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ORIGINAL ARTICLE

A Heat Recovery Device using Oscillating Heat Pipe with Circular and Elliptical Tubes

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ABSTRACT – In this study, an oscillating heat pipe heat exchanger has been used as a heat recovery device in air ductwork, and the characteristics of the thermal performance of the energy-saving were investigated by using a circular and elliptical cross-sectional tubes. An experimental study was conducted by oscillating heat pipe made from copper with an inner diameter of 3.5 mm for the conventional tube, and the major and minor axis of 4.2 and 2.2 mm for the elliptical tube. The working fluid was water with filling ratio of 50% of the total volume. The experimental data implied that the thermal effectiveness and the energy-saving highly affected by the inlet air temperature and velocity. The proposed model of the oscillating heat pipe heat exchanger possessed the effectiveness of 19.5% at 50 ºC and 0.5 m/s, and the potential energy-saving of 1117 W at 50 ºC and 2 m/s. The comparison results between the elliptical and conventional cross-sectional area of oscillating heat pipe heat exchanger indicated that the energy-saving and effectiveness enhanced by the ratio of 18%, and 14%.

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INTRODUCTION

Renewable energy is considered an international priority field; therefore, many investigations focused on this point of research. The process of waste heat recovery is one of the approaches used in many engineering applications of heating, ventilation, and air conditioning (HVAC) systems. This approach can beneficially utilise the heat (temperature) wasted between hot air and cold air with a low-pressure drop [1]. The heat pipe heat exchanger (HPHX) is a strongly recommended choice to recover the wasted heat in many engineering applications [2]. Oscillating heat pipe (OHP) is a highly efficient heat transfer device manufactured from a long meandering tube evacuated and partially filled with a suitable working fluid. There are three types of oscillating heat pipe; open-end OHP, closed-end OHP, and OHP with a check valve, as shown in Figure 1. The structure of OHP consists of three sections: evaporator (heating) region, condenser (cooling) region, and in-between optional adiabatic (insulation) region. The inner diameter of the pipe must be small enough (with 0.1 mm to 5 mm) to produce a pulsation phenomenon and an oscillating motion of working fluid inside the OHP [3-5].

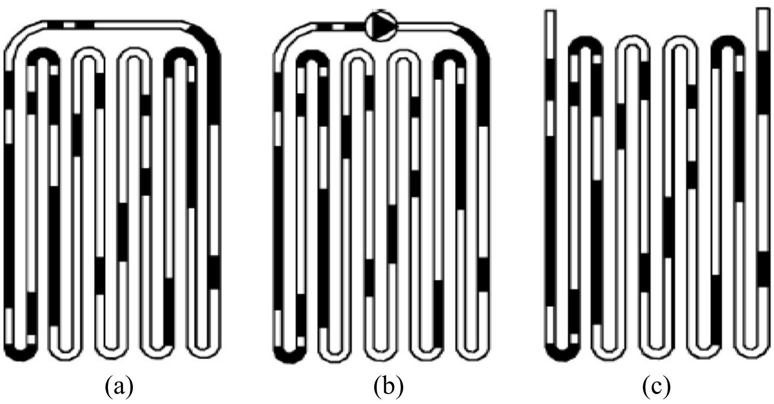

Figure 1. Types of OHP; (a) closed-end OHP, (b) OHP with check vale, and (c) open-end OHP.

An oscillating heat pipe (OHP) with only the evaporator section and condenser section was used as a heat exchanger and filled partially with water and R123 as working fluids [6]. The evaporator section was heated by hot air with conditions of 60 ºC, 70 ºC, 80 ºC, and 3.3 m/s. The results showed that the R123 had a higher heat transfer rate and effectiveness than water. Meena et al. [7] used OHP with a check valve as a heat recovery device in the air dryer unit to decrease the air humidity. They found that the air humidity could be reduced by 89-100% to 54-72%.

Nuntaphan et al. [8] used OHP to increase the outer surface of a heat exchanger. They used methanol, R123, and acetone fluids as working fluids by a filling ratio of 30 %. Also, they examined an OHP with no working fluid (reference case), which gave the same effect of wire metal features. air was supplied with a range of 0.2-1.5 kg/s at 25 ºC, and the

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water temperature was varied by 45 ºC to 85 ºC. The results showed that the thermal performance of the heat exchanger could be increased higher by 10% when charging using methanol, R123, and acetone in comparison with the reference case (without charging).

OHP as the condenser for the vapour compression refrigeration system was adopted by Yeunyongkul et al. [9]. An OHP made from copper with an inner diameter of 2.03 mm, and 250 turns were used. The length of the evaporator, adiabatic, and condenser sections were 80 mm, 90 mm, and 100 mm, respectively. Water was selected to charge inside OHP as a working fluid. The results revealed that the OHP condenser system saved more electrical power than a conventional condenser. The energy efficiency ratio (EER) was higher than the OHP condenser unit by 18.9%, 6.1% and 13.4% although the COP of the conventional condenser system was higher than OHP for all cases.

In the drying system, the thermal and the electrical energies saved by 56.66% and 28.13% when used the oscillating heat pipe with a check valve as the heat exchanger [10]. Supirattanakul et al. [11] investigated the effect of using OHP with a check valve in energy consumption in the split air unit. They studied the effect of inlet air temperature at 50% relative humidity for the system, with and without OHP. The results showed that the energy-saving was about 3.6%, and the COP was higher by 14.9% when OHP used in the unit. Ten turns of copper OHP with an inner diameter of 1.65 mm was used as a heat exchanger in the HVAC system [12]. Unfilled OHP and partly full of by n-pentane with a ratio of 70% was tested. They supplied heat at the evaporator region by the temperature of 45 ºC, and the condenser region was cold at 6 ºC and 0.19 m^3/s. They found that the OHP can recover heat up to 240 W.

Several working fluids were used in OHPHX to improve the humidity removal of the cooling coil [13,14]. Water, methanol, and binary solution were used as working fluids with a filling ratio of 50%. The binary fluid was a blend of water mixed by a ratio of 50:50 by volume. The results showed that the dehumidification process improved by 17% for water, 25% for methanol, and 21% for binary fluid. Also, the energy-saving ratio values and thermal effectiveness of the oscillation heat pipe heat exchanger enhanced about 16 % and 14 % by using the binary fluid as a working fluid instead of water.

Mosleh et al. [15] investigated experimentally and numerically the use of oscillating heat pipe as fins on the heat exchanger. They used a copper OHP with a 3 mm inner diameter, 21 mm evaporator section, 54 mm condenser section, and used R 134s as working fluid. The results suggested that the use of OHP as fins enhanced the heat transfer rate of a heat exchanger. In comparison to fins, the enhancement of the overall heat transfer coefficient for natural and forces convections were 310% and 263% by using OHP. Mahajan et al. [16] used a finned OHP to study heat transfer performance. The nine turns of OHP were fabricated from copper tubing with 1.65 mm inner diameter. The heights of the evaporator, adiabatic, and condenser section were 635 mm, 76 mm and 635 mm, respectively. They compared the OHP charged with n-pentane at 70% filling ratio with an empty OHP. The results showed that about 400 W of wasted heat recovered by using OHP with n-pentane. The OHP with finned caused a pressure drop of about 6.8 Pa.

