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ORIGINAL PAPER

Investigation of heat pipe heat exchanger effectiveness and energy saving in air conditioning systems using silver nanofluid

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Abstract The present study attempts to use the methanol–silver nanofluid filled heat pipe heat exchanger and compares the effectiveness as well as the energy saving with pure methanol. A heat pipe heat exchanger has been tested in a test rig under steady-state conditions. The lengths of both the evaporator and the condenser sections of the heat exchanger were 700 mm, and its central adiabatic section had a length of 160 mm. The heat exchanger had 36 plate finned copper thermosyphons arranged in three rows. The inlet air temperature across the evaporator section was varied in the range of 33–43 °C while the inlet air temperature to the condenser section was nearly constant to be 13 °C. First, pure methanol was used as the working fluid with a fill ratio of 50 % of the evaporator section length, and then dilute dispersion of silver nanoparticles in methanol was employed as the working fluid. The nanofluid used in the present study is 20 nm diameter silver nanoparticles. The experiments were performed to compare the heat pipe heat exchanger effectiveness and energy saving, using nanofluid and pure methanol. The inlet air relative humidity across the evaporator section was varied between 35 and 80 %. The sensible effectiveness of the heat pipe heat exchanger obtained from experiments varied about 5–22 % for pure methanol and 9–32 % for methanol–silver nanofluid. Based on these experimental results, using methanol–silver nanofluid leads to energy saving around 8.8–31.5 % for cooling and 18–100 % for reheating the supply air stream in an air conditioning system.

Keywords Dry-bulb temperature · Methanol–silver nanofluid · Relative humidity · Sensible energy effectiveness

Introduction

One of the important applications of heat pipe heat exchangers (HPHE) for reducing energy consumption is in air conditioning (HVAC) systems. The most interesting function of HPHEs is to increase the dehumidification capacity of the conventional air conditioning systems. In a conventional HVAC 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.

For this purpose, external energy such as electric energy is used. The evaporator of HPHE functions as the air precooler before cooling coil and the condenser of HPHE functions as the air reheat before electric coil in a HVAC system.

Key factors affecting on thermal performance of a HPHE are: velocity, relative humidity (RH) and dry-bulb temperature (DBT) of input air, type and filling ratio (FR)

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of the working fluid, number of rows and pipe material. Many researchers have studied these factors (Vafai and Wang 1992; Akbarzadeh and Wadowski 1996; Noie-Baghban and Majideian 2000; Noie 2005; Vasiliev 2008; Rahimi et al. 2010).

Studies show that solid metal particles suspended in fluids cause heat transfer enhancement. Particles with <100 nm diameter have high potential for increasing heat transfer rate (Keblinski et al. 2002, 2005; Xue 2003; Wang et al. 2003; Fan and Wang 2011). In practical applications, the size and shape of nano particles are very important. Thermal conductivity and convective heat transfer have been studied for many of nano particles in water and ethylene glycol.

Argonne National Laboratory has prepared a new classification of fluids for heat transfer named nanofluid through suspending ultra-fine metallic and non-metallic particles with nanometric sizes in fluids such as water, engine oil and ethylene glycol.

Alumina (Al_2O_3), copper oxide (CuO) and silver are the most common nanoparticles used in experimental investigations by many researchers. Godson et al. (2010) have concluded that the effective thermal conductivity of nanofluids increases with volume fraction of nanoparticles. The dependency of thermal conductivity enhancement of nanofluids on particle shape has been emphasized by Trisaksri and Wongwises (2007). Kakaç and Pramuanjaroenkij (2009) have investigated the convective heat transfer enhancement with nanofluids. In another work Das and Choi (2009) have studied the temperature dependence of thermal conductivity enhancement in nanofluids experimentally.

