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Experimental Investigation of the Performance of a Closed Loop Thermosyphon Solar Drying System

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Abstract

Solar drying systems are extensively used in agricultural and marine for food preservation. Most of the developed solar drying systems employed air-based solar collector in generating hot drying air. However, air-based solar collectors do not always give a steady hot air supply under a fluctuated solar radiation intensity. This is particularly caused by the low thermal storage ability of air. Therefore, the solar drying system proposed in this work employs a liquid-based solar collector with a thermosyphon loop whereby a phase change working fluid is used to transfer the heat energy from solar collector to heat exchanger. The liquid-based solar collector used consists of evacuated glass tube with U-pipe. The effects of series and parallel connection of U-pipe on the performance of solar drying system are investigated experimentally. The performances of water and ethanol as the phase change working fluid are also tested for each of the U-pipe connections. The results show that the average efficiency of the tested system was varied between 10% and 15% under average solar radiation of 750 W/m^2. A higher performance was identified on the system with parallel U-pipe connection. However, the performances of water and ethanol varied between the series and parallel U-pipe connection system. Ethanol shows a higher performance in parallel U-pipe connection system while water shows a higher performance in series U-pipe connection system.

Keywords: Closed loop thermosiphon; natural convection; parallel and series connection; solar drying system; U-pipe.

INTRODUCTION

Solar drying systems (SDSs) have been developed in last few decades. In the past, the drying processes are mostly achieved by direct sun drying and burning of fossil fuel. However, due to increasing concern of food quality and environmental care, solar drying technologies have become more popular nowadays and fit well into industrial scale drying. Various solar drying systems have been developed with difference configurations and drying methods [1-2]. In recent development of solar dryer, solar collector is mostly incorporated to increase the drying efficiency. Air-based solar collector are the most commonly used system in solar drying. However, liquid-based solar collectors can also be used with an air heat exchanger to generate the hot air. In recent studies, researchers still give more priority on air-based solar collector in improving the solar drying efficiency. This is probably due to consideration of a higher overall thermal resistance along the heat transfer path from solar collector to drying air in the drying chamber, which would result in a lower system efficiency. However, liquid-based solar collector systems are advantageous in providing a steady hot air supply under inconsistent solar radiation due to a larger thermal capacity of working fluid compared to air. Liquid-based solar collector was employed in a new solar hybrid dryer proposed by Nabnean et al. which incorporated a heat exchanger and a hot water storage tank. The results show that the air temperature rise is still significant at the late noon when the solar radiation declined [3]. Therefore, liquid-based solar collector is used in this experiment study whereby a heat exchanger is integrated to the solar collector to form a closed loop system

Natural convection or thermosyphon loop operates in the absence of circulating pump. The flow of working fluid is driven by the density difference resulting from the phase change of working fluid and the liquid head in the downcomer. Working fluid absorbs heat from the solar collector and change its phase into gaseous state. The lighter gaseous fluid will rise through the upriser pipe to the heat exchanger where the heat will be dissipated for drying process. The condensed fluid which resulted from the rejection of latent heat flows through the downcomer back into the solar collector under the gravitational pull. The working fluid will recirculate as long as the heat absorbed from the solar collector is sufficient to cause the phase change of working fluid.

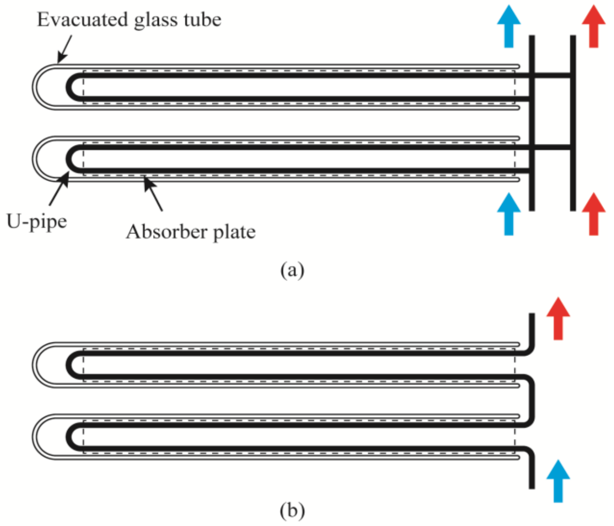
Thermosyphon loop requires zero operating cost since no electrical energy is needed to power the pump. In the past, limited studies have been reported on the solar drying system with closed loop thermosyphon. Most available systems were of the forced convection system whereby circulating pump is needed, as in the system proposed by Nabnean et al. [3]. Air-based solar collector which normally consisted of open loop system requires fan blowers to increase the air mass flow rate in the passage of solar collector. In addition, certain air-based collector designs such as evacuated tube with concentric tube heat exchanger and U-shaped tube heat exchanger would not operate without a force convection system since the air passage involve U-shaped path [4-5]. In order to reduce the operating cost as well as the maintenance cost, the solar drying system used in this experiment investigation would incorporate a natural convection in the closed loop system, forming the closed loop thermosyphon solar drying system (CLTSDS).