Yang et al. [17] studied the thermal effectiveness of oscillating heat pipe heat exchanger and the thermal resistance of OHP. The OHP size was 132 mm, 44 mm, 200 mm with 5mm inner diameter, that charged by water and HFE-7000 as working fluid at 35% and 50% filling ratio. The evaporator section was heated at the air temperature range of 55-100 ºC, and air velocity of 0.5-2 m/s. For all tests, the results showed that the OHP with HFE-7000 behaved as a thermosiphon because the tube inner diameter was not suitable to generate the oscillating effects by vapour plugs and liquid slugs. The effectiveness results suggested that the OHPHX with HFE-7000 was suitable at evaporator temperature lower than 70 ºC. To the best knowledge of the authors, no article dealt with the oscillating heat pipes manufactured from elliptical cross-sectional tubes. Therefore, this work studies the influences of tube geometry design on the thermal performance of OHP used an elliptical cross-sectional area OHP heat exchanger. Also, this study focuses on the comparison of using the elliptic and circular cross-sectional tubes for OHP heat exchanger (OHPHX) as heat recovery devices in the HVAC system. The aims of this work are; the thermal performance criteria and energy saving using the OHP heat exchanger in HVAC that operated under constant inlet air conditions. That improves the thermal performance and enhances the energy-saving due to a possible increase in the heat transfer rate and a possible reduction of the hot air temperature difference that passes through OHP heat exchanger.

METHODOLOGY

In order to satisfy the objectives of this work, an experimental rig was held. The main characteristics and air conditions that affected the thermal performance of OHP heat exchanger and the operation HVAC system were considered to offer a complete description and analysis of a research subject, without limiting the scope of this work. The experimental investigation of the OHP as a heat exchanger was used to recover the wasted heat in the HVAC system over the elliptical cross-sectional tube.

Experimental Setup

The experimental rig was designed and fabricated to be able to conduct the experimental tests. The experimental rig attached all the necessary equipment like a centrifugal fan, heaters, steam humidifier device, removable eight-row OHPHX, and cooling coil, as shown in Figure 2. The centrifugal fan supplied the air at various velocities, while heaters and steam humidifiers were used to produce hot and humid air for the tests.

Two OHPHXs were designed and manufactured from eight rows of OHP. First, one of OHP was fabricated from copper tubing with 3.5 mm a circular inner diameter and 0.6 mm thickness. The second model was the elliptical tube shape that was formed by converting a circular copper tubing with an inner diameter of 3.5 mm, and a thickness of 0.6

mm by using a rolling tool. The major (A) axes, minor (B) axes and thickness of the elliptical channel were 4.4 mm, 2.4 mm, and 0.6 mm respectively, with an axis ratio of 0.55, as shown in Figure 3. An elliptical cross-sectional tube provides a rate of heat transfer higher than a circular tube by increasing the contacting surface area with an airflow [18]. The inner diameter of OHP can be defined as a critical diameter, and the best range for an OHP diameter is given by the following equation [19]:

$$0.7\sqrt{\frac{\sigma}{(\rho_{liq}-\rho_{vap}).\,g}} \leq D \leq 1.8\sqrt{\frac{\sigma}{(\rho_{liq}-\rho_{vap}).\,g}} \tag{1}$$

The OHP was manufactured with seven turns, and lengths of the evaporator, condenser, and adiabatic sections were 300 mm, 300 mm and 210 mm, respectively, as shown in Figure 4 and Figure 5. Two plates were used to isolate an adiabatic section of OHP from the condenser region and the evaporator region of OHP. The adiabatic section was covered by 50 mm thickness of fibreglass isolation as well as the evaporator section, condenser section, and the ductwork to ensure no heat gets in or out to these sections.

Wire fins made from copper were added along the condenser region and the evaporator region by the same space between the fins to increase the heat transfer rate and the thermal effectiveness of the OHPHX. The staggered tube arrangement used among the pipes of eight rows of OHP. The airflow passed across the tube in the case of staggering banks is similar to the flow around a curved canal of regularly converging and diverging cross-section. The flow velocity in the narrowest passage of an internal row mainly specified as the pitch ratio [20].

The working fluid was distilled water because it is a proper working fluid during the temperature range of 30-300 °C. The filling ratio was 50% from the OHP total volume as the active oscillation motion of working fluid can be observed at charging ratios of 40-60 %. The thermal performance of OHP is high at this range of filling ratio due to the circulation velocity worked at its maximum values [21,22].

The experimental tests required many steps as turning on the supply fan, and selecting the speed of electric fan motor to deliver the chosen air velocity (of 0.5 m/s, 1 m/s,1.5 m/s and 2 m/s), turning on the heaters and humidifier system to produce an established air initial conditions that passed through the ductwork, and turning on the air cooling system. The airflow conditions were recorded after more than 30 minutes. This procedure is repeated for different fresh air temperatures of 35 ºC, 40 ºC, 45 ºC, and 50 ºC.

Measuring and Uncertainties Techniques

The temperature of the air was measured at different locations in ductwork by using pre-calibrated k-type thermocouples. Ten k-type thermocouple probes were located in the ductwork (a, b, c, d, and e) shown in Figure 2 to measure the air temperature and then record it by a data logger. The air velocity was measured by using a hot wire probe. The differential approximation approach to the analysis of uncertainties was used to analyse the uncertainties of various experimental [23]. The results indicated that the maximum uncertainties in measuring air temperature and air velocity in the duct region were 4.2%, and 6%, respectively. The maximum relative standard error of thermal effectiveness and heat transfer of OHP was 8.8% and 7.3%, respectively.

Experimental Calculations

The function of the evaporator portion of the OHPHX is a pre-cooling hot inlet air before it moves across the cooling coil, while the condenser portion is rejecting the heat into the airflow, see Figure 6 and Figure 7**.** This thermodynamic air processes can be explained as the following [13, 14]:

Pre-cooling process (1 - 2) at the evaporator section:

$$Q_{eva} = \dot{m_a}(h_1 - h_2) \tag{2}$$

Cooling Process (2 – 3) at the cooling coil:

$$Q_{cc} = \dot{m_a}(h_2 - h_3) \tag{3}$$

Reheat process (3 – 4) at the condenser section:

$$Q_{con} = \dot{m_a}(h_3 - h_4) \tag{4}$$

where, h_1, h_2, h_3, and h_4 are the enthalpies of air inlet and outlet at evaporator and condenser sections, respectively.

