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Full Length Article

An experimental study of using water, methanol, and binary fluids in oscillating heat pipe heat exchanger

Anwar S. Barrak *, Ahmed A.M. Saleh, Zainab H. Naji

Mechanical Engineering Department, University of Technology, Baghdad, Iraq

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ABSTRACT

The aim of this paper is studied experimentally the effect of using oscillating heat pipe heat exchanger as a heat recovery device in the air conditioning system to enhance the dehumidification capability of the cooling coil. Water and Methanol and binary fluid of Water/Methanol used as working fluids with 50% filling ratio. The dehumidification capacity of cooling coil can be enhanced by using oscillating heat pipe heat exchanger by enhancement ratio 25%, 21%, and 17% for Methanol, Binary, and Water respectively. The maximum total energy saved can be reached at 1645 W, 1849 W, and 1932 W for Water, Binary, and Methanol respectively.

1. Introduction

Heat recovery systems are types of air to air heat exchangers that consider as a sensible waste heat recovery in many applications like residential, commercial, and industrial. for example of this kind of heat recovery system can be enthalpy wheels, fixed plate heat exchangers, heat pipe heat exchangers, and oscillating heat pipe heat recovery ventilators [1]. The structure of closed-loop of oscillating heat pipe (OHP) comprised of a long capillary tube (channel) that meanders into many turns through a heat reception and rejection sites [2]. The tube inner diameter must be small enough (0.1 mm–5 mm) to ensure the capillarity condition, which led to form liquid slugs and vapor bubbles due to surface tension property and vapor and liquid regions remain separated. If the one end OHP was heated (evaporator section) and the other ends was cooled (condenser section), pulsation phenomena and oscillation flow of working fluid are observed in the OHP. The repeated process of evaporation in evaporator section and condensation in condenser section will create the non-equilibrium pressure domain and the working fluid circulated by oscillation motion. For this reason the OHP had efficient heat transfer process. The OHP needs a heat source at evaporator section to supply the heat that required to overcome the vaporization latent heat of working fluid and heat sink at condenser section to reject heat [3]. OHP is filed partially via working fluid quantified by filling ratio 50%. Low dynamic viscosity, low surface tension, low latent heat, which aiding quick bubble generation and collapse, and high specific heat are the most important properties of working fluid. Also the working fluid should have the following properties; High value of $(dP/dT)_{sat}$, so for a small change in T_e will generate a large corresponding P_{sat} inside the generated bubble. This aids in the bubble pumping action of the device [4].

In an air conditioning system, to validate comfort conditions in hot and humid weather conditions the dehumidification (or so-called moisture removal) of the inlet supply air is the most important procedure [5]. Therefore, inlet air temperature is cooled down to its dew point temperature in the cooling coil of the heat, ventilation, and air condition (HVAC) system. The moist air releases its moisture, which drained from the system, thus reducing the humidity in the room. The air can be cooled and dehumidified by the cooling coil [6]. In this case the moist air leaving the cooling coil is usually too high in relative humidity and too low in temperature to be used in occupied spaces directly, so the uncomfortable conditions are felt. Besides, the high relative humidity (above 70%) in occupied spaces and low-velocity ducts can cause threatens public health, mold, mildew, etc. Therefore, it is a strong recommendation to keep the supply air humidity below 70% to achieve good indoor thermal comfort and air quality, and of reducing the risk of catching the disease [7].

To solve this problem and to achieve the design air condition in a conventional air condition system, the cold air is reheated then by heater, steam or hot water coils before being delivered to the room as supply air. One of the most important functions of heat pipe heat exchanger (HPHX) is to enhance the dehumidification

* Corresponding author.
E-mail address: anwar.barrak@yahoo.com (A.S. Barrak).

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capacity of the conventional air conditioning systems. The dehumidification principle can be used experimentally as a heat-pipe in air-handling to recover heat from warm air to reheat the air before supply it. The evaporator section of OHP can use as a pre-cooler to the cooling coil when the ambient hot air passed through and the return air used to cool the condenser section or the cold air exit from cooling coil is then reheated by a condenser section of OHP to a temperature that is suitable for the conditioned space [8].

The heat transfer and heat transport capacity of the horizontal OHP in cryogenic environment were studied by [9] using liquid nitrogen as working fluid. The heat input at evaporator changed from 20.5 W to 380 W. The results showed that the operation of OHP can be divided into three region unsteady state, transient state, and a new steady state, and the thermal resistance decreased from (0.256–0.112) °C/W when the input heat load increased from (22.5–321.8) W. The oscillating heat pipe (OHP) was used by [10] to enhance the rate of heat transfer from the heat exchanger. The capillary OHP attached on tubes of the heat exchanger to extend the outer service area of heat exchanger instead of wire metal. Methanol, R123, and acetone fluids used as working fluids. Air supplied at condition 25 °C and flow rate (0.5–1.5) kg/s while water inlet temperature in the tube was 45 °C–85 °C. The results showed that the heat transfer can be enhanced by using OHP by 10% in comparison the conventional wire on tube method. Ref. [11] performed the thermal resistance of OHP by using pure fluids (water, methanol, ethanol, and acetone) and binary fluids with 1:1 vol mixing ratio. 1:1 vol mixing. The results showed that, acetone had low thermal resistance than other pure fluids. While the acetone/water and methanol/water binary fluids had lower thermal resistance than acetone, methanol, and water.