Although extensive researches on the heat pipe and nanofluids have been conducted in literature, investigation on cases combining both the HPHE and the high thermal performance of nanofluids techniques has not been done thoroughly. The idea of utilizing nanoparticles within the working fluid of a heat pipe has become a subject of interest in recent years. Gold nanofluid was used in a heat pipe and the results showed that the thermal resistance of the heat pipe with gold nanofluid is less than that of pure water (Tsai et al. 2004). In addition, the heat transfer surface in the evaporation region is covered by nanoparticles and a thin porous of coating layer is formed on the surface after completion of the evaporation process. Kang et al. (2006) proved that using silver nano particles in distilled water inside the grooved heat pipe increases its thermal performance.

Other researchers have done similar experiments using nanofluid in heat pipes and thermosyphons (Naphon et al. 2008, 2009; Noie et al. 2009; Kang et al. 2009; Qu et al. 2010; Parametthanuwat et al. 2010; Teng et al. 2010; Liu and Zhu 2011; Huminic and Huminic 2011; Huminic et al. 2011; Liu et al. 2011). Shafahi et al. (2010) used a two-dimensional analysis to study the thermal performance of a cylindrical heat pipe utilizing Al_2O_3, TiO_2 and CuO nanofluids as the working fluids. The nanoparticles within the liquid enhance the thermal performance of the heat pipe by reducing the thermal resistance while enhancing the maximum heat load it can carry. They also investigated the effect of particle size on the thermal performance of the heat pipe. It was found that smaller particles have a more pronounced effect on the temperature gradient along the heat pipe.

Because the types and the geometrical sizes of heat pipes, the kinds of the base liquids, the kinds and sizes of nanoparticles and the operating conditions widely varied among these experiments; it is very difficult to quantitatively make the comparison among different experimental data. Also, most of the exiting researches proposed only some qualitative conclusions. However, the qualitative trends that the heat transfer was enhanced by substituting nanofluids for the base fluid are the same.

Thermal performance of HVAC systems can be improved in many ways such as using HPHEs which are high efficient heat conductors and can be used to enhance heat transfer because of phase changes of working fluid inside them. Silver has the highest thermal conductivity of any metal, so the present study tries to use the methanol–silver nanofluid filled HPHE and compares the effectiveness as well as energy saving with pure methanol in a HVAC system.

This research was carried out in Islamic Azad University (Science and Research Branch) in 2010.

Materials and methods

Overview of relevant theory

The rate of energy saving using HPHE in HVAC systems may be calculated by two methods:

1. Investigation of the sensible heat ratio (SHR), i.e., the sensible load divided by the total load to determine the dehumidification enhancement capability of the HVAC system (Yau 2007a).
2. Investigation of the effectiveness coefficient for calculating the performance of the heat pipe heat exchanger itself rather than the whole HVAC system (Yau 2007b).

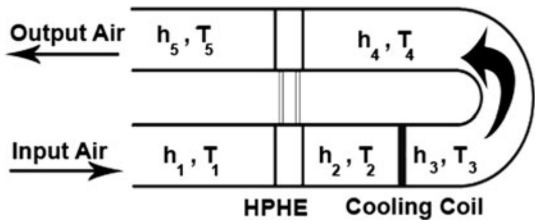

Fig. 1 Schematic of the diagram for setup test

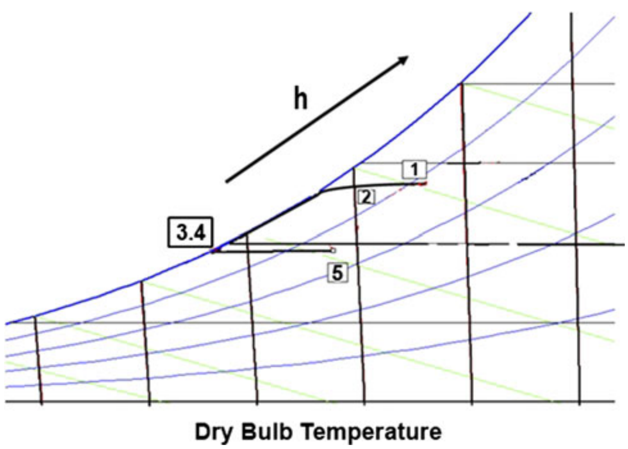

Fig. 2 Psychrometric chart for HPHE overcooled and reheat processes in the test setup

The effectiveness is judged to be the most relevant indicator in determining the performance of a HPHE as a means of energy savings, thus the second method was used.

