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Experimental Investigation for Flow Boiling Heat Transfer Enhancement on R134a Using Nanorefrigerants

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ABSTRACT:
Experimental study exploring the heat transfer increase in double tube evaporator of vapor compression unit using nanorefrigerants is investigated. Aluminum oxide Al_2O_3 and copper oxide CuO nanoparticles are dispersed into refrigerants R134a, to form nanorefrigerant. Aluminum oxide nanorefrigerant void fraction is ranged from 0.1% to 0.70% whereas copper oxide nanorefrigerant void fraction is ranged from 0.06% to 0.16%. Nanorefrigerant absorbs its latent heat of evaporation from hot water flowing in the annular space of the evaporator.
The effect of nanorefrigerant void fraction, heat flux, and the hot water flow rate and its temperature at the evaporator inlet on flow boiling heat transfer is illustrated. The results showed that higher values of heat transfer coefficient (h.t.c) are attained in case of using R134a. Also, a maximum value of the htc at void fraction of 0.09% CuO nanoparticle and 0.5% of Al_2O_3 nanoparticles for R134a is noticed. Empirical correlation equations for the htc in terms of the operating parameter are obtained.

KEYWORDS: Heat Transfer – Flow Boiling – Nanofluids – Vapor Compression

1. INTRODUCTION

Due to considerable amount of energy consumption by thermal systems like refrigerators and air conditioners, so there is a want for enhancing the thermal performance of such systems. There are two techniques for enhancing the performance of the thermal systems: passive and active. One of the proposed passive techniques is the use of nanofluids. Nanofluids, firstly, demonstrated by Choi (1995) at Argonne National Lab. The preparation of nanofluids is achieved by squander solid particles of nano size (1-100 nm) in traditional fluids. The traditional fluids are called base fluids. The thermal conductivity of nanoparticles is always higher than that of the base fluids. The advantage of adding nanoparticles to the refrigeration system can be summarized as Bi et al. (2011): adding nanoparticles can increase the solubility between the lubricant and the refrigerant and improve the tribological properties of the lubricant. So, the performance of the compressor improved. Also, adding nanoparticles to the refrigerant improves the thermophysical properties and the heat transfer properties of the refrigerant which results in the enhancement of the cooling effect. In almost all vapour compression refrigeration systems, it is possible to use nanoparticles via making a suspension of nanoparticles in oil Kedzierski and Gong (2009). Mahbubul et al. (2013a) determined the thermophysical properties of Al_2O_3/R134a nanofluid, pressure drop and heat transfer performance for nanoparticles concentration ranged from 1 to 5% vol., in a flow inside a horizontal smooth tube of uniform mass flux of 100 kg/m^2.s. The viscosity and thermal conductivity from Al_2O_3/R141b nanorefrigerant for 0.5 to 2vol% concentration at temperature range 5-20^{o}C was investigated by Mahbubul et al. (2013b). The density of Al_2O_3/R141b nanorefrigerant increases with the excess of volume concentrations and decrease with temperatures by depicted by Mahbubul et al. (2013c). Zhelezny et al. (2017) presented experimental data for physical properties of a solution of R600a with mineral compressor oil and nanoparticles of Al_2O_3 and TiO_2 over a broad range of temperature and nanoparticles concentration. It was illustrated that the viscosity increased and the surface tension decreased with the addition of nanoparticles to refrigerant oil solutions. Comprehensive reviews were introduced by by Saidur et al. (2011) and Alawi et al. (2015) on the thermophysical characteristics of nanoparticles pending in refrigerant and lubricating oils of refrigeration systems.

