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Review on drying of agricultural produce using solar assisted heat pump drying

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ABSTRACT : Sun drying is an oldest and traditional method used to dry and preserve agricultural products in tropical and sub-tropical countries. But the process is disadvantageous like labour intensive, time consuming and requires a large area for spreading the produce out to dry, loss of produce due to birds and animals, deterioration in harvested crops due to decomposition, insect attacks and fungi, etc. Also the required quality standards are not fulfilled in open sun drying. 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 and improves product quality. The solar-assisted dryers are conventional dryers to which supplementary equipment is added to enable a significant proportion of the thermal energy required for drying to be replaced by solar energy. Heat pump dryers have been known to be energy efficient when used in conjunction with drying operations. The heat pump recirculation mode and solar mode can be used for drying the agricultural produce and allows the drying process to be continues in different weather conditions. In these dryers, a planned and generally optimized drying process can be achieved to obtain superior product quality and good economic performance.

KEY WORDS : Sun drying, Time consuming, Product quality, Solar assisted dryers, Heat pump, Energy efficient

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Drying is one of an important post handling process of agricultural production.It can extend shelf life of the harvested products, improve quality, improve the bargaining position of the farmer to maintain relatively constant price of his products and reduces post-harvest losses and lower transportation costs since most of the water is taken out of the product during the drying process (Fudholi *et al.*, 2014). Drying is the process that requires high energy. Thus, drying units need efficient processes and alternative energy resources (Sevik, 2013). When dealing with agricultural products, the drying under open sun becomes much more important as the chances of spoilage of the product through the activity of micro-organisms are very high (Hawlader *et al*., 2003).

Solar energy is the world's most abundant, permanent and environmentally compatible source of energy. As an alternative to open sun drying, the solar drying system is one of the most attractive and promising applications of solar energy systems (Fudholi *et al.*, 2016). In addition, using renewable energy sources such as solar energy is also considered in the context of the increasingly exhausted fossil fuel sources, environmental protection and anti-greenhouse effect (Huy and Nhut, 2018).

Sun drying is a common farming and agricultural process in many countries, particularly where the outdoor temperature reaches 30^0 C or higher. Solar drying is often differentiated from ‘‘sun drying’’ by the use of equipment to collect the sun’s radiation in order to harness the radiative energy for drying applications (Sharma *et al.*, 2009). Solar drying under controlled conditions of temperature and moisture removing rate ensures perfect drying and desirable product quality (Kumar *et al*., 2016).

Solar drying technology offers an alternative which can process the products in clean, hygienic and sanitary conditions with zero costs but also has some disadvantages (Daghigh *et al.*, 2009).Solar drying systems must be properly designed in orderto meet particular drying requirements of specific products and to give satisfactory performance with respect to requirements. Designers should investigate the basic parameters such as collector area, drying air recirculation factor and product quality (Smitabhindu *et al.*, 2008).

Combined solar dryer and heat pump can satisfy important demands in industrial drying with respect to product quality control, reduced energy consumption and reduced environmental impact (Daghigh *et al.*, 2009). Solar assisted heat pump (SAHP) is a conventional system where solar energy is used as the main or supplementary heat source. Integration of solar energy with conventional heat pump system is considered viable solution to reduce the dependancy on fossil fuel and improve the performance of the system (Hawlader *et al*., 2017).

Solar heat pump systems (SHPs) are hybrid systems in which electrical (in most cases) heat pumps are combined with solar thermal (ST) collectors, solar photovoltaic (PV) collectors or both. Heat pumps combined with ST systems have a superior seasonal performance factor (SPF) compared to heat pumps with no solar, while heat pumps combined with PV use less electricity from the grid. On the other hand, SHPs have higher investment costs than conventional heat pumps due to the additional components. The potential for improvement has led to much work being done in the field of SHPs for domestic applications (Stefano *et al*., 2018). In the current review, the design and performance evaluation factors of different solar-assisted heat-pump drying systems for drying of agricultural produce were studied.

■ METHODOLOGY

Working details of different types of drying systems:

Solar assisted heat pump dryer with multifunctional solar collector:

The system was made by three main components; heat pump system, drying chamber and multifunctional solar collector (Majid *et al*., 2007 and 2009). The heat pump system is the main component of the drying system as it will supply heat through a condenser and a compressor to the drying chamber. An evaporator is used to remove the humidity in air that was produced during drying process. Multifunctional solar collector (MFSC) is used to increase the heat gain from outside environment. It consists of aluminium rods and fins to transfer heat to and from the air passing through the collector. It is covered by the transparent plastic sheet on the top and insulated by rubber foam on the bottom. Thus, it increases the overall efficiency of the system and also extend the operation time and to maintain the power in the drying chamber.

The MFSC shown in Fig. A is designed to operate as heat collector during sunshine hours, as evaporator during night hours or when solar radiation is insufficient and also absorb the energy from the cold environment, as it acts as cooler. It acts as a heater when the solar radiation is available and as a cooler during night or rainy day and also as an evaporator if the temperature is low enough. The solar collector consists of cover, cross absorber and heat absorber. It was observed that the MFSCcould provide energy to the heat pump dryer during drying process with producing heat 8 per cent when function as a cooler, 96 per cent as a heater during open cycle and 98 per cent as a heater during close cycle. The entire process can provide 50 per cent of heat that required by the system in drying process. Also it was observed that the MFSC can be used to obtain heat not mainly from the solar radiation as a heater but also as a cooler or evaporator from the low ambient air temperature. The operation time can be increased, hence will increase solar collector’s efficiency. This dryer is suitable for high quality of drying herbs and other agriculture products.