The HPHE evaporator section functions as a pre-cooler and the condenser section functions as a reheating coil as illustrated in Fig. 1 and psychrometric chart in Fig. 2.

The effectiveness coefficient of the HPHE is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate.

$$\varepsilon_{\mathrm{HPHE}} = \frac{\dot{q}_{\mathrm{actual}}}{\dot{q}_{\mathrm{max}}} \tag{1}$$

where

$$\dot{q}_{\mathrm{actual}} = \dot{m}_s(h_1 - h_2) \tag{2}$$

and

$$\dot{q}_{\mathrm{max}} = \dot{m}_{\mathrm{min}}(h_1 - h_4). \tag{3}$$

From Eqs. (1–3), the total effectiveness coefficient (ϵ_t) can be determined by:

$$\varepsilon_t = \frac{\dot{m}_s}{\dot{m}_{\mathrm{min}}}\left(\frac{h_1 - h_2}{h_1 - h_4}\right). \tag{4}$$

Because the air flow rate is constant in the present research, therefore:

$$\varepsilon_t = \left(\frac{h_1 - h_2}{h_1 - h_4}\right). \tag{5}$$

The enthalpies in Eqs. 1, 2 and 4 are determined from the fundamental psychrometric relationship:

$$h = h_a + Wh_w \tag{6}$$

where h_a is the specific enthalpy of dry air component [KJ/kg$_{\mathrm{air}}$] and W is the humidity ratio in kg$_{\mathrm{water}}$/kg$_{\mathrm{air}}$ and h_w is the specific enthalpy of the water vapor [KJ/kg$_{\mathrm{water}}$].

Equation (6) may be approximated by:

$$h = C_pT + Wh_g \tag{7}$$

where C_p is the specific heat of the dry air [KJ/kg K], T is the dry-bulb temperature [°C] and h_g is the specific enthalpy of water vapor saturated at dry-bulb temperature [KJ/kg$_{\mathrm{water}}$].

In most analyses, because at low water vapor pressures the enthalpy of superheated water vapor is a little different from the enthalpy of saturated water vapor at the same temperature, it may be a very good approximation:

$$h_g = 2501 + 1.84\,T. \tag{8}$$

Taking C_p at a constant value of 1.005 kJ/kg K and using Eq. (8), the Eq. (7) may be rewritten as:

$$h = 1.005T + W(2501 + 1.84\,T). \tag{9}$$

Equation (5) may be used for calculating the sensible energy effectiveness by substituting dry-bulb temperature T instead of specific enthalpy h:

$$\varepsilon_{\mathrm{sen}} = \frac{T_1 - T_2}{T_1 - T_4}. \tag{10}$$

The temperature of the outlet air across the cooling coil of the cooling unit was adjusted manually at 13 °C. According to the psychometric chart, the absolute humidity and the condensed water are calculated.

The percentage of energy saving by the evaporator (S_e) and the condenser (S_c) of the HPHE are calculated, respectively, as:

$$S_e = \frac{\dot{m}_1c_p(T_1 - T_2)}{\dot{m}_1c_p(T_1 - T_3) + \dot{m}_{\mathrm{water}}\lambda} \tag{11}$$

$$S_c = \frac{\dot{m}_4c_p(T_5 - T_4)}{\dot{m}_4c_p(T_6 - T_3)} \tag{12}$$

where T_6 is the desired temperature in conditioned space and λ is the latent heat of water.

In this study, the total effectiveness coefficient and the sensible energy effectiveness coefficient of a HPHE with methanol as well as methanol–silver nanofluid as the working fluids have been investigated in a semi-industrial scale unit. Finally, the percentages of energy saving for both working fluids by the evaporator and the condenser sections of HPHE were calculated.

