Experimental Study of Thermal Performance of Heat Pipe Heat Exchanger

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ABSTRACT
Heat pipe heat exchanger (HPHE) considers one of the most useful devices for the recovery of waste heat energy. In this paper, an Experimental study has been carried out on air to – air HPHE constructed of thermosyphon heat pipes with distilled water as the working fluid and a fill ratio of 75% from the evaporator length. Its model was composed of 4 rows, each row contains 12 copper tubes, each tube have ID= 9.5 mm, OD=10mm and length =950 mm and the rows of tubes were arranged in a staggered manner. Aluminum wavy plate fins of 0.1mm thickness were fixed among the tubes to increase the heat transfer area. Tests were conducted at various flow rates (air flow rate through evaporator and condenser sections) ranged between 0.12 and 0.37 kg/s and at different temperatures of air entering evaporator section (90, 100,110)℃. The results show that the effectiveness of HPHE decreases when the ratio of mass flow rate through the evaporator and condenser ($\dot{m}_e/\dot{m}_c$) is approaching one and increases when ($\dot{m}_e/\dot{m}_c$) is greater than one. Minimum value for effectiveness is found when the flow rate ratio between two air streams is equal to one, also, the effectiveness increases with increasing temperature difference ($T_{e,i} - T_{c,i}$) up to about 90 ℃.

General Terms
$\dot{m}_a$: the mass flow rate of air (kg/s) ,V_{av} : the average velocity (m/s), ρ_a : the density of air (kg/m3), A : the cross section area of duct (m2) , C_e : the heat capacity rate for evaporator (w/k), $\dot{m}_e$: the mass flow rate of air in evaporator (kg/s), $C_{P,e}$: the specific heat for evaporator (kJ/kg.K), C_c :the heat capacity rate for condenser (w/k) , $\dot{m}_c$: : the mass flow rate of air in condenser (kg/s) , $C_{P,c}$: the specific heat for condenser (kJ/kg.K), Q_e: the heat transfer rate for evaporator (w), T_{ei} :the inlet temperature of evaporator(K), T_{eo}:the outlet temperature of evaporator Q_c : the heat transfer rate for condenser (w), T_{co} :the outlet temperature of condenser (K), T_{ci} : the inlet temperature of condenser (K), ε : effectiveness, Q : the actual heat transfer rate (w) , $Q_{\max}$: the maximum heat transfer rate (w), $C_{\min}$: the minimum heat transfer rate (w/k), U_t: the total overall heat transfer coefficient of heat exchanger (w/m2.k), A_t: the total heat transfer area of heat exchanger (m2), $LMTD$: the long mean temperature difference (k), NTU : the number of transfer unit.

Keywords
Heat pipe heat exchanger, effectiveness, mass flow rate ratio, condenser, and evaporator

1. INTRODUCTION
Heat pipe is a high performance heat transfer device which is used to transfer a large amount of heat at high rate with small temperature difference. This is achieved by evaporation of working fluid in the evaporator section and condensing in the condenser section and return of the condensate. If the wick is not used in the construction of heat pipe, it is called thermosyphon, in the thermosyphon return the working fluid from the condenser to evaporator is caused by gravity [1] Heat pipe is used in several utilizations like heat exchanger working as recovery system, solar energy communion system, cooling of electronic part, thermal control of space craft, gas turbine rotor blade cooling, etc [2]. The operating Limits of heat pipe include boiling limit, sonic limit, capillary limit, drag and viscous limit [3].

Thermosyphon Heat exchanger (THE) is one of the most productive devices for waste heat recovery. A thermosyphon heat exchanger is composed of a number of pipes arrayed in rows. It's operating with condenser section with low temperature fluid stream and evaporator section with high temperature fluid stream [4].

The advantages of Thermosyphon Heat Exchanger are Capable of operating even when temperature difference between heat source and heat sink is very low, less alimentation problems owing to containing no moving parts, large rate of effectiveness, No need any external power, Less pressure drop for fluid flow, Full disconnection of cold and hot fluids, Comparative economy and Large fidelity[5].

