Performance investigation of Waste heat recovery heat pipe heat exchanger by using nanofluid with variable source temp

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Abstract— The objective of this research is to develop a thermosyphon heat exchanger for a waste air heat recovery system. The advantage of the system proposed in this work is that it provides useful energy transfer during simultaneous flow of cold supply and warm drain air. While this concept is not new, the conventional fluid is replaced by nanofluid in proposed heat exchanger, makes the present study is significantly different from those used previously. Component experiments were carried out to determine the performance characteristics of a heat pipe heat exchanger by using nanofluid. By replacing the conventional fluid in heat pipe with nanofluid, the performance of heat pipe heat exchanger is increased. A model of a multi-heat pipe heat exchanger predicts the energy savings.

Index Terms—Waste heat, heat pipe, heat exchanger, nanofluid.

I. INTRODUCTION

A. Need of Waste Heat Recovery

Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then “dumped” into the environment even though it could still be reused for some useful and economic purpose. Hot air plays an import role in modem life. The consumption of hot air represents a significant part of the nation's energy consumption. One way of reducing the energy consumption involved, and hence the cost of that energy, is to reclaim heat from the waste warm air that is discharged to the sewer each day. The potential for economic waste air heat recovery depends on both the quantity available and whether the quality fits the requirement of the heating load. To recover heat from waste air in residential and commercial buildings is hard to achieve in quality because of its low temperature range. Nevertheless, efforts to recycle this waste energy could result insignificant energy savings.

The objective of this research was to develop TPCT heat exchanger for a waste air heat recovery system. The advantage of the system proposed in this work is that it provides useful energy transfer during simultaneous flow of cold supply and warm drain air. While this concept is not new, the design of the heat exchanger proposed for the present study is significantly different from those used previously. Component experiments were carried out to determine the performance characteristics of a wickless heat pipe heat exchanger panel by using nanofluid.[6] By replacing the conventional fluid in heat pipe with nanofluid of the heat pipe heat exchanger good performance can be obtained. A model of a multi-heat pipe heat exchanger panel will also develop to predict the energy savings that would be expected.

B. Construction and Working of Two-Phase Closed Thermosyphon

The two-phase closed thermosyphon used in this study is essentially a gravity-assisted wickless heat pipe, which is very efficient for the transport of heat with a small temperature difference via the phase change of the working fluid. It consists of an evacuated-closed tube filled with a certain amount of a suitable pure working fluid. The simple design, operation principle, and the high heat transport capabilities of two-phase closed thermosyphons are the primary reasons for their wide use in many industrial and energy applications. The two-phase closed thermosyphon (TPCT), which is essentially a gravity-assisted wickless heat pipe, utilizes the evaporation and condensation of the working fluid inside the heat pipes to transport heat. In contrast to the conventional heat pipe using capillary force to return the liquid to evaporator, a TPCT uses gravity to return the condensate. Its position is not restricted and it may be used in any orientation.

A cross section of a closed two-phase thermosyphon is illustrated in Fig. 1. The thermosyphon consists of an evacuated sealed tube that contains a small amount of liquid. The heat applied at the evaporator section is conducted across the pipe wall causing the liquid in the thermosyphon to boil in the liquid pool region and evaporate and/or boil in the film region. In this way the working fluid absorbs the applied heat load converting it to latent heat.

The vapour in the evaporator zone is at a higher pressure than in the condenser section causing the vapour to flow upward. In the cooler condenser region the vapour condenses thus releasing the latent heat that was absorbed in the evaporator section. The heat then conducts across the thin liquid film and exits the thermosyphon through the tube wall and into the external environment. Within the tube, the flow circuit is completed by the liquid being forced by gravity back to the evaporator section in the form of a thin liquid film. As the thermosyphon relies on gravity to pump the liquid back to the evaporator section, it cannot operate at inclinations close to the horizontal position.

C. How Does A Heat Pipe Heat Recovery Unit Operate?

The heat pipe heat exchanger is constructed of individual heat pipes, each tested and inspected to insure peak performance. These exchangers provide a simple, efficient and compact method of air-to-air heat recovery. They resemble conventional heating and cooling coils, but have several important differences. First, a partition divides the exchanger into two sections, thus ensuring the separation of supply and exhaust airflows. Second, each heat pipe is an individual heat exchanger not dependent on any other part to ensure operation. The exchanger formed by these heat pipes is a counter flow design. In operation, exhaust air is passed across one section of the exchanger (exhaust side) and supply air is ducted in counter flow direction across the other section (supply side). Heat is transferred from the hot airstream to the cold airstream by the heat pipes. While the heat pipe can recover up to 82% of exhaust air heat under ideal conditions, the economical heat recovery rate is between 50 and 65%. This represents a tremendous saving of energy. In addition, the heat pipe is reversible and can cool outdoor air in summer. Heat pipe is a year round energy savings device. Heat pipes are also well suited to recover heat from moisture laden air. This recovery is, in effect, done through the action of condensing the vapor in the exhaust stream into water. This process has the effect of increasing the capacity of the exchanger while minimizing the danger of frost formation.