The heat pump dryer with assistant MFSC was

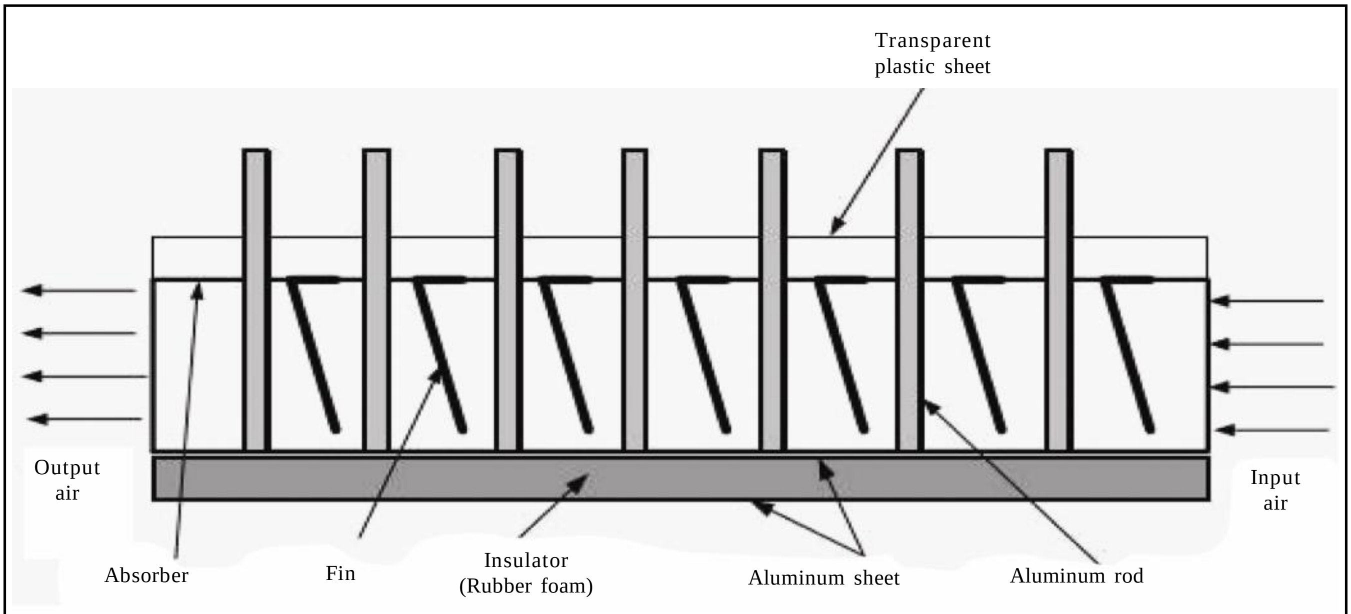


Fig. A : Multifunctional solar thermal collector (Majid *et al*., 2007 and 2009)

installed at Solar Technology Park, UKM Malaysia. The dryer has a length of 0.65 m× 0.65 m × 0.65 m. The dryer chamber consists fins that are covered by transparent plastic sheet on the top and rubber foam on the bottom. It is of a cubic structure made form alluminum sheets. The collector consists of alluminum rods and has length 0.65 m and width of 0.65 m.

The heat pump-solar dryer involves three main systems: heat pump system and solar system and drying chamber. As it is shown in Fig. B (schematic diagram of

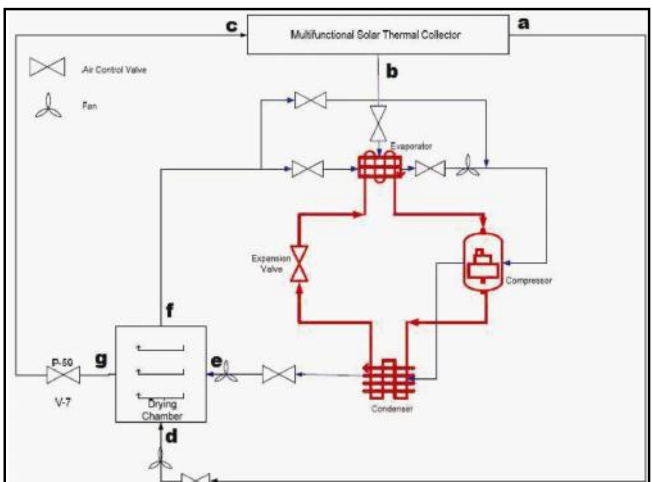


Fig. B : Schematic diagram of the system (Majid *et al*., 2007 and 2009)

the system) is including heat pump system and the multifunctional solar thermal collector that are attached together. In this system, 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 alluminum 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 draying 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.

Solar assisted chemical heat pump dryer:

Sopian *et al*. (2012) designed the system consists of four mean components solar collector (evacuated tubes type), storage tank, chemical heat pump unit and dryer chamber and the schematic sketch is as shown in Fig. C. In this dryer, a cylindrical tank is selected as a storage tank. The chemical heat pump unit consists of

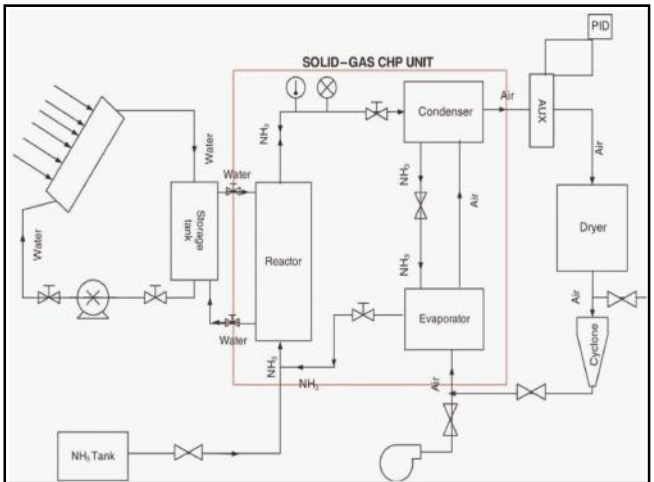


Fig. C : Schematic diagram of solar assisted chemical heat pump dryer

reactor, evaporator and condenser. In the chemical heat pump a solid gas reactor is coupled with a condenser or an evaporator. The reaction used in this study 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 upto 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.