Wadowski et al [6], 1990, investigated the effect of supply and exhaust air stream mass flow rates and temperature difference between two air streams on the thermal performance of thermosyphon heat exchanger. They showed that the effectiveness not be dependent on the temperature difference between two air streams When the input power to evaporator reached maximum.

Noie [7], 2006, studied the influence of temperature and velocity of hot air on the effectiveness of air to air THE with plate fins. He concluded that the effectiveness of THE was over 37% for all operating conditions and he observed the lowest effectiveness of THE occur when (Ce=Cc) so that the equal values of air mass flow rates for condenser and evaporator sections must be prevented.

Zare et al. [8], 2009, studied the heat performance for air to water THE according to (ε − NTU)method. The experimental results showed that the effectiveness and heat transfer rate of THE were affected by heat capacity ratio for high and low temperature fluid streams .When the heat capacity ratio (Ce/Cc) of high and low temperature fluid streams was higher than unity the effectiveness increased due to ability of streams to release and absorb more heat. When the heat capacity ratio was equal to unity the effectiveness was minimum because the releasing and absorption heat was less.

Danielewicz et al [9], 2014, studied the effect of mass flow rate ratio between evaporator and condenser sections on the effectiveness of air to air THE according to ($\varepsilon - \mathrm{NTU}$) method by using methanol as working fluid. They noticed that the effectiveness and heat transfer rate increased when the mass flow rate ratio ($\dot{m}_e/\dot{m}_c$) increased.

Vikramsinh and Mail [10], 2015, studied the thermal performance of THE for a lost air heat recovery system by using nanofluid with variable source temperature. They observed that the thermal performance of THE was enhanced by replacing the conventional fluid in thermosyphon with nanofluid. A model of a multi–thermosyphon heat exchanger predicted the energy savings.

2. THEORTICAL EQUATIONS

The thermal performance of thermosyphon heat exchanger can be calculated as the following:

The air mass flow rate

$$\dot{m_a} = V_{av} \times A \times \rho_a \quad (3.1)$$

The heat capacity rates for evaporator and condenser

$$C_e = \dot{m}_e C_{P,e} \quad (3.2)$$

$$C_c = \dot{m}_c C_{P,c} \quad (3.3)$$

The heat transfer rates for evaporator and condenser

$$Q_e = C_e(T_{ei} - T_{eo}) \quad (3.4)$$

$$Q_c = C_c(T_{co} - T_{ci}) \quad (3.5)$$

The effectiveness of thermosyphon heat exchanger

$$\varepsilon = \frac{Q}{Q_{\max}} \quad (3.6)$$

Where

$$Q = \frac{Q_e + Q_c}{2} \quad (3.7)$$

$$Q_{\max} = C_{\min}\left(T_{e,i} - T_{c,i}\right) \quad (3.8)$$

The overall heat transfer coefficient of the thermosyphon heat exchanger

$$U_t = \frac{Q}{A_t\, LMTD} \quad (3.9)$$

The long-mean temperature difference

$$LMTD = \frac{(T_{ei} - T_{co}) - (T_{eo} - T_{ci})}{\ln\left(\frac{T_{ei} - T_{co}}{T_{eo} - T_{ci}}\right)} \quad (3.10)$$

The number of heat transfer unit

$$\mathrm{NTU} = \frac{U_t A_t}{C_{\min}} \quad (3.11)$$

The minimum heat capacity rate

$$C_{\min} = (\dot{m}c_p)_{\min} \quad (3.12)$$

3. EXPERIMENTAL TEST RIG

The heat pipe heat exchanger using thermosyphon was formed and constructed as shown in figure 1. This module is composed of 4 rows; each row has 12 copper tubes of 10 mm outside diameter. The rows of tubes were staggered and connected by aluminum wavy plate fins. The fin density was 470 fins per meter. A copper tube header of 22 mm nominal diameter was connected to the ends of each row of tubes. Distilled water is utilized as working fluid in thermosyphon heat exchanger. The fill ratio is chosen to be 75% from the volume of evaporator section. A duct and fan system used for testing the performance of thermosyphon heat exchanger, Table (1.1) indicate the specifications of this system Four air heaters of 3.5 Kw each are established inside the inlet duct of evaporator section at different temperatures. All heaters are connected directly to power supply except one is connected to variac (voltage transformer), in order to control the air stream temperature.

