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Review of heat pipe heat exchangers for enhanced dehumidification and cooling in air conditioning systems

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Abstract

Heat pipe heat exchangers could be employed as run-around coils in air conditioning systems for enhanced dehumidification and cooling. This article reviews some of the works conducted on the cooling and dehumidification aspects in various air conditioning systems. They have been proved to be effective in enhancing dehumidification and reducing air conditioning costs especially in hot and humid tropical countries.

Keywords: heat pipe heat exchanger; air conditioning; dehumidification; precool

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1 INTRODUCTION

A building's heating, ventilating and air conditioning (HVAC) system is designed to remove heat and moisture caused by human occupancy, external solar heat load and internal lighting appliances from the building interior. In hot and humid tropical climates, over 90% of the air conditioning load is from latent heat of the moisture from fresh air ventilation while the rest is sensible heat. An air conditioning system provides an environment that is comfortable to occupants by maintaining recommended indoor air temperature and humidity as well as providing sufficient clean fresh air. The American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) [1] recommended new ventilation rates that require more fresh air to be introduced into the enclosed environment for human comfort. This additional ventilation requirement requires large or oversized equipment to cope with increased cooling load of outside air leading to higher costs especially in hot and humid countries.

In an air conditioning system, air is cooled to below its dew point temperature in the evaporator coil of the refrigeration machine or from the cooling coil in a chilled water system. The moist air releases its moisture which collects in a drain pan and subsequently drained from the system, thus reducing the humidity in the room. A simple conventional recirculating air conditioning system is shown in Figure 1. Hot and humid fresh outdoor air (1) is mixed with stale, warm and humid recirculating air (5) returned from the air conditioned space. The mixed air (2) is cooled and dehumidified (3) by the cooling coil. Air at this point may be too cold and saturated for comfort. To provide design air condition, it is reheated electrically or with steam or hot water coils before being delivered to the room as supply air (4). Heat and moisture is picked up in the room and exits as return air (5) which is warmer and more humid than when it first entered. A proportion of return air is recirculated and mixed with incoming fresh outdoor air and returned back to the room. The rest is exhausted to the ambient. The psychrometric process is shown in Figure 2. Normal condition of the air leaving the cooling coil is around 12–13°C and 100% relative humidity. Supply air is normally around 16–18°C and 50% relative humidity. Energy has to be supplied to the cooling coil (Δh_{coil}) for cooling and dehumidification and to the reheat coil (Δh_{reheat}) to bring the air to a comfortable level before discharge to the room.

In clean rooms and surgical operating theaters, 100% fresh air is required. Exhausted cold exhaust air could be utilized to precool the incoming warm fresh outdoor air by employing a heat recovery coil as shown in Figure 3. Conventional heat recovery coils include stationary finned or plate-type air-to-air heat exchangers or rotary heat wheels with or without desiccants. The psychrometric process for the conventional once-through air conditioning system is shown in Figure 4. Heat supplied to

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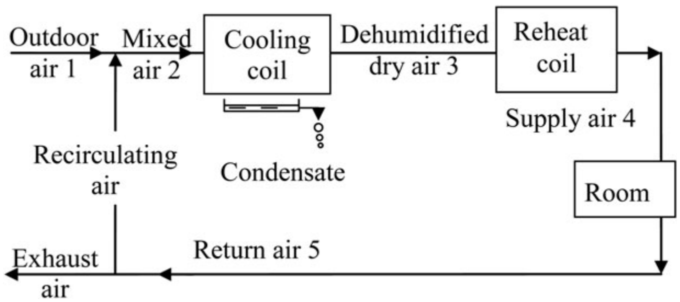

Figure 1. *Conventional recirculating air conditioning system.*

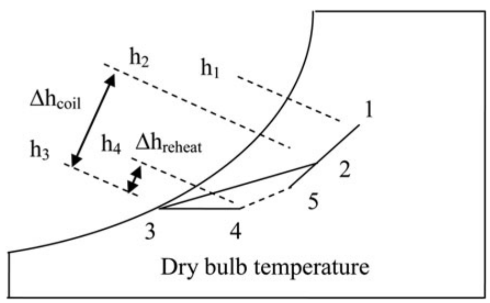

Figure 2. *Psychrometric diagram of conventional recirculating air conditioning system.*

