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An Experimental Study of the Performance of Heat Pipe Heat Exchanger for Heat Recovery in Air Conditioning Systems

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ABSTRACT

In this work, an experimental study is conducted on the performance of heat pipes heat exchanger for the application of heat recovery in air conditioning. To carry out this work, a heat pipe heat exchanger is installed between fresh air and return air to cool the fresh air. Three test sections were used with different inner pipe diameters of 7.9, 10.2 and 16.56 mm. The fresh air inlet temperature was changed to be 30 ºC, 35 ºC, 40 ºC, 45 ºC and 50 ºC in order to simulate the change of ambient temperature. The ratio between cooled and fresh air was chosen to be 1, 1.5, 2 and 3. The results obtained indicated that the effectiveness of the heat pipe heat exchangers increases with both of the increase of fresh air inlet temperature and the ratio between cooled and fresh air.

دراسة تجريبية لأداء مبادل حراري ذو الأنابيب الحرارية لاسترجاع الحرارة في تكييف الهواء

ملخص البحث: في هذا البحث، تم إجراء دراسة تجريبية علي أداء الأنبوب الحراري ذو الأنابيب الحرارية وذلك لاسترجاع الحرارة في تكييف الهواء. لإجراء هذا العمل تم تركيب مبادل حراري ذو الأنابيب الحرارية بين هواء نقي وهواء راجع وذلك لتبريد الهواء النقي. تم استخدام ثلاثة نماذج من المبادل الحراري باقطار 7.9، ١٠.٢ ، ١٦.٥٦ مم. وقد تم أيضاً تغيير درجة حرارة الهواء النقي الداخل علي المبادل ليكون ٣٠، ٣٥، ٤٠، ٤٥، ٥٠ درجة مئوية ليحاكي تغير حالة الهواء الجوي. كما أخذت النسبة بين الهواء الراجع والهواء النقي لتكون ١، ١.٥، ٢، ٣ . وقد بينت النتائج التي تم الحصول عليها زيادة فاعلية المبادل الحراري في حالة ارتفاع درجة حرارة الهواء النقي وكذلك في حالة زيادة نسبة الهواء العادم إلي الهواء الراجع.

Keywords: Heat pipes heat exchanger, Heat recovery, Air conditioning.

1- INTRODUCTION

In recent years, air conditioning has become very important in our lives. This is because of the unsuitable weather during most time of the year. In several applications such as hospitals, it is important to maintain suitable conditions in many places. Besides, totally fresh air is needed in many other places of the hospitals. Accordingly, the required cooling coil capacity, in case of 100% fresh air, becomes higher than that needed in case of mixing fresh air with return air. To overcome this problem, the use of heat exchanger between the fresh air and return air could decrease the fresh air temperature before entering to the cooling coil. The surface area of the heat exchanger depends upon the amount of heat transfer between the two air streams. Therefore, the use of Heat Pipes Heat Exchanger [HPHE] may decrease the surface area since the heat is transferred by latent heat. Heat pipe is a device working on phase change of a working fluid inside it. This phase change of working fluid leads to increasing heat transport efficiency of heat pipe.

Heat pipe technology has found increasing applications in enhancing the thermal performance of heat exchangers in micro-electronics, energy saving in HVAC systems for operating rooms, surgery centers, hotels, clean rooms, temperature regulation systems for the human body and other industrial sectors [1]. Many efforts have been made to study HPHE in many applications. The applications of wickless heat pipes heat exchangers in HVAC systems were investigated by Firouzfar, et al. [2]. Wickless heat pipe (Thermosyphon) heat exchangers are still a new application in an air conditioning (HVAC) system. The purpose of adding a thermosyphon heat exchanger in a HVAC system is to provide control over the relative humidity (RH) and energy saving. The ε-NTU (effectiveness-Number of Transfer Units) method was applied, by YU tao et al. [3], for optimizing analysis of single-level or multi-level separate type heat pipe heat exchangers.

Faghri [4] presented numerical analysis of overall performance of heat pipes with single or multiple heat sources by. The analysis included the heat conduction in the wall and liquid-wick regions as well as the compressibility effect of the vapor flow inside the heat pipe. The two-dimensional elliptic governing equations in conjunction with the thermodynamic equilibrium relation and appropriate boundary conditions were solved numerically for the whole domain. The results showed that, the axial wall conduction tends to distribute the temperature more uniformly for the heat pipe with large solid wall and effective liquid thermal conductivity ratios.

A HPHE has been designed and constructed, by Baghban and Majideian [5] for heat recovery in hospital and laboratories, where the air must be changed up to 40 times per hour. The characteristic design and heat transfer limitations of single heat pipes for three types of wick and three working fluids have been numerically investigated experimentally. Vasiliev [6] studied the effect of heat transfer rate on the heat transfer coefficient for the heat pipes heat exchangers. The results indicated that, the heat transfer coefficient for evaporator and condenser sections was between 10^3-10^5 $W/m^2.K$ and the thermal resistance was about 0.01–0.03 K/W.

