8. COP of Dryer Mode

ISBN: 978-1-61804-175-3

The electrical and thermal efficiencies ranges for PVT evaporator-collector were found above the range of 7.71%-7.9% and 76%-79%, accordingly while water collector obtained electrical and thermal efficiencies 5%-5.4% and 58%-68%, for high irradiation days. The results indicated that the performance of two cooling medium PVT collectors is higher than the performance in the other types of PVT systems. The overall performance of the system is determined by the coefficient of performance of system and solar fraction for each mode. A maximum coefficient of performance of 5.6-6.9, 4.1-4.43 and 12-14.1 obtained from experimental work for water heating, space cooling and drying mode for high irradiation days, respectively. Moreover, the highest values of solar fraction which obtained from the experimental work for water and refrigerant and water based parts are between 0.67 and 0.77 for water heating mode, 0.62 and 0.76 for space cooling and 0.69 and 0.78 for drying mode in high irradiance days, separately. The techno-economical evaluation for the system was conducted using TRNSYS software. A 20-year life-cycle economic analysis generally showed that hybrid system has a payback period of 2.3 years and the average annual savings was USD 3382 [8,9].

4. Solar Dryer with Chemical Heat Pump

The principal advantages of heat pump dryers are energy from the ability of the heat pumps to recover energy from the exhaust gas as well as their ability to control the drying gas temperature and humidity. Heat application can be classified into air source heat-pump drying systems, ground source heat-pump drying systems, and chemical heat-pump drying systems. Chemical heat pump (CHP) is potentially significant technologies for effective energy utilization in drying. CHPs are those systems that utilize the reversible chemical reaction to change the temperature level of the thermal energy which stored by chemical substance. 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.

Fig. 9 and Fig. 10 show the schematics and photograph of a solar dryer with chemical heat pump. The main components are solar collector (evacuated tubes type), storage tank, chemical heat pump unit and dryer chamber.

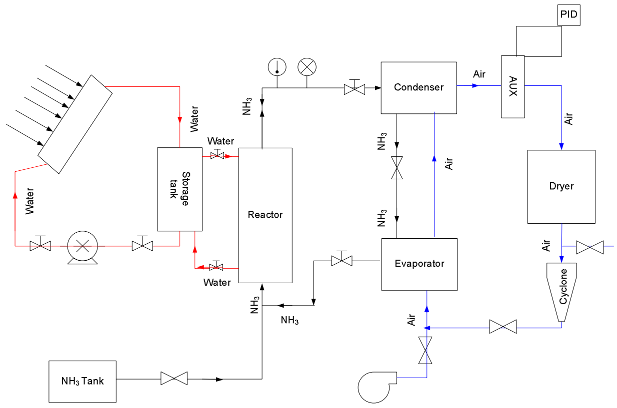

Fig. 9. Schematic of solar dryer with chemical heat pump

Fig. 10. The photograph of solar dryer with chemical heat pump

In this dryer, a cylindrical tank is selected as a storage tank. The chemical heat pump unit consists of reactor, evaporator and condenser. In the chemical heat pump a solid gas reactor is coupled with a condenser or an evaporator. The reaction is:

$$CaCl_2.2NH_3 + 6NH_3 \rightarrow CaCl_2.8NH_3 + 6\Delta Hr$$

The drying chamber contains multiple trays to hold the drying material and expose it to the air flow. The chemical heat pump operates in heat pump mode. The overall operation of 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.

The product used for drying was lemongrass. Lemongrass is commonly used in teas, soups, and curries. It is also suitable for poultry, fish, beef, and seafood. The temperature 55°C and two air drying speed (1m/s, and 3m/s) has been investigated. The weight was recorded on personal computer at 5 minutes intervals, and about 65g of fresh lemongrass was used in each run. The lemongrass was dried from average initial moisture content of 85% (wet basis) to an average final moisture content of 13% (wet basis). Fig. 11 shows the COP of the system for a suns day [10]. The economic analysis for the system was performed to obtain the life cycle saving (LCS) and payback period (PBP). Economic analysis showed that system has a payback period of 3.9 years and the average annual savings was USD 1225 [11].

