A Review of Heat Pipe Heat Exchangers Activity in Asia

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***Abstract*—**Heat pipes are two-phase heat transfer devices with high effective thermal conductivity. Due to the high heat transport capacity, heat exchanger with heat pipes has become much smaller than traditional heat exchangers in handling high heat fluxes. With the working fluid in a heat pipe, heat can be absorbed on the evaporator region and transported to the condenser region where the vapour condenses releasing the heat to the cooling media. Heat pipe technology has found increasing applications in enhancing the thermal performance of heat exchangers in microelectranics, energy saving in HVAC systems for operating rooms,surgery centers, hotels, cleanrooms etc, temperature regulation systems for the human body and other industrial sectors. Development activity in heat pipe and thermosyphon technology in asia in recent years is surveyed. Some new results obtained in Australia and other countries are also included.

***Keywords*—**Heat pipe heat exchanger, Thermosyphone, effectiveness, HVAC system, energy saving, temperature regulation.

I. INTRODUCTION

AS a highly-effective heat transfer element, heat pipes have gradually recognized, and are playing a more and more important role in almost all industrial fields. A heat pipe is an evaporation-condensation device for transferring heat in which the latent heat of vaporization is exploited to transport heat over long distances with a corresponding small temperature difference. The heat transport is realized by means of evaporating a liquid in the heat inlet region (called the evaporator) and subsequently condensing the vapour in a heat rejection region (called the condenser). closed circulation of the working fluid is maintained by capillary action and /or bulk forces. The heat pipe was originally invented by Gaugler of the General Motors Corporation in 1944, but did not truly garner any significant attention within the heat transfer community until the space program resurrected the concept in the early 1960's. An advantage of a heat pipe over other conventional methods to transfer heat such an a finned heat sink, is that a heat pipe can have an extremely high thermal conductance in steady state operation. Hence, a heat pipe can transfer a high amount of heat over a relatively long length with a comparatively small temperature differential. Heat pipe with liquid metal working fluids can have a thermal conductance of a thousand or even tens of thousands of times greater than the best solid metallic conductors, silver or copper.

There are generally at least five physical phenomena that will limit, and in some cases catastrophically limit, a heat pipe ability to transfer heat. They are commonly known as the sonic limit, the capillary limit, the viscous limit, the entrainment limit and the boilling limit.

II. HEAT PIPES IN HVAC SYSTEMS

The application of heat pipes for heat recovery in cold climates is widely recognised. With advancement of heat pipes with a low air pressure drop, made possible by loop configurations, heat recovery applications can be extended to milder climates and still pay for themselves. A new possibility is 'cooling' recovery in summertime, which is now economical enough to be considered. The application of heat pipes to increase the dehumidification capacity of a conventional air conditioner is one of the most attractive applications. By using dehumidifier heat pipes, one can decrease the relative humidity in the conditioned space (typically by 10%) resulting in noticeably improved indoor air quality and reduce power demand. Heat pipe also promise to improve greatly indoor air quality, and at the same time help conserve energy.

Wasim SAMAN examined the possible use of a heat pipe heat exchanger for indirect evaporative cooling as well as heat recovery for fresh air preheating. Thermal performance of a heat exchanger consisting of 48 thermosyphons arranged in six rows was evaluated. The tests were carried out in a test rig where the temperature and humidity of both air streams could be controlled and monitored before and after the heat exchanger. Evaporative cooling was achieved by sparying the condenser sections of the thermosyphons. The parameters considered include the wetting arrangement of the condenser section, flow ratio of the two streams, initial temperature of the primary stream and the inclination angle of the thermosyphons. Their results showed that indirect evaporative cooling using this arrangement reduces the fresh air temperature by several degrees below the temperature drop using dry air alone [1].