Sarraf [7] studied a heat pipe heat exchanger with two levels of isolation for environmental control of manned space craft crew compartment. It has been reported that the, HPHE improved the existing system by providing two levels of isolation between the fluid streams. The heat exchanger was fault-tolerant and could provide advance warning of a leak. Meyer and Dobson [8] considered the thermal design and the experimental testing of a heat pipe (thermosyphon) heat exchanger for a relatively small commercially available mini-drier. The purpose of the heat exchanger was to recover heat from the waste moist air stream to preheat the incoming fresh air. The used working fluid was R134a and correlations were given for the heat transfer coefficients inside evaporator and condenser as well as for the maximum heat transfer rate. The theoretical model used for the thermal design calculations were described.

Heat pipe solar collector was designed and constructed at IROST and its performance was measured on an outdoor test facility by Azad [9]. The thermal behavior of a gravity assisted heat pipe solar collector was investigated theoretically and experimentally. A theoretical model based on effectiveness-NTU method was developed for evaluating the thermal efficiency of the collector, the inlet, outlet water temperatures and heat pipe temperature. An optimum value of evaporator length to condenser length ratio was also determined. Heat pipe heat exchanger for heat recovery in air conditioning was investigated by Abdel-Baky and Mousa [10]. Two streams of fresh and return air were connected with a HPHE to investigate the thermal performance and effectiveness of heat recovery system. Various ratios of mass flow rate between return and fresh air have been adapted to validate the heat transfer and the temperature change of fresh air. The results showed that the performance of HPHE was influenced by fresh air inlet temperature and return to fresh air flow rate ratio.

A theoretical model of fluid flow and heat transfer in a heat pipe with axial ‘‘Ω”-shaped grooves has been conducted by Chen, et al [11] to study the maximum heat transport capability of these types of heat pipes. The influence of variations in the capillary radius, liquid–vapor interfacial shear stress and the contact angle were considered and analyzed. The effect of vapor core and wick structure on the fluid flow characteristics and the effect of the heat load on the capillary radius at the evaporator end cap, as well as the effect of the wick structure on the heat transfer performance were numerically analyzed and discussed. The axial distribution of the capillary radius, fluid pressure and mean velocity were obtained. Fang et al. [12] performed an experimental study on operation performance of ice storage air-conditioning system with separate helical heat pipe. The experimental results showed that the ice storage air-conditioning system with separate helical heat pipe can stably work during charging and discharging period. The ice storage air-conditioning system with separate helical heat pipe can be well adapted to cool storage air-conditioning systems in building.

From the previous discussions, it is seen that the use of heat pipe for heat recovery has little attention. Therefore, the object of the present study is to study the parameters affect the performance of heat pipe heat exchanger. The effect of fresh inlet temperature and the mass flow rate ratio as well as the pipes diameter have been studied.

2- **Experimental Study:**

The experimental apparatus was designed and constructed as shown in Fig. (1). It is consists of an air handling unit, test section and test instruments. The air handling unit is direct expansion system and it is equipped with a variable speed centrifugal fan. Cooled air and exits from the apparatus at 25.6 ºC. The refrigeration system is charged with R-134a.

The test section consists, as shown in Fig. (2), of two air ducts. Each of them is 22cm×30cm cross sectional area. The two ducts are connected together by finned tubes heat pipes heat exchanger. A square slot of 0.3×0.3 m^2 was made at the contact sides of the two ducts for heat pipe heat exchanger installation

Three models of heat pipes heat exchanger were chosen for the experimental studies. Each of them is made of 32 copper tubes of 0.5 m length. The outer diameters of the tubes are 9.5, 12.7 and 19.05 mm. The corresponding inner diameters are respectively: 7.9, 10.2 and 16.56 mm. The pipes were cleaned, evacuated and charged with refrigerant 123 ($C_2HCl_2F_3$). The boiling temperature of R-123 at 1 bar is 27.4 ºC. This makes this refrigerant is suitable for chosen as a working medium for this application. The working medium temperature is chosen to be 30 ºC as an intermediate value between the fresh air and return air in the application of air conditioning. The pipes were charged to a pressure of 1.1 bar which corresponding to this saturation temperature (30 ºC).

Fig. (1) Experimental apparatus

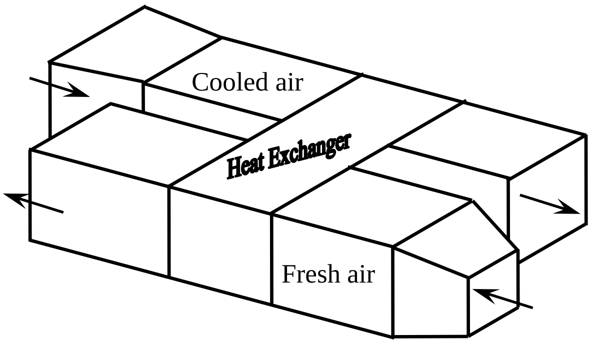


Fig. (2) Test section

The pipes were arranged in staggered manner as shown in Fig. (3). The heat exchanger was supplied with 25 fins at each of the evaporator and the condenser sections for increasing the heat transfer area. The fins were made of 0.5 mm thickness aluminum plates of 30 cm×30 cm cross section.