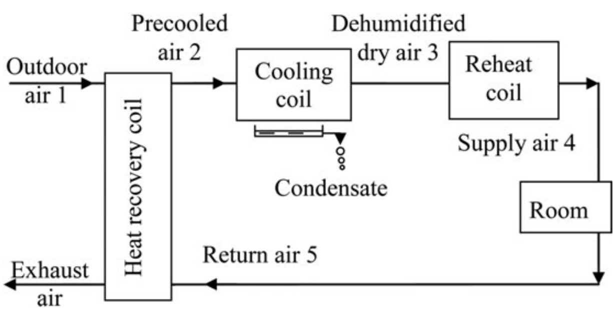

Figure 3. *Air conditioning system with precool and reheat coils.*

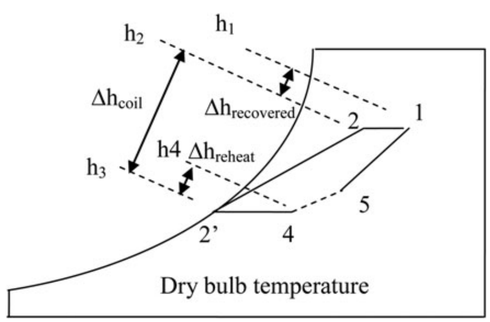

Figure 4. *Psychrometric diagram of air conditioning system with precool and reheat coils.*

the cooling coil is reduced by the energy recovered from the heat exchanger ($\Delta h_{\text{recovered}}$). A conventional recirculating run-around coil system is shown in Figure 5. A precool coil is connected upstream and a reheat coil is connected downstream of the cooling

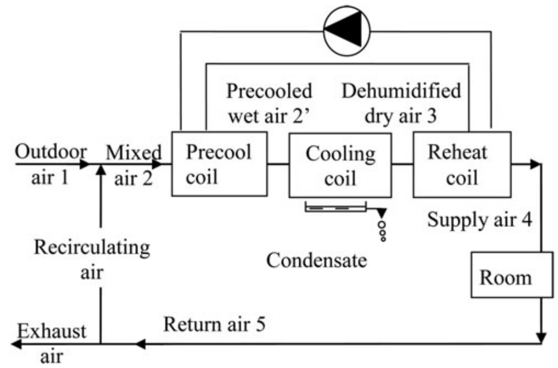

Figure 5. *Conventional recirculating run-around air conditioning system.*

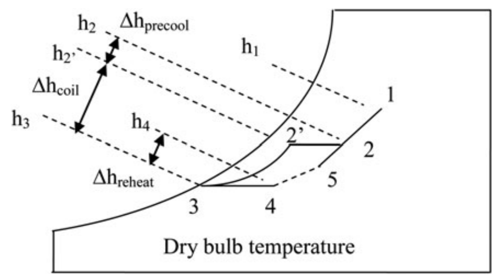

Figure 6. *Psychrometric diagram of conventional recirculating run-around air conditioning system.*

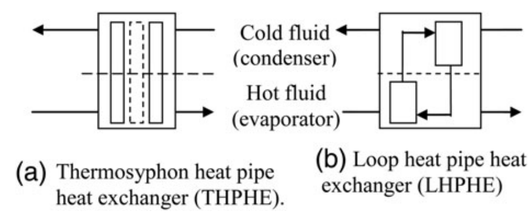

Figure 7. *Thermosyphon and loop HPHEs.*

coil. The precooled air (2′) is hotter than supply (4) after the reheat coil. The psychrometric diagram of the run-around coil system is shown in Figure 6. The energy recovered from precooling ($\Delta h_{\text{precool}}$) is utilized to offset the reheat (Δh_{reheat}) load, resulting in lower operating energy requirements.