For determining the sensible and total effectiveness, the following conditions are assumed:

1. The test rig has a steady flow and the air is well mixed at each measuring state so that all measured psychrometric properties are representative of each air state.
2. The HPHE is operating under steady-state conditions for supply of fresh air and exhaust coil leaving air during each experiment.
3. No external energy is supplied into or lost from the HPHE between its inlet and outlet states (i.e., the HPHE is fully insulated).

The experimental setup

The experiments were run in a test rig shown in Fig. 3, which is consisted of seven different segments connected to each other with a 50 cm × 60 cm duct.

The heating section consists of five 1 kW, U-shaped powered electrical heaters. These heaters are introduced to the setup to control the input air dry-bulb temperature. The 2.2 kW centrifugal fan is controlled by the frequency of the input power. The 0.1 m^3 stainless steel vapor container has 30 1 kW electrical elements for heating water and control vapor mass flow rate in the input air.

Preparation of nanoparticle suspension is the first step of applying nanofluids in heat transfer enhancement. The silver nanoparticles with the average diameter of 20 nm are used in the present study where an ultrasonic homogenizer was implemented to prepare the mixture of 100 mg/l methanol–silver nanofluid.

The HPHE that was used in this research was made of 36 copper pipes with the specifications given in the Table 1.

Table 1 Specifications of the HPHE

External diameter of pipes	16 mm
Internal diameter of pipes	14 mm
Length of pipes	1560 mm
Thickness of pipes	1 mm
Fin type	0.4 mm thickness aluminum plate, 300 fins/m
Pipe arrangement	In-line $S_L = S_T = 30$ mm
Number of pipes	$N_L = 3$, $N_T = 12$, $N = 36$

The heat duty of the cooling unit is approximately 7 kW and a draining pipe is placed underneath the cooling coil for condensed water.

The centrifugal fan blows inlet air into the duct with controlled mass flow rate and its velocity is measured by orifice meter. Before the orifice, the air is preheated by passing through electrical heaters, and then it is humidified inside the vapor container with a certain amount of vapor. This air will be pre-cooled when contacts the evaporator of the HPHE followed by cooling coil of the cooling unit down to 13 °C. In this stage, the humidity of the air has decreased and excess water is drained out of the system. Finally, the air passing through the condenser of the HPHE is reheated.

First, all experiments were carried out using methanol with 99 % purity and 50 % filling ratio of the evaporator volume and then the same procedure was repeated using methanol–silver nanofluid. At the beginning of the experiment, the HPHE was evacuated by a vacuum pump to reach an absolute pressure of 0.1 atm, subsequently, it was filled with working fluid. The effect of inlet air dry-bulb temperature and relative humidity on the effectiveness coefficient of the HPHE with methanol as well as methanol–silver nanofluid as the working fluids have been investigated. Finally, the percentages of energy saving for

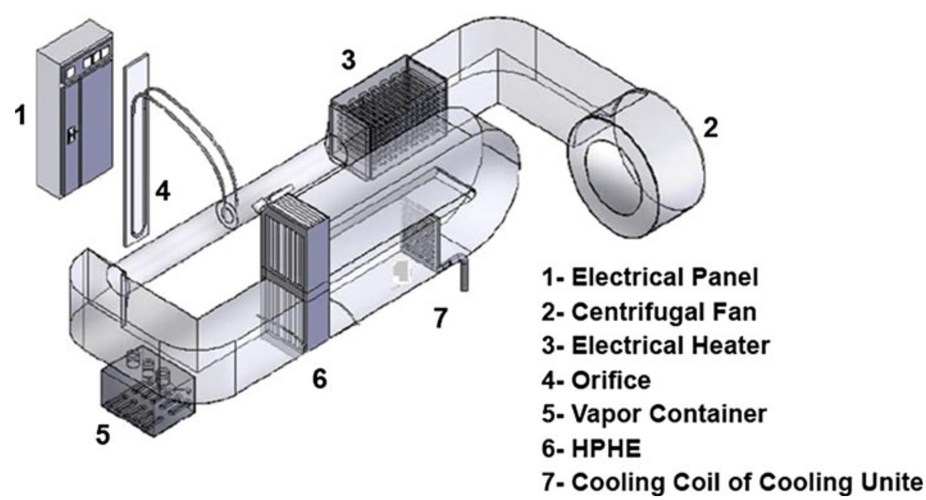

Fig. 3 Schematic of the test rig

both working fluids were calculated using Eqs. (11) and (12).