In the 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 evaporator at low temperature is supplied to vaporize ammonia, which reacts with salt and release heat at medium temperature.

Solar assisted heat pump (SHPD) dryer integrated with biomass furnace:

Yahya (2016) designeda solar assisted heat pump dryer integrated with biomass furnace was designed and installed at the Institute of Technology, Padang, West Sumatra, Indonesia for drying of red chilli. The drying process cannot be conducted or continued during the cloudy, rainy days and the night time because there is either no or low sunlight. Therefore, it is necessary to provide the solar dryers with an auxiliary heater, such as biomass furnace by using biomass as heat energy sources.

The drying system consists of solar collector array, heat pump, biomass furnace, drying chamber and blower shown in Fig. D and E. The solar collector is equipped with transparent cover glass material, absorber plate finned used alluminum and black painted opaque, angle iron frame, inside and outside the collector coated with aluminum 1mm thick and insulation using glass fibre materials.

Fig. D : Photograph of solar assisted heat pump dryer integrated with biomass furance

Two solar collectors are connected in series with an area of 1.8 m² each.The heat pump consists of several main parts: evaporator, condenser, compressor and expansion valve. The working fluid of the heat pump is R-22. Compressor use of electrical capacity is 0.746 kW. The biomass furnace consists of several main parts such as the combustion chamber, heat exchanger, chimney and blower. The wall of the combustion chamber uses

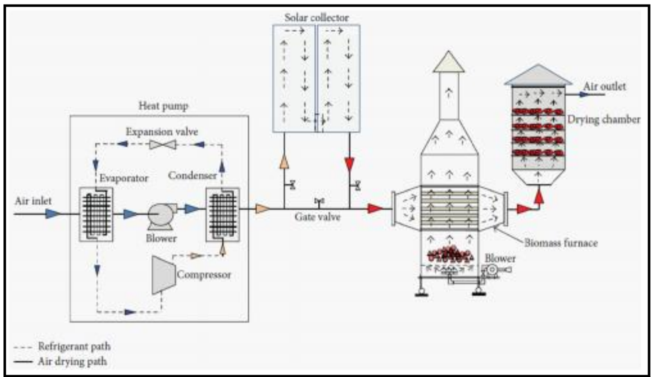


Fig. E : **Schematic diagram of SAHP dryerintegrated with biomass furnace**

brick, cement and steel plate materials and heat exchanger pipes using mild steel with diameter of 2 inch and number of pipes is 16 units. The drying chamber uses the cabinet type and contains the drying trays with adjustable racks to place the red chilli. Its walls consist of triple layers, an outside layer which uses aluminum sheet, a middle one insulated with glass fibre materials and inner layer which uses of aluminum sheet. The drying air is circulated by using blower with electrical capacity of 0.75 kW.

Solar-assisted heat pump dryer (SAHPD) for cassava:

Yahya *et al*. (2016) designed SAHPD consists of a solar collector array, heat pump, drying chamber and blowers which is shown in the Fig. F. The solar collector consists of several main parts: a transparent cover glass material; absorbent finned plate made from aluminum and black-painted opaque; angular iron frame; inside and outside collector coated with 1 mm-thick aluminum; and insulation using fibre glass materials. Two solar collectors are connected in series with an area of 1.8 m² each. The heat pump consists of evaporator, condenser, compressor and expansion valve. The compressor has an electrical capacity of 0.746 kW. The cabinet-type drying chamber has a dimension of 1.0 m × 1.0 m × 1.35 m. The chamber contains drying trays with adjustable racks to place the cassava sample. The triple-layer walls of the chamber consist of an aluminum sheet as outside layer, insulated glass fibre material as middle layer and aluminum sheet as inner layer. Drying air was circulated using a blower with an electrical capacity of 0.75 kW. The cassava chips (approximately 30.8 kg) were placed into the drying chamber. The air temperatures at the inlet and outlet of the solar collector, heat pump and drying chamber were measured using a thermocouple. Solar radiation was measured using a pyranometer and air flow rate was determined using a flowmeter. Changes in the mass of cassava chips were measured using scales. Cassava chips were weighed every 1 h, and temperature was measured every 0.5 h. Heat pumps were not used for solar mode of operation. Solar collectors and heat pumps were employed for SAHPD. Experiments were performed at the Institute Technology, Padang.

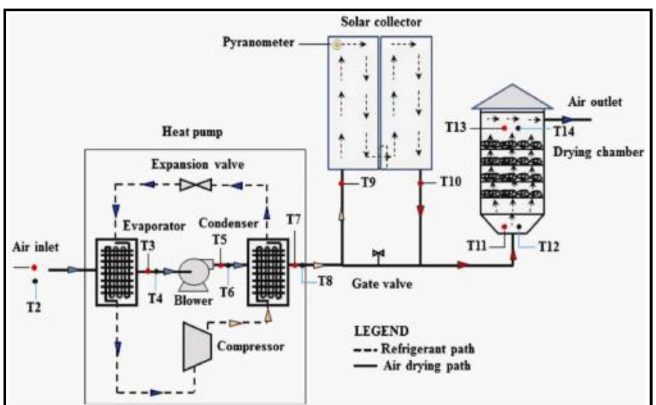
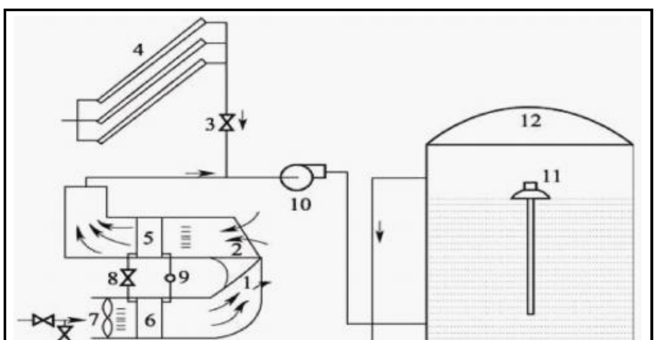


Fig. F : **Schematic diagram of SAHPD for cassava**

Solar assisted heat pump system for grain in-store drying:

Haifeng *et al*. (2010) designed the solar assisted heat pump system for grain drying which is composed of solar air collectors, an air source heat pump, a grain stirrer and a supply and return fan etc. Fig. G shows the schematic diagram of the in-store drying system.