Heat pipes (HPs) were developed initially for cooling of microelectronic components especially for space applications. Heat pipe heat exchangers (HPHEs) are very efficient passive heat exchange devices capable of transferring large quantities of heat over relatively long distances with small temperature difference between heat source and heat sink. They can be used for waste heat recovery from hot exhaust flue gas or from cold exhaust air in air conditioning systems. A wickless HP is known as a two-phase closed thermosyphon. A HPHE consists of an array of HPs or thermosyphons laid out in one or more vertical rows. The thermosyphon HPHE (THPHE) consists of an array or bank of individual thermosyphons laid out in a parallel fashion, Figure 7a. The loop HPHE (LHPHE) consists of separate condenser and evaporator banks, Figure 7b. These are used when there are constraints in the air duct system. Separating the condenser and

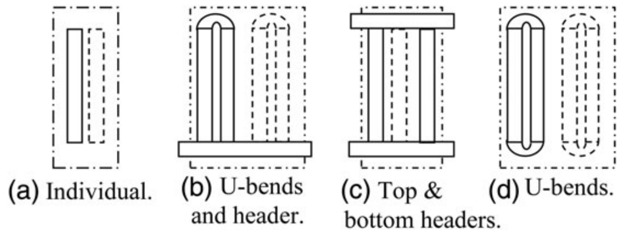

Figure 8. *Connection of pipes in HPHE.*

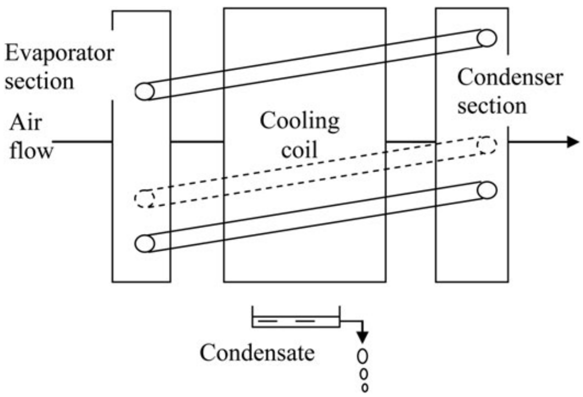

Figure 9. *Wrap-around HPHE.*

evaporator would provide more freedom in locating the LHPHE. In a HPHE, each bank of pipes could consist of individual pipes, Figure 8a, or they could be connected at the top by U-bends and a common manifold at the bottom. Alternately, they could be connected by two common straight headers at the top and bottom, Figure 8c, or two consecutive pipes could be joined by U-bends at the top and bottom, Figure 8d.

A compact and easy to install 'in-line' or 'wrap-around' coil (WHPHE) is shown in Figure 9. It consists of single or multiple rows of single-tube-inclined thermosyphons with each tube bent into a U shape and placed before and after the cooling coil of the refrigerating unit. It is more versatile than the vertically mounted HPHEs and could be retrofitted by 'dropping it in-line' like a cartridge and wrapped around the cooling coil in a horizontal duct. The WHPHE could be considered a special coil designed for ease of installation or for retrofitting into existing air conditioning units.

Possible configurations showing locations of HPHEs are shown in Figure 10. The evaporator section of the HPHE could be located after mixing (Figure 11a) in the return air duct (Figure 11b) or in fresh air supply duct (Figure 11c).

2 HEAT PIPE EFFECTIVENESS

The air temperatures before and after the evaporator and condenser coils of an open-loop THPHE system for heat recovery are shown in Figure 11a with two independent air streams. In Figure 11b and c, the same air mass flows across both evaporator and condenser sections of the HPHE. In the absence of heat losses, heat transferred between evaporator and condenser sections is equal. In this case, energy balance determines that the temperature drop across the evaporator section (precool) is equal to the temperature rise in the condenser section (reheat). In some cases of high humidity, condensation of the air stream occurs in the evaporator coil. When this occurs, the evaporator section experiences both sensible and latent heat transfer while the condenser section would only undergo sensible heat transfer. Hence, the temperature rise across the condenser section (reheat) would be greater than the temperature drop across the evaporator section (precool). This will affect the performance of the HPHE.

The sensible heat, latent heat or total heat effectiveness ε of the HPHE is given as:

$$\varepsilon = \frac{\dot{m}_{\mathrm{e}}(X_{\mathrm{ei}} - X_{\mathrm{eo}})}{\dot{m}_{\min}(X_{\mathrm{ei}} - X_{\mathrm{ci}})} \quad (1)$$

For sensible energy, latent heat energy or total energy effectiveness, X is the dry bulb temperature, humidity ratio or enthalpy, respectively. Evaporator mass flow rate is denoted by $\dot{m}_{\mathrm{e}}$, and $\dot{m}_{\min}$ is the smaller of either of the two air streams.