D. A New Heat Transfer Enhancement Approach With Nanofluid:

There is a great need for more efficient heat transfer fluids in many industries, from transportation to energy supply to electronics. The coolants, lubricants, oils, and other heat transfer fluids used in today's conventional thermal systems (including radiators, engines, and HVAC equipments) have inherently poor heat transfer properties, and conventional working fluids that contain millimeter- or micrometer-sized particles do not work with the newly emerging "miniaturized" technologies because they can clog in micro channels. By applying nanotechnology to thermal engineering, researchers has created nanofluids to solve these problems. These nanofluids have an unprecedented combination of the two features most highly desired for thermal system applications: extreme stability and ultra-high thermal conductivity. It has long been recognized that suspensions of solid particles in liquids have great potential to increase heat transfer rate of fluids. The key idea is to exploit the very high thermal conductivities of solid particles, which can be hundreds or even thousands of times greater than those of conventional heat-transfer fluids such as water and ethylene glycol. Although such suspensions do indeed display the desired increase in thermal conductivity, they suffer from stability problems. In particular, the particles tend to quickly settle out of suspension and thereby cause severe clogging, particularly in mini and micro channels. A novel approach to engineering fluids with better heat-transfer properties, based on the rapidly emerging field of nanotechnology, has recently been proposed. In particular, it was demonstrated that solid nanoparticles colloids (i.e. colloids in which the grains have dimensions of 10-40 nm) are extremely stable and exhibit no significant settling under static conditions, even after weeks or months. Furthermore, the enhancement of thermal-transport properties of such "nanofluids" was even greater than that of suspensions of coarse-grained materials. [5]

II. LITERATURE REVIEW

Lerchai Yodrak, Sampan Rittidech [1] studied heat recovery system at Furnace in a Hot Forging Process; he concluded that the experiment findings indicated that when the hot gas temperature increased, the heat transfer rate also increased. If the internal diameter increased, the heat transfer rate increased and when the tube arrangement changed from inline to staggered arrangement, the heat transfer rate increased.

Yat H. Yau [2] 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, and 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 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).

F. Yang, X. Yuan, G. Lin [3] studied the feasibility of using heat pipe heat exchangers for heating applying automotive exhaust gas. 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.

S. Rittidech, W. Dangeton, S. Soponronnarit [4] 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.

S. Suresh a, K.P. Venkitaraj, P. Selvakumar, M. Chandrasekar (2012) [5] investigated the heat transfer and pressure drop characteristics through a uniformly heated circular tube using Alumina-Copper /water hybrid nanofluids under fully developed laminar flow conditions. In this study, the hybrid particle was synthesized in a thermo chemical route. The volume concentration used was 0.1% and the composition used was 90% Alumina and 10% Copper. A maximum enhancement of 13.56% in Nusselt number was obtained for a Reynolds number of 1730 when compared to Nusselt number of water.

M. Chandrasekar, S. Suresh, A. Chandra Bose (2010) [6] conducted experimental and theoretical investigations of the effective Thermal conductivity and viscosity of Al2O3/water nanofluids. During the experimental investigation it was noticed that both the thermal conductivity and viscosity values increase with that of the nanoparticle volume concentration.

Kyo Sik Hwang , Seok Pil Jang , Stephen U.S. Choi (2008) [7] investigated the pressure drop and convective heat transfer coefficient of water based alumina nanofluids flowing through a uniformly heated circular tube in fully developed laminar flow regime. The experimental results show that the convective heat transfer coefficient enhancement exceeds, by a large margin, the thermal conductivity enhancement. In this study, based on scale analysis and numerical solutions, they have shown the flattening of velocity profile induced from large gradients in bulk properties such as nanoparticle concentration, thermal conductivity and viscosity.