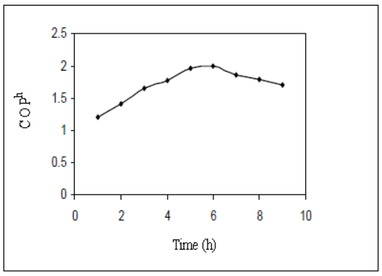

Fig. 11. Coefficient of performance experimental curve against time for sunny day

5. Solar Dryer with Dehumidification System

Fig. 12 and Fig. 13 show the schematics and photograph of the solar dryer with dehumidification system. The main components are solar collector array, energy storage tank, auxiliary heater, blowers, adsorber columns, water-air heat exchangers, water circulating pumps, drying chamber and other ancillary equipment. The sixty evacuated collectors heat pipes tube are use arranged in parallel. The collector area is 6 m^2. The pump electrical capacity is 0.1 kW and used to circulate water from the water tank to the solar collectors. The drying chamber is of the cabinet type. The size of chamber is 1.0 m in length, 1.0 m in width and 2.5 m in height. The chamber contains the drying trays with adjustable racks to place the medicinal herbs. The dry air from the adsorber column entered the drying chamber at the bottom and exit through an air vent at the top. The dry air is circulated by using blower with electrical capacity of 0.75 kW. Water in the heat storage tank is recirculated in the solar collector by the heat collection pump and this recirculation eventually raises the water temperature in the tank. If the solar collector could not raise the water temperature up to this level, then the auxiliary heater is used to supplement the heat energy required to do so. The hot water is first used to produce hot air in the hot water-air heat exchanger for regeneration of adsorbents in one adsober column, and to warm dehumidified air from the other adsorber column in the warm water–air heat exchanger for drying in the drying chamber by manipulation of the two three-way valves. Fresh air for both regeneration and adsoprtion/drying is drawn in by the two blowers. The adsorbents are packed in two adsorber columns so that air dehumidification could run continuously by simultaneous bed regeneration and adsorption in alternate bed as follows. Regeneration of adsorbents in the adsorber column (B) is carried out by heating the air drawn in by the air blower (B) in the hot water-air heat exchanger (B) and passing the hot air into the adsorber column (B) so that moisture is desorbed and removed from the adsorbents into the atmosphere. At the same time, drying is carried out in the drying chamber by heating the air drawn in by the blower (A) that is dehumidified by adsorber column (A) in the warm water-air heat exchanger (A) and passing the warm dehumidified air into the drying chamber. When the adsorbents in the adsorber column (A) are saturated with moisture and the regenerated adsorbents in the other adsorber column (B) are fully regenerated, then the regeneration process is switched to the saturated adsorber column (A) and the adsorption process is switched to the another adsorber column (B) by manipulation of the two three-way valves.

This solar dryer is therefore suitable for drying heat sensitive products or medical herbs leaf without significant loss of quality because of the lower temperature and relative humidity used. The relative humidity and temperature of the drying chamber are 40% and 35°C respectively. This solar dryer has been evaluated for drying pegaga leaf. The initial and final moisture content of pegaga leaf are 88% (wet basis) and 15% (wet basis) respectively. The drying time is about of 12 hours at an air velocity is 3.25 m/s [12,13].

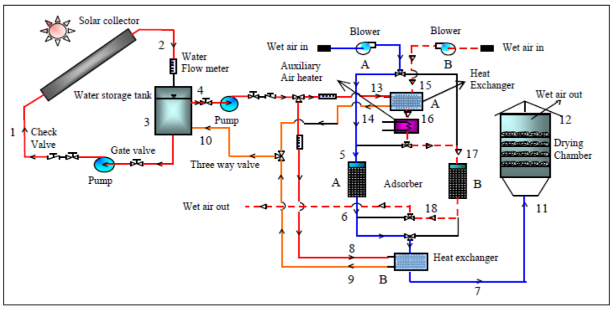

Fig. 12. The schematic of solar dryer with dehumidification system

Fig. 13. The photograph of solar dryer with dehumidification system

6. Solar Dryer with Solid Desiccant Wheel

Fig. 14 to Fig. 16 shows the schematics and photograph of the solar dryer with solid desiccant wheel. The main components are solar collector (heat pipe evacuated tube), solid desiccant wheel (model no. 770 WSG produced by NOVELAIRE), heat exchanger, energy storage tank, auxiliary heater, blowers, and drying chamber. The collector area is 13.32 m^2. The heat exchanger area is 0.62 m^2. The system was designed for drying in a commercial scale. The use of desiccant wheel for absorbing the moisture in the dryer system is appropriate because not only the air becomes drier, but it also becomes hotter due to isotherms process. Performance of the collectors was determined. The water flow rate of 8 liters/minutes was the optimum flow in the drying process. Experiments were conducted with two modes: (1) heat exchanger to heat the air in the regeneration process and (2) heat exchanger to heat the air after the dehumidification process, while the regeneration process utilized an electrical air heater.

