Survey of Hybrid Solar Heat Pump Drying Systems

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Abstract- Solar drying is in practice since the ancient time for preservation of food and agriculture crops. The objective of most drying processes is to reduce the moisture content of the product to a specified value. Solar dryers used in agriculture for food and crop drying and industrial drying process can be proved to be most useful device from energy conservation point of view. It not only save energy but also save lot of time, occupying less area, improves quality of the product, makes the process more efficient and protects environment also. Solar dryers circumvent some of the major disadvantages of classical drying; however using merely solar energy for drying application might cause some difficulties that must be overcome. These difficulties can be eliminated-aside from employing heat pumps and to consider a combination between heat pump technology and renewable solar energy.

Solar assisted heat pump systems have been studied and used since the last decade in order to increase the quality of products where low temperature and well-controlled drying conditions are needed. Within this paper some investigations and developments on these are reviewed. The review shows that for heat sensitive materials improved quality control, reduced energy consumption, high coefficient of performance and high thermal efficiency of the dryer with solar assisted heat pump dryer can be achieved.

Key-words: Heat pump, Coefficient of Performance (COP), Solar Assisted Heat Pumps Dryer (SAHPD), Solar Fraction, Direct Expansion SAHD, Drying Chamber.

1 Introduction

Open air sun drying has been used since ancient times. However for large scale production the limitations of drying using the sun under the open sky are well known. Among these are: high labour costs, large area requirement, lack of ability to control the drying process, spoilt products due to rain, wind, moisture and dust, loss of produce due to birds and animals, possible degradation due to biochemical or microbiological reactions. In order to benefit from the free and renewable energy source provided by the sun numerous attempts have been made in recent years to develop solar drying systems. Solar drying technology offers an alternative which can process the products in clean, hygienic and sanitary conditions with zero costs, but has some disadvantages. First, the intensity of incident radiation is a function of time. This is a circumstance and demands adequate control strategy and the means necessary for such control. Another problem is caused by the low energy density of solar radiation which requires use of large energy-collecting surfaces. Thirdly, it may be necessary to match the drying kinetics of the product to that of the time-varying solar radiation density else thermal-related product quality parameters such as texture and colour can undergo significant degradation. Therefore, it is imperative that, a more scientific method for drying has emerged termed as controlled solar drying.

Combined solar dryer and heat pump can overcome these difficulties and satisfy important demands in industrial drying with respect to product quality control, reduced energy consumption and reduced environmental impact. For heat sensitive materials improved quality control can be achieved due to low drying temperatures and independency of the outdoor air. Reduced energy consumption is achieved due to the high coefficient of performance of the heat pump and the high thermal efficiency of the dryer when properly designed.

2 A systematic classification of Solar Assisted Heat Pump (SAHP)

A heat pump is a machine or device that moves heat from one location (the 'source') to another location (the 'sink' or 'heat sink') using mechanical work. Most heat pump technology moves heat from a low temperature heat source to a higher temperature heat sink. Common examples are food refrigerators and freezers, air conditioners, and reversible-cycle heat pumps for providing thermal comfort. Heat pumps can also operate in reverse, producing heat. This produces an efficient way of drying, and manufacturers such as Panasonic, Toshiba, AEG and Miele have released tumble dryers or washing dryers that utilise this method. It is claimed to be more energy saving and quicker than conventional drying.

Solar assisted heat pump systems can be classified to conventional SAHP systems and direct-expansion SAHP (DX-SAHP) systems. The DX-SAHP system basically consists of a solar collector, a heat exchanger as condenser, a thermostatic expansion valve and a compressor. The solar collector is used as the evaporator of the heat pump system. The refrigerant is directly vaporized in the solar collector–evaporator due to the solar energy input, where phase change from liquid to vapour occurs. Thus, unlike the conventional SAHP systems, where two separate system components are used for the same purpose, both processes, namely collecting solar energy and vaporizing the refrigerant, are realized in one unit only. This leads to several advantages compared to conventional SAHP systems [1]:

(a) The direct vaporization of the refrigerant in the solar collector–evaporator leads to higher heat transfer coefficients.