The inserting of fins in OHP effects was studied by [12]. They experienced finned and unfinned in structuring of OHP made from copper tube mendreing in 8 turns. The copper wires with 1 mm diameter used as fins inserted along only in the condenser section at equal distance between the fins. Methanol and ethanol fluids were used as working fluids and an evaporato section was heated by the heater, while the condenser section was cooled by forced air. The result showed that methanol had lower thermal resistance than ethanol and finned – inserted structure showed better performance than unfinned structure. While [13] investigated the effectiveness of oscillating heat pipe heat exchanger with check valves (OHPHX/CV) to reduce the air humidity in drier system. The staggered arrangement of tubes, R134a and the experimental work had several operation conditions were used in their work. The results showed that the increasing of inlet hot air temperature with lower velocity, the increasing of the air velocity with temperature, and the lower hot air velocity with highest temperature will increase the CLOHP/CV effectiveness. Also the humidity reduced from the range (89–100)% to a range (54–72)%. Also OHPHX/CV was used in drying chamber by [14] with a 0.2 ratio of check valve number to number turn number. Water as the working fluid with filling ratio of 50% was used with different operating conditions. The results showed that OHPHX/CV can be saving thermal energy by 56.66% and saving the electrical energy for any velocity of investigating hot air by 28.13%.

The oscillating heat pipe heat exchanger (OHPHX) with check valves in the split unit air conditioning system was investigated. Results showed that, the energy saved by 3.6% by using a check valve with OHPHX and the coefficient of performance (COP) of the system with check valve will be higher than a system without check valve 14.9% [15]. Oscillating heat pipe heat exchanger (OHPHX) as a heat recovery device was used in HVAC system. OHP tube with inner diameter 1.65 mm and ten turns was used [16]. The empty OHP and partially filled with n-pentane by filling ratio 70% by volume were tested. The evaporator section was heated at the temperature 45 °C and the condenser section was cold at the 6 °C with constant volumetric ratio 0.19 m^3/s. The results showed that the effectiveness were 0.064, 0.05, and 0.02 for theoretical, filled with n-pentane, and empty OHP respectively. While the OHP was able to recover heat up to 240 W.

According to the literatures, there is no enough information about using the OHP heat exchanger (OHPHX) as a heat recovery device in the air conditioning system therefore this study is conducted. The aim of this work is to use OHPHX in HVAC system to enhance the dehumidification process and improve the energy saving by precooling process at evaporator section and reheat load at a condenser section of OHPHX in air conditioning systems, and examined the effect of using pure (Water and Methanol) fluid and binary fluid (mixture of Water/Methanol at mixing volume ratio 50:50%) as working fluids in OHPHX on performance of HVAC system.

2. Experimental set up

The experimental rig required for this work was designed and manufactured typical HVAC system, OHPHX, and all necessary equipment and instruments as shown in Fig. 1.

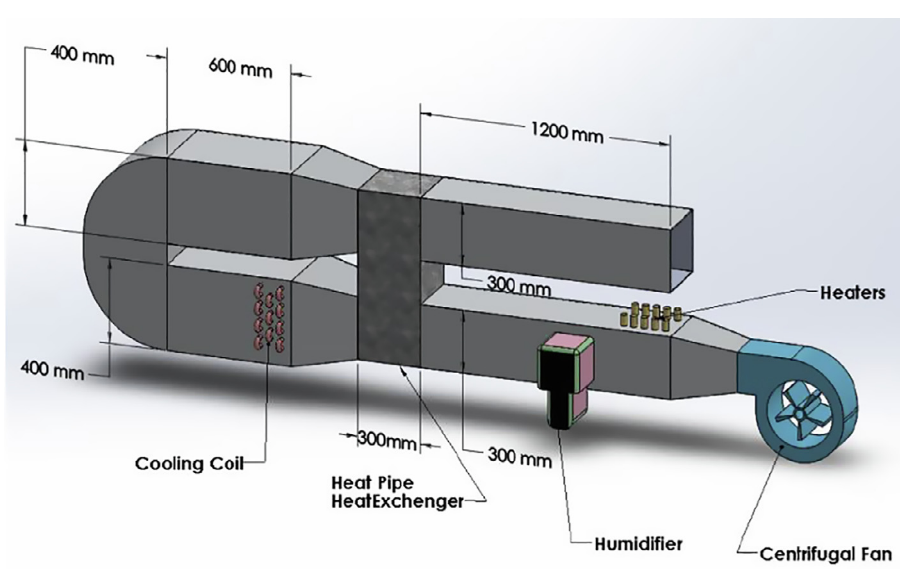

Fig. 1. Schematic diagram of HVAC system.

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The rig was designed and operated with different configurations to satisfy all the required to evaluate the enhanced level. The experimental rig comprised of a centrifugal variable speed fan, heaters, humidifier device, 8-row OHPHX, DX coil (2 kW cooling capacity) and interconnecting duct work as shown in Fig. 2. The centrifugal fan supply air at different velocities while heaters system and humidifier were used as the source of hot and humid outdoor air for the experiments. The maintained hot air state was drawn through OHPHX evaporator. The 7 turns closed loop OHP was designed and manufactured as shown in Fig. 3. The OHP was fabricated from copper tubing with length of the evaporator, condenser, and adiabatic section as 300, 300, and 210 mm respectively. The inner diameter of the OHP is 3.5 mm and an outer diameter of 4.7 mm.

Fig. 2. Experimental Rig.