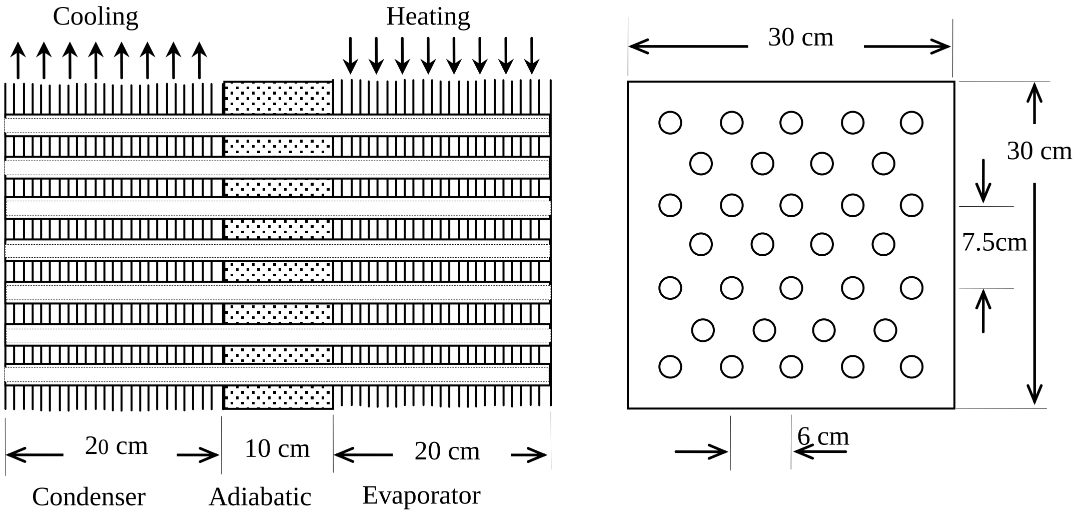


Fig. (3) Arrangement of heat pipe heat exchanger

Three electric heating coils were mounted at the inlet of the fresh air duct for heating the fresh air to different values in order to simulate it with the change of ambient air conditions. The power of each heater was 400 W. The heaters were connected together in parallel. A variac was connected in series with the heaters in order to change electric current that supplied to the heater to obtain the power required achieve the suitable test temperature. A centrifugal fan was installed at the inlet of fresh air duct in order to supply air to the evaporator section of the HPHE.

During the course of the experimental investigation, several parameters have been measured. The dry bulb temperature and relative humidity of air were measured at inlet and outlet of either of fresh and cooled air at each experiment with a calibrated temperature-humidity meter. The velocity was measured with a portable hot wire anemometer at different points along the exit section of each of fresh air duct and cooled air duct. The mean velocity and consequently air flow rate were calculated. All measurements were recorded at steady state operation. The measured temperature and relative humidity for the inlet and outlet of either fresh and cooled air were plotted on the psychrometric chart at various parameters and there values were recorded.

The condition of fresh air at exit of heat exchanger was compared with the condition of mixing, (if mixing is done with the same ratio of fresh to cooled air by weight bases), to indicate the effect of using heat exchanger. The temperature of fresh air was kept constant at five values during the measurements. The fresh air flow rate was also kept constant at each measuring temperature. The values of the temperature and the corresponding air flow rate values were recorded in table (1).

Table (1): Temperature and flow rates of fresh air used in the study.

Temperature [ºC]	30	35	40	45	50
Air flow rate [kg/s]	0.0136	0.0134	0.0130	0.0129	0.0126

The return air flow rate was changed during each case of fresh air. The ratios between return air and fresh air were 1, 1.5, 2 and 3.

3- Results and Discussions

To examine the level to which fresh air temperature is decreased, the parameters affecting the temperature difference between its inlet and outlet to the HPHE had to be studied. Those parameters are inlet fresh air temperature, inlet return or cooled air temperature, mass flow rate of both fresh and cooled air and diameter of the heat pipes. The fresh air temperature changes according to the weather condition. The temperature of cooled air was kept constant at a practical value of 25.8 ºC.

3. 1 Effect of Fresh Air Inlet Temperature

The temperature difference between inlet and outlet of fresh air through the heat exchanger has been recorded for test sections at different ratios between cooled air and fresh air. The test sections differs of each other according to pipes diameters'. Three chosen pipes of inner diameters 7.9, 10.2 and 16.56 mm. The ratios of mass flow rate between cooled and fresh air was adjusted to be 1.0, 1.5, 2, 3.

Figure (4) shows the change in fresh air inlet temperature through the heat pipes heat exchanger at different ratios of mass flow rates for 10.2 mm inner pipe diameter. It is shown that, the temperature difference of fresh air increases with the increase of its inlet temperature for each case of mass flow rate ratios. This is because, for constant cooled air temperature, the temperature difference between the fresh air and cooled air increases as the temperature of fresh air is increased. This means that, the available heat increases when the temperature of fresh air is increased. So, more heat is transferred from the fresh air and hence its temperature difference increases.