III. THEORY OF OPERATION

A. Thermosyphon Heat Transfer Theories

For a single two-phase closed thermosyphon as shown in Figure 1 and for the thermal resistance diagram shown in Figure 2 heat is transferred from a heat source, through the evaporator wall, into the working fluid and then out through the condenser to the heat sink. This heat transfer rate may be conveniently expressed in terms of a temperature difference and a series of thermal resistances as follows. If the heating and cooling water inlet and outlet temperatures and the mass flow rates of the heating and cooling streams are known the evaporator and condenser section heat transfer rates in accordance with the conservation of energy can be calculated as[4]

$$Q_{hp}=Q_e+Q_c \quad (1)$$

Where,

$Q_{hp} = (T_h-T_c)/R$, $Q_e= (T_h-T_i)/R_e$, $Q_c= (T_i-T_c)/R_e$

where

$T_h= (T_{hi}+T_{ho})/2$, $T_c= (T_{ci}+T_{co})/2$

$R= R_e+R_c$

Where,

$R_e= R_{eo}+R_{ew}+R_{ei}$, $R_c= R_{ci}+R_{cw}+R_{co}$,

$R_{eo}= 1/n_{ef}\, h_{ef}\, A_{ef}$, $R_{ew}= \ln(d_o/d_i)/2k\pi L_e$,

$R_{ei}=1/h_{ei}A_{ei}$

$A_{ei}=\pi d_i L_e$

$R_{ci}=1/h_{ci}A_{ci}$

$A_{ci}=\pi d_i L_c$

$R_{cw}=\ln(d_o/d_i)/2\pi k L_c$, $R_{co}=1/n_{cf}\, h_{cf}\, A_{cf}$

The right hand terms Q & loss/gain in equations (2) and (3) account for the heat that is not transferred to the working fluid in the evaporator and from the working fluid in the condenser but that which is lost or gained from the environment and through the supporting structure. The heat

loss/gain terms are however relatively small for a HPHE.

$$Q_e=m_e c_p(T_{hi}-T_{ho})+Q_{loss/gain} \quad (2)$$

$$Q_c=m_c c_p(T_{co}-T_{ci})+Q_{loss/gain} \quad (3)$$

B. HPHE Geometry

A HPHE would normally require a relatively large number of individual pipes. The pipes are then grouped in rows of to form a tube-bank as shown in Figure 3. If the streams are gasses then the pipes would be finned to enhance heat transfer, much the same as typical HVAC coils, except that there is a separator-plate to prevent mixing of the two streams.

C. Performance Calculation

To calculate the amount of heat that can be transferred by the HPHE the theory as given in section 3.1 is applied systematically to each individual heat pipe in turn. The geometry and dimensions must thus be known as well as the heat transfer coefficients and thermal conductivities h_{eo}, k_e, h_ei, h_ci, k_c and h_{co} and the temperatures T_{hi}, T_{ho}, T_{ci} and T_{co}. Correlations for the internal heat pipe heat transfer coefficients h_{ei} and h_{ci} are not normally available in HVAC and heat transfer texts but have to be experimentally determined. The internal temperature Ti can then be found by trial and error by guessing values for Ti in equation 1 such that $Q_c = Q_e$. In a similar way temperature and heat flux dependent variables may be taken into account as well. The basic solution procedure requires that the hot and cold stream inlet temperatures be specified. Starting from the 1st row, of the counter flow heat exchanger configuration is shown for example, cold stream outlet temperatures are estimated and then by “marching” from one row to the next the inlet cold stream temperature is calculated. This iteration procedure is repeated for different values of cold stream outlet temperature until the calculated cold steam inlet temperature corresponds to the initially specified value.[4]

The experimental set-up consisted of the HPHE unit as shown in Figure 4 for a Waste Heat Recovery unit . The specifications of the HPHE ar, its detailed are given in Table 2 and it is manufactured by using heat pipe of copper tube and GI sheet plate. The waste heat recovery unit usually absorb heat from waste heat source at evaporator section and release it to the condenser section. To monitor temperatures, K type thermocouples were used and this measurement was processed by digital thermometer. The atmospheric air is heated by the three electric heating elements 500 W each. After giving part of this heat to the evaporator section, the air is discharged to the atmosphere.

With the HPHE installed, this warm moist air is then fed through the evaporator section of the HPHE. Fresh ambient air is then drawn through the condenser section of the HPHE where it is heated up and is then it can be used for various appliances. Temperature measurements were taken at the inlets and outlet of the respective hot and cold streams and an anemometer was used to measure the flow velocities, from which the air mass flow rates could be calculated. Tests runs at variable temperature source with constant flow rate.