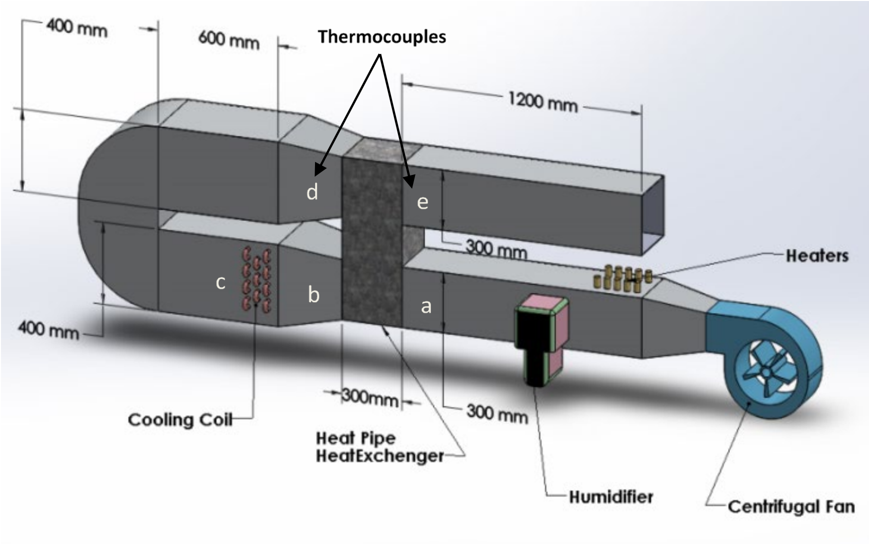
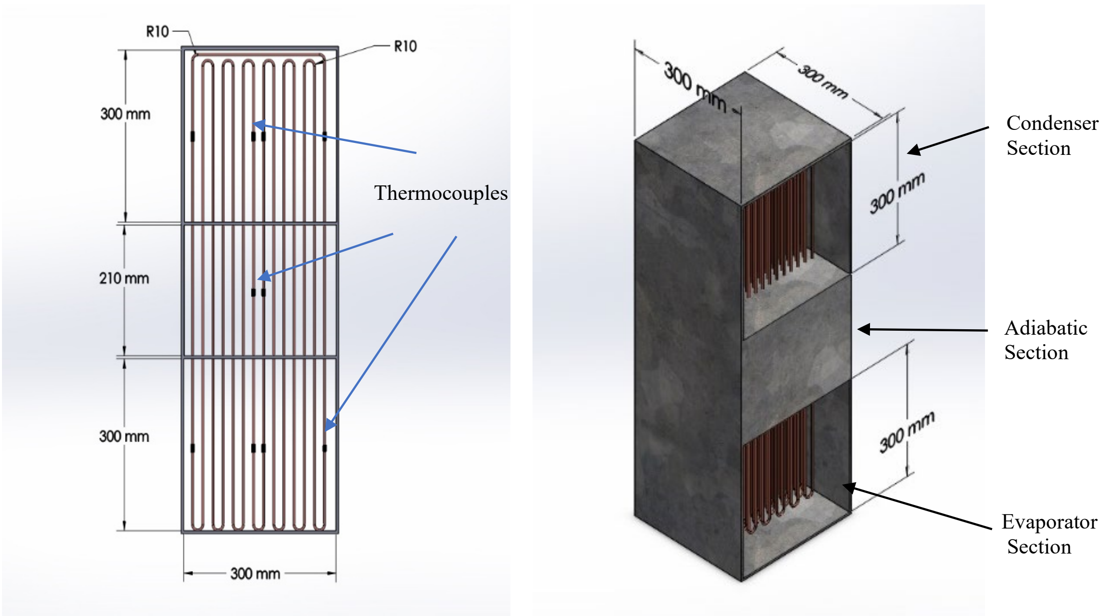


Figure 2. Schematic diagram of HVAC system.

(a) (b) (c)

Figure 3. (a) The tool used to form the oval tubes, (b) oval cross-sectional area of copper tube, (c) schematic oval cross-sectional area.



(a) (b)

Figure 4. Schematic of (a) oscillating heat pipe and (b) oscillating heat pipe heat.

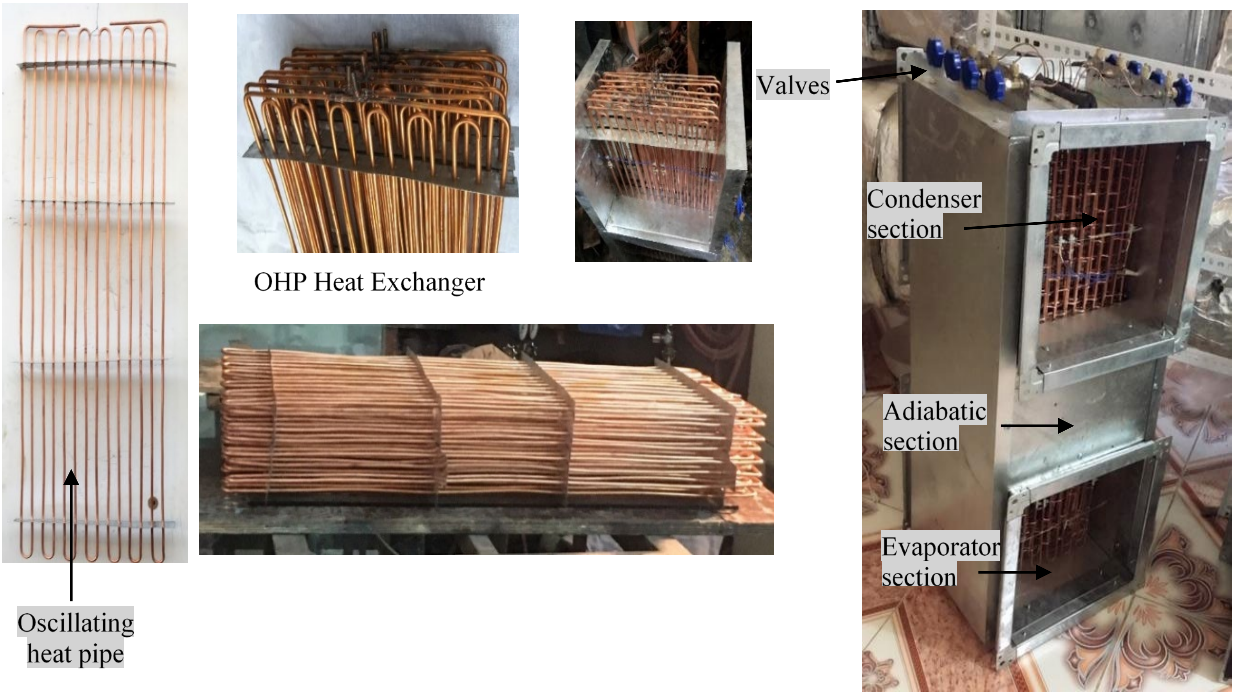


Figure 5. Pictures of OHP heat exchanger.