Results and discussion

Figures 4 and 5 show the effect of inlet air RH on the total effectiveness coefficient, sensible energy effectiveness coefficient, evaporator energy saving and condenser energy saving for nominal inlet HPHE evaporator DBT of 35 °C and mass flow rate of 0.13 kg/s. The experimental results demonstrated that using HPHE in these conditions, it is possible to achieve around 8–10 % energy saving by the evaporator and 16–22 % by the condenser of the HPHE for reheating with pure methanol as the working fluid. But if silver nanofluid is used in the same HPHE without changing the other parameters, the rates of energy saving in the evaporator and condenser will increase by 10–22 and 19–53 % respectively.

The HPHE with nanofluid as the working fluid gives the total effectiveness coefficient of 1.6–3.5 times higher than that with pure methanol (Fig. 4). The reason is that, the silver nanoparticles within the liquid enhance the thermal performance of the HPHE by reducing the thermal resistance while enhancing the maximum heat load it can carry. The low values of the total effectiveness coefficient and the sensible energy effectiveness coefficient were attributed to low mass flow rates and few rows of pipes in the HPHE.

The heat transfer coefficient enhancement may result from two reasons. Firstly, the increase of the effective thermal conductivity of the nanofluid can enhance the conductive heat transfer. The second is attributed to the turbulence effect of random motion (Brownian motion) of nanoparticles in the base liquid and it is a nanoscale effect.

It was observed that for all cases examined, S_e, S_c, ϵ_t and ϵ_s reduced as inlet RH for HPHE evaporator was increased. These results imply that the moisture removal

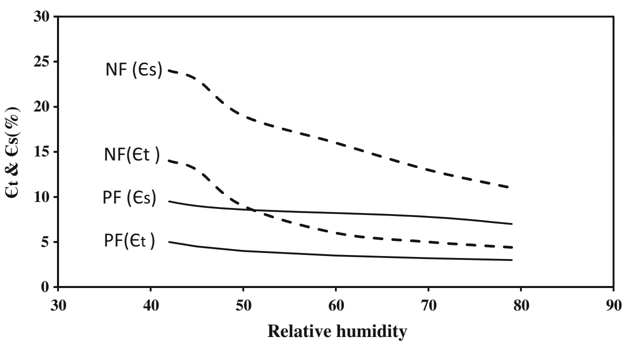

Fig. 4 Effect of relative humidity on total and sensible energy effectiveness coefficients for nominal inlet HPHE evaporator temperature of DBT = 35 °C and mass flow rate of 0.13 kg/s (*NF* nanofluid, *PF* pure fluid)

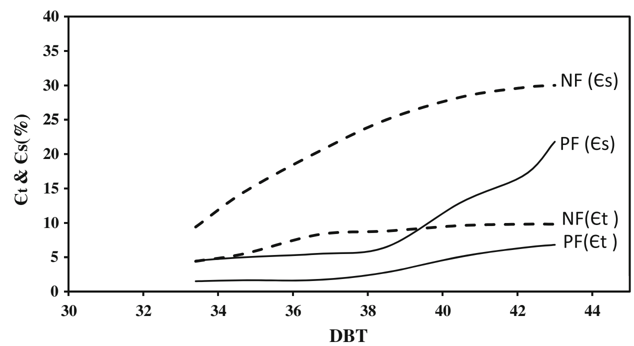

Fig. 6 Effect of nominal inlet HPHE evaporator DBT (°C) on total and sensible energy effectiveness coefficients for mass flow rate of 0.15 kg/s and nominal relative humidity of 60 % (*NF* nanofluid, *PF* pure fluid)