Bartelt et al (2008) showed that, there is no abvious effect on the boiling htc inside a smooth tube with 0.5%wt. nanolubricant in a mixture with R134a but with 1%wt. nanolubricant, an increase by about 42%-82% in htc is observed. Further increase in the nanolubricant to 2%wt. resulted in large improvement of htc between 50% and 101% and insufficient effect on the system pressure drop is noticed. Peng et al. (2009) experimentally investigated the effect of adding nanoparticles on the heat transfer indices of CuO/R113 refrigerant based nanofluid flow boiling inside a horizontal smooth tube under evaporation pressure of 78.25 kPa. The parameters investigated were mass flux, heat flux, inlet quality and mass fraction. Their results showed that a maximum enhancement of htc reached 29.7%. A heat transfer correlation for refrigerant-based nanofluid is proposed and the predictions agree with 93% of the experiential data within a deviation of ±20%. Jwo et al. (2009) experimentally investigated the replacement of refrigerant R-134a and polyolester lubricating oil with a hydrocarbon refrigerant and mineral oil lubricant in a domestic refrigeration unit. Al2O3 nanoparticles were dispersed in mineral lubricant with 0.2, 0.1, and 0.05 wt %. Optimal results showed 2.4% reduction in power consumption and an increase by 4.4% in COP at 60% R-134a and 0.1 wt % Al_2O_3 nanoparticles. Henderson el al. (2010) showed the effect of nanoparticles on the flow boiling of R134a and R134a/Polyolester mixture. It was observed that, htc is decreased by 55% in comparison of pure R134a in case of dispersing SiO_2 due to instability of nanoparticles dispersion, while excellent dispersion of CuO nanoparticles in R134a and Polyolester oil results in more than 100% enhancement in the htc and meager effect on the pressure drop Mahbubul et al. (2013) determined the characteristics of heat transfer and pressure drop of Al_2O_3/R141b nanorefrigerant for different volume concentration. It was found that both the heat transfer and pressure drop increased with the increase of volume concentration of the nanoparticles. Akhavan-Behabi et al. (2014) experimentally investigated the effect of adding CuO nanoparticles on flow boiling of R600a/Polyester mixture inside a horizontal smooth tube. Their experiments were carried out for mass flux ranged from 50 to 400 kg/m^2.s, inlet quality from 0 to 0.9, heat flux from 3 to 8 kW/m^2 and mass fraction of CuO nanoparticles from 0 to 1.5 wt%. Their results showed that the maximum enhancement in the htc was 63% due to nanoparticles addition. Singh and Lal (2014) showed a maximum improvement in the COP of R134a refrigeration cycle ranged from 7.2 to 8.5% with 0.5 wt. of Al_2O_3 nanoparticles. While COP is decreased at using 1%wt. of Al_2O_3 nanoparticles compared with pure R134a. Li et al. (2015) studied experimentally a heat pump performance with nanofluids prepared by dispersing 5wt% TiO_2 nanoparticles in R22. Their results showed small decrease of COP of the cooling mode and significant increase in COP of the heating mode. Mahbubul et al. (2015) showed that adding 5% vol. Al_2O_3 nanoparticles suspended in R134a refrigerant at temperature ranged from 283 to 308 K under a uniform heat flux through a horizontal smooth tube resulting in an increase of about 11%, 13.68% and 28.5% for the density, dynamic viscosity, and thermal conductivity respectively compared with the base refrigerant at the same temperature. Moreover, Al_2O_3/R134a nanorefrigerant shows highest COP of 2.6%, 3.2% and 15% for the three mentioned properties respectively compared with pure R134a refrigerant.

For improving the performance of vapor compression refrigeration system coupled that with evaporative cooling pad, and nanorefrigerant in hot and dry weather is proposed and experimentally investigated by Dhamneya et al. (2018). The experimental results showed that the performance indices of the evaporative cooled condenser are significantly enhanced. Also, the system COP is highly increased in hot and dry climate condition compared with conventional system. The impact of adding nanoparticles to refrigerant and lubricating oils of refrigeration systems on the performance of the refrigeration systems is illustrated in Celen et al. (2014), Alawi et al. (2015), Redhwan et al. (2016), Azmi et al (2017) and Bhattad et al. (2018). Sun and Yang (2014) showed the flow boiling indices to four nanorefrigerants with different mass fraction, quality, and mass velocity in a horizontal tube. Their results indicated that the flow boiling heat transfer process was enhanced by adding nanoparticles Also, the boiling characteristics of nanofluid are reviewed in Alawi et al (2014) and Fang et al. (2016).

2. EXPERIMENTAL SETUP

2.1 Experimental Test Section

A cooling circuit was installed to conduct practical experiments on the effect of using the nanoparticles on refrigeration cycle performance. The circuit used to conduct experiments on it. The experimental work consists of two loops water loop and refrigeration loop. Figure 1 shows a component of the experimental test devices Refrigeration loop consist of compressor used in compressed to the condenser pressure. It is next condensed to liquid in the air cooled condenser. The liquid refrigerant is then flows through an expansion valve which throttle the refrigerant to the evaporator pressure. The water flows around the refrigerant tube in opposite direction and represents the load on the evaporator. In the next part, details of the cooling circuit used will be mentioned.