The relation between the rate of actual heat transfer and the maximum possible heat transfer rate is known as the effectiveness of the heat exchanger. OHP can recover only sensible heat; therefore, the effectiveness of OHP is defined as the ratio of an actual drop of temperature to the maximum drop of temperature. By assuming that all amounts of the dropping heat energy of hot air passed across the evaporator section of OHPHX transported to the fluid flow inside the evaporator part. At an equal air mass flow rate, the sensible effectiveness can be [24]:

$$\varepsilon_s = \frac{T_1 - T_2}{T_1 - T_3} \tag{5}$$

The thermal resistance, R_{th} of OHPs can be determined using the average temperature difference between the evaporator section and condenser section divided by heat input at the evaporator section [25].

$$R_{th} = \frac{\bar{T}\,eva - \bar{T}con}{Q_{eva}} \tag{6}$$

where $\bar{T}\,eva$ and $\bar{T}con$ is the average wall temperature of evaporator and condenser section, Q_{eva} is the heat input at the evaporator section of OHP.

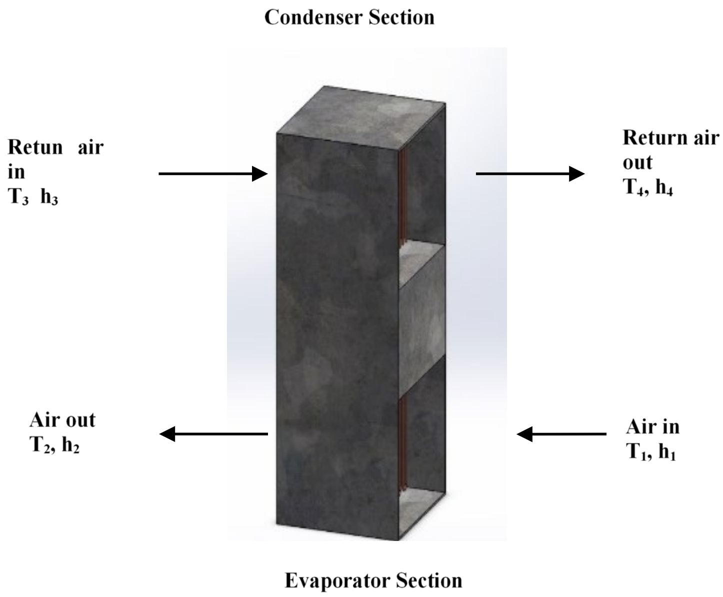


Figure 6. Airflow diagram.

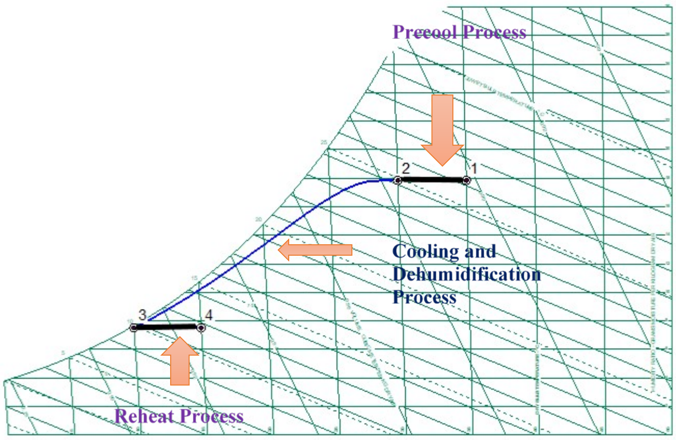


Figure 7. Air thermodynamic processes on psychometric chart.

RESULTS AND DISCUSSION

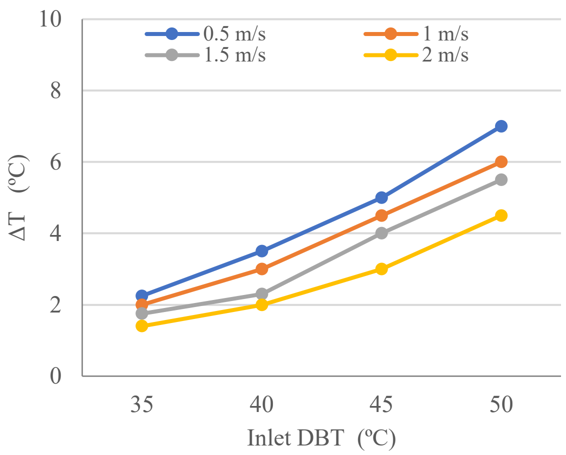
The minor axis of the oval tubes was parallel to the direction of the airflow. The oval tubes of OHP heat exchanger were formed from the outer diameter (of the 5 mm copper circular tubes), which, after forming preserved the same perimeter as the circular tube.

Effect of Air Inlet DBT and Velocity on Temperature Difference across OHPHX

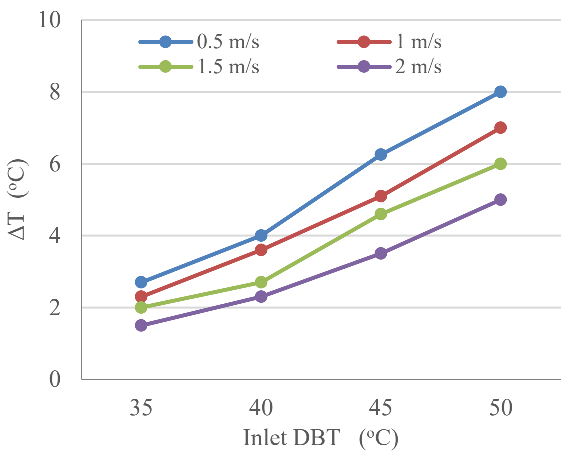
The influences of inlet dry bulb temperature (DBT) on the temperature difference of air that passed across an evaporator section of OHPHX are shown in Figure 8(a) and 8(b). From these figures, it is clear that the temperature difference of inlet air moved through the evaporator tubes increased as the inlet air temperature increased with combination with the air velocity decrease at the evaporator section, and this behaviour recognised for all test velocities. The experimental results showed that the maximum temperatures drop were 7 ºC and 8 ºC for circular and elliptical tubes respectively, captured at 50 ºC and 0.5 m/s.

As the inlet DBT increased, the heat transfer across the walls of evaporator pipes also increased due to the process of heat absorption by working fluid in the evaporator section. This led to an increase in the temperature difference of air passed over the evaporator section. Despite the increase of the air velocity that led to a rising in the heat transport because it enhanced the air-side heat transfer coefficient; it shows the maximum air temperature drop obtained at the lower velocity of 0.5 m/s in all cases. This is due to the increase in time required for heat transport from hot air to a working fluid across the walls of OHP.

