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Review

Application of heat pipe heat exchangers in heating, ventilation and air conditioning (HVAC) systems

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A literature review on the studies and applications of heat pipe heat exchanger in air conditioning systems in recent years is conducted. The related papers were grouped into two main categories and a summary of experimental and theoretical studies is presented. Based on this investigation, the application of a heat pipe heat exchanger or a thermosyphon heat exchanger in the conventional air conditioning systems is recommended as an efficient means for energy savings and dehumidification enhancement to maintain acceptable room conditions. This review shows that the literature on the application of heat pipe heat exchangers in air conditioning systems is very limited. Therefore, much more research is needed to understanding the advantages of these systems for energy saving.

Key words: Heat pipe heat exchanger, dehumidification, energy saving, room sensible heat factor, thermosyphon heat exchanger.

INTRODUCTION

Nowadays, environment pollution and limitations in energy resources have appeared as a serious global crisis. Therefore, energy conservation and energy efficiency are necessary in all energy consuming devices including the air conditioning systems. A heat pipe is a high performance heat transfer device which is used to transfer a large amount of heat at a high rate with a small temperature difference. This is achieved by evaporation of the working fluid in the evaporator section and condensing in the condenser section and return of the condensate, as shown in Figure 1. Simple design and flexibility of heat pipes are important reasons for their extensive applications in industries and air conditioning.

The idea of heat pipes was presented first by Gaugler (1994) in General Motor Company in 1942. The first heat pipe was designed and manufactured by Grover (1966) in National Lab, Los Alamos, in the US in 1964. Since then, heat pipes are being used in many applications such as: heat exchangers (air pre-heaters or systems that use economizers for waste heat recovery), cooling of electronic components, solar energy conversion systems, spacecraft thermal control, cooling of gas turbine rotor blades, etc., (Peterson, 1994).

Because heat transfer mechanism in heat pipes is carried out through boiling and condensation, the effective thermal conductivity of heat pipe exceeds that of copper 200 to 500 times. If the wick is not used in the construction of heat pipe, it is called thermosyphon. In thermosyphon, return of the working fluid from condenser to evaporator is caused by gravity.

Parameters such as the type of pipe, the amount of working fluid (filling ratio), the purity of working fluid, the slope of pipe, the evaporator length and the pipe thickness all affect the thermal efficiency of heat pipes (Noie, 2005).

Heat transfer capability of a heat pipe is limited by at least 5 physical phenomena. The limitations involve the boiling limit, the sonic limit, the viscous limit, the capillary limit and the entrainment limit (Faghri, 1995).

Presently, heat pipe heat exchangers have many applications in space industries, electronics, etc. One of

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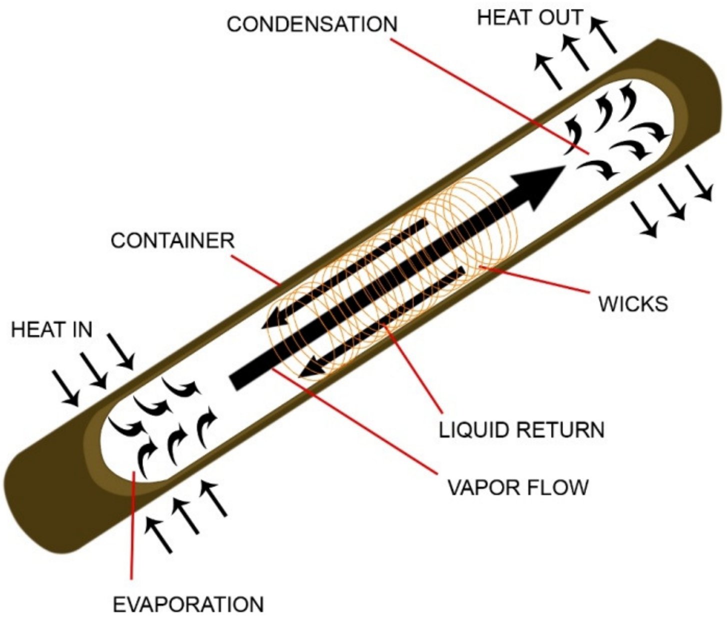

Figure 1. A schematic of heat pipe operation.