(b) The use of the solar collector as the evaporator reduces overall system cost because the need for an additional evaporator in the traditional SAHP system is eliminated.

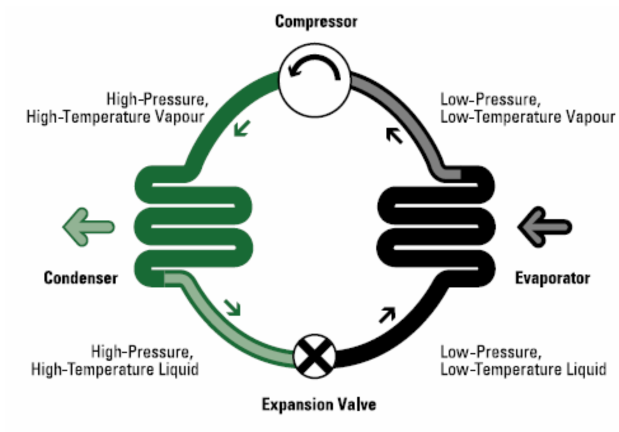

Fig.1. Basic heat pump cycle

(c) Problems, which may occur in water collectors (i.e. corrosion, night freezing), are eliminated due to the use of refrigerants as the working fluid, leading to longer system life.

(d) Using refrigerants as the working fluid in the heat pump cycle results with low temperature during the evaporation process in the solar collector, which leads to lower system losses since the collector loss value is a function of the collector to ambient temperature difference.

(e) The collector, including bare flat-plate collectors, works at high efficiency values based on the low collector to ambient temperature differences, which also reduces collector cost.

3 Heat pump Drying

There are various ways of drying moist materials and it is often necessary to compare the efficiencies of different methods. A convenient parameter to use is ' effectiveness' the amount of water extracted per unit energy input, expressed in $KgH_2O\ kwh^{-1}$[2]. The simplest drying method is to blow heated air over the moist material and to vent the moist air to atmosphere. An improvement is possible by recalculating a proportion of the air but the amount of improvement is limited and it is at the expense of increased drying time.

One of the most efficient and controllable ways of drying moist materials is by using a heat pump drying. For years heat pumps have been known as an efficient method of energy recovery. Heat pump for drying is difference, of the hot heat produced by condenser and cold heat by the evaporator will be use concurrently during the operation. The heat from the condenser will produced hot and will use to heat the material and the cold heat from the evaporator will be use in dehumanization process. Their ability to convert the latent heat of vapour condensation into the sensible heat of an air stream passing through the condenser makes them attractive in drying applications especially when combined with the ability to produced well-controlled drying conditions [3]. For these reasons heat-pump drying has been used for decades in wood kilns to dehumidify air and control lumber quality [4]. Following the general trend to improve product quality and reduce energy consumption, many researcher have acknowledged the specific features of heat pumps, which has resulted in the rapid growth of both theoretical and applied research on heat pump drying (Table 1).The key advantages and limitations of heat pump dryers are as follows:

Advantages:

- Higher energy efficiency with controlled temperature profile to meet product requirements
- Better product quality with control temperature profile to meet product requirements
- A wide range of drying conditions typically from -20ºC to 100ºC (with auxiliary heating) is feasible
- Consistent output of products
- Excellent control of the environment for high value products and reduced electrical consumption for low- valued products
- Suitable for both high-value and low-value products
- Aseptic processing is possible.

Limitations:

- Auxiliary heating may be required for high-temperature drying due to the critical pressure level of some refrigerants
- Initial capital cost may be high de to many refrigerant components. Requires a steady state period for system to attain desired drying conditions.