The major challenge of a thermosyphon loop is the driving pressure. Driving pressure is critical in the design of a thermosyphon system since it has a significant effect on the mass flow rate of working fluid. A closed loop thermosyphon would only operate when the driving pressure in the system is equal to or exceed the frictional pressure losses throughout the system. Therefore, the design of a closed loop thermosyphon system involves several design parameters such as collector inclination angle, type of working fluid, amount of working fluid, circulation flow resistance, height difference and temperature difference. The collector inclination would have a significant effect on the amount of receivable solar heat flux and also the behavior of two-phase flows in the thermosyphon loop. Aung and Li [6] conducted a numerical investigation on the effect of collector inclination on the performance of two-phase closed loop thermosyphon solar water heater. The results show that a maximum solar heat flux could be obtained by a larger collector inclination angle for location at higher latitude. Besides, the optimum inclination angle changes according to local solar hour. Zhang et al. [7] has performed an experimental investigation on a two-phase thermosyphon loop to study the effect of circulation flow resistance, height difference and temperature difference on liquid head in the downcomer. The liquid head in downcomer proved to have self-regulation ability to provide adequate driving force for the thermosyphon flows under difference working conditions. The results show that increasing circulation flow resistance, temperature difference and decreasing height different could raise the liquid column in the downcomer, thus increasing the driving pressure in the system.

Working fluid plays an important role in a closed loop thermosyphon since two-phase heat transfer is involved. Franco and Filippeschi [8] has concluded in his study that the type of working fluid appears to be an important variable in the performance of closed loop two-phase thermosyphon. The selection of appropriate phase-change fluid is so important because every fluid have particular thermophysical properties, thus resulting in different performance of closed loop thermosyphon under various operating condition. Numerous studies involve the investigation of various working fluids such as refrigerant, highly volatile fluid, supercritical CO_2, nanofluid, and water had been presented [9-15]. However, most of the working fluids are tested using closed loop thermosiphon heat pipe. Nanofluid appears to be promising working fluid in heat transfer application due to its enhanced thermophysical properties and heat transfer performance, but its applications are limited by a high production cost. On the other hand, refrigerants such as R134a, R410A and supercritical CO_2 require higher operating pressure inside the thermosyphon loop, which is undesirable due to high initial cost and maintenance cost. Therefore, the only working fluids that possess a saturation temperature within desired drying temperature range (40-70°C) under standard atmospheric pressure are highly volatile fluids such as ethanol, chloroform, ammonia and etc. In this works, ethanol is selected as the phase-change fluid in the closed loop thermosyphon. The performance of ethanol in the CLTSDS is compared to that of water as the working fluid.

Solar collector converts solar energy into useful heat energy. The most common liquid-based solar collector available in the markets today are flat plate collector (FPC) and evacuated tube collector (ETC). ETCs are of better performance compared to FPCs due to its high heat extraction efficiency and considerably less heat loss [16]. A simplified compound parabolic concentrator (CPC) is usually incorporated into ETC to maximize the incident radiation and thus resulting in a higher heat energy. In this work, the evacuated tube collectors would be employed in the proposed closed loop thermosyphon solar drying system. ETC is selected because it has a high thermal collecting efficiency and a high flexibility in changing the number of tubes since the evacuated glass tubes are existed as separate unit. Besides, U-pipes are incorporated in the evacuated glass tubes to provide flow paths for the working fluid.

The open ends of U-pipes can be connected in either series or parallel configuration, as shown in Fig. 1. These two connections are expected to provide different performance of closed loop thermosyphon and thus included as one of the system parameter designs. The series U-pipe connection would result in a higher temperature of working fluid while the parallel U-pipe connection would result in a higher mass flow rate of working fluid. In the past, no study has been reported on the performance of series and parallel U-pipe connections in ETC using thermosyphon loop. Therefore, the objective of this experiment was to investigate the performance of the proposed CLTSDS with both series and parallel U-pipe connection in the ETC. Besides, the performance of water and ethanol were also tested for each of the U-pipe connection.



(a)

(b)

Figure 1: a) Series and (b) Parallel U-pipe connection in evacuated tube collector.

EXPERIMENTAL METHOD

Experimental apparatus

The closed loop thermosyphon solar drying system consists of three main components which are liquid-based solar collector, heat exchanger and drying cabinet. The schematic view of the solar dryer is shown in Fig. 2. The liquid-based solar collector is connected to the heat exchanger through upriser and downcomer pipe, forming a closed loop system. The drying processes are carried out in the drying cabinet whereby the drying materials are protected from the direct sunlight. The drying cabinet is equipped with the heat exchanger where the heat source for drying process is originated from. Blower fans are installed at the outlet opening of drying cabinet to promote an even circulation of drying air.

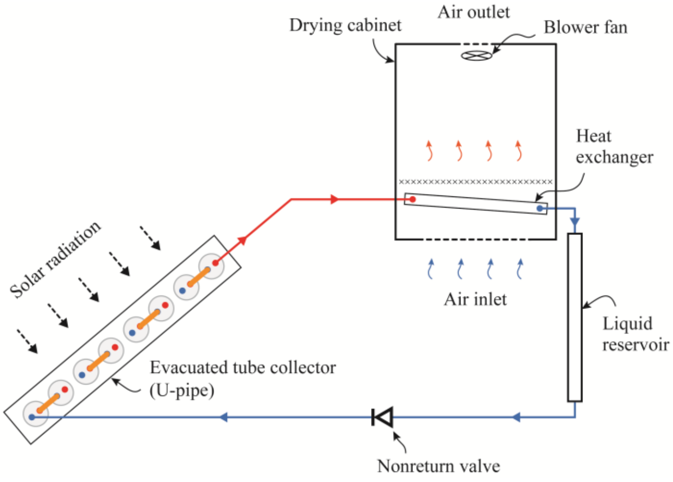
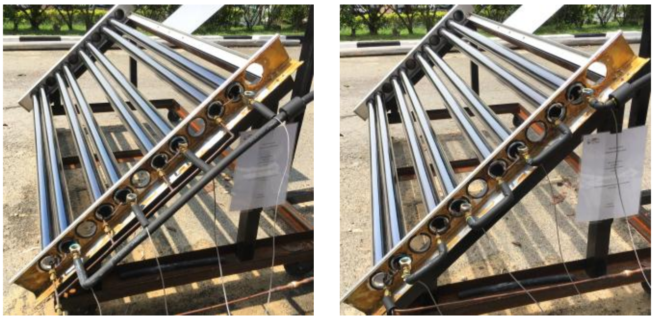