IV. RESULT AND DISCUSSIONS

A number of tests were performed to investigate the performance of the heat pipeheat exchanger, by blowing hot and cold air with variable mass flow rates and different wattage over the heat pipe. The rate of axial heat transfer by conduction of individual heat pipe was calculated and found to be negligible in comparison with heat transport to air. With reference to mass flow rate of warm and cool air, the heat transfer rates to the evaporator and condenser sections are calculated for various source temperatures, after experiment we get some values of temperatures at evaporator and condenser section as follows

T_{hi}=92.7, T_{ho}=76.3, T_{ci}=26.5, T_{co}=35.7

By neglecting the $Q_{loss/gain}$, Q_e and Q_c is calculated by equations,

$Qe= m_e c_p(T_{hi}-T_{ho})$

$Qc = m_c c_p(T_{co}-T_{ci})$

The effectiveness of the heat exchanger is defined as the ratio of the actual rate of heat

transfer by the heat exchanger to the maximum possible heat transfer rate between the air

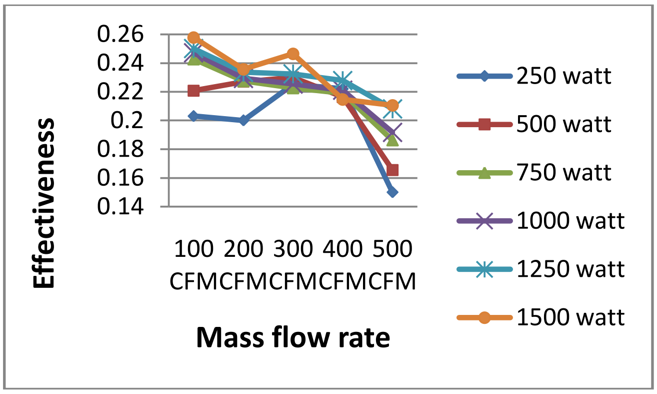
streams. Effectiveness Ɛ is calculated by

$Ɛ= Q_e / Q_c = (T_{hi}-T_{ho}) / (T_{co}-T_{ci}) = 0.247$

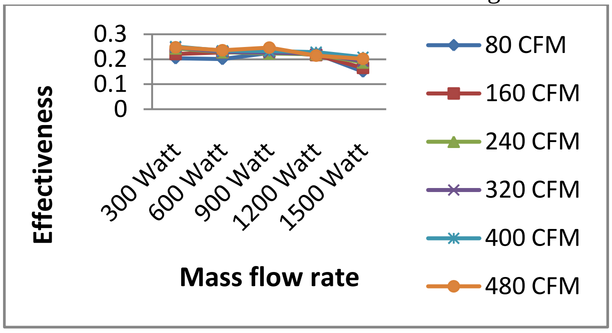
Graphs 1,2,3,4 shows the variation of effeteness with various parameters

Graph 1

Variation of effectiveness with variable mass flow rate

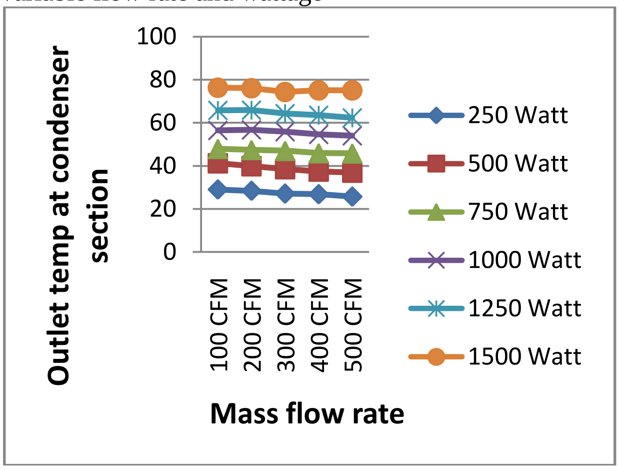


Graph 2
Variation of effectiveness with variable wattage



Graph 3
Variation in inlet temperature of condenser section at variable flow rate and wattage

Graph 4
Variation in outlet temperature of condenser section at variable flow rate and wattage



V. CONCLUSIONS

1) The heat transfer rate between the hot and cold streams of the heat pipe (thermosyphon) heat recovery heat exchanger is accurately predicted by the theoretical model for average temperature difference between the two streams of greater than 15 °C.

2) The experimental evaluation of the heat recovery heat exchanger with boron nitrategives better results and increases effectiveness as compared to other fluids.