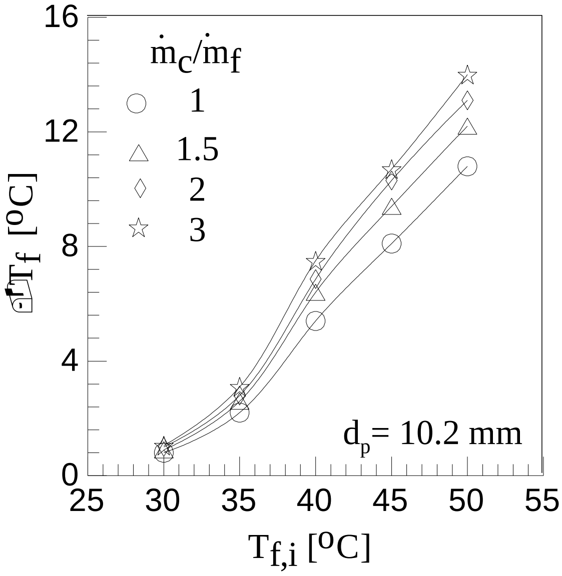


Fig. (4) Temperature difference of fresh air at different mass flow rate ratio

For different mass flow rate ratios, the temperature change of fresh air is increased when the ratio increase. This can be explained as, the higher values of the mass flow rate ratio means higher value of cooled air flow rate. This in turn tends to absorb more heat by the cooled air from the fresh air. Consequently, more reduction of fresh air temperature and hence the fresh air temperature difference increases.

3. 2 Effect of Pipes Diameters on Temperature Difference of Fresh Air

The temperature difference of fresh air through the heat exchanger is obtained at different diameters of heat pipes for cooled to fresh air mass flow rate ratio of 2 and is illustrated in Fig. (5). For the same inlet temperature, it can be seen that, the temperature change of fresh air increases when the heat pipes diameter is increased. This is because the surface area of heat transfer increases with the increase of the diameter of the heat pipe, consequently, the rate of heat transfer by convection on the surface of the pipe increases leading to an increase of the temperature difference.

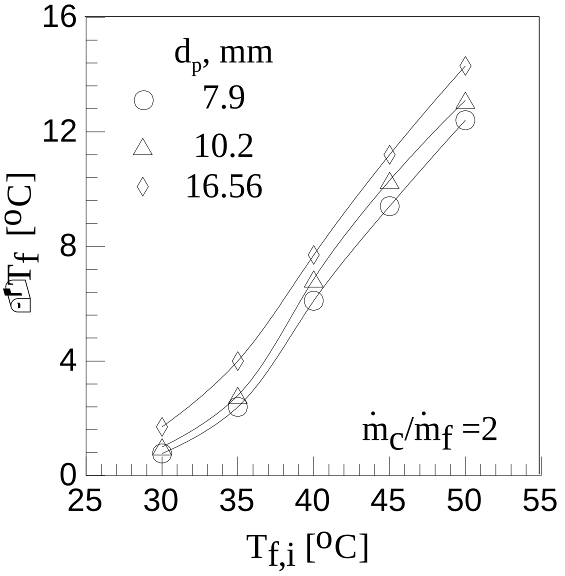


Fig. (5) Temperature difference of fresh air at different heat pipe diameters

3. 3 Effect of Mass Flow Rate Ratio on Temperature Difference of Fresh and Cooled Air

The temperature change of fresh and cooled air at various mass flow rate ratios are illustrated in Fig. (6) for constant cooled air temperature at 25.8 ºC and different values of fresh air temperature. It is observed that for each value of mass flow rate ratio, the temperature change for fresh and cooled air increases when the fresh air inlet temperature is increased. This is because the increase of fresh air temperature leads to an increase in the temperature difference between it and the working medium temperature. Accordingly, the heat transfer rate between the fresh air and heat pipes increases leading to an increase of fresh air temperature difference. On the other hand, the increase of heat transfer rate in fresh air side is transferred to the cooled side resulting in an increase of cooled air temperature difference.

For each case of fresh air temperature, a gradual increase of the temperature difference is noticed with the increase of mass flow rate ratio. However, the rate of increasing of temperature difference decreases at the higher values of the mass flow rate ratio between cooled air and fresh air. This can be explained as when the cooled air flow rate increases the heat transfer between the cooled air and heat pipes surface increases resulting in an increase of condensation rate of working medium and consequently the rate of evaporation in the evaporator zone. This leads to an increase in both fresh and cooled air temperature differences. At higher values of mass flow rate ratio, the rate of increase of temperature difference is decreased and tend to be constant. This is because the charged mass of refrigerant is limited and the condensation and evaporation process reach a constant rates.

The increase in temperature change for fresh air with increasing mass flow rate ratio between return and fresh air is slightly positive. But, the temperature change of return cold air is going down with increasing mass flow rate ratio.