Figure 2: Schematic diagram of closed loop thermosyphon solar drying system.

In general, the proposed solar drying system consists of two circulation loops — the fluid circulation in closed thermosyphon loop and the air flow inside the drying cabinet. The fluid circulation is driven by natural convection via the density differences resulting from the phase change of fluid in the thermosyphon loop. On the other hands, the air flow is driven by force convection using the fan blower installed at the outlet opening of drying cabinet.

Liquid-based solar collector

The liquid-based solar collector used consists of evacuated glass tube, absorber plate and U-pipe. A total of 8 evacuated glass tubes with a 60 mm O/D × 42 mm I/D × 1800 mm length form the array of the solar collector. The evacuated glass tube is made of two concentric borosilicate glass tubes with an opening end. The outer surface of inner tube is coated with a layer of selective coating to increase the heat absorptivity. The spaces between the inner and outer tubes are evacuated to prevent heat losses through conduction and convection. The opening end of evacuated glass tubes are sealed to prevent heat losses from the interior space. The absorber plate is made of aluminium and it contacted well with inner wall of the glass tube and U-pipe to increase the heat transfer rate. The U-pipe is made of U-shape copper pipe with an inner and outer diameter of 6.05 mm and 3.85 mm respectively. In this experiment, the collector is comprised of four set of evacuated tube arrays, each array consisted of two U-pipe evacuated glass tubes connected in series. The opening ends of the U-pipes are connected together in either series or parallel for the purpose of investigation conducted in this work. Flared fittings are used for all the end connection of the U-pipe to allow the change of connection from series to parallel or vice versa. The arrays of evacuated tube collector are inclined at 40 degrees to the horizontal. The collectors are supported on a steel column structure. A photograph of the arrays of evacuated tube collector is shown in Fig. 3.



(a) (b)

Figure 3: Solar collector arrays with (a) series U-pipe connection and (b) parallel U-pipe connection

Heat exchanger

The heat exchanger is used to heat the air inside the drying cabinet to a higher temperature and lower relative humidity. It is placed at a height of 370 mm above the solar collector and connected to the collector outlet through the connecting pipes (uprisers). The heat exchanger with a series flow is made of 6.12 mm O/D × 4.5 mm I/D copper pipe with a total length of 5.70 m. The copper fins with a dimension of 380 mm × 15 mm × 0.48 mm are attached to the copper pipe to increase the heat transfer area of heat exchanger. The heat rejection of heat exchanger is achieved through natural convection, whereby the air particles surrounding the heat exchanger was heated up and raised to the top of drying cabinet as a result of density drop. There is no direct air flowing across the heat exchanger. The heat exchanger is inclined at a small angle of 15 degrees to the horizontal in order to facilitate the flow of condensed liquid back to the reservoir using gravitational forces.

Drying cabinet

The drying cabinet is an enclosed space equipped with the air inlet and outlet openings which are located at the bottom and top end of the drying cabinet respectively. Fresh air enters through the air inlet opening and heated up by the heat exchanger to a relatively high temperature and low relative humidity. As a result, the low density drying air rises and passes through the drying materials to drive the evaporation of moisture from the surfaces. The resulting moist air eventually leaves the drying cabinet through the air outlet opening with the aid of blower fan. The drying cabinet is made of 1” × 1” aluminium square column covered with 3 mm thick acrylic walls. The walls of the drying cabinet are insulated with 1” thick polystyrene board to reduce the heat losses to the surrounding. The drying cabinet with a dimension of 568 mm × 568 mm × 700 mm is equipped with drying tray which is positioned at 65 mm above the heat exchanger. The drying tray is made of braided wire steel net with a dimension of 509.2 mm × 509.2 mm. A 90 mm × 90 mm blower fan is installed at the top end of the drying cabinet to promote the air circulation and remove moist air from the drying cabinet. The location of drying tray and fan blower is shown in Fig. 4.

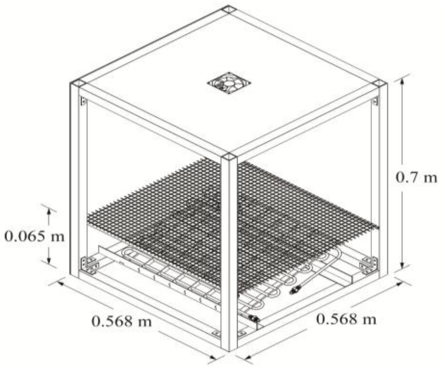


Figure 4: Schematic diagram of the drying cabinet (Isometric view).