1,2,3- Air valve; 4- Solar air collector; 5-Condenser; 6-Evaporator; 7-Exhaust fan; 8-Expansion valve; 9-Compressor; 10-Supply fan; 11-Stirrer; 12-Granary

Fig. G : **Schematic diagram of a solar assisted heat pump for in-store drying**

The solar air collectors are connected one by one in parallel. The solar heating unit and the heat pump unit are also arranged in parallel to reduce flow resistance. Both the condenser and the evaporator of the heat pump are the finned tube heat exchanger. Considering the grain bulk's resistance, the solar collector fan, the condenser and the evaporator fan are installed and combined with the air supply system to form an integral drying ventilation system. The system can work in three operation modes, the solar assisted heating and ventilation mode, the heat pump heating and ventilation mode and the heat pump dehumidification and ventilation mode.

The solar assisted heating and ventilation mode can be adopted on sunny days. On a sunny day, when the supply and return fan is turned on, air valves 1 and 2 are moved to the position of the solid line. Ambient air is heated by the solar collectors and the heat pump, respectively. The airflows that come from the solar collectors and the heat pump are mixed by the supply fan and then sent to the granary to dry the grain. The return air from the granary is introduced to the evaporator for heat recovery.

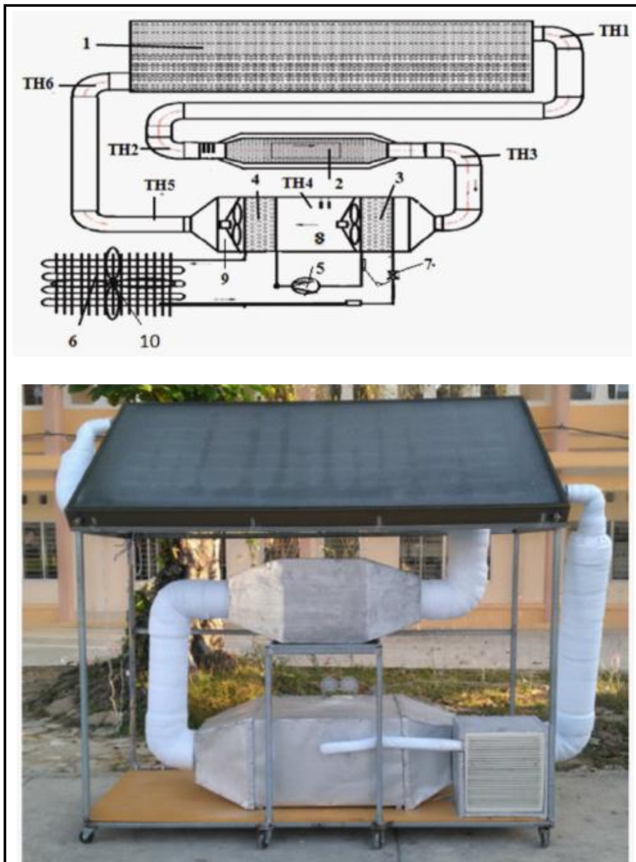
The heat pump heating and ventilation mode can be feasible at night. In this mode, the collector fan is turned off and the air valve 3 is closed. Air valves 1 and 2 are moved to the position of the solid line. Ambient air is heated by the heat pump and then sent to the granary to dry the grain. Also, the return air from the granary is introduced to the evaporator for heat recovery.

The heat pump dehumidification and ventilation mode used on rainy or cloudy days. In this mode, the collector fan is turned off and air valve 3 is closed. Air valves 1 and 2 are moved to the position of the dashed line. Ambient air is introduced first into the evaporator where the air is cooled and dehumidified and then sent into the condenser for reheating. Thereafter, it is sent to the granary for grain drying.

It should be noted that during the drying process, the stirrer keeps working all the time so that a uniform drying effect can be ensured. To ensure the uniformity of drying and to solve the problem of the grain at the bottom of the bulk being dried exceedingly while that at the upper part not being dried sufficiently, a stirrer is also necessary because it can guarantee drying uniformity in the vertical direction with a lower power consumption apart from the reasonable air distribution unit.

Solar assisted heat pump dryer for chilli :

Huy and Nhut (2018) designed this system consists of a flat plate collector, a heat pump, a drying chamber, exhausted fan and pipes covered by 10mm layer of polyurethane insulation. Flat plate collector is 1m x 2m x 10 cm in dimension. It is made of chromium plated and black copper tubes and plates and protected by 6- mm reinforced glass panels. The drying chamber is of 38 cm x 38 cm x 40 cm in dimension and is divided into 5 compartments for 5 trays of chili. Heat pump includes a 750W compressor, expansion valve, main and auxiliary condenser, evaporator, and two 38W exhaust fans. When the radiation on the collector is large enough to generate useful energy, the sensors will record the value and transmit it to the Arduino processor to turn off the resistors to save power. Power consumption is measured by the



1-Flat plate collector; 2-Drying chamber; 3-Evaporator; 4-Main condenser; 5-Compressor; 6-Secondary condenser; 7-Expansion valve; 8, 9-Exhaust fans;
TH1, TH2, TH3, TH4, TH5, TH6- Temperature- humidity sensors

Fig. H : Schematic diagram and photograph of solar-assisted heat pump dryer for chilli

electricity meter. The schematic sketch and photograph are as shown in Fig. H.