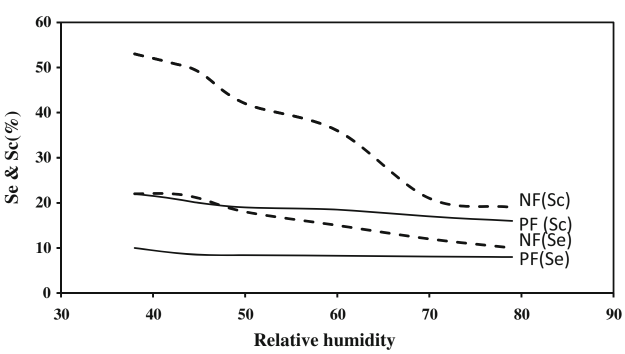

Fig. 5 Effect of relative humidity on evaporator and condenser energy savings for nominal inlet HPHE evaporator DBT = 35 °C and mass flow rate of 0.13 kg/s (*NF* nanofluid, *PF* pure fluid)

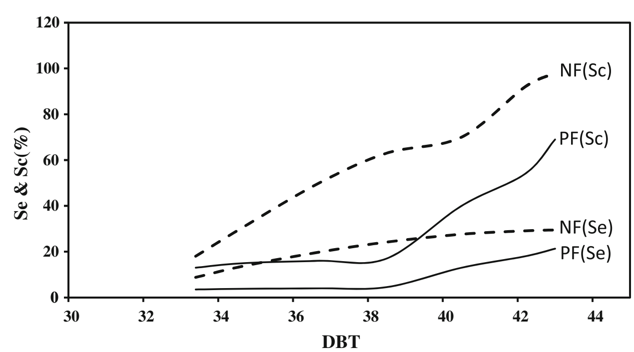

Fig. 7 Effect of nominal inlet HPHE evaporator DBT (°C) on evaporator and condenser energy savings for mass flow rate of 0.15 kg/s and nominal relative humidity of 60 % (*NF* nanofluid, *PF* pure fluid)

capability for the HVAC system with HPHE was increasing with as the inlet RH for the HPHE evaporator is increased. This was due to the fact that for the same inlet DBT for HPHE evaporator, the higher RH means the smaller enthalpy change to achieve apparatus dew point temperature, and therefore the HPHE evaporator and cooling coil, utilized a significant part of the cooling capacity for dehumidification rather than temperature reduction as shown by process 2–3 in Fig. 2.

The influence of inlet air DBT on S_e, S_c, ϵ_t and ϵ_s for silver nanofluid and pure methanol for mass flow rate of 0.15 kg/s and nominal relative humidity of 60 % are shown in Figs. 6 and 7.

It is evident that, S_e, S_c, ϵ_t and ϵ_s have been increased as the nominal inlet HPHE evaporator DBT increased. In other words, the results imply that the moisture removal capability for the HVAC system with HPHE was increasing with the inlet air DBT increment. The apparent deviation at different inlet air DBT of ϵ_t and ϵ_s may be attributed to the fact that, the main reason for the effectiveness of HPHE is the evaporation and condensation of the working fluid. The rate of vapor traveling from the evaporator to the condenser is governed by the difference in vapor pressure due to density differences caused by temperature variations.

The vapor pressure over the hot liquid working fluid at the evaporator section is higher than the equilibrium vapor pressure over condensing working fluid at the condenser section of the HPHE, and this pressure difference drives a rapid mass transfer to the condensing end where the excess vapor condenses and releases its latent heat.

At the same condition, test results showed the average increase of 2.15 times in ϵ_t and 1.7 times in ϵ_s of HPHE with nanofluid as compared with pure methanol.