When both air flow rates are equal, effectiveness of the HPHE is as follows:

$$\varepsilon = \frac{(X_{\mathrm{ei}} - X_{\mathrm{eo}})}{(X_{\mathrm{ei}} - X_{\mathrm{ci}})} \quad (2)$$

3 GENERAL REVIEWS OF RECENT DEVELOPMENT OF HEAT PIPE TECHNOLOGY AND APPLICATIONS

A tremendous amount of work has been conducted on HPHEs. This article attempts to review some works on HPHEs for enhanced dehumidification and cooling in air conditioning systems.

Polasek [2, 3] conducted surveys on >40 Institutions and Research establishments involved in R&D of HPs in East European countries. The widest applications were on flue gas waste heat recovery for power production and for providing fresh cool air environment for livestock. Other applications were in HP solar collectors, cooling of electrical equipment and machinery, air conditioning devices and cooling of molds in the plastic injection industry. Maydanik [4] and Vasiliev [5] reviewed the development of HPs in Russia, USA and Europe. Their reviews showed that maximum heat transfer capabilities of LHPs are dependent on operating parameters like type of fill liquid, fill charge ratio, wick geometry, evaporator and condenser temperatures and inclination. Launey *et al.* [6] presented a review on works carried out to investigate how operating parameters affect the LHP performance.

Firouzfar and Attaran [7] reviewed HP activities in Asia for industrial heat recovery, HVAC and for temperature regulation in the human body. Yau and Ahmadzadehtalatapeh [8] reported on the activities and applications of HPHEs in HVAC in tropical