The working fluid of OHP depends on some of the important properties as fluid ability to generate a large corresponding P_{sat} for a small change in T_e inside the nucleation bubble. Also, low dynamic viscosity, lower surface tension, low latent heat, which assisting fast bubble nucleation and collapse, and high specific heat are useful fluid properties [17]. In this work three kinds of working fluids were used: Distilled water, Methanol and methanol and water mixture fluid (50:50 by volume) were used in OHP with filling ratio by 50% of the total volume for all tests in experimental work. The using of binary fluid mixtures because it till now, binary fluid blends used as working fluids in OHPHX have not been completely investigated. Thermal conductivity of Fluid can be enhanced which led to enhance passively the convective heat transfer. The flow around a tube in the first row is similar to that around a single tube, but the flow pattern in subsequent rows is different. The tubes of OHP are arranged as staggered configuration as shown in Fig. 4. In staggered banks, the flow is comparable to flow in a curved channel of periodically converging and diverging cross section. The velocity distribution in the minimum cross section of an inner row is mainly determined by the pitch ratio [9]. The transverse pitch (S_T), the longitudinal (axial) pitch (S_L), and diagonal pitch (S_D) were 15, 15, and 16.8 mm respectively. The adiabatic section is separated from the evaporator and condenser sections of OHP by two plates and it is well-insulated with fiberglass insulation as well as the evaporator and condenser sections to insure no heat transfer. Wire fins added to OHPHXs to provide additional surface area to the condenser section this increased the rate of heat transfer and the effectiveness of the OHPHX will enhanced. Copper wires (diameter 1 mm) on tube fins are added along the evaporator and condenser sections with equal distance between the fins. The duct work was insulated with fiberglass of

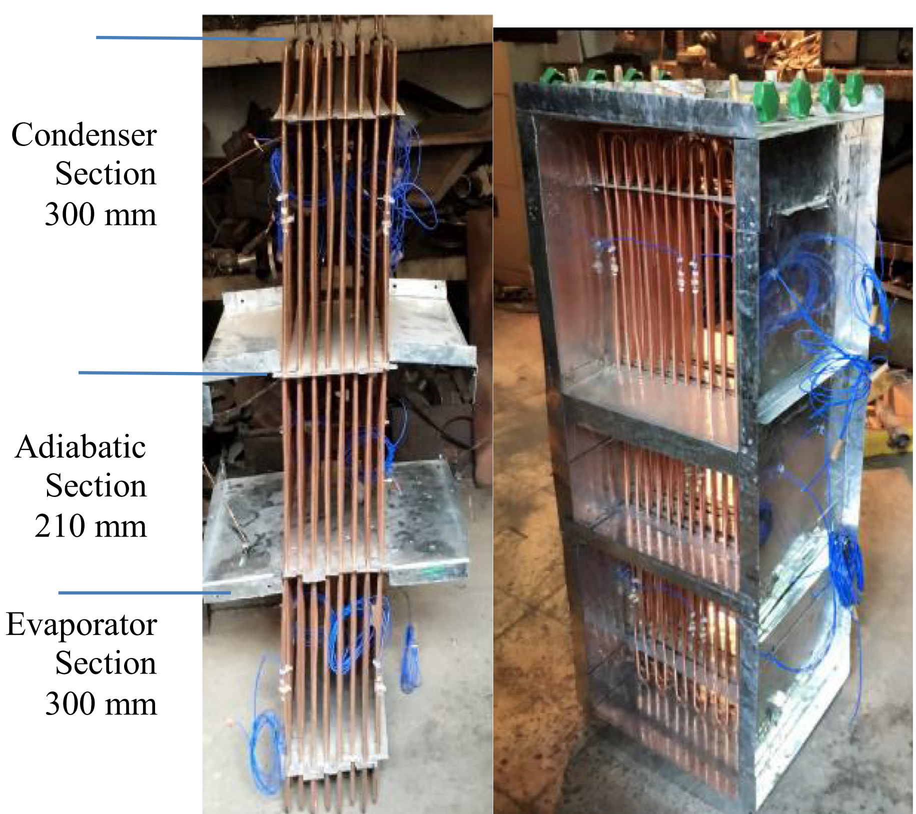

Fig. 3. Oscillating heat pipe heat exchanger.

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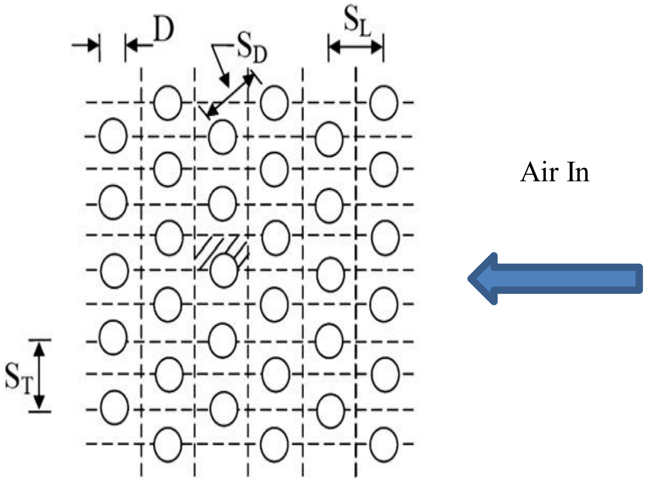

Fig. 4. The staggered arrangement of heat exchanger tubes.