their important applications is in Heating, Ventilation and Air conditioning (HVAC) systems. The aim of HVAC systems is to prepare a desirable ambient air with suitable temperature, humidity, freshness and velocity. The optimal values of these variables are varied depending on the objective of air conditioning. For example, comfort conditions for human are 22 to 25°C and 40 to 60% of relative humidity (ASHRAE, 1989). One of the most interesting functions of HPHEs is to increase the dehumidification capacity of the conventional air conditioning systems. In a conventional air conditioning system, the humidity is controlled by cooling the supply air stream below its dew point temperature. The cold air is then reheated to a temperature that is suitable for the conditioned space. Heat Pipe Heat Exchangers (HPHEs) in HVAC systems are usually used to recover heat from the outlet air for cooling or heating the inlet air or increasing dehumidification capability.

To reduce energy consumption in HVAC systems, air is usually conducted to the conditioned space with high relative humidity. But, the humid and very cold air with high relative humidity (about 95%) results in discomfort for human. In addition, higher than 70% relative humidity in air distribution channels results in fungi growth and a threat for people's health and incident of Legionella disease. Therefore, less than 70% relative humidity is normally recommended in HVAC systems. To achieve this relative humidity in common cooling systems, external energy, like electrical energy, is used for reheating the air to decrease the relative humidity.

To decrease the energy consumption for reheating air, HPHE could be used. Also, evaporator of HPHE can act as a pre-cooler of the inlet hot air before entering the cooling coil which increases dehumidification capability of the cooling coil.

This paper focused on the energy saving and dehumidification enhancement aspects of HPHE and thermosyphon heat exchanger (THE). The related papers were grouped into two main categories and a summary of experimental and theoretical studies was made.

HEAT PIPE HEAT EXCHANGER (HPHE)

Theoretical studies

Wan et al. (2007) theoretically investigated the effect of a loop heat pipe air handling coil on the energy consumption in a central air conditioning system with return air for an office building. Based on the results, the air conditioning system installed with HPHE could save cooling and reheating energy.

The rate of energy saving (RES) is defined by:

$$\alpha = \frac{Q_o - Q'_o}{Q_o} \quad (1)$$

Where Q_o is the cooling load or total energy consumption in a central air conditioning system with returned air at constant indoor design temperature (Kw) and Q'_o is the cooling load or total energy consumption with HPHE at constant indoor design temperature (Kw).

In the temperature range of 22 to 26°C indoor design and 50% relative humidity, the rate of energy saving in the office building was 23.5 to 25.7% for cooling load and 38.1 to 40.9% for total energy consumption. The rate of

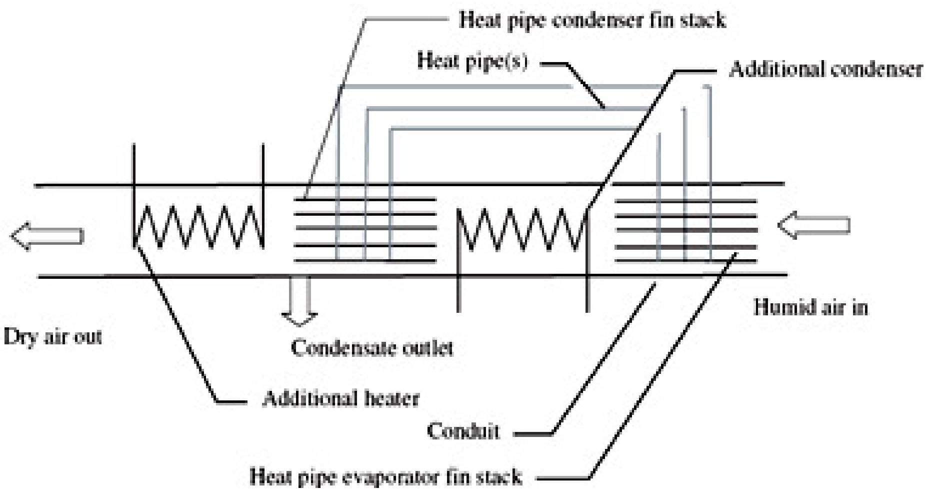

Figure 2. Heat recovery system using HPHE in drying cycle.