The experimental results from Fig. 7 demonstrated that using HPHE in a HVAC system, it is possible to achieve around 3.5–25 % energy saving by the evaporator for precooling and 13–80 % by the condenser of the HPHE for reheating with pure methanol as the working fluid. But if silver nanofluid is used in the same HPHE without changing the other parameters, the rates of energy saving by the evaporator and condenser will increase by 8.8–31.5 and 18–100 % respectively.

It was also found that where air supply was needed above 40 °C DBT, the condenser of the HPHE could be used as a reheater to replace the conventional reheating coil to control relative humidity as shown in Fig. 7.

Figures 4, 5, 6, 7 illustrated that using silver nanofluid causes the enhancement of heat transfer and the effectiveness coefficient of the HPHE in all experiments.

This is fully compatible with previous results reported by researchers because metallic nano particles such as silver due to its high conductivity coefficient, leads to improving the heat transfer rate of the working fluid. Addition of nanoparticles to fluid changes the heat transfer mechanism so that besides thermal conductivity increase, Brownian motion, dispersion, and fluctuation of nanoparticles especially near wall it leads to increase in the energy exchange rates and augments heat transfer rate between the fluid and the evaporator section wall (Zeinali Heris et al. 2006, 2007). An increase in the nanoparticles volume fraction intensifies the interaction and collision of nanoparticles. Also diffusion and relative movement of these particles near the tube wall leads to rapid heat transfer from the HPHE wall to nanofluid. In other words, increasing the concentration of nanoparticles intensifies the mechanisms responsible for enhanced heat transfer. A major thermal resistance of HPHE is caused by the formation of vapor bubbles at the liquid–solid interface. A larger bubble nucleation size creates a higher thermal resistance that prevents the transfer of heat from the solid surface to the liquid. The suspended nanoparticles tend to bombard the vapor bubbles during the bubble formation. Therefore, it is expected that the nucleation size of vapor bubble is much smaller for fluid with suspended nanoparticles than that without them. Also during nucleate boiling some nanoparticle precipitate on surface and form a layer whose morphology depends on the nanoparticle materials. It is well known that a thin liquid microlayer developed underneath a vapor bubbled growing at a solid surface. Therefore, it is postulated that microlayer evaporation of the nanoparticle initially contained in it could be the reason for the formation of porous layer. Therefore, using nanofluid of a metal such as silver increases the thermal efficiency of HPHE and saves energy consumption in air conditioning systems.

Conclusion

New experimental data on the effectiveness of HPHE and energy saving enhancement with nanofluids in HVAC systems are presented. The following conclusions were drawn from the present study:

1. The experiments carried out in this work show using HPHE in a HVAC system, it is possible to achieve around 3.5–25 % energy saving by the evaporator for pre-cooling and 13–80 % by the condenser of the HPHE for reheating with pure methanol as the working fluid.

2. If silver nanofluid is used in the same HPHE without changing the other parameters, the rates of energy saving by the evaporator and condenser will increase by 8.8–31.5 and 18–100 % respectively.
3. The HPHE with nanofluid as the working fluid gives the total effectiveness coefficient of 1.6–3.5 times higher than that with pure methanol.
4. It was also found that where air supply was needed above 40 °C DBT, the condenser of the HPHE could be used as a reheater to replace the conventional reheating coil to control relative humidity.
5. The low values of the total effectiveness coefficient and the sensible energy effectiveness coefficient were attributed to low mass flow rates and few rows of pipes in the HPHE.
6. The investigation showed that the effectiveness of the HPHE can be increased with increasing the inlet air dry-bulb temperature and it is reduced as the evaporator inlet air relative humidity is increased.
7. As a result, the higher thermal performance of the nanofluid has proved its potential as substitute for conventional pure fluids in the HPHE. Therefore, on the basis of the results obtained in this work, the application of this type of heat exchanger instead of conventional reheat coils with silver nanofluid as the working fluid results in energy saving.

To reveal this unprecedented phenomenon, further studies on nanofluid behavior in HPHE and properties of nanofluid must be performed.

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