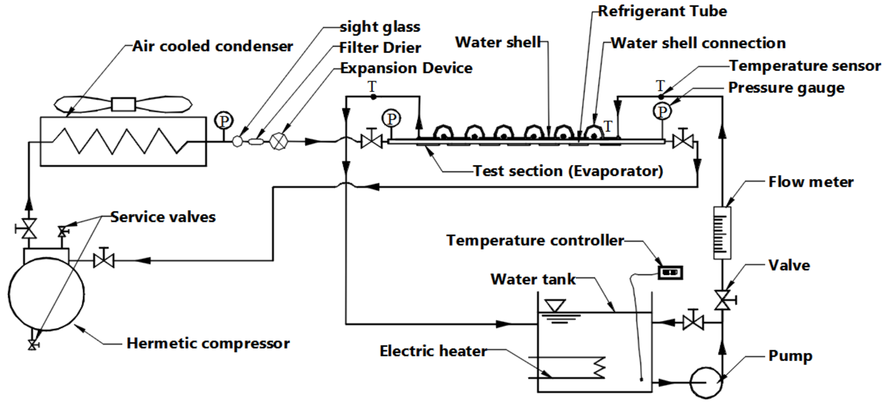


Fig. 1: layout diagram of experimental setup

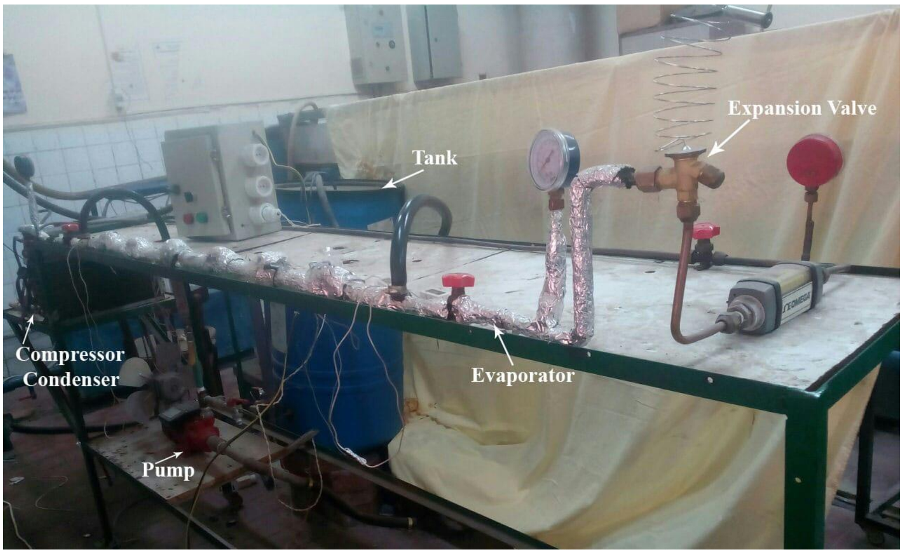


Fig. 2: Photograph of experimental setup

The evaporator used in the present work is a tube in tube heat exchanger type. The evaporator is made of copper tubes. The refrigerant flows through the inner tube which has 1400 mm length and an outer diameter of 9.52 mm (3/8 inch), and inner diameter of 7.72 mm (2.47/8 inch). The load is given to the refrigerant in the evaporator via the water coming from the water tape source. The water is flow in the outer annulus generated between the outer and inner tubes. As shown in Fig. 2. The outer tube has an outer diameter of 9.52 mm. The outer tube is divided into 10 segments each of which has an independent inlet and exit terminals. These segments are connected together by copper tubes to allow cold water to flow through these segments. Experimental runs are performed for various values of inlet water temperature, inlet water flow rate and different void fraction. The temperature is measured at 6 locations along the inner tube surface. The pressure is measured at inlet and exit the evaporator used. Also, the water flow rate is measure using a flow meter with uncertainty of ±5.0%. Figure 2 shows the experimental test rig.

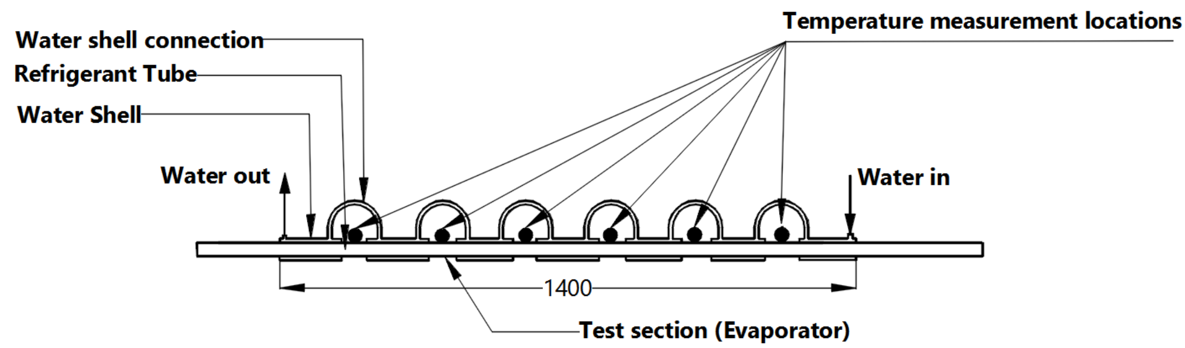


Fig. 3: Schematic diagram of evaporator (test section)

Refrigerant pressures are measured by three pressure gauges, two of them used in the measured the low pressure between the expansion valve outlet and inlet compressor a pressure range from -30 to 150 psi. The third gauge used in measuring the high pressure in the refrigeration cycle at exit condenser this gauge has a pressure from 0 to 300 psi.

2.2 Preparation of Al_2O_3 and CuO / Polyol Ester

The materials used in the study were two different types of nanoparticles materials (Al_2O_3, CuO), used on refrigerant R134a, and polyolester oil that used as lubricating oil. The nanoparticles used here were purchased from MKNANO (M K Impex Corp.) with purity of 99% with average particle size of 50nm as given by manufacturer data sheet. The lubricating oil used here was the synthetic Emkarate RL68H having viscosity and density values of 7.06×10^{-2} Pa.s and 0.977 g/ml respectively. This type of lubricating oil is formulated specifically for use in air conditioning and refrigeration compressors. The low temperature and the thermal stability enable the use of Emkarate RL68H over a wide operating temperature range.