The geometry effect using elliptical tubes OHPHX on the air temperature drop is shown in Figure 9(a) to 9(d). The reduction in inlet hot temperature air across the evaporator section is due to the pre-cooling process. The comparison between both types of circular and elliptical OHPHX showed that the elliptical model could produce a higher temperature difference than the circular one. The geometric change of the tube is one of the passive heat transfer enhancement approaches in heat exchanger technology. One of the important concepts of passive approaches to convective heat transfer enhancement is to increase the heat transfer area and enhanced the convective heat transfer coefficient. This explains the enhancement of the temperature difference of the air passed across the evaporator section of OHPHX.



(a) circular tube



(b) elliptical tube

Figure 8. The air temperature difference vs inlet DBT for the OHPHX evaporator for different inlet air velocities.

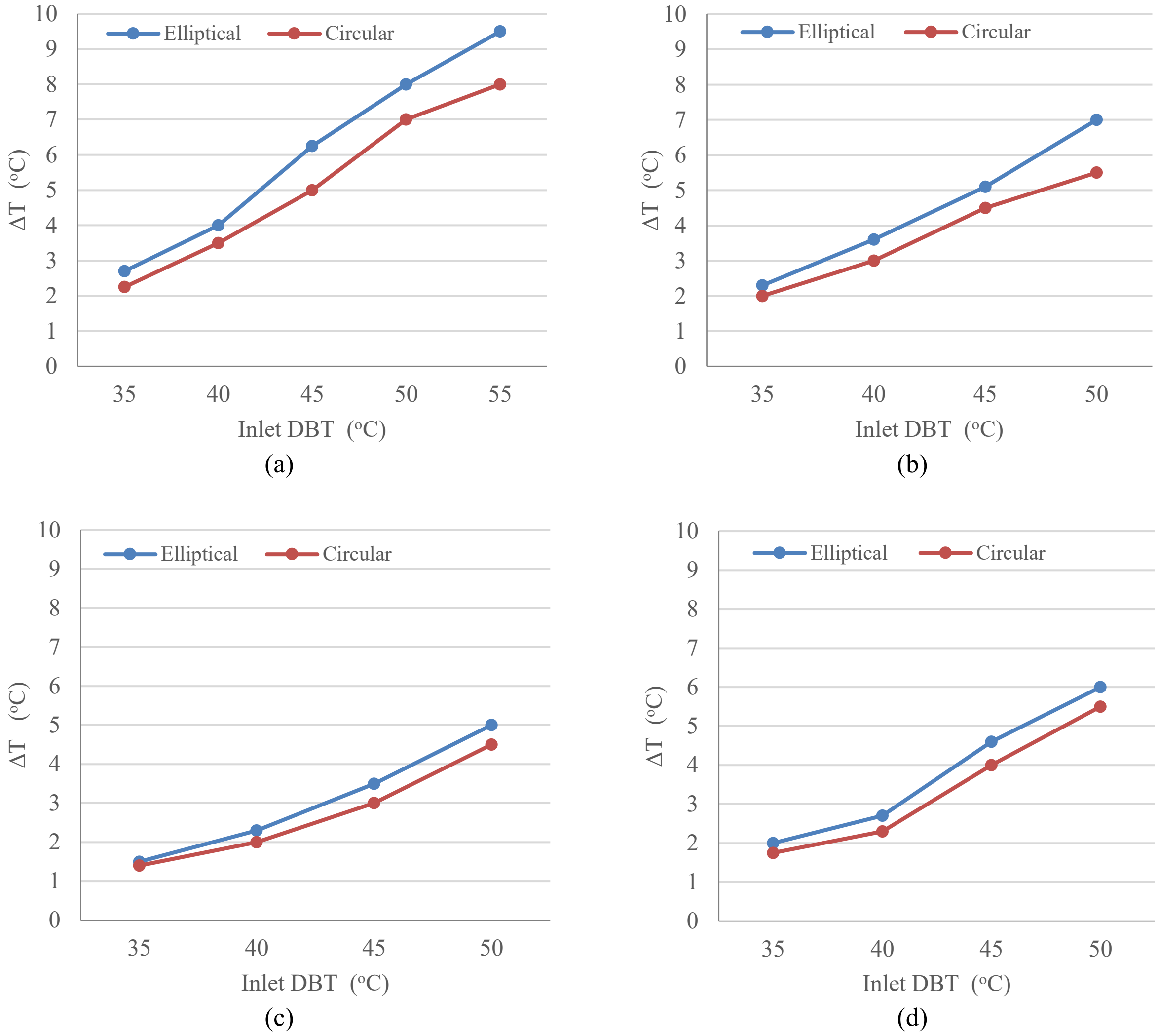


Figure 9. The comparison between elliptical and circular OHPHX for temperature difference evaporator section at constant air velocity of (a) 0.5 m/s, (b) 1 m/s, and (c) 1.5 m/s, and (d) 2 m/s.

The Thermal Performance of Oscillating Heat Pipe Heat Exchanger

To specify the OHPHX's thermal performance, the effectiveness is estimated. Thermal performance indicates which design of the heat exchanger of OHP is better from the heat exchanger thermal performance view. Figure 10(a) and 10(b) revealed the effectiveness of the OHPHX with the circular and elliptical cross-sectional area obtained from experimental data. Also, these figures showed the effect of inlet DBT and air velocity on OHPHX effectiveness. The experimental data showed the thermal effectiveness increased when the inlet DBT increased while the effectiveness decreased when the air velocity increased. This is due to the drop-in temperature of air that moved through the evaporator section increased as inlet DBT increased in combination with decreasing air velocity. The maximum effectiveness value of OHPHX is 17.5% and 19.5% at 50 °C and 0.5 m/s, for circular and elliptical tubes respectively.

The comparison between both kinds of elliptical and traditional models of OHPHX at 0.5 air velocity is shown in Figure 11(a), 11(b), 11(c) and 11(d). This observation indicated that the effectiveness enhancement attained by using an elliptical cross-sectional tube OHP alternatively a circular one. The maximum effectiveness enhancement ratio was 14% by using the elliptical cross-sectional area OHP. This enhancement in the thermal performance of the heat exchanger resulted in the shape of the geometry because the airflow left the first row of OHP as jets led to having a high momentum. Then, the airflow reached and passed through the second row of elliptical OHP that led to the jet streams acceleration and redirected to the inner passages between the tubes of OHP. This operation induced an increase in the turbulence level of flow, forming a vortex across the heat exchanger tubes and improved the heat transfer rate.