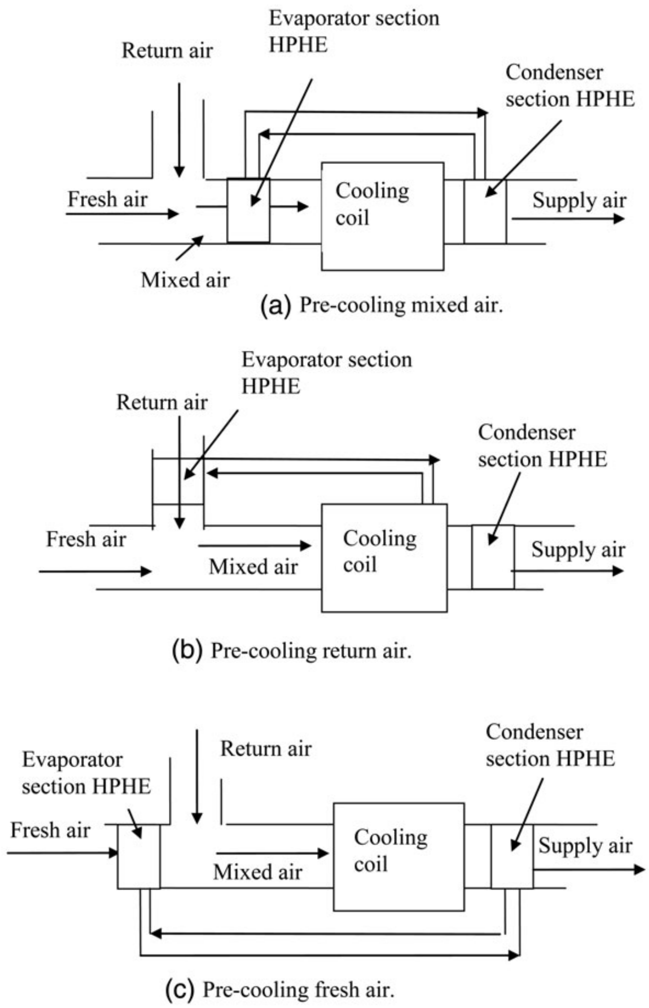

Figure 10. *Possible HPHE configurations in HVAC systems.*

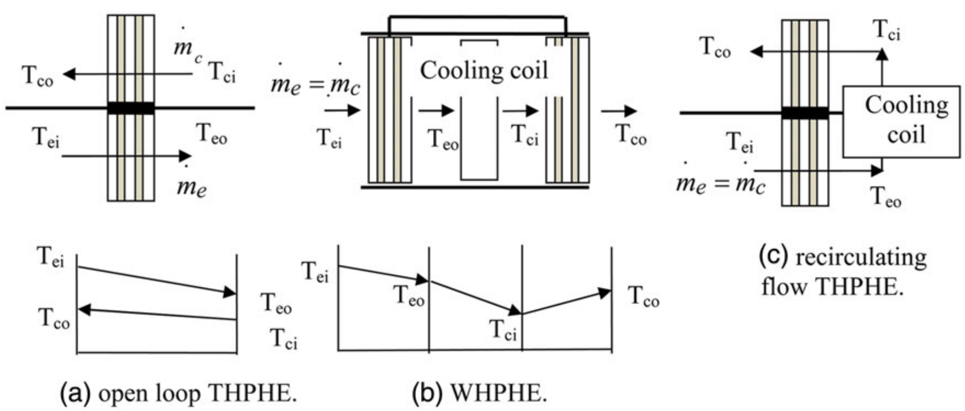

Figure 11. *Air temperature distribution and effectiveness in HPHE coils.*

Asian climate. They focused on the energy recovery and dehumidification enhancement aspects of horizontal HPHEs and concluded that HPHEs are efficient energy recovery units for HVAC purposes but that research into their use in tropical climate countries like Malaysia, Singapore and Thailand is limited.

Yang *et al.* [9] reviewed recent developments of lightweight and high-performance HPs and summarized the primary methods of achieving lightweight and high-performance HPs. From a material standpoint of view, aluminum, titanium or magnesium alloys could be used with water as the fill liquid. If other working fluids like ammonia and acetone are used, their applications are limited to low-temperature environment. An alternative method would be to improve the wick structure with fiber and sintering. Other methods to minimize the size of standard HPs is by considering flat HP, vapor chamber and loop HP type of designs. Future research on HPs would be on lightweight pipes coupled with good heat transfer performance and low costs.

4 HEAT PIPES FOR COOLING

El-Baky and Mohamed [10] investigated the effects of ratio of return to fresh air mass flow rates and fresh air inlet temperature on the effectiveness of a HPHE for heat exchange between a hot and a cold air stream similar to Figure 11c. The HPHE consisted of multirows of horizontally laid pipes with brass mesh wick and R11 fill liquid. Their results showed that both evaporator and condenser side effectiveness increased with increase in fresh air inlet temperature. However, while the evaporator side effectiveness increases with increased air mass flow rate ratio, condenser effectiveness decreased. Effectiveness and heat transfer for both evaporator and condenser sections increased to $\sim$48% when fresh air temperature increased to 40°C.

5 HEAT PIPES FOR COOLING AND DEHUMIDIFICTION

Hill and Jeter [11] examined the theoretical impact of the run-around coil HPHE system, Figure 10a, for enhanced dehumidification using a combination of a HPHE thermal node model and manufacturer's air conditioning data. They found the HPHE reduces the sensible heat ratio of a conventional air conditioner as well as increases the latent capacity and moisture removal efficiency.

Beckwith [12] proposed two novel applications of HPs in air conditioning systems. The first involves a WHPHE system, Figure 10a, with precooling and reheat of the supply air. The second application involves the addition of a HPHE with a conventional subcooling and de-superheating heat exchanger coil to provide additional reheat in a controlled manner to provide humidity control at low cooling load conditions. Different strategies for precise control of temperature and relative humidity in a chilled water system were discussed. Their simulations showed the proposed systems could economically control humidity and improve indoor air quality. Considering only operating cost, payback period was 1.2 years with a return on investment of 81%. By considering capital cost differential of a 41.54-kW system, a payback of 6 months could be realized.

Wu *et al.* [13] investigated the use of a vertically mounted three-row R22-filled THPHE connected to a laboratory-sized 0.56-kW air conditioning unit with variable air flow, Figure 11c. Intake air was heated with an electric heater and humidified by steam generated in an electric boiler. Tests were carried out with fresh air/recirculating supply air ratios from 10 to 100%. Their results showed that the cooling capacity for the system increased by 20–32.7% and that the condenser of the THPHE can be used to replace the conventional reheater to perform relative humidity control where supply air is required below 70% relative humidity. In their theoretical model, Wu *et al.* [14] considered both sensible and latent heat effects of water vapor condensing on the surfaces of the finned heat exchanger.