When the system is in operation, the air shall be fed by fan through the evaporator for cooling and separating a part of the water vapour from the air. Then air shall be passed through condenser for heating and passed through flat plate collector to absorb heat from incoming solar radiation and enter the drying chamber. If solar radiation is insufficient to maintain pre-set heat value in the drying chamber, then the resistant bars shall be switched on to heat the heat pump. Once the solar radiation received by the collector is sufficient to maintain the temperature in the drying chamber, they shall be turned off. During the drying process, the heat pump works continuously. In the refrigerant cycle, the refrigerant is compressed by the compressor and compressed to high pressure and enters the condenser. In the condenser, a part of the heat is discharged to the ambient environment at auxiliary condenser and other part is for heating the air at the main condenser. Refrigerant vapour from the condenser is in the liquid state and goes to the expansion valve to reduce its pressure, low pressure liquid refrigerant will be injected into the evaporator to collect the heat of the drying agent. The cycle is repeatedly closed to perform the air treatment in the drying system.

Performance evaluation of solar assisted heat pump dryers:

Performance evaluation of solar assisted chemical heat pump dryer:

Solar fraction:

The Solar Fraction (SF) is defined as the utilized solar heat divided by the total heat demand and calculated from the following relationship given by Sopian *et al.* (2012).

$$SF = \frac{Q_u - Q_S}{Q_C}$$

Chemical heat pump co-efficient of performance:

For the integrated chemicalheat pump with solar collector and storage tank the heating performance of chemical heat pump could be calculated from the equation given by Sopian *et al*. (2012).

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

where, Q_C is the condenser heat rejection, Q_r is the reaction heat.

In the solar collector the useful energy gain ofcollector surface area is given by Sopian *et al.* (2012).

$$Q_u = \eta A_C I$$

where η is the collector efficiency, A_C is the collector area and I is the instantaneous solar radiation incident on the collector per unit area.

The collector efficiency for the evacuated tube collector is given by Ucar and Inalli (2008):

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

where T_m is the mean collector temperature and T_a is the ambient air temperature. The heat loss from the tank on groundis calculated by:

$$Q_S = UA_{strg} (T_1 - T_a)$$

where Q_s is the heat loss from the storage tank, T_1 is the water temperature in the tank and UA_{strg} is the loss co-efficient of storage tank and calculated using the following equation by Chung *et al*. (1998).

$$UA_{strg} = \frac{As}{\frac{k}{d} + \frac{1}{h}}$$

where k and dare the thermal conductivity and thickness of insulation and his the convective heat transfer co-efficient.

Moisture ratio:

The moisture ratio (MR) is the ratio of the moisture content at any given time to the initial moisture content (both relative to the equilibrium moisture content). It can be calculated for each time intervalusing the following formula given by Sopian *et al*. (2012).

$$MR = \frac{M - M_e}{M_o - M_e}$$

Performance evaluation of SAHP dryer integrated with biomass furnace:

Performance of drying system:

The performance of solar assisted heat pump dryer integrated with biomass furnace is characterized by drying rate, specific moisture extraction rate and dryer thermal efficiency. It is highly depending on the performance of each of the drying system components such as solar collector, heat pump and biomass furnace Yahya (2016).

The thermal efficiency of a solar collector is the ratio ofuseful heat gain by solar collector to the energy incident in the plane of the collector. It is calculated from the equation given by Amer *et al*. (2010).

$$\eta_{coll} = \frac{m_{air} C_{Pair} (T_{o,coll} - T_{i,coll})}{I_T A_C} \times 100\%$$

where m_{air} is air mass flow rate, C_{Pair} is specific heat of air and $T_{i,coll}$ and $T_{o,coll}$ are inlet and outlet air temperatures of solar collector, respectively. A_C is an area of collector and I_T is solar radiation incident in the collector.

The co-efficient of performance of a heat pump is the ratio of useful heat or heat energy released by the refrigerant in the condenser to the electrical energy consumed by compressor. It is calculated from the equation given by Hawlader *et al*. (2001).

$$COP_{hp} = \frac{m_{air} C_{Pair} (T_{o,cond} - T_{i,cond})}{E_{comp}}$$

where, $T_{i,cond}$ and $T_{o,cond}$ are inlet and outlet air temperatures of condenser, respectively and E_{comp} is the electrical energyconsumed by the compressor.

The thermal efficiency of a biomass furnace is the ratio of useful heat by biomass furnace to the heat energy generated by the combustion of the biomass fuel. It is calculated from the equation given by Swasdisevi *et al.* (1997).

$$\eta_{bf} = \frac{m_{air} C_{Pair} (T_{o,bf} - T_{i,bf})}{m_{bmf} CV_{bmf}} x100$$

where, $T_{i,bf}$ and $T_{o,bf}$ are the inlet and outlet air temperatures of biomass furnace, respectively is biomass fuel consumption rate and CV_{bmf} is caloric value of biomass fuel.

The specific moisture extraction rate (SMER) is the ratio of the moisture evaporated from wet red chillies to the energy input to drying system. It is calculated from the equation by Hawlader *et al*. (2006).

$$SMER = \frac{m_{water}}{E_S + E_{bmf} + E_{comp} + E_{bl}}$$

where, E_S is energy incident in the plane of the solar collector and E_{bmf} is heat energy generated by the combustion of biomass fuel. E_{comp} and E_{bl} are electrical energy consumedby compressor and blower, respectively.

The thermal efficiency of SAHP dryer is the ratio of the energy used for moisture evaporation to the energy input to drying system. It is calculated from the equation given by Shanmugam and Natarajan (2007).

$$\eta_{dryer} = \frac{m_{water} H_{fg}}{E_S + E_{bmf} + E_{comp} + E_{bl}}$$

where H_{fg} is the latent heat of vaporization of water.