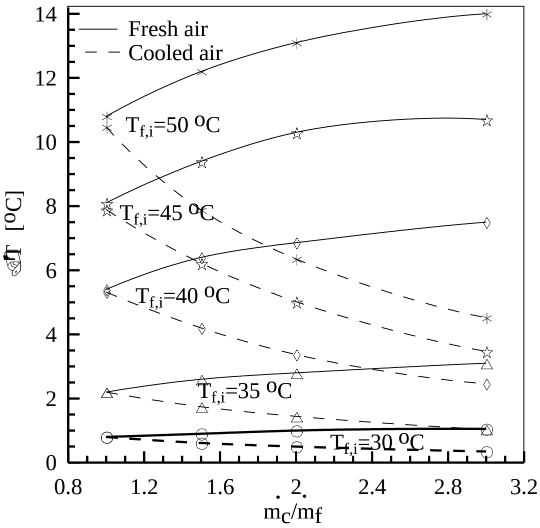


Fig. (6) Temperature difference of fresh and cooled air for d_p = 10.2 mm

In the same manner, the distribution of temperature difference of both fresh and return air is illustrated at the three diameters of heat pipes; 7.9, 10.2 and 16.56 mm. Figure (7) represents the temperature difference of both fresh and cooled air versus mass flow rate ratios for the three pipes diameters and at various fresh air temperatures. It can be seen from this figure that, the temperature difference of both fresh and cooled air increases when the pipes diameters were increased. The increase of pipes diameter means increase of surface area and consequently an increase of the convection heat transfer takes place. Accordingly, the temperature difference of air increases.

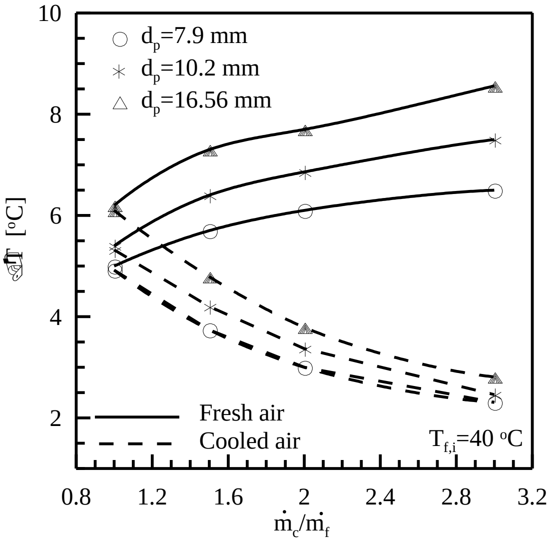


Fig. (7) Temperature difference of fresh and cooled air

Figures (8) and (9) illustrate the temperature difference of fresh air versus the pipes diameters. In Fig. (8), the inlet fresh air temperature is maintained at 40 ºC for different values of mass flow rate ratios. In Fig. (9), the inlet mass flow rate ratio was maintained at 2 while the fresh air inlet temperature was changed. Aslight increase in the temperature difference is seen when the pipes diameters were increased.

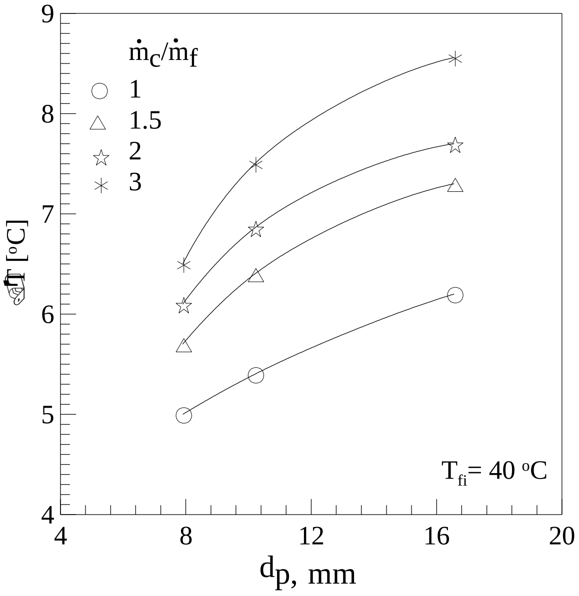


Fig. (8) Temperature difference of fresh and cooled air versus pipes diameter

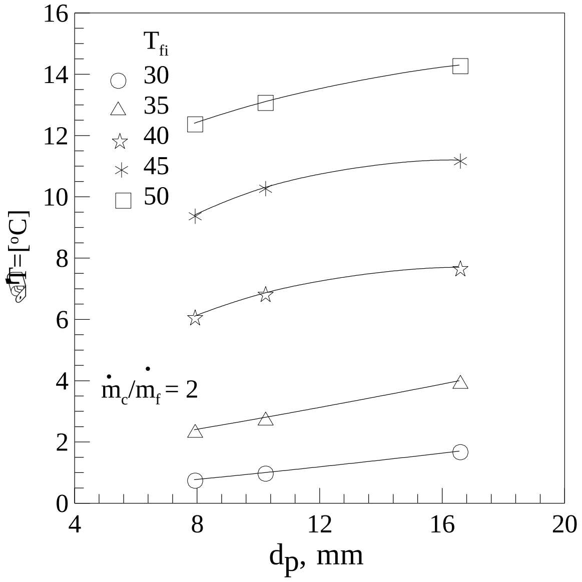


Fig. (9) Temperature difference of fresh and cooled air versus pipes diameter

3. 4 Effectiveness of Heat Exchanger:

To predict how much the heat exchanger reduces the temperature of fresh air, the temperature of both fresh and cooled air was measured before and after the heat exchanger. Both of the cooling of fresh air and the heating of cooled air processes are represented on psychrometric chart for each case, as shown in Fig. (10).