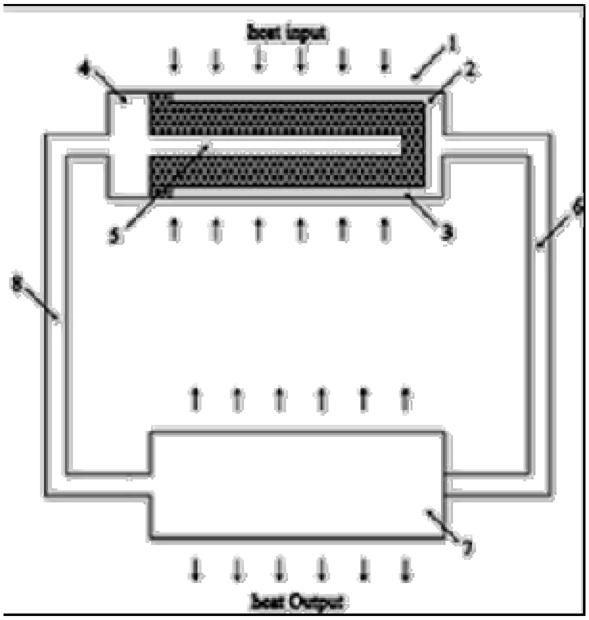

Figure 3. The basic configuration of the loop heat pipe (LHP), 1: evaporator, 2: wick, 3: vapor removal passage, 4: compensation chamber, 5: central core of the evaporator, 6: vapor line, 7: condenser and 8: liquid line.

energy saving was increased with the increase of the indoor design temperature and decrease of indoor relative humidity. The study demonstrated that by employing a HPHE in an air conditioning system, the energy consumption could be significantly reduced and the indoor thermal comfort and air quality also could be improved.

Numerical study on the application of HPHE in heat recovery systems has been carried out by Lin et al. (2005), using a CFD package called FLOTHERM for simulation of a drying cycle (Figure 2).

The simulation showed that the efficiency of a dehumidification process is completely affected by inlet operational conditions. In general, higher temperature and flow rate of the inlet saturated air result in more heat transfer in the system, but it needs more heating to achieve the mentioned relative humidity.

Alklaibi (2008) has studied the possibility of using a loop heat pipe (LHP) in air conditioning systems along with investigating the coefficient of performance (COP) which is the ratio of the absorbed heat from refrigerated space to the energy supplied into the compressor of refrigeration cycle (Dossat, 1997). Principles of heat transfer in HPHE and LHP are the same, but arrangement of their components is different. In loop heat pipe (LHP), wick is limited to the evaporator section. Whereas in conventional heat pipe the wick structure exists in all parts of evaporator, condenser and the liquid return line. The advantage of LHP compared to common heat pipe is that, since the wick is limited to the evaporator, it is possible to use capillary structure with quite small pores which can create tens kilopascals capillary pressure (Maidanik, 1999). In addition, because the liquid and the vapor lines of LHP do not have wicks, the pressure drops are reduced along these lines, allowing for larger mass flow rates (Figure 3).

In hot and humid areas or in places with heavy physical activity, like sports clubs, the room sensible heat factor (RSHF) is defined as:

$$RSHF = \frac{Q_L}{Q_s+Q_l} \qquad (2)$$

Where $\mathbf{Q_L}$ and $\mathbf{Q_S}$ are the latent and sensible heat gains, respectively.

To make a room with comfortable conditions in hot and humid climates, an air conditioner should be able to decrease both temperature and humidity.

Alklaibi has studied the possibility of using LHP in small air conditioners (such as the window or split type) in two situations: (1) LHP evaporator in front of air conditioner evaporator followed by a LHP condenser, (2) LHP condenser after air conditioner evaporator and LHP evaporator in front of air conditioner condenser. Also, he has studied the use of LHP in larger air conditioning systems. Results of this theoretical study show that the system's COP in each of the three above-mentioned situations increases in comparison with the situation where LHP is not used. In humid climate where RSHF is low, use of LHP results in increasing of COP as much as two times more than the use of heating elements, which results in decreasing the consumed energy by compressor.

Experimental studies

An experimental investigation was carried out by McFarland et al. (1996) to determine the effect of a HPHE on the performance of a conventional residential air conditioning system. In this study, the influence of HPHE on the moisture removal, the amount of auxiliary reheat required to maintain the room conditions, and the latent energy efficiency ratio of the air conditioning system were examined. The system was operated at three configurations: with the HPHE installed, a conventional system without the HPHE and the air flow subject only to typical restrictions, and a dampered system with the HPHE removed but dampering added to return the airflow to the same value as when the HPHE was installed. It was demonstrated that for the nominal room conditions of 22°C and 50% relative humidity, the HPHE increased the moisture removal by 62%, decreased the amount of reheat energy required by 20%, and increased the latent energy efficiency ratio by 90%. He declared that the application of HPHE in the conventional air conditioning system could be an efficient technique to control the humidity and reduce the amount of reheat energy required.