Miscellaneous / others

Other than the three main components mentioned earlier, there are some minor components for the CLTSDS. Connecting pipes which consist of upriser and downcomer connect the solar collector and heat exchanger to form the closed loop thermosyphon. Upriser connects the solar collector outlet to the heat exchanger inlet while downcomer connects the heat exchanger outlet to the solar collector inlet. The connecting pipes are made of 6.12 mm O/D × 4.5 mm I/D copper pipe. The upriser pipes are insulated with flexible elastomeric foam insulation to reduce the heat losses to the surrounding. Reservoir tank is installed at the outlet of heat exchanger to store the liquid working fluid returned from the heat exchanger. The reservoir tank serves two functions in the closed loop thermosyphon. The first is certainly to store the liquid working fluid as to prevent dry out phenomenon in the U-pipe evacuated tube collector and also flooding phenomenon in the heat exchanger. The second is to provide a liquid head in driving the fluid circulation in the thermosyphon loop. The reservoir tank is made of 610 mm long copper tube with 54 mm O/D and 1 mm thickness. A transparent tube is protruded out from the reservoir tank and set in parallel to observe the fluid liquid level. Nonreturn valve is installed on the downcomer pipe right before the inlet of solar collector. The nonreturn valve serves as the check valve to ensure one-way flow of the liquid working fluid into the solar collector. The location of the reservoir tank and the nonreturn valve is illustrated in Fig. 2. Besides, sight glasses are installed at each outlet ports of the U-pipe to allow the monitoring of dry out phenomenon inside the U-pipes.

Experimental procedure

The performance of CLTSDS is tested with the series and parallel connection of U-pipe in the evacuated tube as shown in Fig. 4. The performances of water and ethanol are also investigated for each of the U-pipe connection. Therefore, there is a total of four systems involves in this work. System A, B, C and D are used to represent the four systems which comprise the ethanol-parallel, ethanol-series, water-parallel and water-series respectively. The closed loop thermosyphon solar dryer was set up at Universiti Kuala Lumpur Malaysia France Institute (UniKL MFI) located in Bandar Baru Bangi, Malaysia. Each of the four systems was tested for 90 minutes from 11:10 am to 12:40 pm on different days.

During the first part of experiment test, the performance tests for both series and parallel U-pipe connection are conducted with ethanol as the working fluid. The closed loop thermosyphon is filled with ethanol via the opening spout located on the top of reservoir tank. The U-pipe in the evacuated tube collector is filled with filling ratio of 1.0 (ratio of volume of working fluid to volume of U-pipe in ETC). After the filling process, the system is leave for 30 minutes before commence of data recording.

The second part of experiment test involve the performance test for both series and parallel U-pipe connection with water as the working fluid. Before the filling process, water is allowed to pass through the closed loop system for about 30 minutes to remove all the ethanol content left inside the system. Afterward, the same filling process for ethanol is repeated for the water.

Instrumentation

Several measuring devices and instruments are installed to measure the parameters required for the performance evaluation of CLTSDS. Instantaneous solar radiation was measured using a pyranometer (Model 240-8101 Star Pyranometer, ISO First Class), an instrument used to measure direct and diffuse solar radiation (global radiation). The pyranometer was positioned at the inclination angle of solar collector, which is 40 degrees to the horizontal. Thermocouples type-K were used to measure the fluid temperature and air temperature inside the thermosyphon loop and drying cabinet respectively. The points of temperature measurement are shown in Fig. 5. The voltage signals from the pyranometer and thermocouples were recorded with 1s interval using a multi-channel data logger (midi LOGGER GL220: GRAPHTEC). The relative humidity of ambient air and drying air were measured using hygrometer (Mini Digital LCD hygrometer with probe, accuracy ± 5%). The air speed at the outlet of the drying cabinet was measured using anemometer (KIMO vane probe thermo-anemometer LV50, accuracy ± 3%).

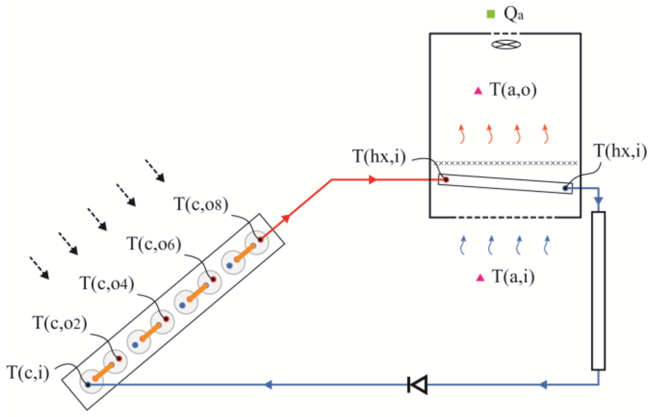


Figure 5: Location of data measurement

Performance of CLTSDS

The overall efficiency of CLTSDS is defined as the heat energy gained by the drying air to the solar energy input on the solar collector, as given by Eq. (1).

$$\eta_s = \frac{Q_a}{IA_c} = \frac{\dot{m}_a c_{p,a}\left(T_{a,o} - T_{a,i}\right)}{IA_c} \tag{1}$$

Where Q_a is the heat energy gained by drying air, $T_{a,i}$ and $T_{a,o}$ are the inlet and outlet temperature of drying air respectively. I is the instantaneous solar radiation and A_c is the aperture area of solar collector.

In this experiment, the performance of series and parallel U-pipe flows as well as the performance of water and ethanol would be evaluated based on the overall thermal efficiency of CLTSDS.