Table 1 The specifications of duct and fan system:

Name of section		**Length (m)**	**Area (m^2)**	**Type of fan**	**Air flow rate control type**
Cond. section	**Inlet duct**	1.25	0.4 ×0.4	Centrifugal fan (CFM)	without
	Outlet duct	1	0.4 ×0.4	Without	Grill
Evap. section	**Inlet duct**	1.25	0.4 ×0.4	Centrifugal fan (CFM)	without
	Outlet duct	1	0.4 ×0.4	Without	Grill

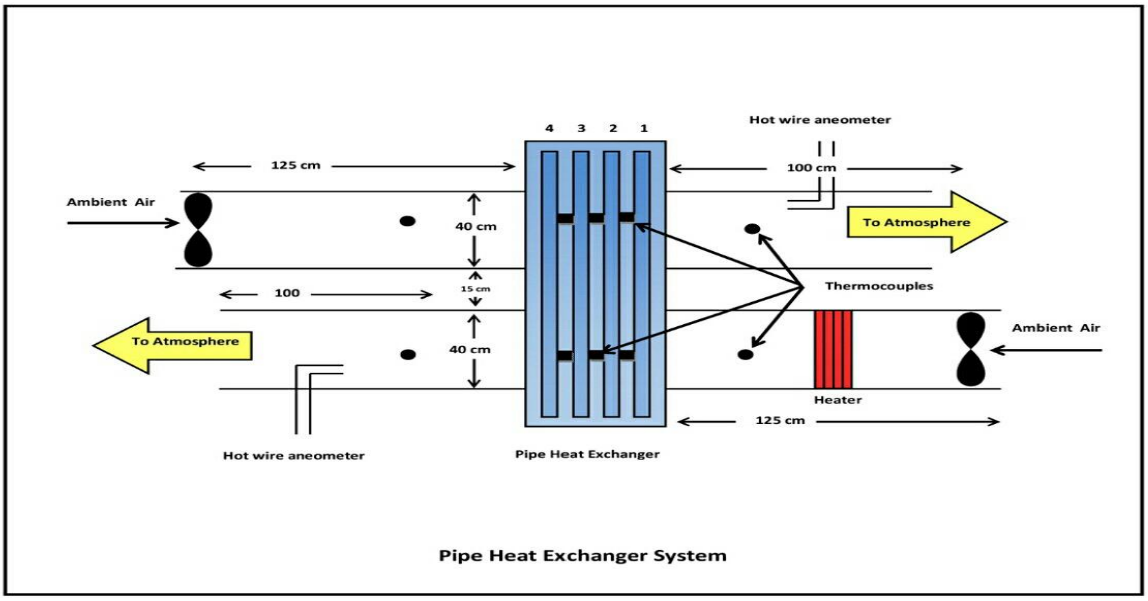

Fig1: Schematic of heat pipe heat exchanger

4. EXPERIMENTAL RESULTS AND DISSUCSSION

Fig 2: illustrates that, effectiveness decreases with increase of flow rate at different inlet temperature of air to evaporator and that can be indicated from the effectiveness correlation as below:

$$\varepsilon = \frac{Q_e or Q_c}{(\dot{m}\, C_p)_{min}\ ((T_{e,i} - T_{c,i})} \qquad (5.1)$$

It is observed from the above correlation that there is inverse relationship between effectiveness and flow rate. Although, increasing of flow rate also causes increase values of (Q_e and Q_c), the amount of the increasing occur in (Q_{max}) more than that occur in the actual heat transfer, therefore, the effectiveness decreases.