Dehumidifying characteristic of HPHEs in humid climates was investigated by Abtahi et al. (1988). By using the HPHE between the warm return air and cold supply air, heat recovery was achieved with supply air reheat and return air pre-cooled. Pre-cooling lowered the sensible cooling fraction and therefore, improved the moisture removal capacity of the system. An analytical overview of the HPHE was also explained in this study. The analysis involved thermal modeling of the whole system and also individual components such as the fin-tube assembly, the pipe-wick interface and the fluid loop conductance. It was recommended that boiling mechanism and heat transfer coefficients of the air side were the main factors affecting the performance. The fin efficiency for a high heat transfer coefficient occurring in liquid film falling cases were in the range of 97 to 98%. In addition, for nucleate boiling in the range of 1000 to 3000 w/m^2 k, the fin efficiency decreased significantly to less than 39%.

Abd El-Baky and Mohamed (2007) also stated that by the application of a HPHE between two streams of fresh and return air in an air conditioning system, the incoming fresh air could be cooled down. Ratios of mass flow rate between return and fresh air of 1, 1.5, and 2.3 were tested to validate the heat transfer and the temperature change of fresh air. During the tests, fresh air inlet temperature was controlled in the range of 32 to 40°C, while the inlet return air temperature was kept constant at about 26°C. In their study, thermodynamic properties of moist air and working fluids have been estimated using Cool Pack and NIST software. Effectiveness of a HPHE at evaporator side is defined as:

$$\varepsilon = \frac{T_{O_i} - T_{O_o}}{T_{O_i} - T_{R_i}} \tag{3}$$

Where T_{O_i}, T_{O_o}, and T_{R_i} are inlet air temperature, outlet air temperature and inlet return air temperature to condenser of HPHE, respectively. Finally, regarding the sonic limit and entrainment limit, the optimum effectiveness coefficient of HPHE has been calculated theoretically and has been compared with experimental results. According to the experimental results, the temperature changes of fresh and return air were increased with the increase of fresh air inlet temperature. The effectiveness and heat transfer rate of both the evaporator and condenser sections were also increased up to 48%, while the inlet fresh air temperature was increased up to 40°C. Furthermore, the enthalpy ratio between the heat recovery and conventional air mixing was increased to about 85% with the increase of fresh air inlet temperature. Optimum effectiveness was obtained at fresh air inlet temperature near the fluid operating temperature of the HPHE.

Because of restrictions in mixing return air with fresh air in hospitals, operating rooms and laboratories, the HVAC systems for these places are found to be energy inefficient. Therefore, the application of a HPHE as a waste heat recovery device was investigated for the surgery rooms in the hospitals by Noie-Baghban and Majideian (2000). They theoretically simulated the design parameters and limitations of heat transfer for 3 types of wicks and 3 kinds of working fluids. In a heat pipe designation, the limitations on heat transport must be examined for each working fluid. Although heat pipes are very effective heat transfer devices, they are subjected to a number of heat transfer limitations. These limitations determine the maximum heat transfer rate that a particular heat pipe can achieve under certain working conditions. Figure 4 shows schematically the axial heat flux as a function of heat pipe working temperature for different limitations. The operating point should be chosen in the area lying below these curves. The actual shape of this area depends on the working fluid and wick

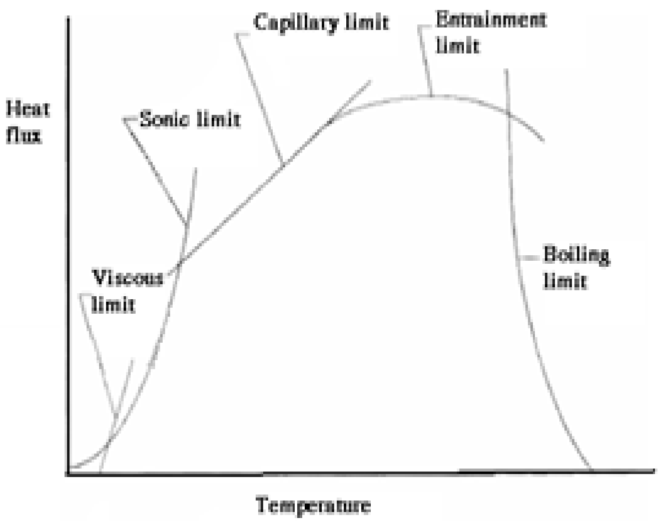

Figure 4. Limitations to heat transport in the heat pipe.

material and will vary appreciably for different heat pipes.