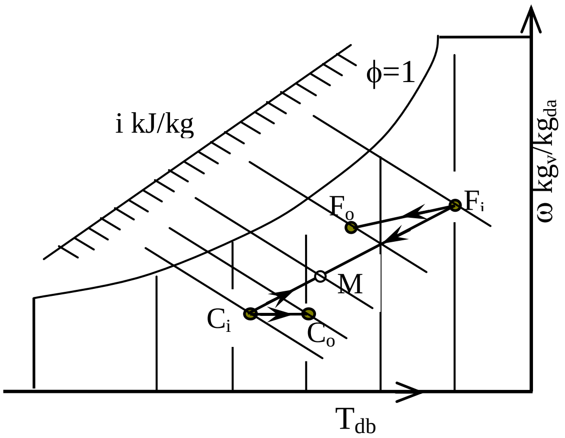


Fig. (10) Representation of the processes on the Psychrometric chart

The cooling of fresh air is indicated by the process $F_i \rightarrow F_o$ while the heating processes of cooled air is sensible and represented by the line $C_i \rightarrow C_o$. Considering that mixing takes place between fresh and cooled air. Point M represents the mixing point. Now, the fresh air outlet temperature ($T_{f,o}$) is compared with the temperature of mixing point (T_M) to indicate the effectiveness of the heat exchanger.

The heat losses from the fresh air can be calculated as:

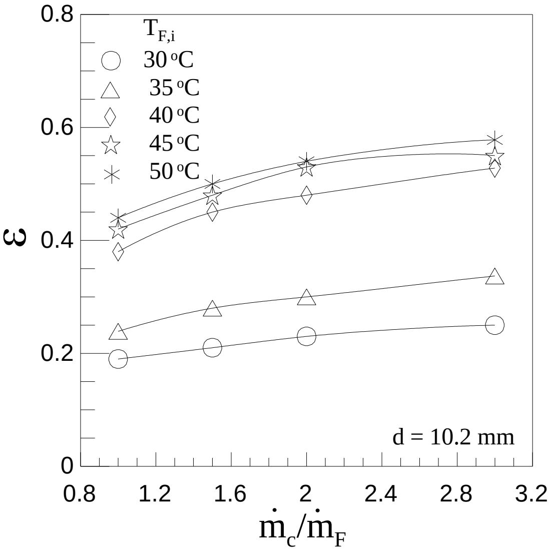
$$\dot{Q}_f = \dot{m}_f (i_{f,i} - i_{f,o}) \qquad (1)$$

The effectiveness of the heat exchanger is defined as the ratio of actual rate of heat transfer by the heat exchanger to the maximum possible heat transfer rate between the two air streams [5, 14]. Neglecting the heat loss to the surrounding, the heat loss from fresh air equals to the heat gained by the cooled air. Thus the effectiveness of the heat exchanger becomes:

$$\varepsilon = \frac{\dot{m}_f (i_{f,i} - i_{f,o})}{\dot{m}_f (i_{f,i} - i_{c,i})} \qquad (2)$$

In the case of operation without heat exchanger is used, the fresh air would be cooled by the Air handling unit cooling coil from condition (f,i) to condition (c,i). Now, after using the heat pipes heat exchanger, the fresh air will be cooled by the air handling unit from condition (f,o) to condition (c,i). Accordingly, the effectiveness of the heat exchanger represents the percentage decrease of the energy and consequently percentage decrease of power consumption by the unit which is followed by percentage decrease of running cost of the air conditioning system.

The effect of cooled air to fresh air mass flow ratio on the heat pipe heat exchanger effectiveness at different fresh air inlet temperature is indicated through Fig. (11) for the three heat pipe heat exchanger test sections. From this figure, it can be seen that, the heat exchanger effectiveness increases slightly with the increase of mass flow rate ratio of the air streams. This is because when the mass flow rate ratio increases, the mass flow rate of the cooled air increases which in turn leads to absorb more values of heat from the fresh air. This tends to increase the heat exchanger effectiveness.



Fig, (11) Effect of mass flow rate ratio on the HPHE effectiveness at d_p = 10.2 mm

Figure (12) represents heat pipe heat exchanger effectiveness versus the fresh air inlet temperature. It is seen that, the effectiveness of the heat exchanger increases gradually at the lower values of the fresh air temperature. At the higher values of measured inlet air temperature, slight increase of the effectiveness is observed. This may be explained as, the temperature difference between inlet and outlet of fresh air may be small at higher values of fresh air inlet temperature and consequently the heat pipe heat exchanger effectiveness is slightly affected.

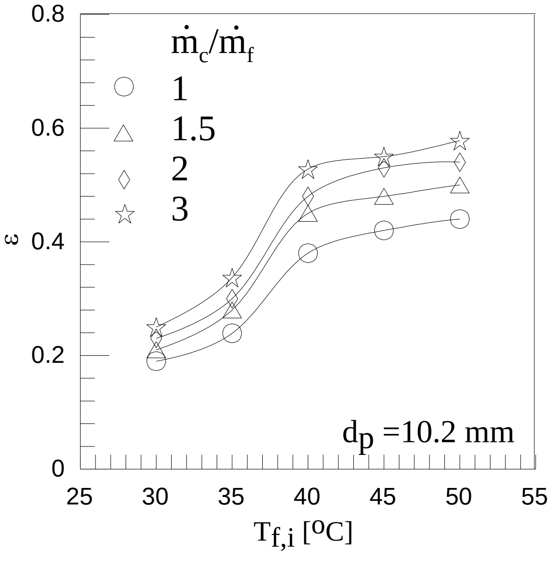


Fig. (12) Effect of fresh air inlet temperature on the HPHE effectiveness at d_p = 10.2 mm