RESULT AND DISCUSSION

Four experimental tests which comprise of the series and parallel U-pipe connection with ethanol and water as the working fluids were conducted on the proposed solar drying system. The tests were carried out during the period of Jan–Mar, 2017. Each experiment was run about 90 minutes from 11:10 am to 12:40 pm. During this period, the incident solar radiation is perpendicular to the tilted surface of the solar collector. The experimental results are illustrated in Figs. 6–10. During the experiment tests, the values of solar radiation, drying air temperature and drying air relative humidity were range from 217 W/m^2 to 1046 W/m^2, 38.8 °C to 51.1 °C and 27% to 39% respectively.

The variations of solar radiation during each of the four experimental tests are shown in Fig. 6. There was a substantial fluctuation of solar radiation during the experimental tests. A constant solar radiation is hardly obtained since Malaysia is fall within the tropical climate. Therefore, the computation of the CLTSDS performances is based on the solar radiation value range between 550 W/m^2 to 950 W/m^2. The average solar radiations obtained from each experiment tests are shown in Table 1. The variation of solar radiations from each experiment tests show a value of less than 2.5%.

Table 1 shows the comparison of several essential parameters in solar drying system among the four systems which comprise the series and parallel U-pipe connections with water and ethanol as the working fluids. The average drying air temperature obtained for each of the four systems is about 45 °C except system B which is only 42.8 °C. Besides, all the average air temperature rise given are more than 10 °C except system B. From the efficiency measure, system B also shows the lowest value among the other systems. It is also observed that the efficiency values given by system A, B and C are approximate to 14.5%.

U-pipe connection in evacuated tube collector

From Table 1, it is significant that system A has a higher efficiency compared to system B while system C and D have almost the same efficiency value. From Eq. (1), the efficiency of CLTSDS is defined as the ratio of heat gain by the drying air to the solar energy input. The heat gain by the drying air depends on numerous parameters such as heat exchanger efficiency, air flow rate across the heat exchanger, mass flow rate of working fluid in heat exchanger and type of working fluid. The heat exchanger efficiency and air flow rate are constant throughout the four system performance tests as the similar heat exchanger and fan speed are used. Therefore, the rest of the parameters are used to compared the performance of each systems

Ethanol as working fluid

For ethanol, the parallel U-pipe connection system give a higher performance compared to series U-pipe connection system. Since specific heat of working fluid remains constant in both system A and B, the mass flow rate of working fluid in the heat exchanger is the only variable that could affect the performance of the both systems. However, there is a limitation in measuring the mass flow rate of fluid in the thermosyphon loop as the fluid is consisted of liquid-vapor mixture. Besides, a lower mass flow rate of working fluid in thermosyphon loop imposes a larger percentage error on the measured value. Therefore, the inlet and outlet temperature of working fluid at the heat exchanger, as illustrated in Fig. 8 were used to indicate the mass flow rate of working fluid in the thermosyphon loop. It is observed that the inlet temperature of fluid is comparatively constant for both system A and B. However, the outlet temperature of fluid at the heat exchanger in system A rises steadily and remains constant at 75 °C, which is same as the inlet fluid temperature. The main reason behind the high temperature of fluid at the heat exchanger outlet is a higher mass flow rate of vapor fluid in the heat exchanger. Due to this higher mass flow rate of fluid, the heat exchanger was fully filled with saturated vapor fluid and thus resulted in a relatively high temperature of working fluid at the heat exchanger outlet. On the other hands, system B with a series U-pipe connection shows a relatively constant fluid temperature at the heat exchanger outlet at 38.5 °C. This shows that the heat exchanger was partly filled with saturated vapor fluid while the rest was filled with condensed fluid, which also indicate a smaller mass flow rate of working fluid in the heat exchanger.

However, the mass flow rate of fluid in the heat exchanger depends heavily on the amount of vapor fluid generated by the solar collector. Therefore, the parallel U-pipe connection is said to provide a larger mass flow rate of fluid in the thermosyphon loop, which also resulted in a higher mass flow rate of fluid in the heat exchanger. This is mainly caused by a smaller total resistance of flow in parallel U-pipe connection when compared to series U-pipe connection. Referring to Fig. 7, it is noticed that in system A the temperature at each of the U-pipe outlet ports remains relatively constant at 77.2 °C, where the ethanol had reached its saturation temperature and the vapor formation had taken place. On the other hands, in system B the average fluid temperature increases from each U-pipe outlet ports up to the next, causing the fluid to reach superheated state. However, there is a significant drop in temperature at the eighth U-pipe outlet port when compared to sixth U-pipe outlet port. This is mainly due to the vapor clogging phenomenon, where the vapor is stuck in the U-pipe due to large resistance flow. In series U-pipe connection, the pipe length that the vapor fluid required to travel to the outlet port is four times the length required by vapor fluid in parallel U-pipe connection. Based on Poiseuille's law, it states that the volume flow rate in a circular pipe is inversely proportional to the pipe length. The volume flow rate and mass flow rate through a circular pipe are given by

$$Q = \frac{\pi D^4 \Delta p}{128 \mu \ell} \tag{2}$$

$$\dot{m} = \frac{\pi D^4 \Delta p}{128 \nu \ell} \tag{3}$$

where Q is the volume flow rate, $\dot{m}$ is the mass flow rate, D and *l* are the pipe diameter and pipe length respectively, Δp is the pressure difference between upstream and downstream, μ and ν are the dynamic viscosity and kinematic viscosity respectively.