Fig 3: illustrates that, overall heat transfer coefficient increases with the increasing of flow rate, because the increasing of flow rate leads to increase velocity of air passing on pipes and fins for thermosyphon heat exchanger. This causes decrease the external resistance, therefore, overall heat transfer coefficient increases

Fig 4: illustrates that, increasing of flow rate causes decrease number of transfer unit, The increasing of mass flow rate causes increase the value of C_{min} and at the same time leads to increase the value of U. the experimental results showed that the amount of increasing occur in C_{min} is more than that occur in U, so that with increasing mass flow rate the number of transfer unit decreases

Fig 2, 3and 4: illustrate that, generally the increasing of evaporator inlet air temperature ($T_{e,i}$) leads to increase the values of (ε, U, and NTU)

Fig 5: illustrates that, the influence of flow rate ratio on performance of thermosyphon heat exchanger, when the flow rate in condenser is constant at value 0.228 kg/s and flow rate in evaporator is changing between (0.119 - 0.320) kg/s. at $(\dot{m}_e/\dot{m}_c) > 1$, we observed that the effectiveness increases with increasing this ratio and this can be indicated from the relation of effectiveness as follows:

$$\varepsilon = \frac{(T_{c,o} - T_{c,i})}{\frac{(\dot{m}\, C_p)_{min}\ (T_{e,i} - T_{c,i})}{\dot{m}_c C_{p,e}}} \qquad (5.2)$$

The amount $((\dot{m}C_p)_{min} / \dot{m}_c C_{p,c})$ is equal to 1, so that increasing of flow rate in evaporator causes increase ($T_{c,o}$), therefore, the effectiveness increases. at $((\dot{m}_e/\dot{m}_c) < 1$) we observed that, effectiveness increases with decreasing the flow rate ratio. Decreasing of flow rate in evaporator causes decrease of the values of Q_{max} and Q_e . The rate of decreasing in Q_{max} is more than that of Q_e therefore the effectiveness increases.

Fig also shown that, the gradient of the curve when $(\dot{m}_e/\dot{m}_c)$ >1 is more than that when $(\dot{m}_e/\dot{m}_c)$ <1, and the lowest value of effectiveness occurs at $(\dot{m}_e/\dot{m}_c)$ equal to one.

Fig 6: illustrates that, the effect of the flow rate ratio on performance of thermosyphon heat exchanger in case of the flow rate in evaporator was kept constant at value (0.2 kg/s) and the mass flow rate in condenser was changed between (0.1344 and 0.374) kg/s. at $(\dot{m}_e/\dot{m}_c)$ >1, we observed that the effectiveness increases with decreasing of mass flow rate the condenser section. Decreasing the flow rate in the condenser ($\dot{m}_c$) leads to decrease of the value of C_{min} and then decreasing the value of Q_{max} .Although, the value of (Q_c) decreases, the effectiveness increases because of the amount of the decreasing of Q_{max} is more than that of Q_c. at $(\dot{m}_e/\dot{m}_c)$ <1, we observed that, effectiveness increases with increasing the flow rate in evaporator, and this can be indicated from the concept of effectiveness as follows

$$\varepsilon = \frac{(T_{e,i} - T_{e,o})}{\frac{(\dot{m}C_p)_{min}\ (T_{e,i} - T_{c,i})}{\dot{m}_e C_{p,e}}} \qquad (5.3)$$

The amount $((\dot{m}C_p)_{min} / \dot{m}_e C_{p,e})$ is equal to one, so that any increasing in the mass flow rate of condenser section leads to decrease ($T_{e,o}$), therefore, the effectiveness increases. Fig 6 illustrates also the curve gradient when $(\dot{m}_e/\dot{m}_c)$ >1 is more than that when $(\dot{m}_e/\dot{m}_c)$ <1, and the effectiveness has the minimum value when $(\dot{m}_e/\dot{m}_c)$ =1

Fig 7: illustrates the effectiveness as function of temperature difference $(T_{e.i} - T_{c.i})$ at the three different flow rate ratio. Effectiveness increases with increasing temperature difference by reaching the limiting value when the temperature difference increases above (90℃). The Fig shows also the effectiveness at flow rate ratio equal to (1.385) is higher than that when flow rate ratio is equal to one and 0.535.