In this study, the quantity of compressor oil of POE type was kept fixed at 782 cm^3, and the mass of Al_2O_3 or CuO nanoparticles was calculated to achieve nanoparticles volume fraction to take values of 0.25%, 0.3%, 0.5% and 0.7% for Al_2O_3 and the values of 0.1%, 0.15%, 0.2% and 0.25% for CuO respectively. The specified amount of nanoparticles is dispersed into POE oil using magnetic stirrer for 5 minutes. To prevent clustering of the particles in the mixture, and to obtain good homogeneity the mixture was then sonicated using ultrasonic vibrator at room temperature for two hours. This sonication time enhances the dispersion of nanoparticles within the fluid and consequently enhances the stability of nanofluid. The median diameter of Al_2O_3 nanoparticles used is 11.nm whereas the average diameter of CuO nanoparticles used is 16 nm and the TEM (Transmission Electronic Microscope) photographs of Al_2O_3 and CuO nanoparticles are shown in Figs. 4a, 4b respectively. The properties of nanoparticles and polyolester oil base fluid are listed in figure (4).

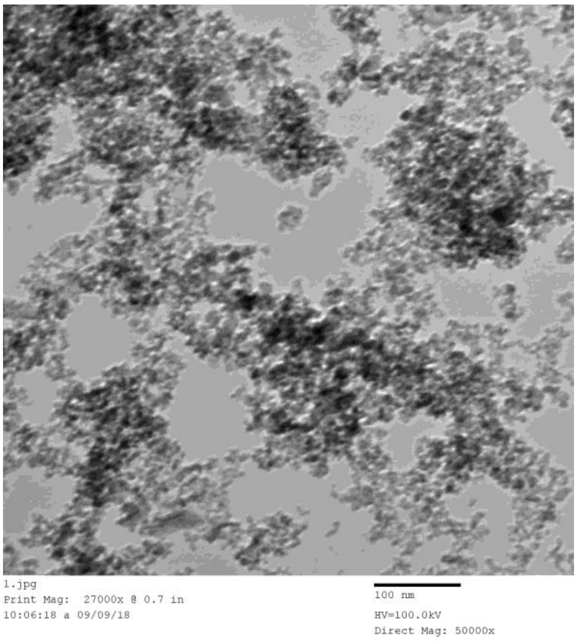


Fig. 4a. TEM photograph of Al_2O_3 nanoparticles

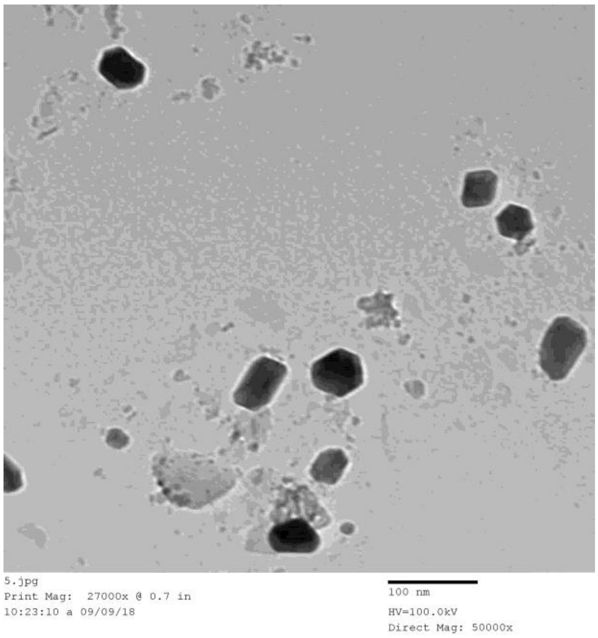


Fig. 4b. TEM photograph of CuO nanoparticles

3. EXPERIMENTAL PROCEDURES

The following test procedures were conducted to perform required experiment:

- Prepare the sample of Al_2O_3/POE or CuO/POE (polyolester oil) nanofluid with the specified volume fraction.
- The prepared sample of nanofluid is charged into the refrigeration cycle via the service port of the compressor.
- The water tank is filled with cold water below 10ºC by placing ice blocks and the electric heater is switched on. After the water reaches the desired temperature, the water is then pumped from the tank to the test section (evaporator) and the compressor is switched on.
- The water flow rate is adjusted and aforementioned steps are repeated for different inlet water temperature to the test section to achieve different heat flux.
- For a certain heat flux, the experimental setup is allowed to operate until steady state condition is reached which can be indicated by negligible changes of evaporator wall temperatures, inlet and outlet water temperatures.
- Once the steady state condition has been reached, the measurements of the temperatures, pressures, and water flow rate are recorded.
- After completing the experiment, the setup is switched off and nanofluid is extracted from the compressor via the service port.
- The above steps are repeated for another sample of nanofluid having various volume fraction of nanoparticles.