Humidity control is a never-ending war in tropical hot and humid built environment. Heat pipes are passive

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components used to improve dehumidification by commercial forced-air HVAC systems. They are installed with one end upstream of the evaporator coil to pre-cool supply air and one downstream to re-heat supply air. This allows the system's cooling coil to operate at a lower temperature, increasing the system latent cooling capability. Heat rejected by the downstream coil reheats the supply air, eliminating the need for a dedicated reheat coil. Heat pipes can increase latent cooling by 25-50% depending upon the application. Conversely, since the reheat function increases the supply air temperature relative to a conventional system, a heat pipe will typically reduce sensible capacity. In some applications, individual heat pipe circuits can be controlled with solenoid valves to provide improved latent cooling control. Primary applications are limited to hot and humid climates and where high levels of outdoor air or low indoor humidity are needed. Hospitals, supermarkets and laboratories are often good heat pipe applications. You and Tucker [2] mentioned that for many years, heat pipe heat exchangers (HPHEs) with two-phase closed thermosyphons, as show in Fig. 1, have been widely applied as dehumidification enhancement and energy savings device in HVAC systems.

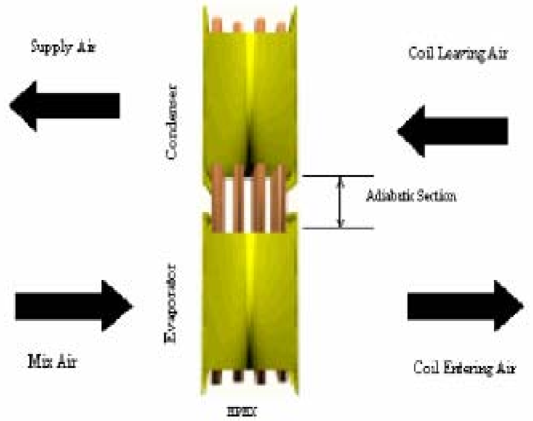

Fig. 1 A typical heat pipe heat exchanger (HPHE) applied in HVAC systems

Literature review indicated that research work related to energy recovery using HPHE carried out in sub-tropical climates is hardly found. Niu et al. [3] studied a HVAC system combining chilled ceiling with desiccant cooling for maintaining the indoor air humidity within a comfort zone and to reduce the risk of water condensation on chilled panels. The results reveal that chilled ceiling combined with desiccant cooling might conserve up to 44% of primary energy use compared to a conventional constant volume all-air system.

In a separate study, Zhang et al. [4] conducted a research on energy consumption for conditioning ventilation air and the annually performance of a membrane-based energy recovery ventilator (MERV) in Hong Kong.The results indicated that approximately 58% of the energy needed for cooling and heating fresh air might be saved yearly with an MERV, while only roughly 10% of the energy might be saved via a sensible-only energy recovery ventilator (SERV). In a similar study, Zhang et al. [5] conducted a study on a thermodynamic model built with an air moisture removal system incorporated a membrane-based total heat exchanger to estimate the energy use annually. The outcomes suggested that the independent air moisture removal could save 33% of primary energy.

Yat H. Yau [6] studied an 8-row thermosyphon-based heat pipe heat exchanger for tropical building HVAC systems experimentally. This research was an investigation into how the sensible heat ratio (SHR) of the 8-row HPHE was influenced by each of three key parameters of the inlet air state, namely, dry-bulb temperature, relative humidity and air velocity . On the basis of his study, it is recommended that tropical HVAC systems should be installed with heat pipe exchangers for dehumidification enhancement. The HPHE evaporator section functions as a pre-cooler for the AC system and the condenser section as a reheating coils as shown in Fig. 2.