Figures (13) and (14) show the variation of heat pipe heat exchanger effectiveness versus mass flow rate ratios for the three pipe diameters test sections. In Fig. (13), the fresh air temperature was kept constant at 40 °C while in Fig. (14), the air flow rate ratio was kept constant at 2. It is seen that, effectives is increased when pipe diameters was increased. This is because the increase of pipe diameter tends to increase the surface area of heat transfer which affect in increasing the heat transfer rate accordingly the effectiveness increases.

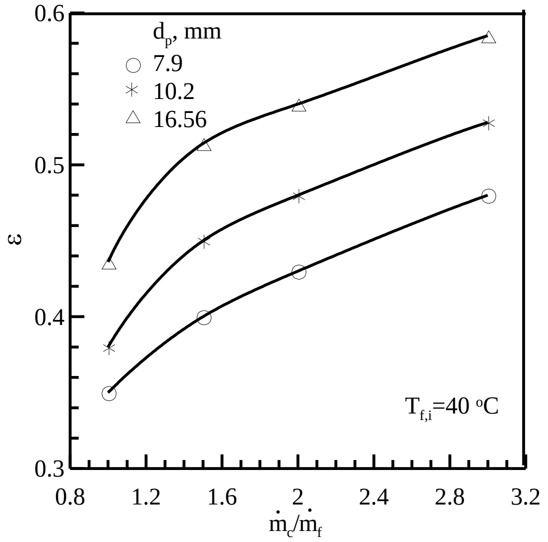


Fig. (13) Effect of mass flow rate ratio on the HPHE effectiveness at different pipe diameters at constant fresh air temperature of 40 °C

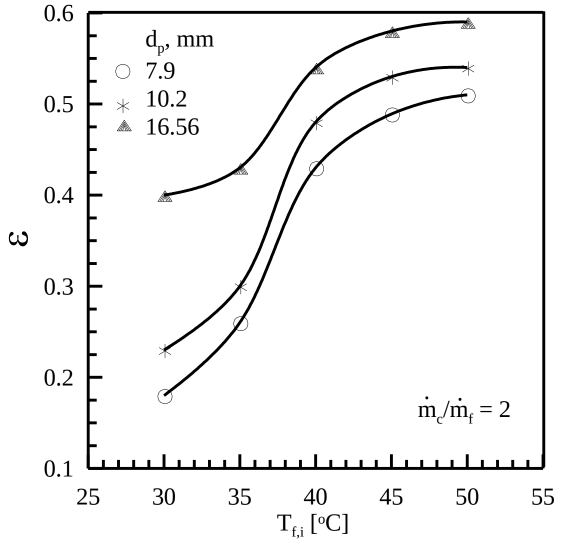


Fig. (14) Effect of fresh air inlet temperature on the HPHE effectiveness at different pipe diameters at constant flow rate ratio of 2

The ratio of utilized heat in the heat recovery process to the utilized heat in the conventional mixing air process defined by enthalpy ratio is given by equation (3), [5,10]:

$$\zeta = \frac{i_{f,i} - i_{f,o}}{i_{f,i} - i_M} \tag{3}$$

The above procedures were conducted for each experiment at various mass flow rate ratios of 1, 1.5, 2 and 3 and fresh air temperatures of 30, 35, 40, 45 and 50 ºC, while the cold air temperature was kept constant at 25.8 ºC. The relative humidity of each case of measured fresh and cooled air was measured and recorded. All measured cases for both fresh and cooled air were represented on the psychometric chart and the enthalpy was obtained and hence the corresponding value of "ζ" could be calculated.

The effect of cooled air to fresh air mass flow rate ratio on the ratio of heat recovery to conventional mixing air is indicated at different fresh air inlet temperature through Fig. (15) for pipe diameter of 10.2 mm. From this figure, it can be seen that, the heat exchanger enthalpy ratio of heat recovery to conventional mixing air with the increase of mass flow rate ratio of the air streams. It is found that the heat recovery is increased with increasing inlet fresh air temperature up to 40 °C. However, the value of ζ was almost the same for inlet fresh air temperature of 45 °C and 50 °C. The increase of fresh air inlet temperature affecting in increasing its heat capacity and consequently the enthalpy difference of fresh air between its inlet and outlet increases. This explains the increase of ζ when inlet air temperature is increased.

It can also be noticed from Fig. (15) that, the value of ζ is nearly constant with the increase of mass flow rate ratio. This can be explained as, when the cooled air mass flow increases, the mixing condition moves slowly to the direction of cooled air condition.