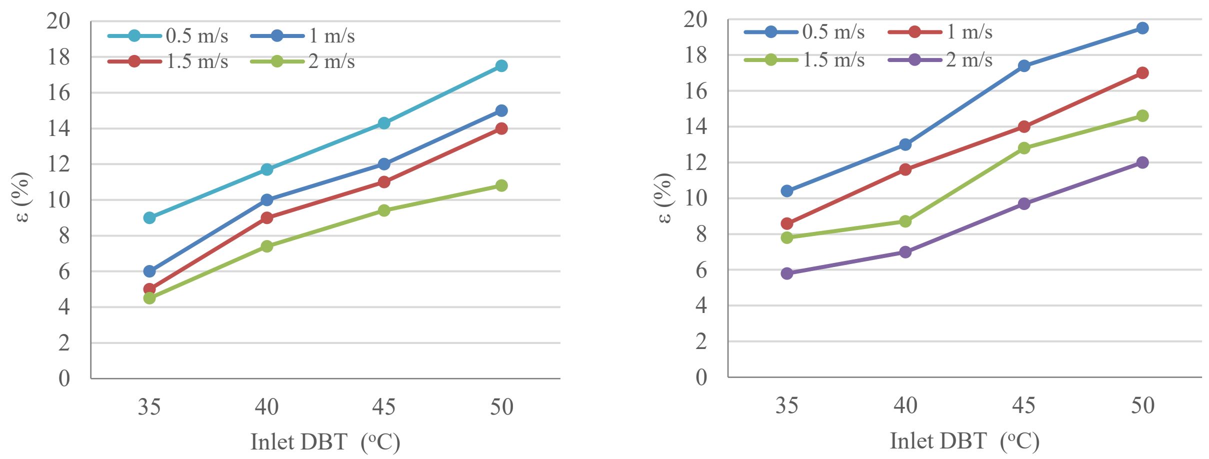


Figure 10. Thermal effectiveness vs, inlet DBT for the OHPHX evaporator on sensible using (a) circular tubes, and (b) elliptical tubes.

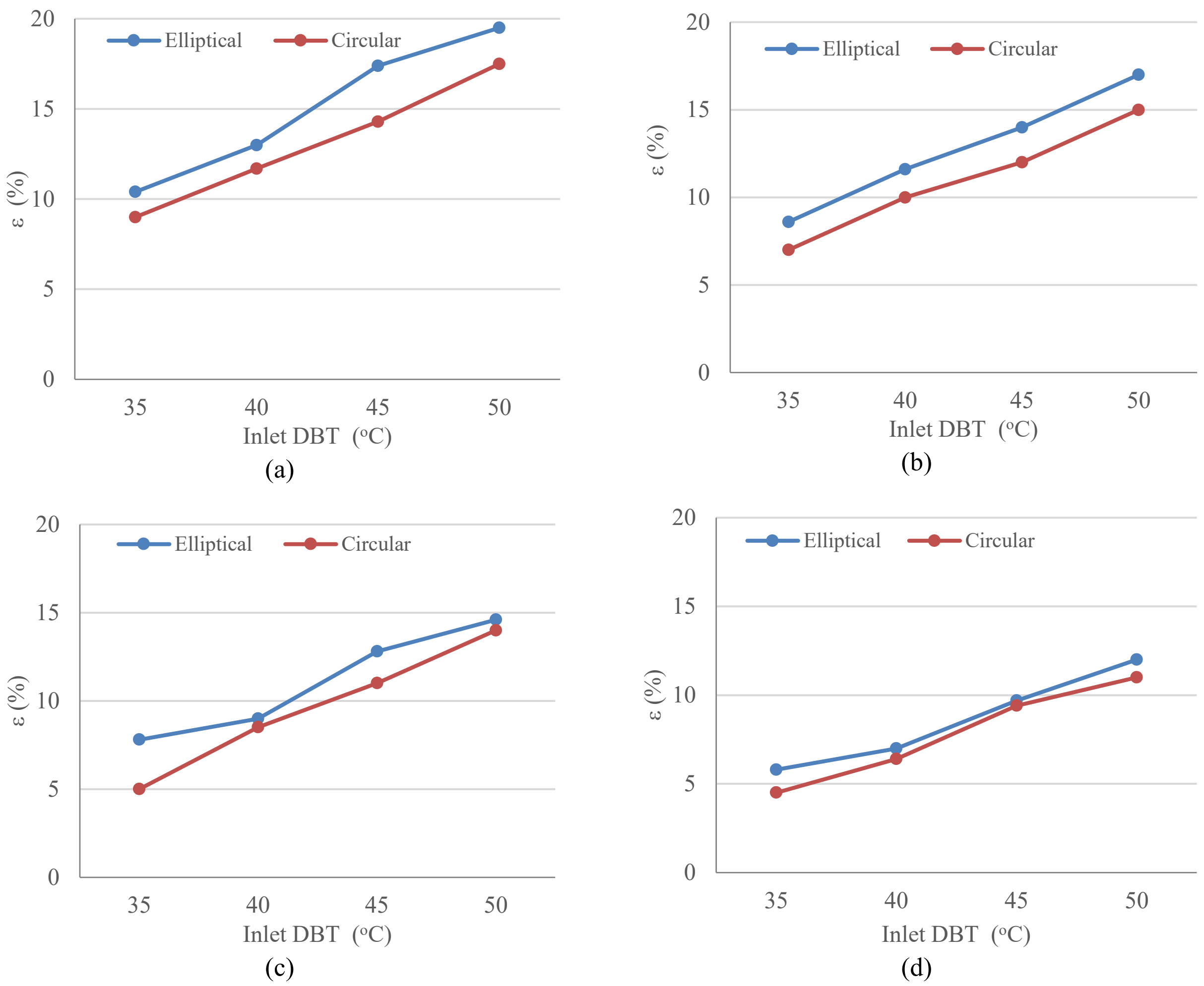
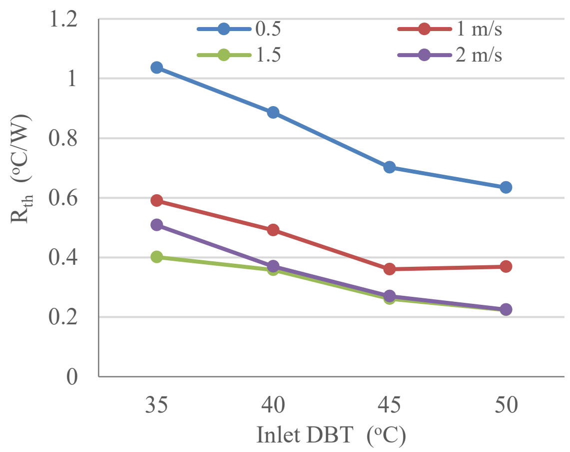


Figure 11. Comparison of effectiveness between circular and elliptical OHP heat exchangers for different air velocities (a) 0.5 m/s, (b) 1 m/s, (c) 1.5m/s, and (d) 2 m/s.