Therefore, the mass flow rate reduced significantly in the series U-pipe connection due to a larger total pipe length which imposes a higher flow resistance compared to parallel U-pipe connection. As a result, the vapor fluid experiences a larger pressure drop as it rises along the U-pipe to the collector outlet. This results in the formation of large vapor bubble in the U-pipe from the combination of smaller vapor bubble, leads to the vapor clogging phenomenon. The clogged vapor continues its heat absorption and resulted in superheated state. This occurrence can be proved by the dry-out phenomenon in the sight glass located at the fourth and sixth U-pipe outlet ports. Therefore, it indicates that a larger total resistance of flow leads to vapor clogging, which reduces the mass flow rate of vapor fluid into the heat exchanger.

Water as working fluid

For water, both series and parallel U-pipe connection systems show an almost similar efficiency value. This is because both system C and D give a similar drying air temperature of about 45 °C with an air temperature rise approximate to 12 °C. However, both systems show some performance differences at the heat exchanger and the solar collector, as illustrated in Figs. 7 and 8. Referring to Fig. 8, system C shows a higher average temperature of fluid at the heat exchanger outlet when compared to system D. This indicates that the mass flow rate of water in parallel U-pipe connection system is higher compared to series U-pipe connection system. Referring to Fig. 7, the collector in both system C and D give a relatively constant outlet temperature of working fluid at around 98 °C, where the water had reach its saturation state. However, the collector in system D give a higher inlet temperature of working fluid when compared to system C. This is mainly caused by a higher flow resistance in series U-pipe connection system which resulted in a lower flow rate of liquid-vapour mixture toward the collector outlet. As a consequence, the temperature build-up resulted from the heat absorption propagates toward the inlet of solar collector.

Performance of ethanol and water

From the system efficiency obtained in Table 1, water shows a higher performance in series U-pipe connection system, while ethanol shows a higher performance in parallel U-pipe connection system. Besides, the system efficiency given by system A, C and D are approximate to 15% with a variation of less than 7%. This small variation of efficiency value indicates that the performance of each systems varied only by a small difference. However, the performances of water and ethanol in both solar collector and heat exchanger show a significant difference as illustrated in Figs. 7 and 8. Referring to Fig. 8, ethanol in system A shows a higher fluid mass flow rate in the heat exchanger when compared to water in system C. This is mainly caused by the fact that ethanol have a lower dynamic viscosity at its saturated vapor state (78.4 °C) when compared to water. Therefore, the flow of vapor ethanol from the solar collector outlet into the heat exchanger experiences a smaller pressure drop and thus resulted in a higher mass flow rate.

On the other hands, water is performing well in term of its large thermal capacity since water have a larger value in both the specific heat and latent heat of vaporization when compared to ethanol. Therefore, the total amount of heat carried by water from the solar collector to the heat exchanger is larger compared to ethanol. In addition, the vapor clogging phenomenon as found in series U-pipe with ethanol does not happened to series U-pipe with water, as shown by the outlet temperature at the heat exchanger in referring to Fig. 8. This is because water have a lower vapor density at its saturation state (100 °C) when compared to ethanol. Therefore, the water vapor formed in the U-pipe tends to rise up more easily compared to vapor ethanol and thus eliminate the vapor clogging phenomenon which adversely affect the mass flow rate of vapor fluid.

As an overall, the performances of water and ethanol are almost equal in parallel U-pipe connection. However, it is noticed that ethanol utilizes the maximum area of heat exchanger to dissipate latent heat for drying process. On the other hands, water utilizes only parts of heat exchanger in releasing the latent heat while utilizes the rest for sensible heat. Therefore, ethanol is recommended as the working fluid in parallel U-pipe connection system, as it utilized the maximum capacity of heat exchanger as well as the latent heat in the heat transfer between the working fluid and the air. On the other hands, water is the preferred working fluid in series U-pipe connection system since the performance of water is much higher than ethanol in series U-pipe connection system.

FINDING AND RECOMMENDATION

Upon the experiment, some improvement can be made on the CLTSDS to increase its performance. A parallel flow heat exchanger can be used to reduce the flow resistance and increase the mass flow rate of working fluid in the heat exchanger. Besides, the number of fin can be increased to increase the total surface area for heat rejection. Force convection can be employed to increase the heat transfer of heat exchanger by applying direct air flow across the heat exchanger. In addition, a larger diameter of pipe can be used for the U-pipe in evacuated glass tube as well as the upriser pipe to increase the mass flow of working fluid since a doubling of pipe diameter produces a 16-fold increase in the mass flow rate, as shown by Eq. (3). In future studies, the effect of solar collector inclination and height different between solar collector and heat exchanger on the performance of CLTSDS can be investigated.