Table1. Some studies in heat-pump drying

Source	Location	Application (s)	Conclusions
Theerakulpisut (1990) [5]	Australia	Grain	An open cycle HPD performed better during the initial stage when the product drying rate is high.
Meyer and Greyvenstein (1992) [6]	South Africa	Grains	The HPD is more economical than other dryers.
Nassikas et al. (1992) [7]	Greece	Paper	---
Rossi et al. (1992) [8]	Brazil	Vegetable (Onion)	Better product quality and energy saving of the order of 30% was obtained.
Mason and Blarcom (1993) [9]	Australia	Macadamia nuts	---
Strommen and Karmmer (1994) [10]	Norway	Marine products (fish)	The high quality of the dried products was Highlighted as the major advantage of HPD.
Prasertsan et al. (1997); Prasertsan and Saen-saby(1998) [11,12]	Thailand	Agricultural food drying (bananas)	HPD is economically feasible and for drying high moisture materials is so appropriate.
O'Neill et al.(1998) [13]	New Zealand	Apples	Modified atmosphere heat pump (New Zealand) heat pump system drying (MAHPD) produces products with a high level of open pore structure, contributing to the unique physical properties
Carrington et al. (1996); Sun et al. (1996) [14-16]	New Zealand	Timber and wood drying	----
Chou et al. (1998, 2001);Chua et al. (2000) [17-20]	Singapore	Agricultural and marine products (mushrooms, fruits, sea cucumber and oysters)	With scheduled drying conditions the quality of products can be improved
Hawlader et al. (2006) [21]	Singapore	Apple, guava and potato	Modified atmosphere heat pump dryer produced better physical properties.

- Required regular maintenance of components
- Leakage of refrigerant to the environment if cracking of pipes occurs due to pressurized systems.

4 A brief description of Solar Assisted Heat Pump Drying (SAHPD) technology

Heat pumps have been known to be energy efficient when used in conjunction with drying operation. The principal advantages of heat pump dryers emerge from the ability of heat pumps to recover energy from the exhaust gas as well as their ability to control their ability to control their dryer gas temperature and humidity.

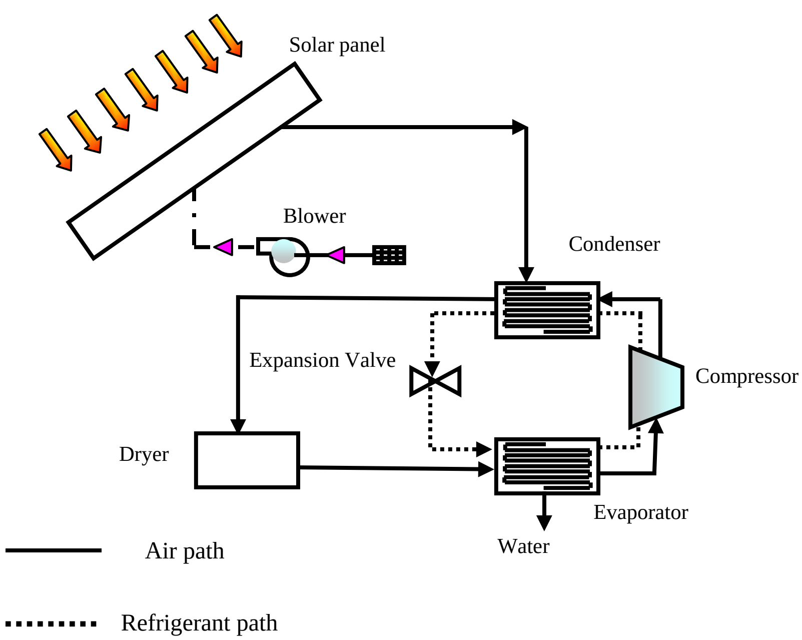

Fig. 2.Schematic of a simplified SHPWD system

There can be a variety of SAHPD designs depending on nature of the direct application such as one with and without heat storage facility. Fig. 2 illustrates the schematic of a simplified SHPWD system. It represents a schematic layout of the various refrigeration components and solar system integration with the drying chamber. The inlet drying air passes through the drying chamber and picks up moisture from the product. The moisture-laden air is then directed to the evaporator coil. During the dehumidification process, the air is first cooled sensibly to its dew point. Further cooling results in water being condensed from the air. Both sensible and latent heats are then absorbed by the evaporator for boiling of the refrigerant. The recovered heat is pumped to the condenser. Art the solar collector, the solar radiation from the sun is converted to sensible heat. Air passing through the number of pipes in the panel is then heated up. This heated air entering the condenser. The pre-heated and dehumidified air absorbs more heat from the condenser and then one that is higher temperature and properly dehumidified which readily flows through the drying chamber for drying application.