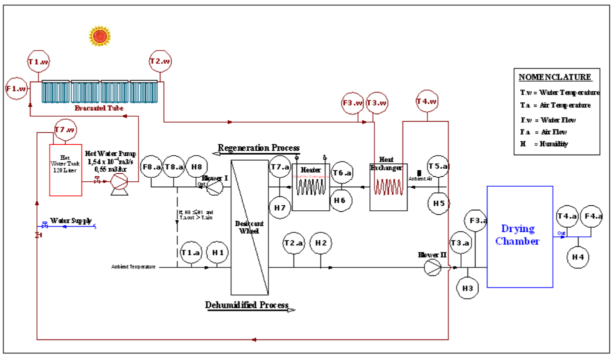

Fig.14 schematic of solar dryer with solid desiccant wheel (system mode 1)

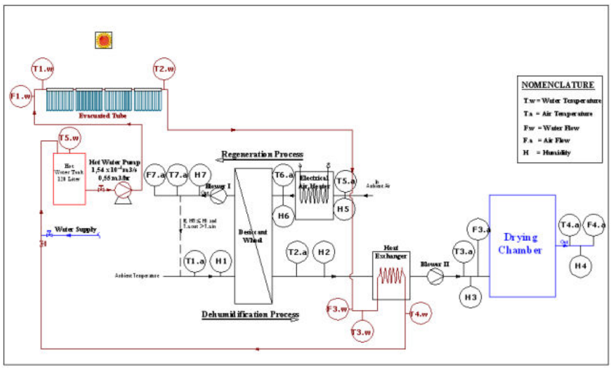

Fig.14 schematic of solar dryer with solid desiccant wheel (system mode 2)

Fig. 15. The photograph of solar dryer with solid desiccant wheel

Experiment on the desiccant wheel of mode (1) showed that the average effectiveness of sensible dehumidification, sensible regeneration, latent dehumidification and latent regeneration were 72.61%, 82.13%, 79.32% and 78.91% respectively. In mode (2), the average effectiveness of sensible dehumidification, sensible regeneration, latent dehumidification and latent regeneration were 71.4%, 71.99%, 66.97% and 72.8% respectively. Mode (1) was better than mode (2) with mean drying air temperature and absolute humidity were 58°C and 0.0167 $kg_{(H2O)}/kg_{(dry\ air)}$ respectively. The system was able to evaporate 10.8 $kg_{(H2O)}$/h of water in the materials at drying efficiency of 60% [14]

7. Conclusions

Drying is one of the oldest and most important preservation methods for reduction of moisture content of foods or other heat sensitive, biologically active products. Beside removal of water the quality of the dried product must be taken into consideration. The quality of the products depends on many factors including the drying temperature and duration of drying time. Some product such as medicinal herbs requires low temperature to prevent the active volatile essential ingredient from being removed during conventional high temperature drying.

The technical directions in the development of solar dryer are compact collector design, high efficiency, integrated storage, and long-life drying system. Air based solar collectors are not the only available systems. Water based collectors can also be used whereby water to air heat exchanger can be used. The hot air for drying of agricultural produce can be forced to flow in the water to air heat exchanger. The hot water tank acts as heat storage of the solar drying system. Heat pump drying system can be effective use for as part of solar assisted drying systems. Moreover, innovative applications of photovoltaic thermal system for simultaneous production of heat and electricity are suitable as standalone applications and totally operated on solar energy.

Acknowledgements

The authors would like to thank the Yayasan Felda for funding this research (RMK9 RS-DL-001-2007), CIMB Bank for funding this research (UKM-HEJIM-KOMUNITI-13-2010), Malaysian Ministry of Science, Technology and Innovation, the Ministry of Higher Education and the Solar Energy Research Institute (SERI), University Kebangsaan Malaysia for providing the laboratory facilities and technical support.

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