After obtaining the appropriate heat flux, the HPHE was designed and tested with methanol as the working fluid in 15 to 55℃ temperature range. Since the HPHE was designed to use in the surgery rooms, the tests were run under low temperature of 15 to 55℃ operating conditions. From the experimental results, using finned pipes, increasing the number of rows and complete insulation of the test rig have a significant effect on the increasing of HPHEs effectiveness.

THERMOSYPHON HEAT EXCHANGER (THE)

Theoretical studies

Theoretical studies on thermal performance of THE have been done by different people (Lee and Bedrossian, 1978). Azad and Geoola (1984) introduced the total effectiveness coefficient of THE with theoretical relation as follows:

For the evaporator section:

$$\varepsilon_{hn} = \frac{\left(\frac{1-\frac{C_h}{C_L}\varepsilon_{h1}}{1-\varepsilon_{h1}}\right)^{n}-1}{\left(\frac{1-\frac{C_h}{C_L}\varepsilon_{h1}}{1-\varepsilon_{h1}}\right)^{n}-\frac{C_h}{C_L}} \quad (4)$$

For the condenser section:

$$\varepsilon_{cn} = \frac{\left(\frac{1-\frac{C_c}{C_L}\varepsilon_{c1}}{1-\varepsilon_{c1}}\right)^{n}-1}{\left(\frac{1-\frac{C_h}{C_L}\varepsilon_{c1}}{1-\varepsilon_{c1}}\right)^{n}-\frac{C_c}{C_L}} \quad (5)$$

Where $C=\dot{m}c$ and ***h, c,*** and **n** are for hot fluid, cold fluid and number of pipes rows, respectively. Also for $C_h/C_L = 0$ and $C_c/C_L = 0$ the aforeseen equations reduce to:

$$\varepsilon_{hn} = 1-(1-\varepsilon_{h1})^{n} \quad (6)$$

and

$$\varepsilon_{cn} = 1-(1-\varepsilon_{c1})^{n} \quad (7)$$

The overall effectiveness of THE, ε_t is written as:
If $C_h > C_c$

$$\varepsilon_t = \left(\frac{1}{\varepsilon_{cn}}+\frac{\frac{C_c}{C_h}}{\varepsilon_{hn}}\right)^{-1} \quad (8)$$

If $C_c > C_h$

$$\varepsilon_t = \left(\frac{1}{\varepsilon_{hn}}+\frac{\frac{C_h}{C_c}}{\varepsilon_{cn}}\right)^{-1} \quad (9)$$

The air outlet temperatures of evaporator and condenser sections were obtained from the following relations:

$$T_{h,out} = T_{h,in} - \varepsilon t\frac{(\dot{m}C_p)_{min}}{(\dot{m}C_p)_h}\,(T_{h,in}-T_{c,in}) \quad (10)$$

$$T_{c,out} = T_{c,in} + \varepsilon t\frac{(\dot{m}C_p)_{min}}{(\dot{m}C_p)_c}\,(T_{h,in}-T_{c,in}) \quad (11)$$

The thermal performance of a THE was simulated using a computer program and the temperature distribution across the THE, its thermal performance, and overall effectiveness of THE were considered in the research. Yau and Tucker (2003) also studied the overall effectiveness of a wet 6-row THE for a tropical building HVAC system using a computer simulation program. The effects of inclination angle and inlet evaporator relative humidity on the heat transfer coefficient for the THE were determined by using the TRANSYS software.

Wu et al. (1996) stated that in hot and humid climates with over 70% relative humidity, latent heat is an important parameter to calculate the thermal performance of THE. They showed that if only the sensible heat is accounted for the calculation of the number of heat transfer units (***ε .NTU***), the results will not be exact (Figure 5).