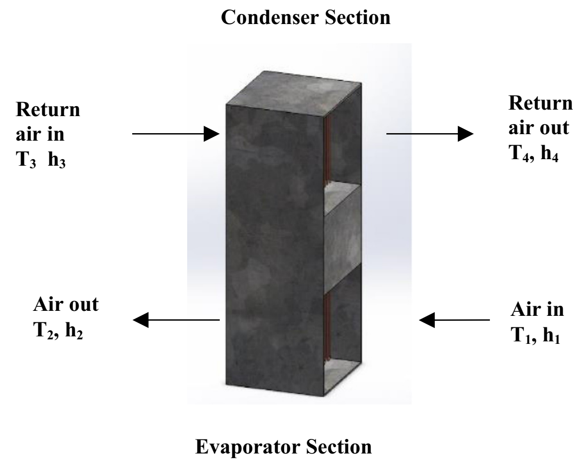

Fig. 5. Air flow diagram.

50 mm thickness to minimize the heat loss from the duct to the surrounding environment. The experimental procedures included following steps: Fixing all parts of the system as shown in the Fig. 1, selection the type of working fluids (water, methanol, and binary fluid), selection the required initial air temperature conditions like supply air velocity (0.5 m/s, 1 m/s, and 1.5 m/s), inlet air dry bulb temperature (DBT) (35, 40, 45, and 50) C, and different relative humidity (RH) values (10, 20, and 30) %. Note that all data were recorded after thirty minutes to ensure that the system has reached steady state. Air temperatures were measured by a set of calibrated thermocouple probes (K-Type) were positioned in duct to measure the air temperatures of inlet fresh air, evaporator inlet air, evaporator outlet air, cooling coil outlet air, condenser inlet air, and condenser outlet air and the signals were recorded by a temperature data logger. The centrifugal variable speed fan used to generate air flow through the duct work and across the heat exchanger with a velocity controllable range of 0.5–2.5 m/s. Heaters and humidifier device used to deliver the required air conditions. The humidity and velocity of air stream were measured by a digital relative humidity meter and hot wire anemometer having ±3% RH and ±0.2 m/s accuracy respectively.

3. Theoretical background

The evaporator section of the OHPHX is used as pre cooling the hot fresh air before it passes through the cooling coil while the condenser section is rejecting the heat to (reheat) the air flow. This will enhance the cooling and dehumidification capacity for the conventional system see Fig. 5.

The thermodynamic processes (shown in Fig. 6) can be explained by the following equations [18,19]:

Line 1–2 represents precooling process: heat input to the evaporator section of OHPHX, the air will be cool down from T_1 to T_2 without any change in its specific humidity.

$$Q_{eva} = m_a^{\cdot}(h_1 - h_2) \quad (1)$$

Line 2–3 represents cooling and dehumidification process: cooling load at the cooing coil.

$$Q_{cc} = m_a^{\cdot}(h_2 - h_3) \quad (2)$$

Line 3–4 represents reheat process: heat reject from the condenser section of OHPHX, the air will be reheat to T_4

$$Q_{con} = m_a^{\cdot}(h_3 - h_4) \quad (3)$$

Where

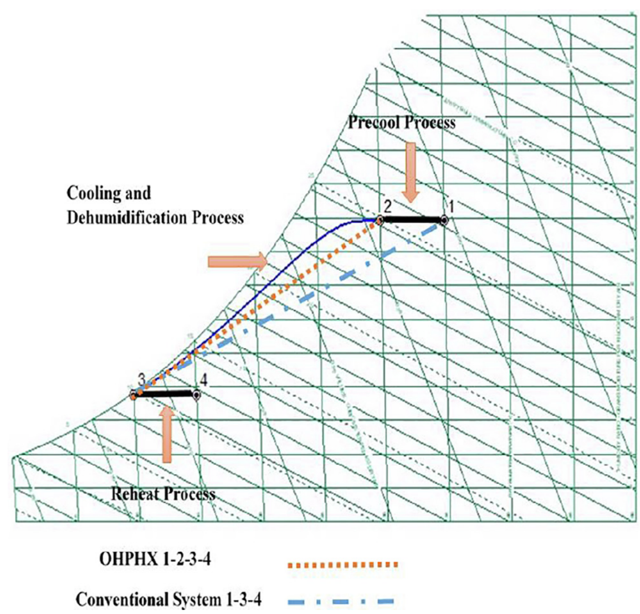

Fig. 6. Compared of conventional and OHPHX in psychometric chart.

h_1 is the enthalpy of fresh air inlet to the evaporator section of OHPHX
h_2 is the enthalpy of fresh air outlet from the evaporator section of OHPHX
h_3 is the enthalpy of cooled air exit from the cooling coil.
h_4 is the enthalpy of cooled air exit from the condenser section of OHPHX.