4. DATA REDUCTION

The average pressure in the evaporator is estimated as:

$$p = (p_{in} + p_{exit})/2 \qquad (1)$$

The temperature of the refrigerant can be considered as the saturation temperature$T_{r,sat}$. Also, water mass flow rate is calculated as:

$$m_W = \rho_w V_w \qquad (2)$$

The heat rate absorbed by the refrigerant from circulating hot water is estimated from measured water temperatures and water flow rate by:

$$Q_w = m_W \, C_W \, (T_{W,in} - T_{W,out}) \qquad (3)$$

Then, the heat flux is calculated from:

$$q = \frac{Q_w}{2\pi r_o L} \quad (4)$$

The evaporating htc is calculated from:

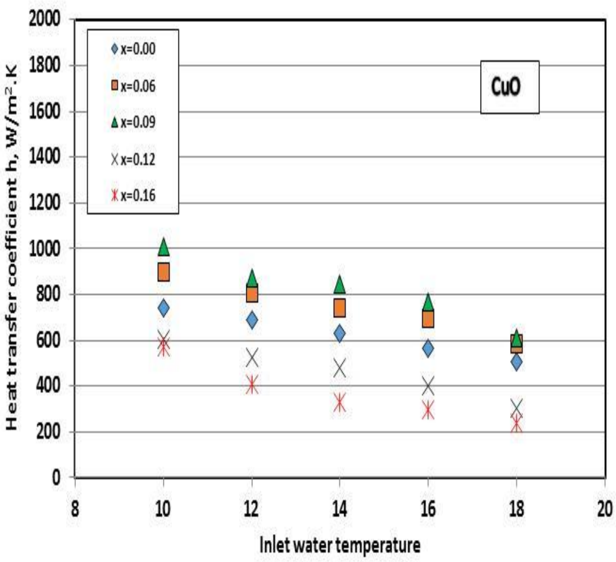
$$\bar{h} = kQ_w / [2\pi r_i kL(\bar{T}_w - T_{r,sat}) - Q_w R_i \ln\left(\frac{R_o}{R_i}\right)] \quad (5)$$

The average wall temperature $\bar{T}_w$ of refrigerant tube is calculated from the following equation:

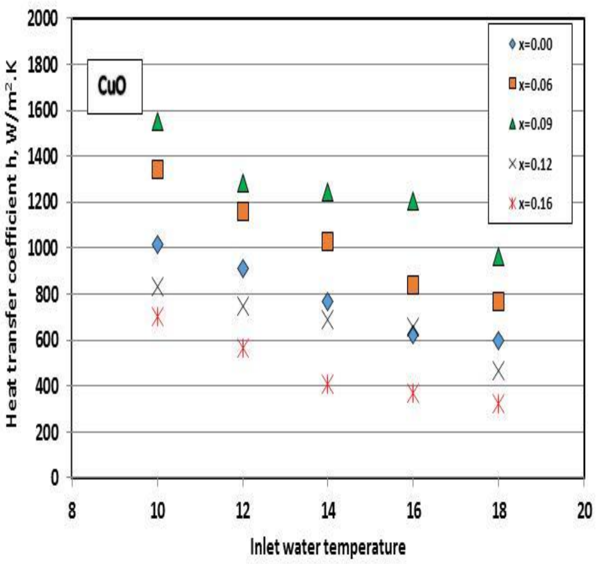
$$\bar{T}_w = \frac{\sum_{i=1}^{6} T_{ev,i}}{6} \quad (6)$$

5. RESULET AND DISCUSSION

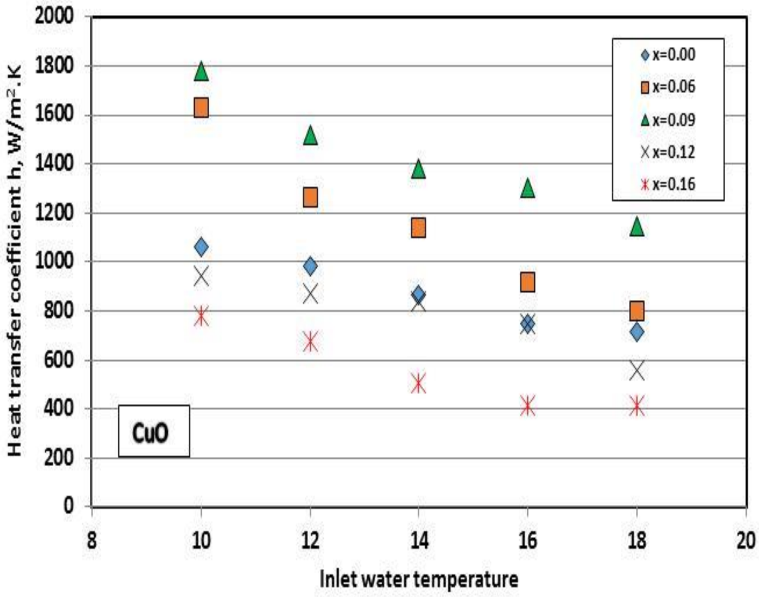
Figure 5a-c depicts the variation of the evaporating htc with inlet water temperature to the evaporator for different void fraction of CuO-R134a based nanofluid and different water flow rate of 1, 2 and 3 LPM respectively. It is illustrated from the figure that as the inlet water temperature increases the htc decreases and this may be due to the decrease of the heat flux. Also, as the inlet flow rate increases the htc increases and this can be attributed to the increase of fluid velocity and turbulence level inside the annulus passage. Also; it is observed that the use of nanofluid enhances the heat transfer process in case of using void fraction x=0.06% and 0.09%, whereas the increase of void fraction to x=0.12 and 0.16 leads to deterioration of heat transfer process.