To define the effect of latent heat on the total heat transfer, condensing coefficient (ζ) is defined as the ratio of the total heat to sensible heat:

$$\zeta = \frac{h_1-h_2}{c_p(t_1-t_2)} \quad (12)$$

When THE is working in the wet fin condition, $\zeta>1$, and when THE is working in the dry fin condition, $\zeta=1$. Then

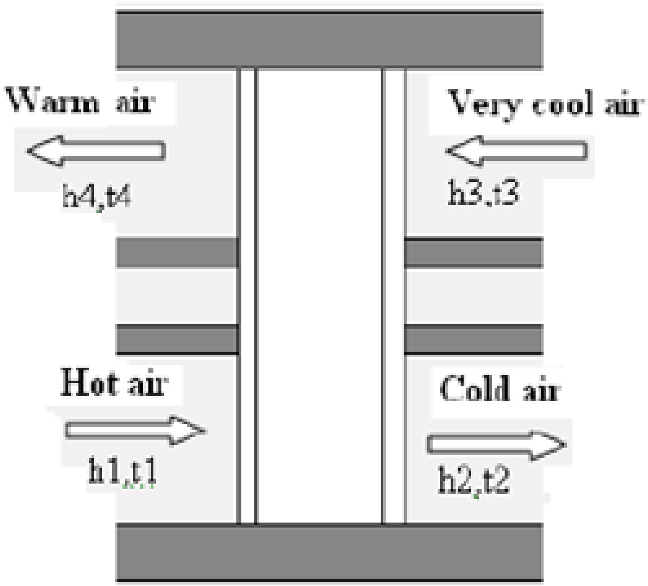

Figure 5. Streams to and from the THE.

the precool effectiveness of evaporator section versus air face velocity curves and also, effectiveness of THE versus the number of heat transfer units (***ε* -NTU**) curves were plotted using theoretical relations and the results were compared with experiments. Finally, it was concluded that the condensing coefficient has an important role in THE effectiveness and if it is neglected, 20% difference will be observed in the results.

Dinh (1996), in a study of the application of THE in air conditioning systems, mentioned that while a common cooling coil has about 70 to 80% of the typical ratio of sensible cooling to total cooling (SHR), it can have 50 to 60% SHR, if it receives pre-cooled air from THE. This means that more moisture will be omitted from air for a same cooling capability. So by using dehumidifier THE, one can decrease the relative humidity in the conditioned space (typically by 10%) resulting in noticeably improved indoor air quality and reduced power demand.

Considering the design of THE according to ***ε* –NTU** method (Noie et al., 2002), simulation of an air conditioning system with THE was performed by Sarmasti et al. (2005). Simulation stages were:

1. Calculation of thermo-physical properties of hot and cold flows. To do this, the outlet temperatures should be first guessed from THE.
2. Calculation of Reynolds number over the heat exchanger pipes, considering hot and cold flows velocities.
3. Calculation of the Stanton-Colburn coefficient.
4. Calculation of the convection heat transfer coefficient over the pipe handle.
5. Calculation of the fin efficiency and total efficiency in evaporator and condenser sections.
6. Calculation of the overall heat transfer coefficient in evaporator and condenser sections.
7. Calculation of the outlet temperatures and heat transfer rate.
8. Comparison of the outlet air temperatures resulted from calculation and the primary guesses. If the difference is not acceptable, refer to step one and repeat.
9. Calculation of the effectiveness coefficient.

Experimental studies

Because of simplicity in design and manufacturing of THE, most of the researchers employed this type of HPHE in their studies. For example, a 3-row THE was studied using the Hilton Air-Conditioning laboratory Unit in RMIT by Wu et al. (1996). The test conditions in the research could be considered as the representative of a humid area in Australia in summer. Three aspects of THE, including temperature effectiveness, capability of energy recovery and relative humidity control of supplied air was considered in this study. According to experimental results, the cooling capability for the system was improved by 20 to 32.7%. It was also found that where air supply was needed below 70% relative humidity, the condenser of the THE could be used as a reheater to replace the conventional reheating coil to control relative humidity. On the basis of the results, the application of this type of heat exchanger instead of conventional reheat coils resulting in energy saving and enhancing the cooling capability of the cooling coils was suggested.