5. CONCLUSION

- Increasing the equal flow rates for both condenser and evaporator sections leads to decrease effectiveness and the number of transfer unit of THE.
- Increasing the equal flow rates for both condenser and evaporator sections leads to increase overall heat transfer coefficient of THE.
- Effectiveness is minimum when $(\dot{m}_e/\dot{m}_c)$ is equal to one, so that this ratio must be avoided.
- The effectiveness increases when the mass flow rate $(\dot{m}_e/\dot{m}_c) > or < 1$.the effectiveness when $(\dot{m}_e/\dot{m}_c)$ >1 is greater than when $(\dot{m}_e/\dot{m}_c)$ <1.
- The effectiveness increases with increasing the inlet temperature to evaporator $(T_{e,i})$.
- When the value of the temperature difference$(T_{e,i} - T_{c,i})$ reaches above 90℃, then the effectiveness is nearly kept constant.

6. RECOMMENDATIONS

- The work can be developed by charging the pipes with a different percentage fill ratios for working fluid.
- In this work, the working fluid may be replaced (distilled water) may be replaced by another one such as methanol and study its influence on the performance of heat exchanger.
- Study the influence of inclination of thermosyphon on the performance of THE

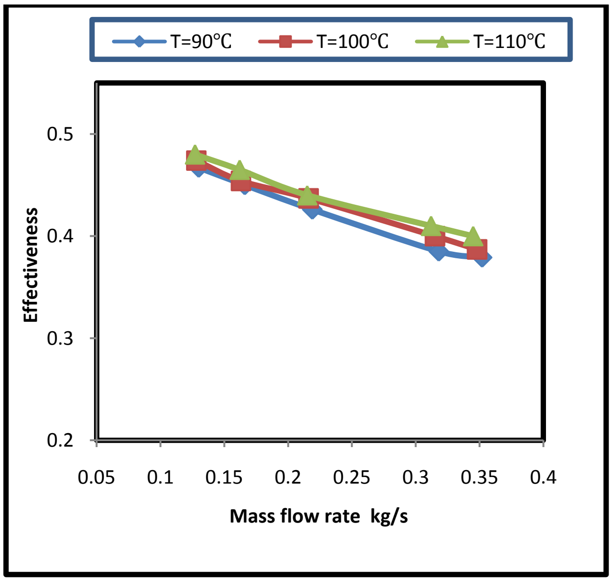

Fig 2: The effect of mass low rate on the effectiveness for a four row heat pipe heat exchanger subjected to equal flow rates in both air streams at different inlet temperature.

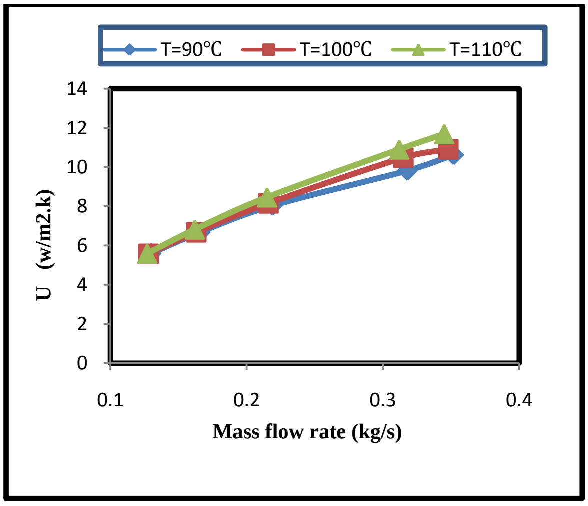

Fig 3: The effect of mass flow rate on U for a four row heat pipe heat exchanger subjected to equal flow rates in both air streams at different inlet temperature

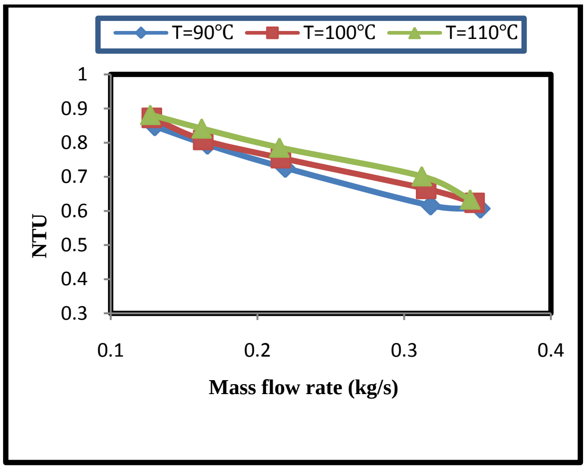

Fig 4.The effect of mass flow rate on NTU for a four row heat pipe heat exchanger subjected to equal flow rates in both air streams at different inlet temperature.