Like many mechanical systems, the SAHPD has a set of advantages and disadvantages. The potential advantages of SAHPD are:

- Easy conversion of natural energy for direct heating and storage resulting in significant saving of energy and better system efficiencies
- Better product quality with well-controlled drying condition schedules to meet specific production requirements
- Easy to implement control strategy
- Higher operating drying temperature compared to a standalone heat pump drying system

Disadvantages are as follows:

- Higher capital costs incurred for additional solar panels, blowers, storage tanks , …
- The amount of available solar energy varies significantly throughout the day.

5 Solar Assisted Heat Pump Drying System: a review

A solar assisted heat pump drying prototype system operated. The prototype had a drying chamber 3.78 meter. Long divided in six sections, two of them with four drying trays and the other four sections with three each for a total of 20 trays [22]. The heat pump consisted of modified 7KW packaged air conditioning

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system. The compressor and the condenser were mounted in the frontal part of the equipment and the evaporator at the end of the drying chamber. The solar collector was fixed on top and consisted of a horizontal single glazed flat plate collector with air flowing on both sides of the black painted absorber. The advantage of the low temperature and better control in the drier showed that the heat pump assisted solar drying system is an excellent alternative to traditional drying systems.

A solar assisted heat pump dryer and water heater designed and built, as shown in figure 3 [23]. The set-up consists of two distinct paths, namely air and refrigerant. The air path deals with the air, which has to be maintained at a desired condition at the inlet to the dryer. The various components in the air path are: solar air collector, air-cooled condenser, auxiliary heater, blower, dryer unit, evaporator, and temperature and flow control devices. The incoming air is heated by the solar air-collector, and then flows over the condenser coil, where it is heated further by the heat released by the condensing refrigerant. The magnitude of the desired dryer's inlet temperature and the meteorological conditions determine the amount of auxiliary energy required for a particular application. The air at the pre-set drying condition enters the dryer inlet and performs drying. The air leaving the dryer is cooled and dehumidified to get rid of the moisture absorbed in the dryer, thereby, a rejection of sensible and latent heat occur at the de-humidifier. Subsequently, this heat is available at the air-cooled condenser for the re-processing of the air for the next cycle. The cycle is repeated until the required moisture level of the drying material is attained. The refrigerant path consists of a vapour-compression heat-pump unit, with collector evaporator, an open-type reciprocating compressor, evaporator pressure regulators, expansion valves, condenser tank, and a fan-coil unit. The two evaporators are connected in parallel with individual expansion valves, as shown in Fig. 3. Evaporator1 acts as a dehumidifier and Evaporator2 performs as an evaporator collector. The refrigerant coming out of the air-cooled condenser passes through the coil immersed in a tank and heats the water in the tank to ensure complete condensation. A simulation program is developed using FORTRAN language to evaluate the performance of the system and the influence of different variables. The performance indices considered to evaluate the performance of the system are: Solar Fraction (SF) and Coefficient of Performance (COP) with and without a water heater. The values of COP, obtained from the simulation and experiment are 7.0, and 5.0, respectively, whereas the solar fraction (SF) values of 0.65 and 0.61 are obtained from simulation and experiment, respectively.

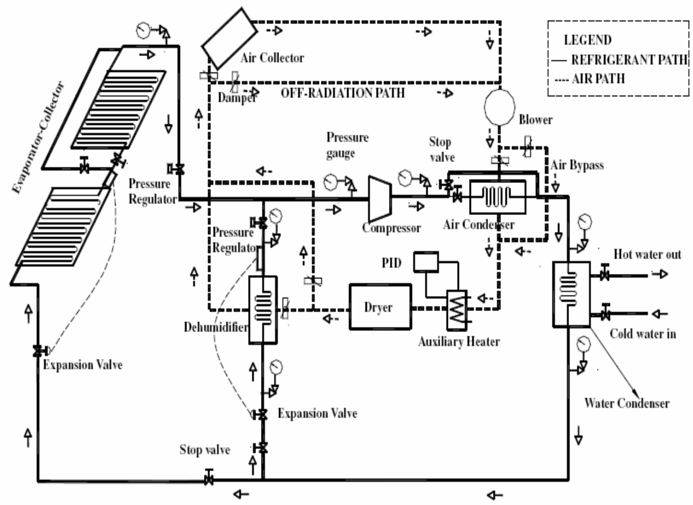

Fig. 3. Schematic diagram of the solar assisted heat pump dryer and water heater.