Saman (1996) studied the possible application of a THE for indirect evaporator cooling with heat recovery for the fresh air preheating. In this study, the thermal performance of a THE consisting of 48 wickless heat pipes arranged in 6-row was tested. The dry bulb temperature and relative humidity of both air streams were controlled in a test chamber and monitored before and after the THE.

The wetting arrangement of the condenser section, flow rate of the two flows, original temperature of the main flow, and the inclination angle of the wickless heat pipes were considered in this study. The findings indicated that the cooling performance factor in the range of 0.55 to 0.84 increased to the range of 0.65 of 0.88 with the increase of the evaporator inlet temperature from 27 to 41.5°C. In terms of effectiveness, it was improved from the range of 0.25 to 0.66 to the range of 0.27 to 0.83 with the increase of the evaporator inlet temperature from 27 to 41.5°C. This indicated that the application of THE for this purpose decreased the fresh air temperature by a number of degrees below the temperature drop achieved when using dry air alone.

In another study, Martinez et al. (2003) designed a mixed energy recovery system consisting of two THE and indirect evaporative recuperators for air conditioning. The energy characterization of the mixed energy recovery

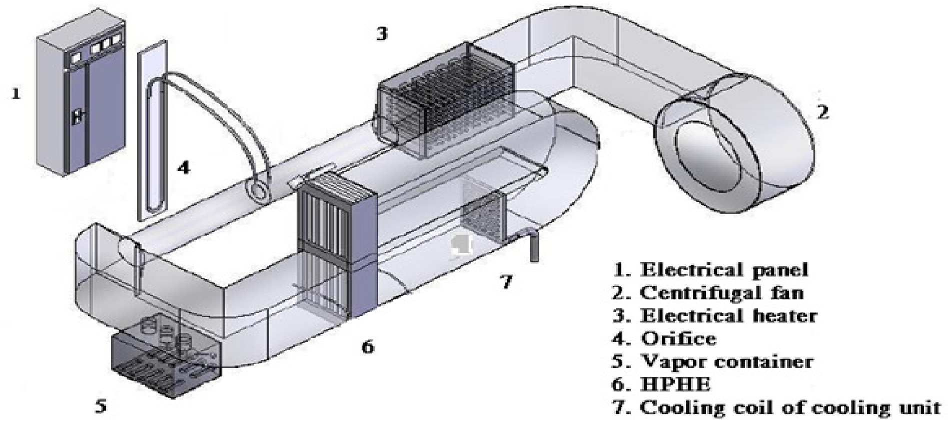

Figure 6. Schematic of the test rig.

system was performed by means of the experimental design techniques. As a main result, it was found that by application of the mixed energy recovery system in the air conditioning installations consisting of two THE and indirect evaporative systems, part of the energy from the return air flow could be recovered, thus improving energy efficiency and reducing environmental impact.

In a case study in Thailand by Terdtoon et al. (1996), thermal properties of a THE for air conditioning system in a clean room with constant temperature and relative humidity (25℃ and 50%, respectively) were investigated. In this study, a LHP without wick in the form of a U-shaped was used to heat the return air before passing cooling coil. Absorbed heat of return air was used for heating fresh air before passing electrical heater. Therefore, energy savings both in cooling and heating were achieved. The working fluid used in this study was R-134a and thermal effectiveness coefficient of the heat pipe dehumidifier was 0.31. It was shown that the energy saving as well as the system pressure drop were acceptable.

In another study, Noie (2006) investigated theoretically and experimentally the effect of velocity and input heat on heat transfer characteristics of a THE under normal operating conditions. The air face velocity ranged from 0.5 to 5.5 m/s and the heat input into the evaporator section was varied between 18 and 72 Kw. He concluded that: (1) the overall experimental effectiveness of the thermosyphon was over 37% for each of the conditions of all experiments and can be increased up to 65% with decreasing the inlet hot air velocity down to 0.5 m/s and (2) the minimum effectiveness of the thermosyphon took place at $C_h = C_c$ .Therefore, equal value of air face velocities in evaporator and condenser sections should be avoided.

Yau (2006, 2007a, b, 2008) studied the effect of addition of THE on the reduction of sensible heat ratio (SHR) of air conditioning system and observed that SHR reduced from 0.688 to 0.188. He concluded that the higher temperature of the inlet air, the higher dehumidification capability of the system can be achieved. For low inlet air temperatures (20℃) and low relative humidity (<50%), dehumidification of cooling coil does not increase significantly. This is because most of the cooling capability of cooling coil is used for sensible cooling of air.