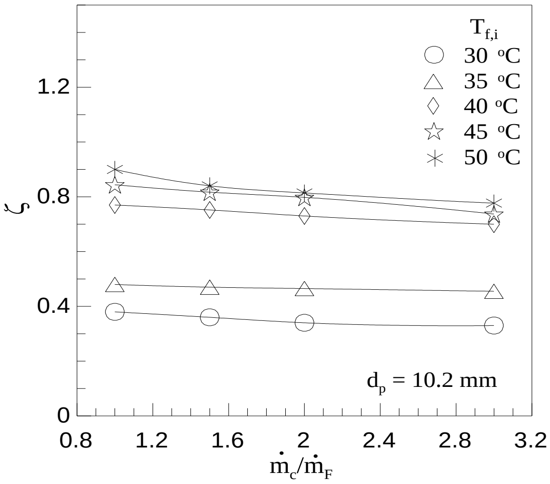


Fig. (15) Effect of mass flow rate ratio on "ζ" at different inlet fresh air temperature

Figure (16) represents the heat exchanger enthalpy ratio of heat recovery to conventional mixing air versus the mass flow rate ratios and at different pipe diameters at a constant fresh air temperature of 40 °C. It can be seen that, the heat exchanger enthalpy ratio of heat recovery to conventional mixing air increases when the heat pipes diameter is increased. With the increase of mass flow rate ratios, the value of ζ begins to decrease slightly.

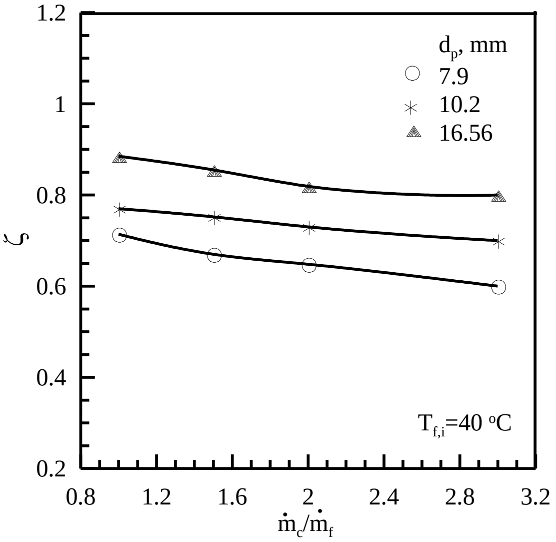


Fig. (16) Effect of mass flow rate ratio on "ζ" at different pipe diameters

Figure (17) shows the heat exchanger enthalpy ratio of heat recovery to conventional mixing air versus fresh air temperature at different pipe diameters and constant air mass flow rate ratio of 2.

It is seen that, the value of ζ is increased when pipe diameters was increased. This is because the increase of pipe diameter tends to increase the surface area of heat transfer which affect in increasing the heat transfer rate accordingly the effectiveness increases. It is also seen that, the value of ζ increases with the increase of fresh air inlet temperature.

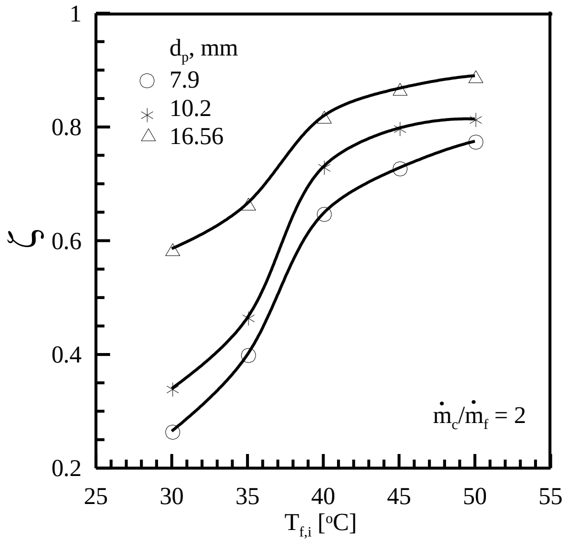


Fig. (17) Effect of inlet fresh air temperature on "ζ" at different pipe diameter

4- Conclusions

The experimental study of heat pipe heat exchanger for cooling fresh air with cooled air in air conditioning leads to the following conclusions:

1- The temperature change of fresh air increases with increasing the mass flow rate ratios in all cases.
2- The temperature change of fresh air increases with increasing the diameter heat pipes.
3- The effectiveness of heat pipes heat exchanger is increased with increasing the inlet fresh air temperature in all cases.
4- The effectiveness is increased with increasing the mass flow rate ratios in all cases.
5- The effectiveness is increased with increasing the diameter heat pipes.
6- The heat exchanger enthalpy ratio of heat recovery to conventional mixing air ζ increases with increasing the inlet fresh air temperature in all cases.
8- The heat exchanger enthalpy ratio of heat recovery to conventional mixing air ζ

increases with increasing the diameter heat pipes.

9- The heat exchanger enthalpy ratio of heat recovery to conventional mixing air ζ decreases slightly with increasing the mass flow rate ratios in all cases.

Nomenclature

English Symbol

C: cooled air
d: diameter
F: fresh air
i: enthalpy, kJ/kg
M: mixing point
$\dot{m}$: mass flow rate, kg/s
$\dot{Q}$: heat transfer rate, kW
T: temperature, ºC

Greek Symbol

Δ: difference
Ɛ: heat exchanger effectiveness of the
ζ: enthalpy ratio.

Subscript

c: cooled
f: fresh
i: inlet
o: outlet
p: pipe

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