The ratio of sensible heat gains to total heat gains can be defined as SHR. This sensible heat ratio describes the most relevant in determining the capability of OHPHX in energy saving and the enhancement of dehumidification. The equation of sensible heat ratio for conventional system as:

$$SHR_{Conv.} = \frac{sensibleheat}{totalheat} = \frac{m_a^{\cdot} C_{p13}(T_1 - T_3)}{m_a^{\cdot}(h_1 - h_3)} = \frac{C_{p13}(T_1 - T_3)}{h_1 - h_3} \quad (4)$$

And cooling coil sensible heat ratio for OHPHX as

$$SHR_{OPHX} = \frac{m_a^{\cdot} C_{p23}(T_2 - T_3)}{m_a^{\cdot}(h_1 - h_3)} = \frac{C_{p23}(T_2 - T_3)}{h_1 - h_3} \quad (5)$$

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where w_1, w_2, and w_3 are the water vapor content in the air at ambient, exit from the evaporator section, and exit from the cooling coil locations respectively. C_p is the specific heat of the dry air component at T_1 and T_3 [kJ/kgK], T is the dry-bulb temperature, W is the humidity ratio in kg_{water}/kg_{air}, and h_g is the specific enthalpy of the water vapor saturated at dry-bulb temperature T [kJ/kg_{water}].

4. Error analyses

The root-sum-square (RSS) method is one of error analysis methods used for many thermal environmental engineering data analysis. The calculations of heat transferred to the evaporator section and extracted from the condenser section of heat pipe heat exchanger are the main source of uncertainty. The propagation of uncertainties related to calculations of heat of evaporator and condenser sections values (S_{Qeva} and S_{Qcon}) reference to [20].

$$\frac{S_{Q_{eva}}}{Q_{eva}} = \sqrt{\left(\frac{S_{(T_1-T_2)}}{T_1-T_2}\right)^2 + \left(\frac{S_{(u)}}{u_{eva}}\right)^2} \quad (6)$$

Where

$$S_{(T_1-T_2)} = \sqrt{S_{T_1}^2 + S_{T_2}^2} \quad (7)$$

$$\frac{S_{Q_{con}}}{Q_{con}} = \sqrt{\left(\frac{S_{(T_4-T_3)}}{T_4-T_3}\right)^2 + \left(\frac{S_{(u)}}{u_{con}}\right)^2} \quad (8)$$

$$S_{(T_4-T_3)} = \sqrt{S_4^2 + S_{T_3}^2} \quad (9)$$

$S_{(T1-T2)}$ and $S_{(T4-T3)}$ are the error associated with (T_1–T_2) and (T_4–T_3) respectively.

The maximum error of heat transfer of evaporator and condenser sections of OHP due to the root-sum-square method error transfer are 7.8% and 8.9% respectively

5. Results and discussions

5.1. Dehumidification enhancement

From the definition of sensible heat ratio, SHR can be used as a judgement on the dehumidification capability enhancement of cooling coil. The experimental results described the sensible heat ratio process for conventional system ($SHR_{conv.}$ (1–3) and sensible heat ratio for HVAC system with OHP heat exchanger (SHR_{OHPHX}) process (2–3) in Fig. 6.

Fig. 7 showed the comparison between the effects of using the different working fluid on the sensible heat ratio by using OHPHX in HVAC system. The experimental data implied that SHR_{OHPHX} can be reduced when the inlet air dry bulb temperature (DBT) increased and reduction ratio reached to 41%, 39%, and 38% for methanol, binary, and water working fluids, respectively at inlet air temperature 50 °C and relative humidity 20%. In other word, the experimental results imply that the increasing of inlet temperature led to increase the moisture removal capability for the HVAC system.

The effects of inlet air dry bulb temperature (DBT) on moisture removal process may be found in Figs. 8–10. It is clear from these figures that the increasing of inlet air temperature to the OHPHX evaporator resulted the reduction of SHR values. The drop in the SHR could be 30% for all working fluid tests at inlet air temperature 50 °C and relative humidity 20%.

The influence of inlet relative humidity on the SHR_{OHPHX} shown in Figs. 11–13 which observed that the SHR_{OHPHX} values were reduced. In the other word, the dehumidification capability of cooling coil will be enhanced well when the relative humidity of inlet hot air to the evaporator section of OHPHX is increased. This reduction in SHR_{OHPHX} values because of the truth for the equal inlet temperature in the evaporator section of OHPHX, the high value of relative humidity implies to the lower value of the enthalpy

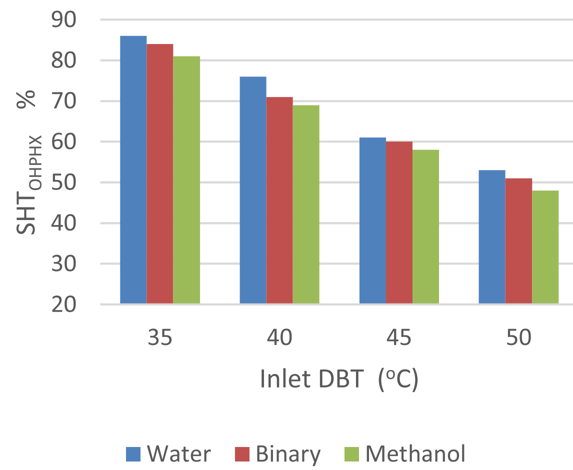

Fig. 7. Compared of using different working fluid in OHPHX on SHR.

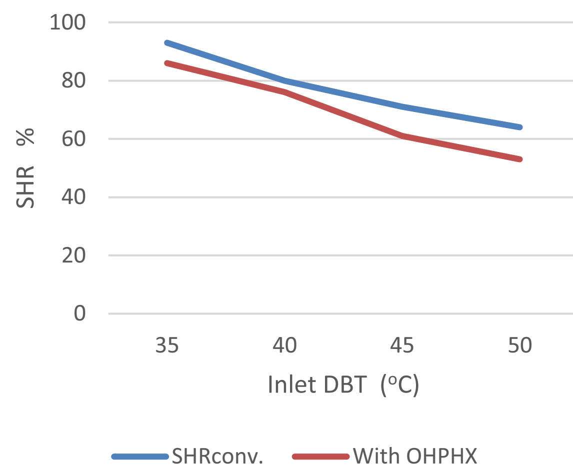

Fig. 8. $SHR_{conv.}$ Vs SHR_{OHPHX} by using Water.