Performance index in-store drying process by solar assisted heat pump unit:

The performance of the heat pump unit is usually evaluated with the co-efficient of heating performance (COP_H), whose definition is given by Haifeng *et al*. (2010).

$$COP_H = \frac{Q_{con}}{P_{com}}$$

The solar assisted heat pump system for in store grain drying, the performance of the whole system can be evaluated by another index, COP_S, expressed by Haifeng *et al*. (2010).

$$COP_S = \frac{Q_{con} + Q_u}{P_{com} + P_C}$$

The power consumption of the in-store drying, dehydration quantity per unit of power can be used as its evaluation index, whose definition is given by Jianguo *et al*. (2008).

$$SMER = \frac{\text{Dehydration quantity}}{\text{Input power}}$$

Performance evaluation of solar-assisted heat pump dryerfor cassava and chilli:

The thermal efficiency of the solar collector is the ratio of heat gained by the solar collector to the solar radiation incident on the plane of the collector. This parameter is calculated by (Yahya *et al*., 2016).

$$\eta_{coll} = \frac{E_{U\,coll}}{E_S} x\,100\%$$

where $E_{U\,coll}$ is the useful heat gain by the solar collector (kW) and E_S is the energy incident in the plane of the solar collector (kW).

The useful heat gain of the solar collector $E_{U\,coll}$ and energy incident in the plane of the solar collector (E_S) are calculated usingthe equations given by Yahya *et al*. (2016).

$$E_{U\,coll} = m_{air} C_{Pair} (T_{o,coll} - T_{i,coll})$$

and $E_S = GA_C$

where, m_{air} is the air mass flow rate (kg/s) and C_{Pair} is the specific heat of air (J/kg ^{0}C). $T_{i,coll}$ and $T_{o,coll}$ are air temperatures at the inlet and outlet of the solar collector (^{0}C), respectively. A_C is the area of the collector (m^2) and G is the solar radiation incident on the collector (W/m^2).

The co-efficient of performance of the heat pump is the ratio of thermal energy released by the condenser to the electrical energy consumed by the compressor. This co-efficient is calculated by Yahya *et al*. (2016).

$$COP = \frac{E_{R,Cond}}{E_{Comp}}$$

where, $E_{R,Cond}$ is the thermal energy released by the condenser (kW) and E_{Comp} is the electrical energy consumed by the compressor (kW).

The thermal energy released by the condenser can be calculated by Yahya *et al*. (2016).

$$E_{R,Cond} = m_{air} C_{P,air} (T_{O,cond} - T_{i,cond})$$

where, $T_{i,cond}$ and $T_{O,cond}$ are the air temperatures at the inlet and outlet of the condenser (^{0}C), respectively.

The drying rate (DR) is the mass of water evaporated from the product per unit time and calculated by Yahya *et al*. (2016).

$$m_{water} = \frac{m_{water}}{t}$$

where, m_{water} is the mass of water evaporated (kg) and t is the drying time (s).

Solar fractions (SFs) are the ratio of the useful heat gain or the energy extraction of heat from the solar collector to the energy available for drying. SFs of the solar assisted heat pump drying system (SAHPD) are calculated by Yahya *et al*. (2016).

$$SF_{SAHPD} = \frac{E_{U\,coll}}{E_{U\,coll} + E_{comp} + E_b}$$

The energy input to the drying system can be calculatedby Yahya *et al*. (2016).

$$E_{input} = E_S + E_{comp} + E_b$$

Specific moisture extraction rate (SMER) is the ratio of the moisture evaporated from the wet product to energy input to the drying system and calculated byYahya *et al*. (2016).

$$SMER = \frac{m_{water}}{E_{input}}$$

where, E_{input} is the energy input to the drying system (kW).

The thermal efficiency of the drying system is the ratio of the energy used for moisture evaporation to energy input todrying system and calculated by Yahya *et al*. (2016).

$$\eta_{th} = \frac{E_{evap}}{E_{input}}$$

Pick-up efficiency is the ratio of moisture evaporated from thewet product or the moisture picked-up by air in the drying chamber to the theoretical capacity of the air to absorb moisture. This parameter is calculated by Yahya *et al*. (2016).

$$\eta_{pick\ up} = \frac{m_{water}}{m_{da}\, t\, (Y_{as} - Y_i)}$$

where m_{da} is the mass flow rate of dry air (kg dry air/s) Y_i is the absolute humidity of air that enters the drying chamber (kg water/kg dryair) and Y_{as} is the adiabatic saturation humidity of air that enters the drying chamber (kg water/kg dryair).

■ RESULTS AND DISCUSSION

Sopian *et al*. (2012) evaluaed the performance of the solar assisted chemical heat pump dryer experimentally under different climate conditions. For a typical sunny day the maximum value of solar fraction was 0.713 and the solar fraction of system decrease as a solar radiation decrease. For sunny day a maximum value of COP_h as 2 was obtained for sunny day. Any reduction of energy at condenser as a result of a decrease in solar radiation will decrease the co-efficient of performance. Any increasing in solar radiation will increase the COP_h. These results show that any reduction of energy in the condenser as a result of a decrease in solar radiation will decrease the co-efficient of performance as well as decrease the efficiency of drying. The lemongrass was dried from average initial moisture content of 85 per cent to an average final moisture content of 13 per cent. The total energy required to maintain a drying temperature of 55^{o}C is 60 kWh. The system contributed 51 kWh which amounts approximately 85 per cent of the overall energy requirement for sunny day.