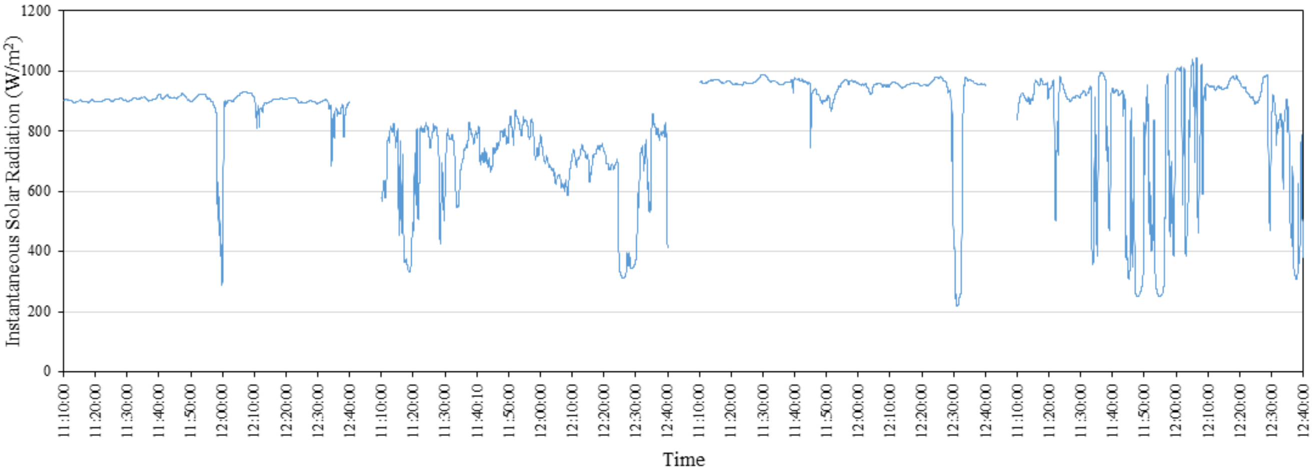


Figure 6: Variation of solar radiation intensity during each experimental tests.

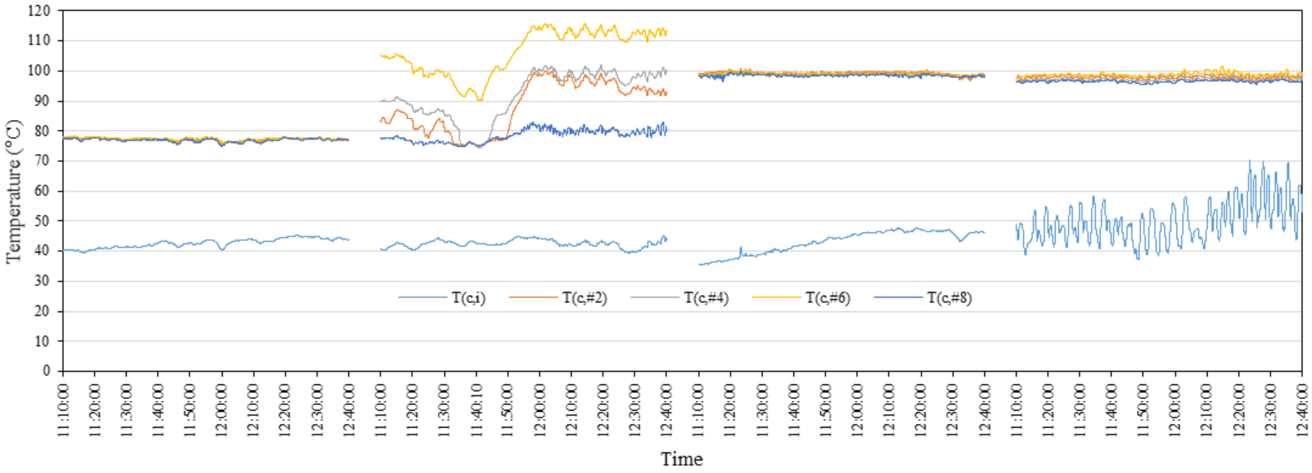


Figure 7: Comparison of the inlet and outlet temperature of working fluids in evacuated tube collector for each experiments.

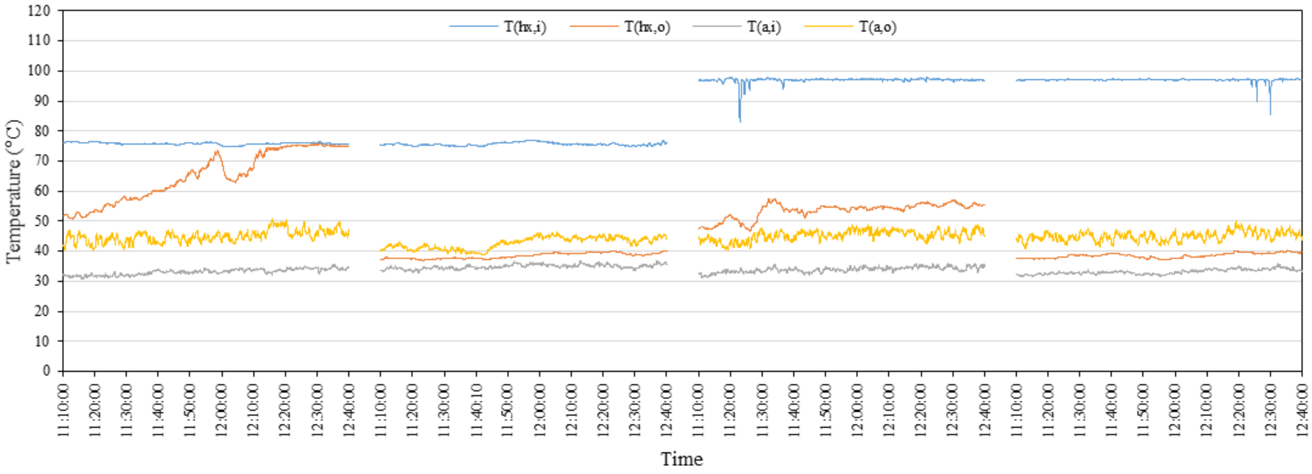


Figure 8: Comparison of the inlet and outlet temperature of working fluids and drying air in heat exchanger and drying cabinet respectively for each experiments.