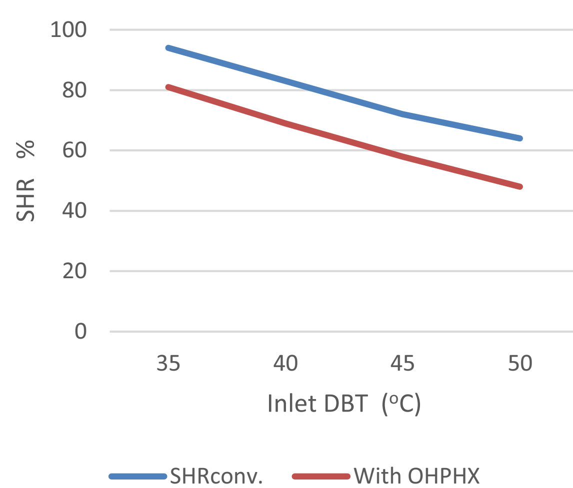

Fig. 9. $SHR_{conv.}$ Vs SHR_{OHPHX} by using Methanol.

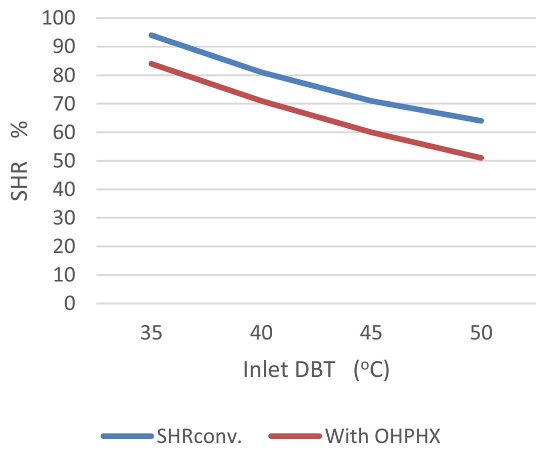

Fig. 10. $SHR_{conv.}$ Vs SHR_{OHPHX} by using Binary fluid.

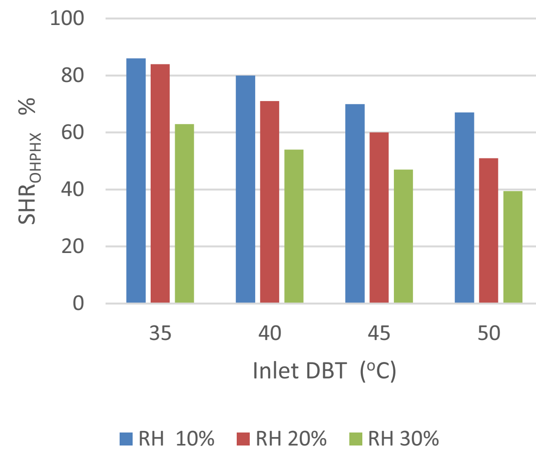

Fig. 13. Effect of inlet air relative humidity on SHR_{OHPHX} by using Binary fluid.

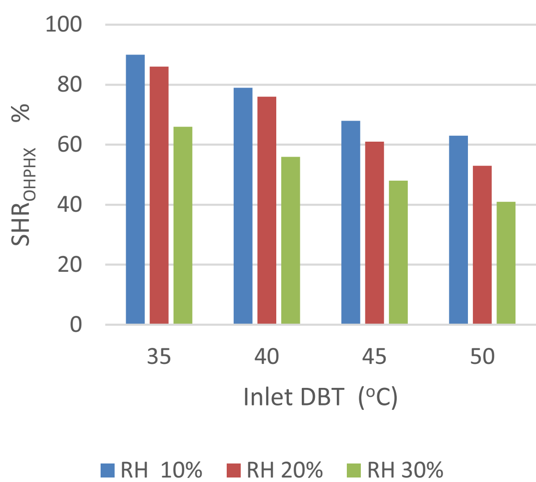

Fig. 11. Effect of inlet air relative humidity on SHR_{OHPHX} by using Water.

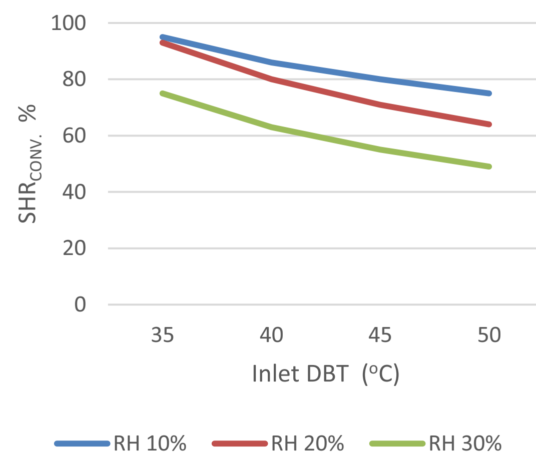

Fig. 14. Effect of inlet air relative humidity on $SHR_{conv.}$ by using Water.