Figure 12(a) and 12(b) show the effect of inlet air temperature on the thermal resistance of conventional and elliptical tubes OHP at different air velocities. These figures displayed that the thermal resistance decreased with increasing inlet air temperature for all velocities conducted in this work. OHP depicted low thermal resistance (better thermal performance) at high inlet temperature 50 ºC for all velocities, as manifested by references [13,17]. The increase of inlet air temperature at the evaporator section of OHP led to increasing the heat input at this section of the device. So the evaporator temperature raised, resulting in a higher fluid density gradient in the OHP tubes and lower liquid viscosity (lower wall friction). This reduction in thermal resistance of OHP at high heat input can also explain that the working fluid temperature of the evaporator section is high enough to make the liquid boiling rate increase, and the working fluid flows smoothly in one direction. The lower thermal resistance was 0.2248 ºC/W for conventional OHP, and 0.1786 ºC/W for elliptical tube OHP, at 50 ºC and 2 m/s.

While at a low temperature (of 35 ºC) of inlet air, which means low heat input to the evaporator section, the working fluids of OHP showed the highest thermal resistance for all velocities because, at low heat input, the OHP cannot sustain stable behaviour. The maximum thermal resistance was 1.036 ºC/W for circular tube OHP and 0.8292 ºC/W for elliptical tube OHP, at 35 ºC and 0.5 m/s.



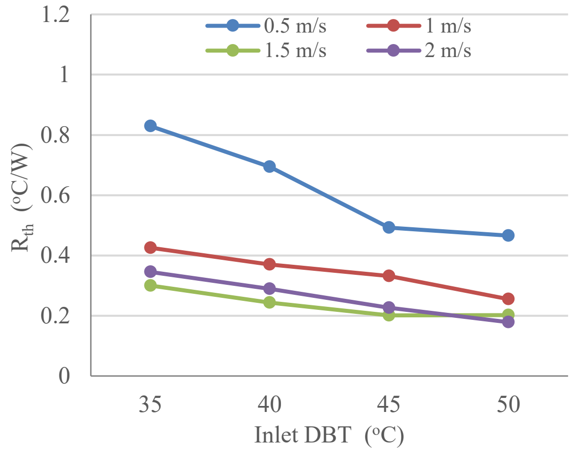


Figure 12. The thermal resistance vs inlet DBT of the OHP evaporator for (a) conventional tube and (b) elliptical tube.

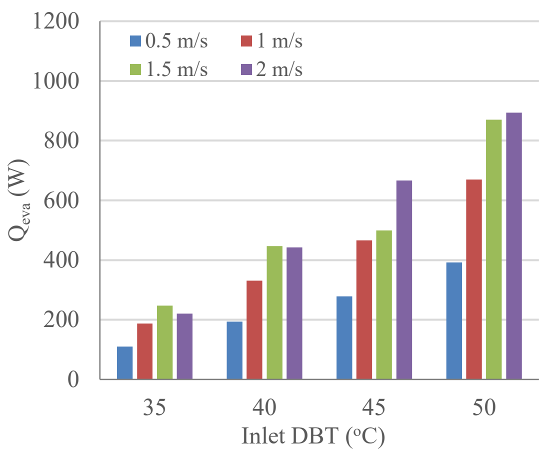
The Energy Saving Enhancement

The experimental data of energy saved by the evaporator section (Q_{eva}) of OHP heat exchanger due to the pre-cooling process of hot air that passed through this part is shown in Figure 13. This figure demonstrated the effect of inlet air temperature on the energy saving of cooling load at different air velocities. The results showed that the energy saved by the pre-cooling process increased as the inlet air temperature increased, as indicated by the references [14,17].

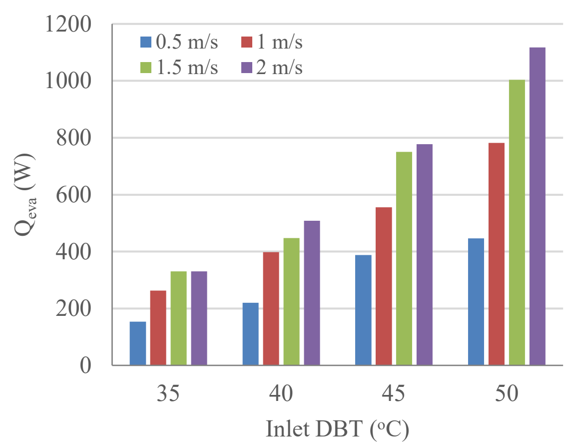
The maximum heat saved by the evaporator section of OHPHX (Q_{eva}) was 900 W and 1117 W for circular and elliptical tubes at 50 ºC and 2 m/s. Figure 14 evinced the comparison between using elliptical and circular cross-sectional area tubs OHPHX. The maximum energy-saving enhancement ratio was 18% at 2 m/s and 50 ºC, which was achieved using the elliptical tubes OHPHX compared to conventional OHPHX.

The total energy saving is represented by the summation of the two terms of energy, energy saved by the evaporator section (Q_{eva}) and energy saved by the condenser section (Q_{con}). Figure 15(a) and 15(b) depict the effect of inlet air temperature on the total energy saving using the elliptical tube and circular one at different air velocities. The increase of fresh air temperature led to an increase in the total energy saved by OHPHX for all tests recorded. The maximum values of total energy saving were 1890 W and 1626 W for the elliptical and circular tubes OHPHX at 50 ºC and 2 m/s. The minimum values of total energy saving were 240 W and 215 W for the elliptical and circular tubes OHPHX at 35 ºC and 0.5 m/s. The results showed that the total energy saving using elliptical tubes had higher values than circular ones by 16%.

One of the important concepts of passive approaches to convective heat transfer enhancement is to increase the heat transfer area that consequently leads to an increase in the convective heat transfer coefficient. The elliptical cross-sectional tube offers a heat transfer area larger than another tube shape. The enhancement in energy-saving was due to the tube shape that produced the improvement of the heat transfer coefficient on the air-side that led to raising the heat transfer rate to the working fluid inside the OHP.



(a) circular tube



(b) elliptical tube

Figure 13. Q_{eva} vs inlet DBT for evaporator section of the OHPHX.