a) 1 LPM



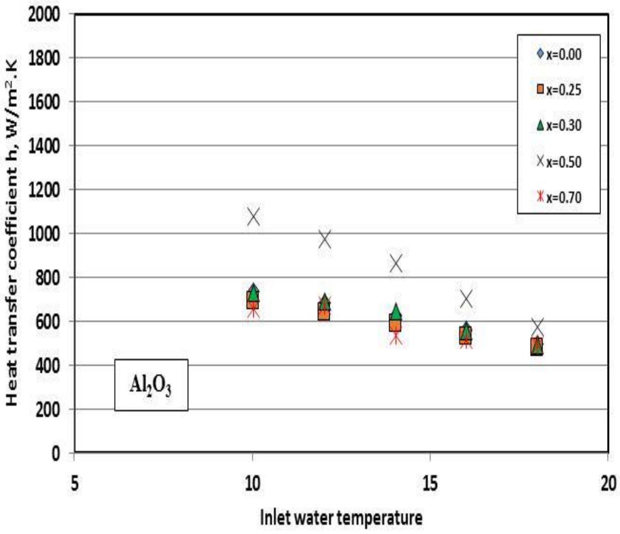
b) 2 LPM



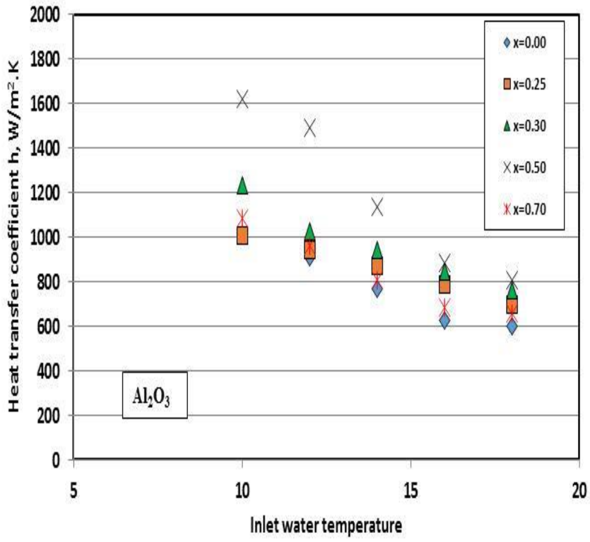
c) 3 LPM

Fig. 5: Variation of evaporating htc with heat flux for different void fraction of for CuO-R134a based nanofluid at different mass flow rate

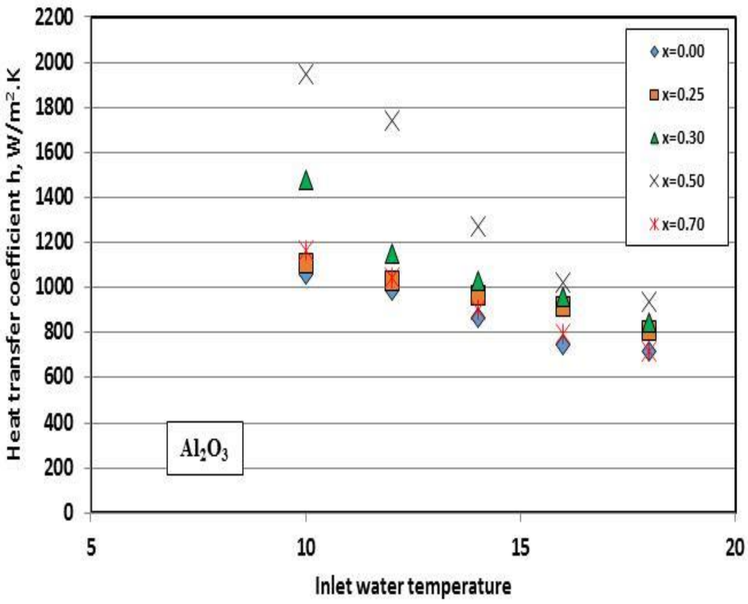
The variation of the evaporating htc with inlet water temperature to the evaporator for different void fraction of Al_2O_3-R134a based nanofluid and different inlet water flow rate is depicted in Fig. 6. The same effect of inlet water temperature and water volume flow rate on the evaporating htc is observed. Also it is noticed that the increase of water flow rate results in higher value of void fraction that enhance the process of heat transfer.



a) 1 LPM



b) 2 LPM



c) 3 LPM

Fig. 6: Variation of evaporating htc with heat flux for different void fraction of for Al_2O_3-R134a based nanofluid at different mass flow rate.