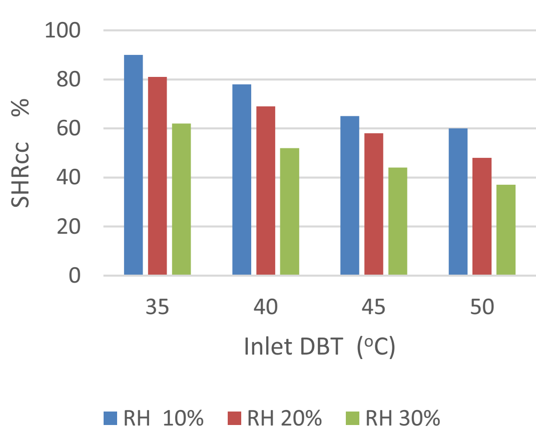

Fig. 12. Effect of inlet air relative humidity on SHR_{OHPHX} by using Methanol.

drop across the evaporator section of OHPHX ($h_1 - h_2$) to achieve an apparatus dew point (ADP) temperature. So the cooling system here used important part of cooling capacity to remove the moisture from the passing air (dehumidification process) instead of the sensible cooling.

Fig. 14 showed that the calculations of SHR for conventional system recorded the maximum values at the lower combination of (35 °C and RH 10%) for all tests at equal air velocity. So there is no significant enhancement of dehumidification capability of cooling coil because when the cooling system operated under this condition, the cooling coil used the most part of its cooling capacity on sensible cooling.

In spite of that, the effect of the inlet relative humidity on SHR is more significant in comparison to the inlet air temperature. The reduction of air humidity can recognized by comparison of SHR curves for both $SHR_{conv.}$ and SHR_{OHPHX} which imply the enhanced of dhimmification process capacity of cooling coil can be reached to 25, 20, 17% by using methanol, binary, and water respectively.

5.2. Energy saving results

The important of using OHPHX as recovery system is its ability to supply free energies in both processes of precooling hot air and reheat over cool air. From the experimental results, the energy saved by a system were by two parts: precooling heat (Q_{ev}) and reheating heat (Q_{con}). So the total energy saved can be represented by summation of this two terms of energy. Figs. 15–17 showed the comparison between total energy saved by using water, binary, and methanol as working fluids in OHPHX at different inlet air dry bulb temperature (DBT) and constant velocity. The increasing of fresh air temperature may led to increase the total energy absorbed by the evaporator section of the OHPHX and rejected by condenser section. The maximum values of total energies saved were 1645 W, 1849 W, and 1932 W for water, binary, and metha-

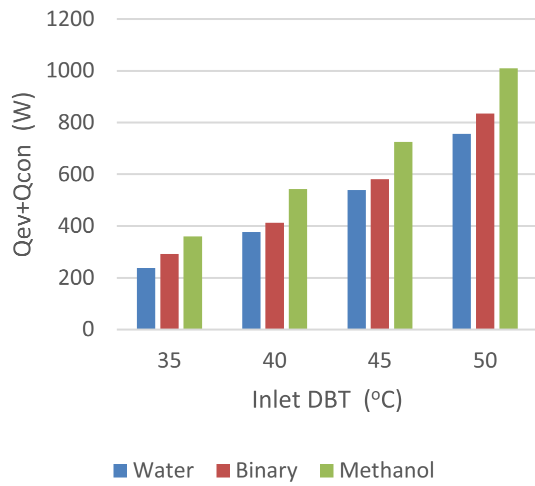

Fig. 15. Effect of using different working fluid on total energy saving at 0.5 m/s air flow.

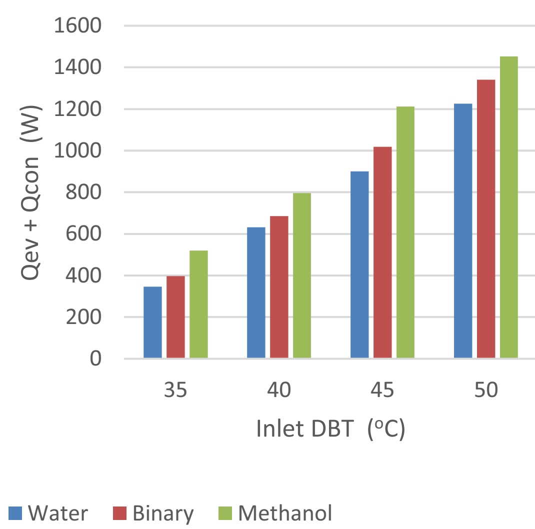

Fig. 16. Effect of using different working fluid on total energy saving at 1 m/s air flow.

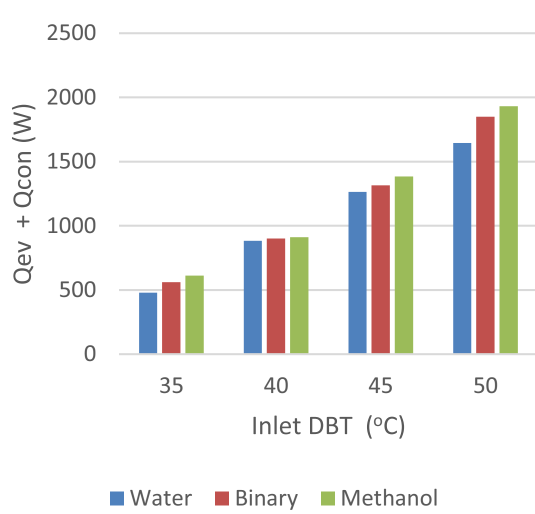

Fig. 17. Effect of using different working fluid on total energy saving at 1.5 m/s air flow.

nol fluids respectively at 50 °C and 1.5 m/s. While the minimum values were 237 W, 292 W, and 359 W for water, binary, and methanol fluids respectively at 35 °C and 0.5 m/s. The results implied that the total energy saving increased with increasing the air velocity because of the increasing of the air velocity will lead to increase the heat transfer and lead to enhance the air side heat transfer coefficient.