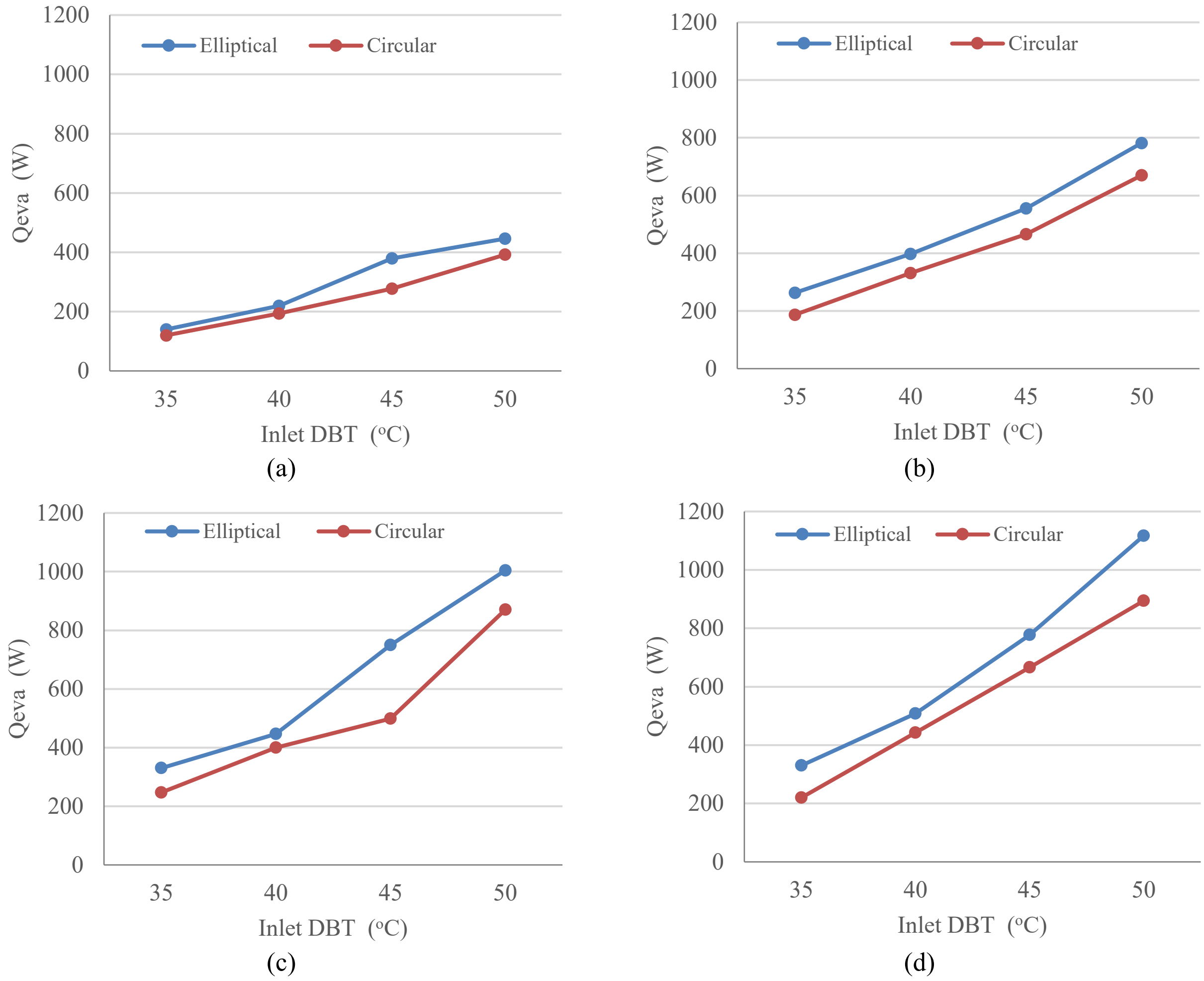


Figure 14. The Q_{eva} vs inlet DBT air velocity for the elliptical and circular OHPHX evaporator at (a) 0.5 m/s, (b) 1 m/s, (c) 1.5 m/s, and (d) 2 m/s.

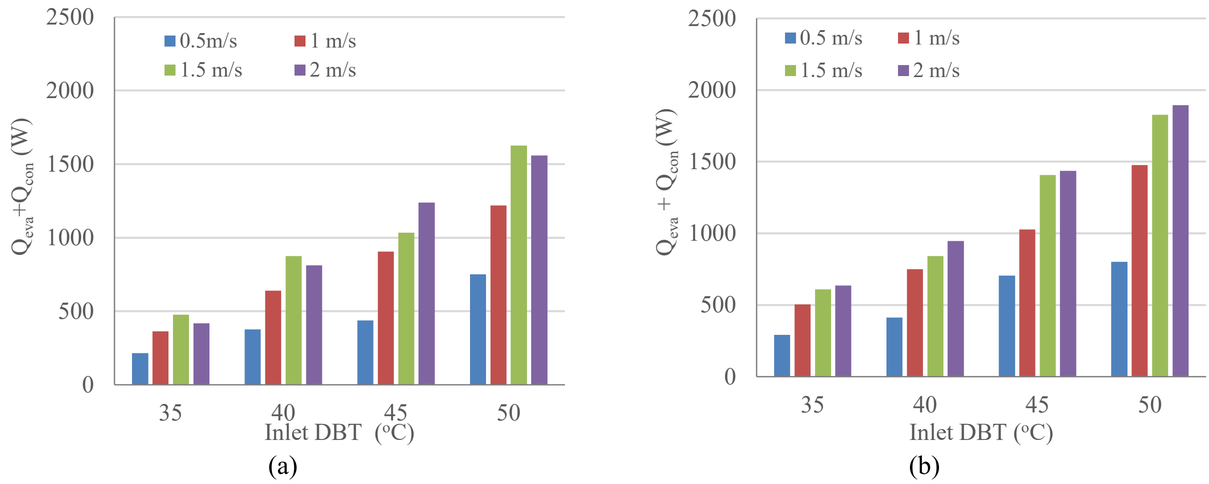


Figure 15. Total energy saving vs inlet DBT for the OHPHX evaporator using (a) circular tube with and, (b) elliptical tube.

CONCLUSION

The oscillating heat pipes as the heat exchanger is successfully used as a heat recovery device. In this study, to improve thermal performance, a new model of OHPHX was designed and implemented by replacing circular cross-sectional tubes with elliptical ones. The experimental tests strongly recommend using the OHP as a heat exchanger to recover the wasted heat and to enhance the thermal performance of the HVAC system. The main conclusions from the study are:

i. The elliptical tubes OHPHX produces an enhancement in the heat transfer rate between the air and the working fluid inside OHP. From results, the thermal performance of the OHP heat exchanger in terms of thermal effectiveness was affected by the inlet air conditions, and the maximum value is 17.5% and 19.5% for circular and elliptical tubes at 0.5 m/s and 50 ºC.

ii. The thermal resistance (thermal performance) of the OHP is affected by heat input on the evaporator section of OHP. For both models, the thermal resistance decreased with increasing the inlet air temperature. The thermal resistance can be enhanced by 20% using the elliptical tubes OHP.

iii. The energy that saved by OHP with elliptical tubes was better than the conventional tubes. The experimental results elucidated that energy-saving and the total energy saving enhanced by ratio of 18%, and 16% using elliptical shape tube of OHP.

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