The effect of the void fraction of Al_2O_3 –R134a based nanofluid on the htc is illustrated in Fig. 7. It is noticed that these is a maximum value of htc at void fraction at 0.50% at heat flux of 12.5 kW/m^2.

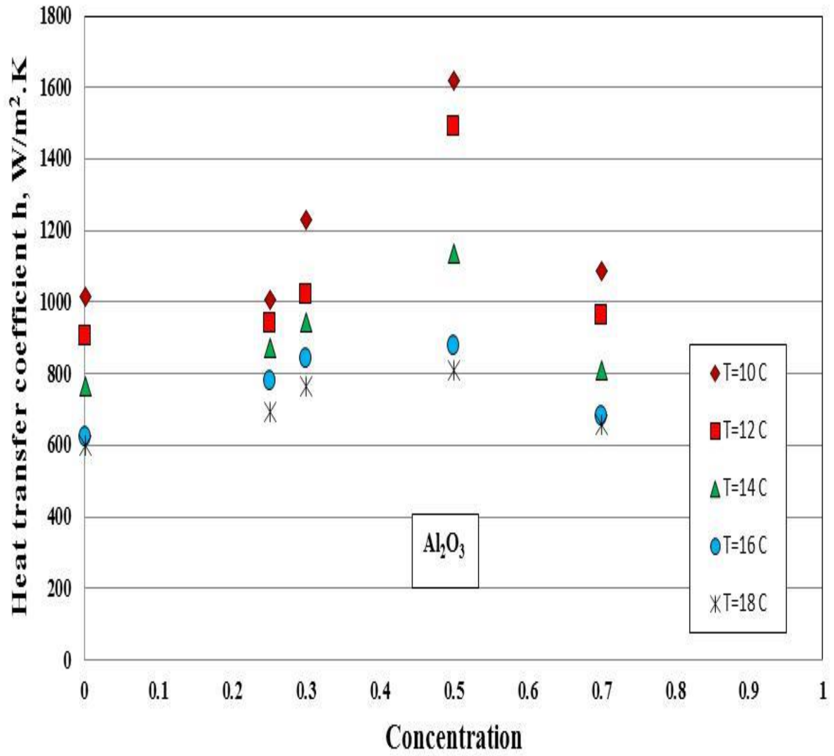


Fig. 7: Variation of evaporating htc with void fraction of Al_2O_3-R134a based nanofluid for different inlet water temperature at 2LPM

Figure 8 depicts the variation of that htc with the void fraction CuO-R134a based nanofluid for inlet water temperature at heat flux value of 12.5 kW/m^2.

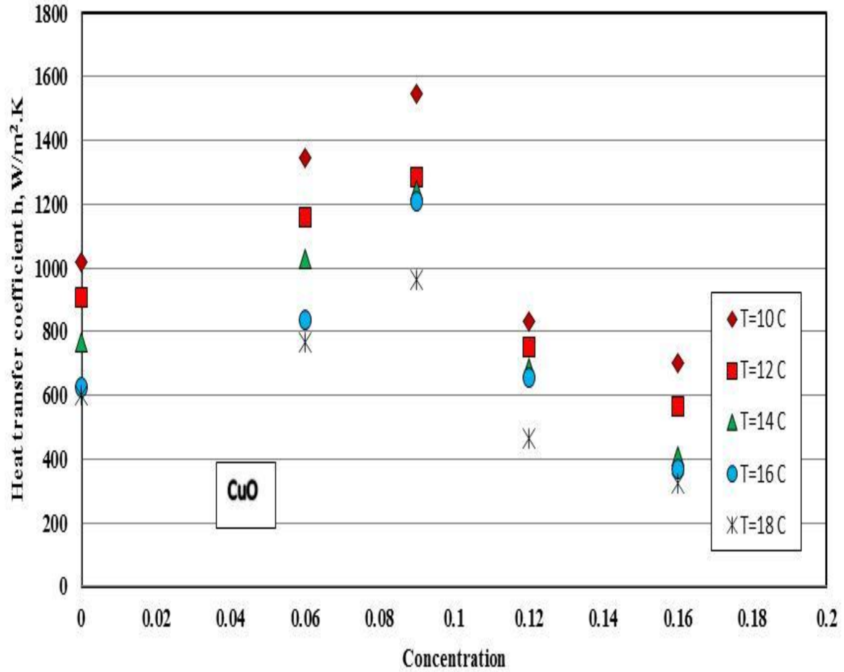


Fig. 8: Variation of evaporating htc with void fraction of CuO-R134a based nanofluid for different inlet water temperature at 2LPM

Figure 9 shows the variation of the evaporating htc with the heat flux for different inlet water temperature for Al_2O_3 – R134a based of void fraction 0.50%. It is observed for the figure that the increase at heat flux bead to increase in the htc for all inlet water temperature.

Also, it is observed htc has a maximum value at void fraction of 0.09% for all inlet water temperature.