Mathur [15–17] simulated the performance of an existing 5-ton (17.6 kW) air conditioning system with an energy efficiency ratio (EER) of 8 by retrofitting it with a HPHE to improve cooling and dehumidification, Figure 11c. Using Dallas weather data, he showed that additional moisture could be removed from the cooling coil and that the performance of the retrofitted system increased by 96%. The system EER increased to 15.7 and that the HPHE retrofit system will pay for itself in less than a year.

Budaiwi and Abdou [18] presented a mathematical model to evaluate the performance of a HP system incorporated with the cooling coil of an air conditioning system. They found that a proper selection of both the HP and the cooling coil characteristics was necessary for a satisfactory performance under given operating coil conditions.

Alkaibi [19] evaluated three possible configurations of incorporating the LHPHE into air conditioning systems to perform the reheat process as shown in Figure 10. His simulations showed that the configuration of Figure 10c had the highest COP followed by that of Figure 10b. In humid climates when RHSF is low, using HPs can improve the COP by $\sim$2 times that of conventional reheat.

Yau and Tucker [20] investigated the overall effectiveness of a 6-row R134a-filled THPHE in tropical buildings, Figure 11a. They found that the heat transfer coefficient increased with inclination angle and relative humidity. Overall effectiveness was minimum when face velocities were equal. They also observed that the THPHE failed to perform as a dehumidifier effectively if installed in a vertical position. Yau [21, 22] also investigated the enthalpy change with an 8-row THPHE in a tropical air conditioning system, Figure 11c. He showed that the overall sensible heat ratio of the HVAC system was reduced as inlet air temperature to the HPHE evaporator increased. Air mass flow rate did not have any effect on the sensible heat ratio results. Using the TRYNYS HVAC model, Yau [23] presented a transient simulation study on an operating theater in Malaysia and found significant improvement in dehumidification capability and reduced energy consumption with possible payback periods of $<$5 years.

Wan *et al.* [24] carried out a theoretical investigation on the effect of a HPHE with precooling of fresh air before mixing, Figure 10c. Assuming a range of conventional indoor design temperature, they showed that, for a three-story, 2673-m^2 office building in China, the rate of energy savings amounted to 23.5–25.7% for the cooling load and 38.1–40.9% for total energy consumption. They concluded that the energy saving in both cooling and total energy consumption increases with increase in indoor design temperature and decrease in indoor humidity.

McFarland *et al.* [25] investigated the effect of a THPHE on the performance of a conventional 3-ton split-unit air residential air conditioning system in relation to dehumidification and auxiliary electric reheat, Figure 11c, but with a reheat section added on after the condenser coil of the HPHE. They operated their system in three modes. A conventional system with reheat was used to establish the baseline operating case. Second, the HPHE was installed to observe its integrated effect on the system performance and room conditions. The last configuration dampered the conventional air conditioning system so that the airflow would equal its value when the HP was installed. They found that for an average room kept at a nominal 22°C and 50% relative humidity, the HP system increased the dehumidification by 62%, decreased the amount of reheat by 20% and increased the latent energy efficiency by 90%. For a 1000-h yearly operation, a simple payback period of 4 years was achieved compared with the conventional system and slightly over 5 years with the dampered system.