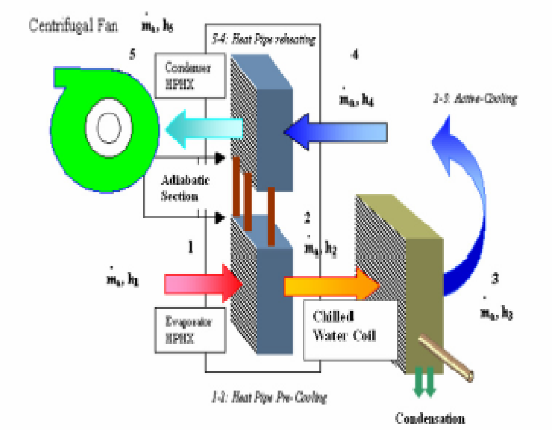

Fig. 2 Simple schematic diagram for HVAC model running with a HPHE [2]

By doing this the cooling capacity for the original system is re-distributed so that latent cooling capability of the conventional cooling coil is enhanced.

In hot and humid tropical climates, the moisture removal capability of the chilled water coil in the HVAC systems can be enhanced if the supply air is pre-cooled before reaching the chilled water coil. For instance, a typical HVAC system at average ambient condition of 32^0C and 58% relative humidity (RH) with total cooling load at 58.5 kw can save 14.4 kw if HPHE is added into the HVAC system as shown in Fig. 3.

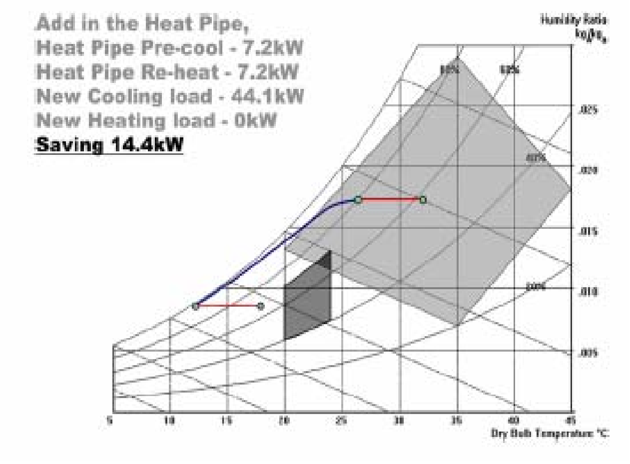

Fig. 3 Simple psychrometric processes for a typical HVAC system with an added HPHE at average ambient conditions of 32^0C and 58% RH

Fig. 4 represents this situation with the present experimental air state numbering system superimposed.

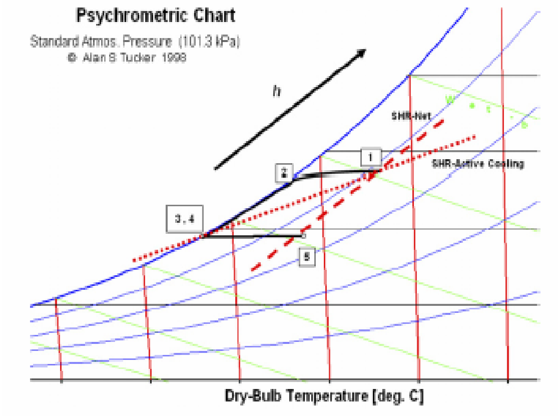

Fig. 4 HPHE overcooled and reheat processes in a HVAC system

The latent heat is a considerable factor in calculating the performance of the HPHE in humid conditions. An inaccurate result will be gained if only sensible heat is taken into account by using the Number of Transfer Units (ε-NTU) method, which is quit often used for HPHE calculations.

An analysis of the evaporator and condenser sections of the thermosyphon HPHE, modelling both warm and cold gas streams as moist air, has been conducted, and the modelled results compared with experimental data by X.P. WU et al.[7]. It was observed that inclusion of latent heat in HPHE modelling can significantly improve accuracy.

A new kind of heat pipe dehumidifier is designed and tested by Zhao et.al. [24]. The energy-saving ratio with the heat pipe dehumidifier ranges from 11.81% to 30.34% compared with the normal dehumidifier ,according to the performance testing. The dehumification capacity and the surface cooler power increases, but the energy saving ratio is reduced with the increase of air relative humidity, dry bulb temperature and air quantity.