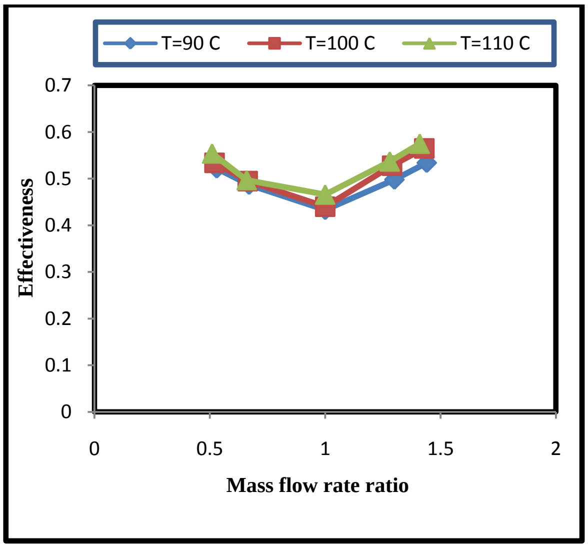

Fig 5: The effect of mass flow rate ratio on (ε) for a four – row heat pipe heat exchanger subjected to constant flow rate in the condenser section at0.228 kg/s and varying evaporator flow rate.

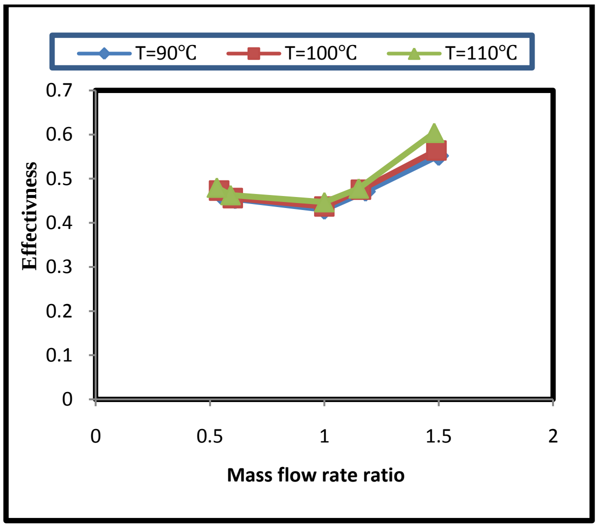

Fig 6: The effect of mass flow rate ratio on (ε) for a four – row heat pipe heat exchanger subjected to constant flow rate in the evaporator section at 0.2 kg/s and varying condenser flow rate.

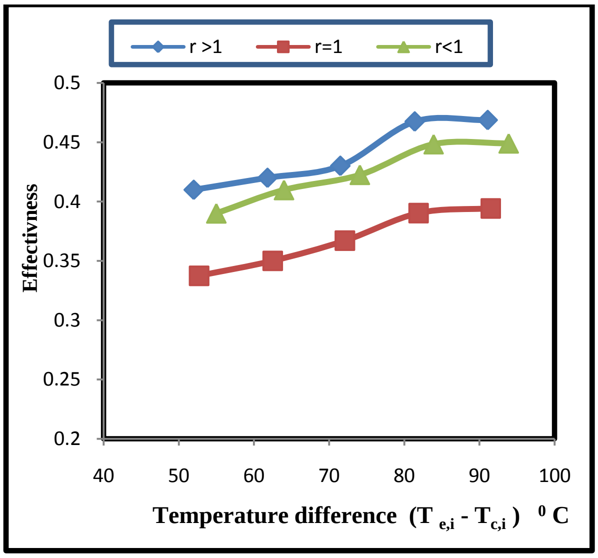

Fig 7: Effectiveness as function of temperature difference for four row heat pipe heat exchanger at flow rate ratio (0.535, 1, 1.385)

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