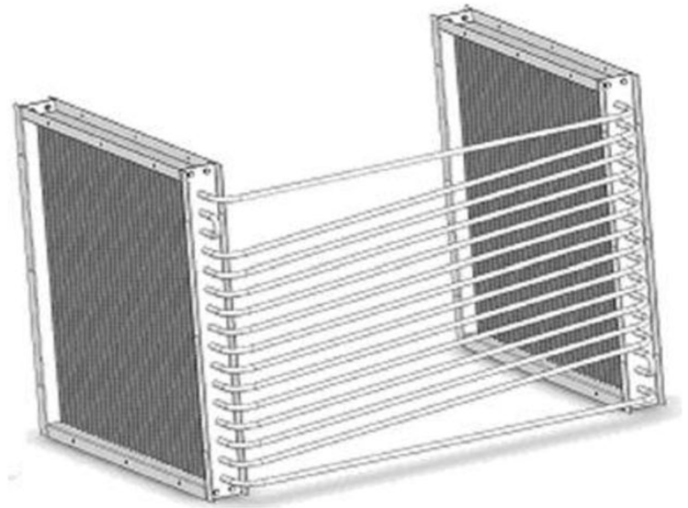

Figure 12. *Three-dimensional view of WHPHE of Jouhara and Meskimmon [27].*

6 WRAP-AROUND HEAT PIPE HEAT EXCHANGER

Jouhara [26] performed a quantitative analysis to determine the potential for energy and cost savings with the use of a 3-m^3/s air flow WHPHE system. Simulations were performed with various outside air conditions and supply air temperature. He showed that an annual saving of nearly 134 MWh could be realized and that the initial additional cost of the WHPHE is marginal when taking into account of the reduced size of the other equipment and operating energy cost. A simple payback period of net additional cost divided by annual energy saving is ~1 month.

Jouhara and Meskimmon [27] investigated experimentally the relationship between effectiveness and air flow velocity with a 7-loop single-row R134a-charged WHPHE shown in Figure 12. They used a 15-kW electric heater located after the condenser coil of the WHPHE instead of an evaporator cooling coil to reverse the temperature difference imposed upon the precool and reheat coils. Tests conducted using six different volumetric air flow rates showed that effectiveness increased as velocity increased. A cost analysis showed that the energy savings can pay for the additional initial cost of the HPHE system within 1 month of operation.

Jouhara and Ezzuddin [28] investigated the R134a-filled WHPHE as shown in Figure 13. The unit consisted of a two-pass evaporator section and a two-pass condenser section with 330 mm long × 11.2 mm diameter bare copper tube. The upper evaporator pipe was at the same level as the lower condenser pipe. Heating (50–500 W) was provided by resistance wires wrapped around the pipe, and coolant water flow rates were between 3.33 and 13.33 × 10^{-3} m^3/s. Their results indicated that the vapor flowed from the upper evaporator pipe to the upper condenser pipe and then flowed back down to the lower evaporator pipe. The thermal resistance was found to decrease with increasing power throughputs up to 250 W (wall heat flux = 9.36 kW/m^2) after which it was found to stabilize to as low as 0.048°C/W.

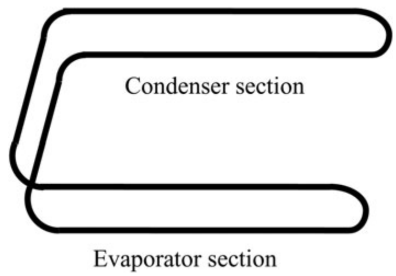

Figure 13. *Three-dimensional view of WHPHE of Jouhara and Ezzuddin [28].*

Zhao *et al.* [29] experimented with the run-around HPHE system, Figure 11c, with various air flow rates, dry bulb temperatures and relative humidity. They showed that dehumidification and cooling capacities increased with the use of the HPHE system. The energy saving varied from 11.8 to 30.3% and was reduced when supply air inlet temperature, air relative humidity and air quantities were increased.

Beckert and Herwig [30] showed that the overall performance of an inclined 6-row 19 pipes/row R22-filled THPHE, Figure 11a, was still satisfactory even up to 6° inclination. Maximum hot air temperature was at 55°C, and cold air supply temperature was between 17 and 29°C. Jouhara *et al.* [31] investigated an ethanol–water azeotrope filled (filling ratio, 0.5) thermosyphon with an inclined (12°) 400-mm-long water-cooled condenser and 1-m-long horizontal evaporator electrically heated to 0.8 kW. They showed that the unit performed satisfactorily even when the evaporator section was inclined from 0 to 90°.

Hagens *et al.* [32] compared the performances of conventional plate-type exchangers with a 4-row R134a-filled THPHE, Figure 11c. Instead of a cooling coil, they incorporated a water–air heat exchanger to heat the air after the condenser section and before the evaporator section of the HPHE. They obtained heat transfer coefficients of 10–40 and 20–50 W/m^2 K for evaporator and condenser sections, respectively. Their results show that the THPHE can replace a water-cooled heat exchanger without loss of performance.

Meskimmon [33] presented simulations for 100% outside make-up air with and without WHPHE under hot and humid climate for moderate climates and showed significant energy savings. He cautioned that because HPs incur penalties in terms of cost and space within the air handling unit, they should be considered for extreme applications where the variation in latent and sensible load changes dramatically. Other case studies of WHPHEs applied to HVAC systems are available in Refs. [34–37].