Yahya (2016) evaluated the performance of a solar assisted heat pump dryer integrated with biomass furnace for drying red chillies. The averages of the solar collector efficiency, COP of the heat pump and the efficiency of biomass furnace were estimated to be about 35.1 per cent, 3.84 and 30.7 per cent, respectively with an air mass flow rate being about 0.124 kg/s. The biomass furnace efficiency achieved is quite low, because of a lot of heat loss to the environment. The results indicated that the air drying temperatures in solar assisted heat pump integrated withbiomass furnace were higher than the ambient temperature and the relative humidity in this dryer was lower than the ambient relative humidity. The drying rate was found that in the dryer is higher than in open sun drying. The solar assisted heat pump integrated with biomass furnace had a shorter drying time compared to open sun drying and was found to be about 62 hours, with an average ambient air temperature and ambient relative humidity of about 34.1^{0}C and 57.4 per cent, respectively. In other words, the dryer reduced the drying time or saved the drying time of about 82 per cent compared to open sun drying. The decrease in drying time could be due to the values of higher temperature and lower relative humidity obtained in the dryer. The SMER and thermal efficiency of the dryer were estimated in average to be about 0.14 kg/kWh and 9.03 per cent, respectively.

According to the design requirements of Haifeng *et al*. (2010), in-store drying process by solar assisted heat pump unit was evaluated. The heat supplied bythe heat pump will account for about 75 per cent of the total heat produced by the whole system. Hence, the performance of the heat pump may have an important impact on the drying effect. On a typical day, the heat capacity is about 102–115 kW which indicates that the performance of the heat pump is relatively steady and can ensure the safety of the drying process. If the system works in the heat pump heating mode, because the temperature rise of the air is not high, the COP of the heat pump is more than 4.72. If the solar heating unit is also involved, the heating performance of the whole system can be improved significantly. The maximum COP_S of the whole system can reach 6.25. During daytime, the average COP_S can reach 5.66. If night time heating is also considered, the average of the system will be upto 5.19. SMER is selected as the evaluation index of power consumption for in-store grain drying. A higher value of SMER means lower power consumption. According to the computation results, the SMER of the in-store grain drying process by the solar assisted pump system is 3.05 kg/kWh, indicating that the in store drying method by the solar assisted heat pump system can meet the requirement for low power consumption.

Yahya *et al.* (2016) evaluated the solar assisted heat pump dryer (SAHPD) decreased the mass of cassava from 30.8 kg to 17.4 kg, with a mass flow rate of 0.124 kg/s. The moisture content of cassava decreased from 61 per cent (wet basis) to 10.5 per cent within 13 and 9 hours at average temperatures of 40^0 C and 45^0 C by using solar dryer (SD) and SAHPD, respectively. The DR for SD ranged from 0.15 kg/h to 2.3 kg/h, with an average of 1.33 kg/h. The DR for SAHPD ranged from 0.55 kg/h to 0.28 kg/h, with an average of 1.93 kg/h. The SMER ranged from 0.04 kg/kW h to 0.61 kg/kW h for SD and from 0.21 kg/kW h to 0.76 kg/kW h for SAHPD, with average values of 0.38 and 0.47 kg/kW hr, respectively. The thermal efficiencies ranged from 2.4 per cent to 40.6 per cent for SD and from 13.7 per cent to 49.9 per cent for SAHPD with average values of 25.6 per cent and 30.9 per cent, respectively. The SF ranged from 43.2 per cent to 75.4 per cent and from 22.4 per cent to 58.4 per cent for SD and SAHPD, respectively, with corresponding average values of 66.7 per cent and 44.6 per cent. The pick-up efficiencies ranged from 3.9 per cent to 65.8 per cent and from 15.9 per cent to 70.4 per cent for SD and SAHPD, respectively, with corresponding average values of 39.3 per cent and 43.6 per cent.

Huy and Nhut (2018) experimented the solar assisted heat pump dryer in three different weather conditions: clear day, intermittent cloud sky day and overcast sky day to evaluate the performance of the heat pump combined solar energy dryer in drying chili. The findings also showed that the useful energy generated by the collector in clear day, intermittent cloud sky day and overcast sky day are of 14.5 kWh, 8.91 kWh and 0 kWh, respectively and power consumption for the above cases is of 19.2 kWh, 21.4 kWh and 26.1 kWh, respectively. The COP of heat pump for the three cases are of 3.45, 3.46 and 3.51, respectively. During drying, the chili weight is decreased from 5 kg to 1.48 kg and it takes 21 hours for drying. Total useful energy generated by the collector during the daytime sunshine is of 14.5 kW. Power consumption for the entire drying process is of 19.2 kWh including power consumption of resistant bars, heat pumps and exhausted fans. The findings showed that on sunny days, the drying time from the initial moisture content until the moisture of 11 per cent is faster than the two other experiments. From the findings of such experiments, it was found that drying in sunny days saves time and electricity consumption more than in cloudy or rainy days.

Conclusion :

In this review, instead of using solar energy directly for drying purpose, the option to use solar heat with the dual sources like heat pump, chemical pump, absorbers with fins and grooves, photovoltaic and multifunctional thermal collectors it can be concluded that this option has a higher potential for improving the designed drying system's energetic performance with high temperatures on the demand side and low temperatures on the side of the heat source and the ambient air. With this solar assisted dryers, improved quality control, reduced energy consumption, high co-efficient of performance and high thermal efficiency of the dryer can be achieved. Furthermore, colour and aroma qualities of dried agricultural products using this solar assisted dryer systems are better than those products using conventional hot air dryers. Reduced energy consumption is achieved due to the high co-efficient of performance of the heat pump and the high thermal efficiency of the dryer when properly designed. Forheat sensitive materials improved quality control can be achieved due to low drying temperatures and independency of the outdoor air. These solar assisted drying systems have the advantages of heat storage, auxiliary energy source, integrated structure control system and can be used for a wide range of agricultural and marine produce. Furthermore, these innovations of green technology can improve the quality of drying agricultural and marine products.

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■ REFERENCES

Amer, B.M.A., Hossain, M.A. and Gottschalk, K. (2010). Design and performance evaluation of a new hybrid solar dryer for banana. *J. Energy Convers. & Mgmt.*, **51** (4) : 813–820.