In another study, the performance of a solar assisted heat pump dryer and water heater investigated [24], a COP value of 7.5 for a compressor speed of 1800 rpm was observed. In the drying of green beans, a specific moisture extraction rate value of 0.65 for a material load of 20 kg and compressor speed of 1200 rpm was obtained.

A solar assisted heat pump dryer designed, fabricated and tested by [25]. Experiments were conducted to compare the performance of an evaporator-collector and an air collector used in an integrated solar system. It was found that the evaporator- collector performed better than the air collector in a solar assisted heat pump drying system. Higher mass flow rates of air and use of a dehumidifier played important roles in increasing the air collector efficiency. The range of efficiency of the air collector, with and without dehumidifier, was found to be about 0.72–0.76 and 0.42– 0.48, respectively. The results showed that the evaporator- collector efficiency increases with increasing refrigerant mass flow rate. It was also revealed that the efficiency of the evaporator- collector is higher than that of the air collector. A maximum evaporator-collector efficiency of 0.87 against a maximum air collector efficiency of 0.76 was obtained.

6 A new hybrid SAHPD system in Malaysia

A heat pump dryer using multifunctional solar thermal collector studied at Universiti Kebangsaan Malaysia (UKM). This system consists of five main components: vapour compression heat pump system, multifunctional solar thermal collector, drying chamber, air duct and solar collector hot air channel. The multifunctional solar thermal collector designed for the heat pump is consists of aluminium rods and fins to transfer heat to and from the air passing through it. The collector is covered by the transparent plastic sheet on the top, and insulated by rubber foam on the bottom.The multifunctional collector is designed to operate as heat collector during sunshine hours and as evaporator during night hours or when solar radiation is insufficient. Therefore, it will increase the overall efficiency of the system and also extended the operation time. The preliminary results of experimental work revealed that this system is environment friendly and can be used anywhere in four season countries. Now the system is ready for drying of high quality products [26].

7 Future trends in SAHPD research and development

Looking into the future direction of SAHPD technologies, it is possible to consider new demands on better energy efficiency, lower environmental impact, and utilization of renewable energy for drying and better quality products at lower total cost. Currently the major driving force for innovate drying techniques is the need to produce better quality products at higher throughputs. This goal can be reached in several possible ways; using multiple stages solar assisted heat pump dryer that can produce a high quality dried product at a lower cost is of these methods.

Solar collectors are used for drying products in solar assisted heat pump drying technologies. Collector performance should be increased in order to accept for commercial application. Many studies have been conducted on enhancement of the thermal performance of solar collectors, but the performance of PV/T water based collectors of solar assisted heat pump systems have not been investigated. A lot of research works should be carried out in this area for investigating the effects of using PV/T water based on improving Coefficient of Performance (COP) of dryer.

8 Conclusions

In this study a review of the some available literature on SAHPD systems with the view of enabling an easier comparison of the findings obtained by various researchers has been conducted. However, a lot of research work still needs to be done for large-scale applications in industry and for the replacement of conventional dryers and heat pump dryers. The results of studies of SAHPD systems indicated that the COP of these systems can be much better than that of conventional heat pump dryers and also quality of products has been improved. SAHPD systems with respect to product quality control, reduced energy consumption and reduced environmental impact can be very useful. For heat sensitive materials improved quality control can be achieved due to low drying temperatures and independency of the outdoor air. Reduced energy consumption is achieved due to the high coefficient of performance of the solar assisted heat pump dryer and the high thermal efficiency of the dryer when properly designed.

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