7 TESTING OF HPHEs

There are numerous works on performance testing of HPHEs. This article will only review some of the works that the author deems are more relevant to the current subject.

Guo *et al.* [38] employed an experimental setup with two staggered rows of HPs that could be rotated such that condenser section could be raised or lowered with respect to the evaporator section. External air chilling or air heating was employed. Air flow varied from 1.57 to 2.91 kg/m^2 s, temperature from -10 to 40°C and tilt angles from -8.9 to 1.2°. They showed that energy effectiveness was not equal even though water vapor condensation effects were insignificant. In the case when equal air flow rates were maintained, effectiveness decreased with air mass flow rate. For unbalanced air mass flow rates, a minimum sensible heat effectiveness was reached when the air flow rates were equal to each other. They also showed that the HPHE performed better when the condenser section was placed higher than the evaporator section.

Azad and Geoola [39] derived an overall effectiveness for an air-to-air HPHE based on the ε-NTU method presented by Kays and London [40].

Noie [41] developed a computer simulation program based on the ε-NTU method formulated by Azad and Geoola [39] for an air-to-air HPHE. His experimental setup, shown in Figure 11a, consisted of 6 rows of 90 vertical thermosyphons joined with top and bottom headers (Figure 8d). The pipes were filled with 60% of distilled water. Condenser air face velocity was maintained at 3 m/s and 25°C. Electrical power input of 18–72 kW allowed the evaporator section inlet temperature to be heated from 100 to 250°C. Evaporator flow rate ranged from 0.5 to 5.5 m/s. He obtained sensible heat effectiveness of around 37–65% and showed that the overall sensible heat effectiveness of the HPHE increases with increasing temperature and stabilized around 150°C. Also, a minimum value was obtained when evaporator and condenser air streams were equal.

Than *et al.* [42] and Than and Ong [43] investigated the performances of air-to-air 2, 4 and 6-row water-filled THPHE as shown in Figure 10a with top and bottom with headers (Figure 8c). Fill ratio was 0.7, evaporator temperature was between 45 and 100°C and condenser temperature was ~30°C. They found that sensible heat effectiveness increased with higher temperature difference and more rows but tapered off significantly beyond a temperature difference ranging from 50 to 80°C depending on the number of rows employed. A 10–20°C temperature difference between evaporator and condenser temperatures was required to operate the water-filled THPHE. The effectiveness was found to be at a minimum when equal flow rates were employed.

Ong and Lum [44] experimented with a 6-row water-filled air-to-air LHPHE as shown in Figures 7b and 8c. Tests were carried out with evaporator and condenser flow rates from 0.25 to 1.00 m/s, evaporator inlet temperature at 60, 75 and 90°C and condenser inlet temperature around 30°C. Their results showed that heat transfer rate increased as evaporator inlet temperature and air flow rates increased. Also, overall sensible effectiveness was found to be at a minimum when both air streams were equal. They managed to obtain an effectiveness of 0.88 at evaporator flow rate of 1 m/s, condenser flow rate of 0.25 m/s and evaporator inlet temperature of 90°C.

Ong and Wong [45] experimented with a 4-row R134a-filled THPHE similar to that shown in Figures 7a and 8b. Tests were carried out with evaporator temperatures from 30 to 48°C and air flow rates from 0.15 to 0.65 m/s. Their results showed that heat transfer rate increased as evaporator inlet temperature and air flow rates increased and that overall sensible effectiveness was minimum when both air streams were equal. They managed to obtain an effectiveness of 0.80 with the THPHE. Similar results were obtained by Ong [46] using the R410-filled LHPHE.

8 CONCLUSIONS

This article reviews some of the works conducted on HPHEs as run-around coils in a HVAC system for cooling and dehumidification. The evaporator section could be located on the fresh air intake duct or after mixing to provide precooling to the cooling coil of an air conditioning system. They are effective in enhancing dehumidification and reducing air conditioning costs especially in hot and humid tropical countries. Numerous investigations have been carried out on thermosyphons using various fill liquids and the effects of fill ratio, inclination and the aspect ratio on their performances. The effects are interlinked. However, very few have been done in an integratSed and comprehensive manner on the HPHEs. There is few work on simulation models especially for the WHPHEs.

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