Chung, M., Park, J. and Yoon, H. (1998). Simulationof a central solar heating system with seasonal storage in Korea. *J. Solar Energy*, **64** : 163–78.

Daghigh, R., Sopian, K., Ruslan, M.H., Alghoul, M.A., Mat, L.C., Ali, B., Yahya, M., Zaharim, A., Haw, S. and Sulaiman, M.Y. (2009b). Survey of hybrid solar heat pump drying systems. Proceeding of the 4th IASME/WSEAS International Conference on Energy and Environment, Cambridge, UK, February 21-26, 411-418.

Fudholi,A., Sopian, K., Othman, M. Y. and Ruslan, M. H. (2014). Energy and exergy analyses of solar drying system of red seaweed. *Energy & Building*, **68** :121-129. https://doi.org/10.1016/j.enbuild.2013.07.072

Fudholi, A., Yendra, R., Basri, D.F., Ruslan, M.H. and Kamaruzzaman Sopian, K. (2016). Energy and exergy analysis of hybrid solar drying system. *J. Contemporary Engg. Sci.*, **9** (5) : 215 – 223.http://dx.doi.org/10.12988/ces.2016.512323.

Haifeng, L., Jianguo, D., Xibo, W., Lei, W. and Yanjun, D. (2010). A solar assisted heat pump drying system for grain in-store drying. *J. Frontiers Energy & Power Engg. China*, **4**(3): 386–391. DOI 10.1007/s11708-010-0003-3.

Hawlader, M.N.A., Chou, S.K., and Ullah, M.Z. (2001). The performance of a solar assisted heat pump water heating system, *Applied Thermal Engg.*, **21** (10): 1049–1065.

Hawlader, M.N.A., Chou, S.K., Jahangeer, K.A., Rahman, S.M.A. and Eugene Lau K.W. (2003). Solar-assisted heat-pump dryer andwater heater. *J. Appl. Energy*, **74**: 185–193.

Hawlader, M.N.A. and Jahangeer, K.A. (2006). Solar heat pump drying and water heating in the tropics. *J. Solar Energy*, **80** (5) : 492–499.

Hawlader, M.N.A., Baradey, Y., Ismail, A.F M. and Hrairi, M. (2017). Comparative study of R134a and R744 driven solar assisted heat pump systems for different applications, *IOP Conf. Series: Materials Sci. & Engg.*, **184** : 1-8. doi:10.1088/1757-899X/184/1/012060.

Huy, B. Q. and Nhut, L. M. (2018). Experiment investigation on a solar assisted heat pump dryer for chili, *Internat. J.Energy & Environ. Sci.*, **3**(1): 37-44.

Jianguo, D., Xibo, W., Lei, W. and Yanjun, D. (2008). Simulation and analysis of heat pump in-store drying, *J. Grain Storage*, **37**(3): 25–29.

Kumar, M., Sansaniwal, S.K. and Khatak, P. (2016). Progress in solar dryers for drying various commodities, *Renew. & Sustain. Energy Rev.*, **55**: 346–360.

Majid, Z.A.A., Othman, M.Y., Ruslan, M.H. and Sopian, K. (2007). Development of a close loop solar assisted heat pump dryer using multifunctional solar thermal collector. Proceeding of the Regional Conference on Engineering Mathematics, Mechanics, Manufacturing and Architecture, Mathematical Sciences in Engineering, pp. 48-53.

Majid, Z.A.A., Othman, M.Y., Ruslan, M.H., Mat, S., Ali, B., and Sopian, K., (2009). Multifunctional solar thermal collector for heat pump application, Proceeding of the 3rd WSEAS International Conference on Renewable Energy Sources, University of La Laguna, Tenerife, Canary Islands, Spain, July 1-3 pp. 342-346.

Sevik, S. (2013). Design, experimental investigation and analysis of a solar drying system, *J. Energy Convers. & Mgmt.*,

68 : 227–234.

Shanmugam, V. and Natarajan, E. (2007). Experimental study of regenerative desiccant integrated solar dryer with and without reflective mirror. *J. Appl. Thermal. Engg.*, **27** (8-9): 1543–1551.

Sharma, A., Chen, C.R. and Lan, N.V. (2009). Solar-energy drying systems: A review, *Renew. & Sustain. Energy Rev.*, **13** : 1185–1210.

Smitabhindu, R., Janjai, S. and Chankong, V. (2008). Optimization of a solar-assisted drying system for drying bananas. *J. Renewable Energy*, **33**: 1523–1531.

Sopian, K., Fadhel, M.I., Daud, W.R.W., Alghoul, M.A. and Zaharim, A. (2012). Design and performance evaluation of solar assisted chemical heat pump dryer. *J. Models & Methods Appl. Sci.*, 118-123. ISBN: 978-1-61804-082-4.

Stefano, P., Nelson, S., Chris, B., Hatef, M. and Per, L. (2018). Techno-economic review of solar heat pump systems for residential heating applications. *Renew. & Sustain. Energy Rev.*, **81**: 22–32.

Swasdisevi, T., Soponronnarit, S., Shujinda, A., Wetchacama, S. and Thepent, V. (1997). Rice husk furnace for fluidized bed paddy dryer, Proceedings of the 2nd Asean Renewable EnergyConference, Puket, Thailand, pp.603–612.

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

Yahya, M. (2016). Design and performance evaluation of a solar assisted heat pump dryer integrated with biomass furnace for red chilli. *Internat. J. Photoenergy*, 1-14. https://doi.org/10.1155/2016/8763947

Yahya, M., Fudholi, A., Hafizh, H. and Sopian, K. (2016). Comparison of solar dryer and solar-assisted heat pump dryer for cassava. *J. Solar Energy*, **136** : 606–613. https://doi.org/10.1016/j.solener.2016.07.049.