By installing a THE in an air conditioning system, Wu et al. (1997) have shown that the cooling capacity of the system can be increased between 20 to 32%. Nevertheless, addition of this heat exchanger results increasing pressure drop, manufacturing costs and size of air conditioning system.

In another study, Fye et al. (2008) experimentally studied the effect of relative humidity and blower speed on Coefficient of Performance (COP) with R410A working fluid in air conditioning systems with a THE. It was concluded that THE can be used for dehumidification purposes. The reduction of the relative humidity after the condenser side of the thermosyphon was more apparent at low fan speeds. Whereas at higher fan speeds reduction is less. It was also shown that the COP of the system was lower when the THE was installed.

Although the study of nanofluid two-phase flow (both for boiling and condensation) is rather limited, it is likely that the nanofluids will also enhance the thermal performance of a THE as compared with the pure fluid due to the increase of the thermal conductivity. In addition, the circulation motion of the working fluid in a THE keep the nanoparticles suspended, which facilitates nanoparticle migration and prevents sedimentation. Application of methanol-silver nanofluid filled THE in an air conditioning system was investigated and compared the effectiveness as well as energy saving with pure methanol by Firouzfar et al. (2011). First, the influence of two key parameters of the inlet air namely dry bulb temperature and relative humidity, on the effectiveness of a 3-row THE with pure methanol as the working fluid was investigated at pilot scale (Figure 6). Then the experiments were repeated using methanol- silver nanofluid as the working fluid. Experimental results showed that using methanol-silver nanofluid, leaded to energy saving around 8.8 to 31.5% for cooling and 18 to 100% for reheating the supply air stream in an air conditioning system. Therefore, using nanofluid of a metal such as silver increases the thermal efficiency of THE saves energy consumption in air conditioning systems.

The effect of inclination angle on the performance of THEs was reported in a number of literatures. For instance, Beckert and Herwig (1996) carried out a research on the impact of inclination on the heat transfer rate of a THE applied in an air conditioning system. A set of thermosyphons was investigated to find out how far they can be inclined without considerable decrease in the heat transfer rate. It was found that even in a nearly horizontal position (up to ± 6° with the horizontal) the overall performance is still good enough. It was observed that turning the set of pipes by an angle of about 12° from –6° to + 6° with respect to the horizontal will switch the overall heat transfer from one direction to the other. It was also observed that in an air conditioning system, where the THEs operate as a heat exchanger between the outside channel and the exhaust air, it can be used in a position of –6° to preheat the fresh air in winter and in a position of +6° to pre-cool the fresh air in summer.

CONCLUSION

This review on the application of heat pipe heat exchangers (HPHEs) in HVAC system shows that HPHEs are very efficient heat transfer devices, which can be easily implemented as thermal links and heat exchangers in air conditioning systems to ensure the energy saving and environmental protection. So by using HPHE, one can decrease the relative humidity in the conditioned space (typically by 10%) resulting in noticeably improved indoor air quality and reduce power demand. HPHE also promise to improve greatly indoor air quality, and at the same time help conserve energy. It was revealed that these heat recovery devices are still a new application in HVAC systems before they can be used at commercial scales. This indicates that much more research is needed to understand the applications of these systems for energy saving.

Nomenclature: ***C,*** air specific heat [kJ/kg k]; **CFD,** computational fluid dynamics; **COP,** coefficient of performance; **HPHE,** heat pipe heat exchanger; **HVAC,** heating, ventilating and air conditioning; **LHP,** loop heat pipe; $\dot{m}$**,** mass flow rate [kg/s]; **NTU,** number of heat transfer units; **Q,** cooling load or total energy consumption [kW]; **RES,** rate of energy saving; **RH,** relative humidity [%]; **RSHF,** room sensible heat factor; **SHR,** sensible heat ratio; **T,** temperature; **THE,** thermosyphon heat exchanger.

Greek symbols: $\boldsymbol{\varepsilon}$**,** effectiveness coefficient; α rate of energy saving [%]; ζ water condensing coefficient.

Subscripts: C, cold fluid; **H,** hot fluid; **l,** latent heat; **n,** number of pipes rows; $\mathbf{o_i}$, inlet air; $\mathbf{o_o}$, outlet air; $\mathbf{R_i}$, return air; **s,** sensible.

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