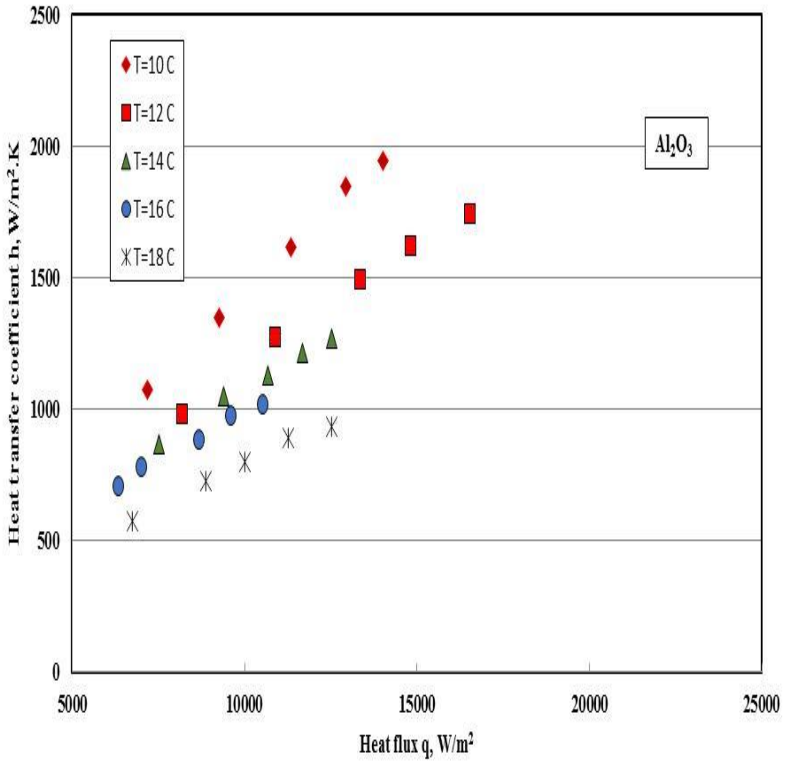


Fig. 9: Variation of evaporating htc with heat flux for different inlet water temperature for Al_2O_3-R134a based nanofluid of void fraction of 0.50%.

The variation of evaporating htc with the heat flux for different inlet water temperature for CuO-R134a based nanofluid at void fraction of 0.09% is illustrated in Fig. 10. It is observed that the htc increases with the increase of heat flux and the decrease in inlet water temperature.

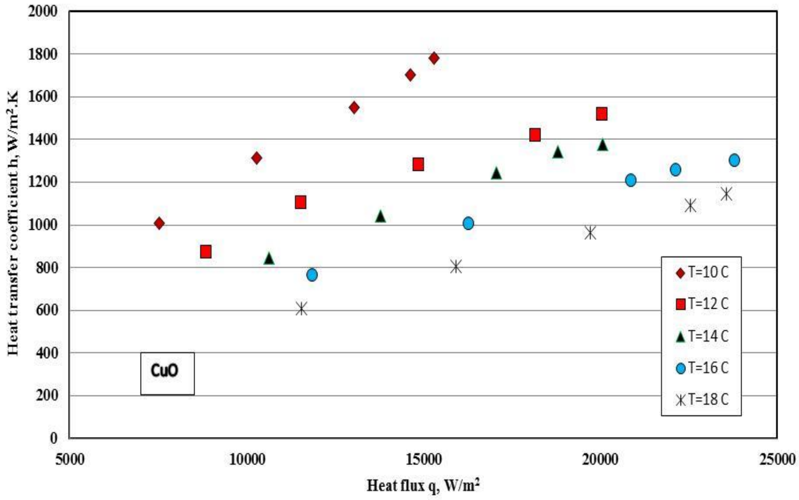


Fig. 10: Variation of evaporating htc with heat flux for different inlet water temperature for CuO-R134a based nanofluid of void fraction of 0. 09%.

6. CONCLUSIONS

From the previous discussion and the adoption of the previous results, the following summary is explained:

- The poloyster oil and R134a refrigerant mixtures with Al_2O_3 and CuO nanoparticles with different concentration of nanoparticles have been successfully prepared and showed perfect working.
- The htc increases with the increase of heat flux, i.e. water flow rate.
- For R134a based nanorefrigerant, the inlet water temperature of 10°C gives higher values of htc.
- Higher htc is obtained for a void fraction of 0.09% of CuO nanoparticles and 0.5% of Al_2O_3 nanoparticles.

Nomenclature:

symbols	
m_W	Mass flow rate of water (kg/s)
$T_{W,in}$	Temperature inlet water of evaporator (ºC)
$T_{W,out}$	Temperature outlet water from evaporator (ºC)
k	Thermal conductivity of the tube wall (W/m ºC)
L	Test section length (m)
R_i & R_o	Inside and outside diameters of test section
$\overline{T}_w$	Average temperature to the tube wall (ºC)
$T_{r,sat}$	Saturation temperature

Subscripts:

symbols	
W	Water
w	Wall
r	Refrigerant
sat	Saturation
in	Inlet
out	Outlet
i	Inside
o	Outside

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