III. TEMPERATURE REGULATION SYSTEMS FOR THE HUMAN BODY

The need to regulate body temperature exists where human activities are conducted in extreme temperature environments. Very cold environments are encountered by undersea divers, inhabitants of polar regions, pilots, mountain climbers and snow skiers, as well as by individuals who work in more pedestrian cold environments such as refrigerated containers. Very hot environments are encountered by those in diverse occupations such foundry workers. The need for body temperature regulation also exists in the treatment of medical conditions. Individuals with impaired body temperature regulation systems, such as the elderly, stroke patients, and patients with spinal cord injuries or multiple sclerosis, may be subject to chronic hypothermia or hyperthermia. Victims of exposure, as well as patients having fever, dehydration, infection, and drug reactions may suffer temporarily from hypothermia or hyperthermia, and may require treatment including body temperature regulation. Deliberate inducement of whole body hyperthermia has been found to be useful as a treatment for cancer, and has met with success. However, side effects range from fatigue to occasional mortality. Injury to temperature-sensitive body parts, such as the liver, has also been associated with whole body hypothermia. Because of these side effects, and the high labor costs associated with monitoring such treatment, regional, rather than whole body, hypothermia has found favor in the treatment of cancer. Inducement of regional or localized hyperthermia has, thus, also been used in the treatment of cancer, as well as in the treatment of joint diseases, such as capsulitis, tendinitis and lower back pain. Various means have been developed to warm and cool the human body to achievebody temperature regulation needed for such activities and medical treatments. Cold suits, such as the glove shown (Fig. 5), include circulating fluid systems powered by a pump for circulating in the serpentine tubes extend along the arms of thewearer and converge at inlet and outlet manifolds. Cold suits, however, have the disadvantage of being heavy and are typically restrictive, causing exhaustion and cardiopulmonary distress in the wearer. In the blanket of Sgroi, the heat pipes converge at one side of the blanket to be cooled by a refrigeration device or, alternatively, heated by a thermal energy source. Suits and blankets having circulating fluid loops in similar configurations may also be used to provide heat to persons suffering from hypothermia. However, the same general disadvantages of weight, restriction of movement, and resulting exhaustion are present.

Electric blankets are also well-known but often provide uneven heating, and subject the user to low-level electromagnetic radiation. Nonetheless, whether used for heating or cooling, such suits and blankets generally disadvantageously require external connections and/or require external power sources. Numerous devices have been developed for regional, therapeutic heat transfer. Faghri's invention [25] meets the need for lightweight, comfortable suits and blankets for body temperature regulation by using heat pipes to redistribute body heat and to provide supplemental heat from external sources. A temperature regulation system for the human body results, taking the form of garments, blankets and pads. This invention further provides for an improved pad incorporating heat pipes for use in regional, therapeutic heat transfer. The heat pipes are positioned to provide heat transfer between one or more separate portions of the body. A garment for use in cold environments, such as a body suit, pants or jacket, may, thus, include heat pipes which extend from the torso of the body, which is typically warmer, to an extremity. The torso is thereby used as a heat source to warm any extremity such as the head, arms, hands, legs and feet, or portions thereof. As well, warmer, more central portions of the torso may be used in a garment, such as a vest, to distribute heat to other parts of the torso. A garment for use in warm environments, such as shorts, vests or hooded articles, may include heat pipes which extend from the head or other heat-sensitive areas, to cooler portions of the body, or to the outer surface of the garment to remove heat from the head or other heat-sensitive areas. The first embodiment, thus, permits body temperature to be regulated to a more uniform level by redistributing heat, as needed, to provide warming or cooling from one body area to another to enable an individual to carry out activities, or to assist a patient in satisfying medical needs for heating or cooling. In a second embodiment, the garment of the first embodiment further includes a heat exchanger, a portion of which intersects one or more of the heat pipes to provide heat transfer between one or more portions of the body and the heat exchanger. The heat exchanger includes a heat exchanger element which is preferably disposed in the torso area of the garment, a circulating fluid loop, and a means for heating or means for cooling. Where the garment is to be used in cold environments, the heat exchanger includes means for heating the circulating fluid, and where used in hot environments, includes means for cooling the circulating fluid. Alternatively, the heat exchanger may include a heat exchanger element including electrical resistive heaters, preferably disposed in the torso area, and an external source of electrical power. The heat exchanger, further, preferably includes a temperature control device, such as a thermocouple or thermostat. Temperature control is of particular interest where the present invention is used for deliberate inducement of hyperthermia for medical treatment, or to provide controlled heating or cooling for hypothermia or hyperthermia patients. A third embodiment of the garment of the invention is a hybrid of the first and second embodiments thereof. The third embodiment includes a heat exchanger of the second embodiment to supply supplemental heating or cooling from the heat exchanger to at least one portion of a body, while one or more heat pipes provide heat transfer between portions of a body in accordance with the first embodiment. In a fourth embodiment, the garment of the present invention includes at least two heat exchangers which intersect separate groups of one or more heat pipes to provide heat transfer between separate portions of a body and the heat exchangers, permitting selective and simultaneous heating or cooling of separate portions of the body. For example, in a garment such as a body suit, this fourth embodiment provides a means to overcome problems with damage to heat-sensitive organs when whole body hyperthermia is induced for medical treatment. Heat may be applied to major portions of the body to induce hyperthermia with one heat exchanger having means for heating, while portions of the body having heat-sensitive organs may be cooled with another heat exchanger having means for cooling.