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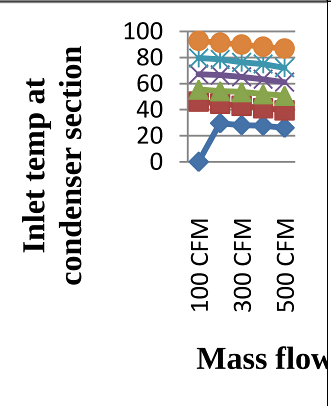
Heat Recovery Unit's required specification for the HPHE

Inlet hot temperature	30-100°C
Inlet cold temperature	Ambient air
Desired outlet temperature	Whatever is attainable
	100 CFM-500CFM
Mass flow of the air into the condenser section	
Mass flow of the air into the	100 CFM-500CFM

evaporator section	

Table 2
Design and manufactured definition of the HPHE to be tested

Working Fluid	**Nano Fluid of Water and Boron Nitrate**
Tube bank configuration	GI Sheet Plate and Cu tube
Evaporator length	300 mm
Condenser length	300 mm
Number of tube	8
Outside diameter of tubes	15.88 mm
Inside diameter of tubes	14.90 mm

Figure 1
A typical two-phase closed thermosyphon.

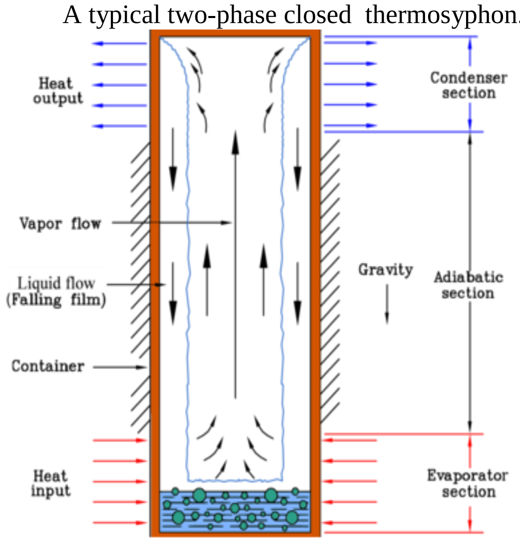


Figure 2
Thermal resistance diagram for a thermosyphon

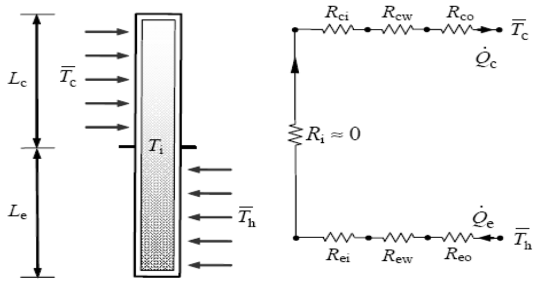


Figure 3
Basic design configuration of the HPHE[2]

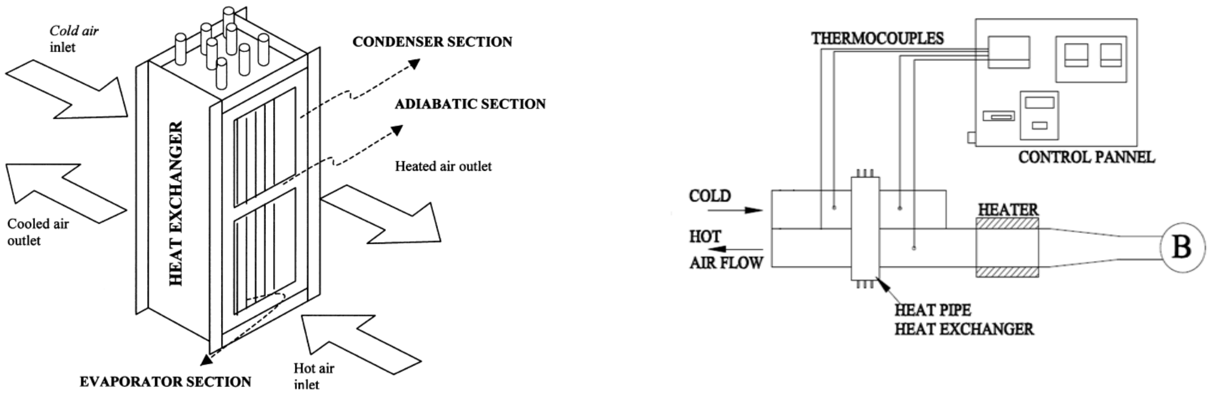


Figure 4
Schematic diagram of the experimental set up

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