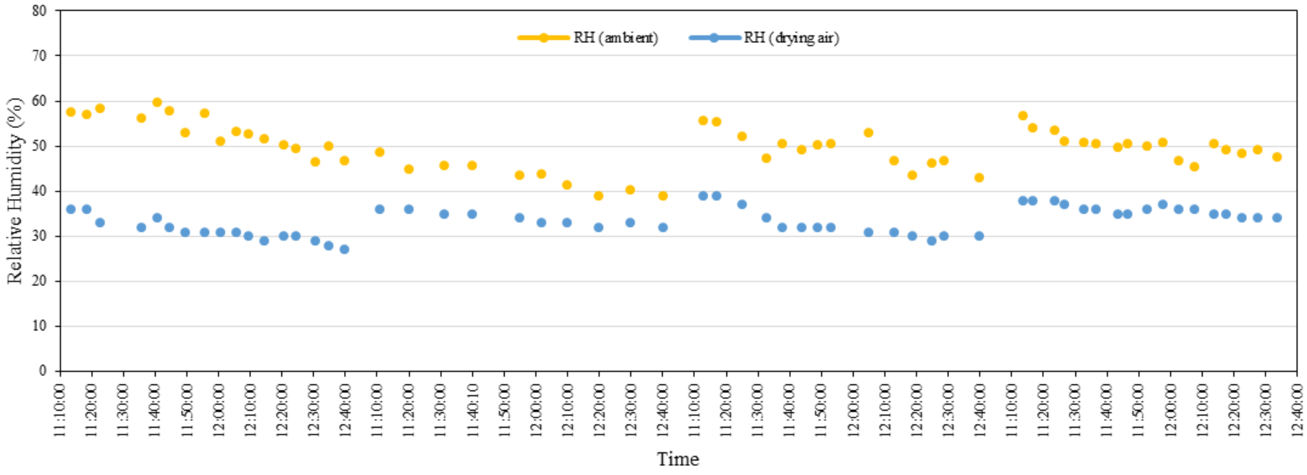


Figure 9: Comparison of the relative humidity of drying air and ambient air for each experiments.

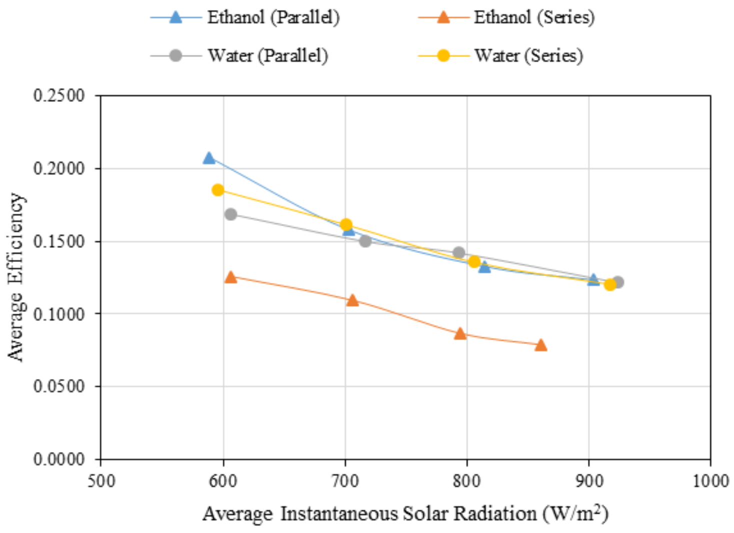


Figure 10: Average efficiency of the CLTSDS for each experiments.

Table 1: Details and Test Results of CLTSDS

System	Ethanol		Water	
	Parallel (A)	Series (B)	Parallel (C)	Series (D)
Average drying air temperature (°C)	45.6	42.8	45.7	45.0
Air temperature difference (°C)	12.1	7.8	11.6	11.8
Average relative humidity of drying air (%)	29.7	34.4	31.3	35.6
Average change in relative humidity (%)	22.1	10.5	17.8	13.5
Average system efficiency (%)	15.54	10.03	14.55	15.07
Average instantaneous solar radiation (W/m^2)	752.10	741.90	760.00	754.96

In summary, parallel connection of U-pipe in the evacuated tube collector provides a higher mass flow rate of working fluid due to smaller total resistance of flow compared to series U-pipe connection. Besides, water and ethanol perform differently in both series and parallel U-pipe connection system. Water gives a higher performance in series U-pipe connection system while ethanol gives a higher performance in parallel U-pipe connection system. Phase-change working fluid with a low vapor density and dynamic viscosity will give a higher performance in the closed thermosyphon loop.

CONCLUSION

The performance of series and parallel U-pipe connection in the closed loop thermosyphon solar drying system was tested experimentally using water and ethanol as the working fluid. The temperature of drying air was varied between 40 °C and 50 °C with a maximum air temperature difference of 18 °C.

The system efficiency was varied for each U-pipe connection system with water and ethanol as the working fluid. The average efficiency for each of the systems was varied between 10% and 15% under average solar radiation of 750 W/m^2. In general, parallel U-pipe connection shows a higher performance of CLTSDS compared to series U-pipe connection. However, the maximum performance of water and ethanol varied between series and parallel U-pipe connection. Ethanol shows a higher performance in parallel U-pipe connection system while water shows a higher performance in series U-pipe connection system.

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