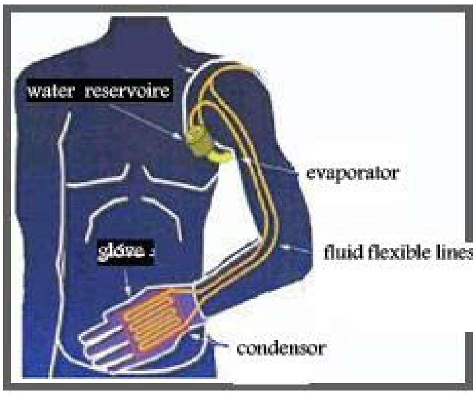

Fig. 5 A method for temperature regulation in hand

IV. HEAT PIPE HEAT EXCHANGER (HPHE) IN INDUSTRIAL SYSTEMS

Since the 1970s, HPHE have been extensively applied in many industries such as energy engineering, chemical engineering and metallurgical engineering as waste heat recovery systems. One of the important applications of heat pipes as HPHE is the recovery of heat from exhaust gases in industrial plants.[8-11]. As exhaust gases enter the surrounding, not only waste energy but also damage the environment. Due to the high transport capacity, heat exchangers with heat pipes are smaller than traditional heat exchangers in handling high heat fluxes .S.H.Noie [12] investigated the thermal performance of a heat exchanger consisting of 90 thermosyphons arranged in six rows in a test rig. The variable parameters which were being altered were the air velocity and the inlet temperature to the evaporator section.

A computer program was developed to analyze the thermosyphon heat exchanger using the ε- NTU method. In order to verify its accuracy and conformity, the experimental results were compared to those predicted by the simulation program. The temperature across the evaporator section was varied in the range of 100-250 ^{0C} while the inlet temperature to condenser section was nearly constant 25 ^{0C}. Distilled water was used as the working fluid with a fill ratio of 60 % of the evaporator section length. 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 using electric heating elements. The overall effectiveness of the thermosyphon heat exchanger obtained from experiments varied between 37% and 65%. The experimental results showed the minimum effectiveness of the thermosyphon took place at $C_h = C_c$. Therefore, equal value of air face velocities in evaporator and and condenser sections should be avoided.