Water was recorded lower values of energy saving in comparison to methanol for all cases. This is due to the working fluid properties like the latent heat of vaporization property which had a strong effect on motion of working fluid in OHP and then the heat transfer rate. The Methanol has a lower boiling temperature, lower latent heat of vaporization, and lower surface tension than water. When the surface tension decreases the vapor bubble tends to form a smaller bubble instead of long vapor plug since smaller bubble have lower vapor mass than longer bubble. This causes the buoyancy force to be higher and vapor plug can flow from evaporator to condenser section which locates at the top of OHP with shorter time duration, this would be led to increase the heat transfer rate. These lower values can be enhanced around 14% when methanol was added to water to use as binary fluids.

The effect of changing the inlet fresh air dry bulb temperature (DBT) on the energy saving at the evaporator section of OHPHX of different relative humidity were shown in Figs. 18–20. These fig-

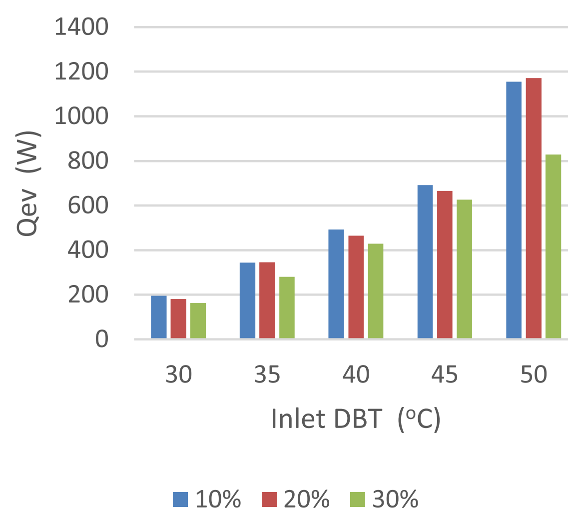

Fig. 18. Effect of inlet air relative humidity on evaporator energy saving by using Water at 2 m/s air flow.

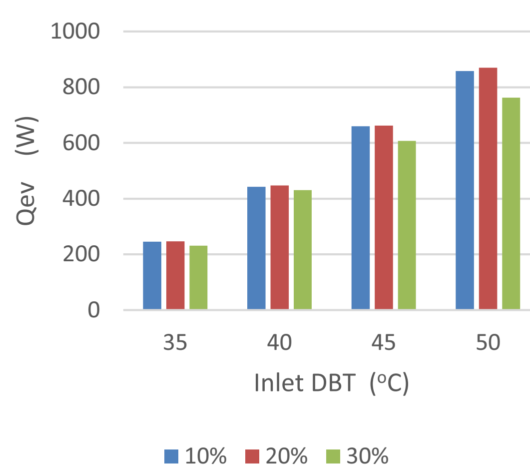

Fig. 19. Effect of inlet air relative humidity on evaporator energy saving by using Methanol at 2 m/s air flow.

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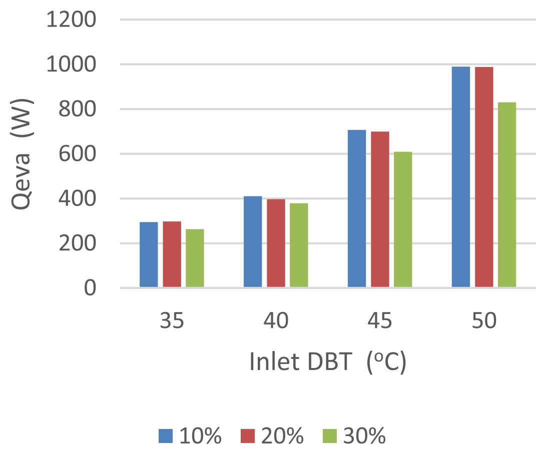

Fig. 20. Effect of inlet air relative humidity on evaporator energy saving by using Binary fluid at 2 m/s air flow.

ures showed for all working fluids, the rate of heat transfer to the evaporator section would increase when the inlet air (DBT) temperature increased. Also the increasing of air temperature at low levels of relative humidity is little better than that for the same temperatures but at higher RH (i.e., tropical climatic conditions).

6. Conclusions

The oscillating heat pipe is high efficient heat transportation device. OHP heat exchanger can used as heat recovery device in HVAC system with the advantages over conventional methods are that high amount of heat can be recovered through a small cross-sectional area over a considerable distance and a highly efficient heat recovery unit which is recommended for hot and humid climates. The experimental results concluded that the dehumidification process capacity of HVAC system can be enhanced by using OHP heat recovery heat exchanger by enhancement ratio 25%, 21%, and 17% for methanol, binary, and water, respectively. The maximum values of total energy saving by using this device were 1645 W, 1849 W, and 1932 W for water, binary, and methanol fluids respectively. The adding Methanol to Water can be enhanced the energy saving around 14%.

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