Research and applications of water-based HPHE for heat recovery have been reported in some works [13-15] but appear still limited in comparison with organic-based fluids. As an extension of the work by Than et al. [15,16], experimental testing on more water-based HPHE configurations and comparison with the prediction by the effectiveness- NTU method have been carried out and the results are presented. They showed effectiveness increases with the number of rows, the increase is about 30% .from 2 to 4 rows and 10-20% from 4 to 6 rows. Comparison between the 4-row and 2X2-row modules shows the latter has higher effectiveness especially at flow rate ratio>1, suggesting that the gap between the 2-row modules serves to break up the thermal boundary layer in the air passages between the fins.

The feasibility of using heat pipe heat exchangers for heating applying automotive exhaust gas is studied by F. Yang et al. [17]. Practical heat pipe heat exchanger was set up for heating a large bus. Simple experiments were carried out to examine the performance of the heat exchanger. It was shown that the experimental results, which indicate the benefit of exhaust gas heating, are in good agreement with numerical results. A closed-ended oscillating heat-pipe (CEOHP) air-preheater for energy thrift in a dryer was investigated by S. Rittidech et.al.[18]. The CEOHP air-preheater design employed cooper tubes: thirty –two set of capillary tubes with an inner diameter of 0.002 m, an evaporator and a condenser length of 0.19 m, and each of which has eight meandering turns. The evaporator section was heated by hot-gas, while the condenser section was cooled by fresh air. In the experiment, the hot-gas temperature was 60,70 or 80 ^{0C} with the hot-gas velocity of 3.3 m/s. The fresh air temperature was 30 ^{0C}. Water and R123 was used as the working fluid with a filling ratio of 50%. It was found that, as the hot-gas temperature increases from 60 to 80 ^{0C}, the thermal effectiveness slightly increases. If the working fluid changes from water to R123, the thermal effectiveness slightly increases. The designed CEOHP air-preheater achieves energy thrift.

An experimental study was carried out for the heat transfer characteristics and the flow patterns of the evaporator section using small diameter coiled pipes in a looped heat pipe (LHP) by Jie Yi et.al. [19]. Two coiled pipes: the glass pipe and the stainless steel pipes were used as evaporator section in the LHP, respectively. Flow and heat transfer characteristics in the coiled tubes of the evaporator section were investigated under the different filling ratios and heat fluxes. The experimental results show that the combined effect of the evaporation of the thin liquid film, the disturbance caused by pulsation and the secondary flow enhanced greatly the heat transfer and the critical heat flux of the evaporator section.

Wangnipparnto et.al.[23] investigated a numerical method to analyze the thermosypon heat exchanger with and without the presence of electrohydrodynamics. The proposed model was capable of handling both balanced and unbalanced thermosyphon heat exchangers. For the balanced thermosyphon heat exchanger, the calculated results of heat transfer rate for water and R-134a agreed well with experimental data. For the unbalanced thermosyphon heat exchangers, it was found that the performance improvement increased with the ratio of m'_e / m'_c when electrohydrodynamics was applied at the condenser alone. Fig. 6 shows the schematic diagram of the experimental apparatus.

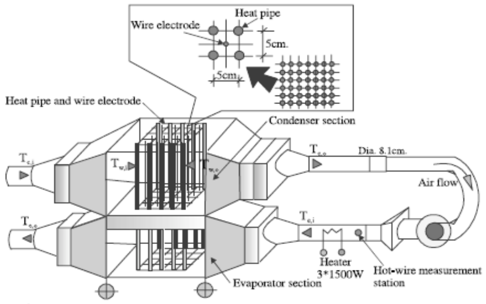

Fig. 6 Schematic of the experimental apparatus

V. CONCLUSION

A short review of heat pipe applications and technology contains mainly data from some country in Asia which testifies, that heat pipes are very efficient heat transfer devices, which can be easily implemented as thermal links and heat exchangers in different systems to ensure the energy saving and environmental protection.

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