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Experimental Study on R404a Vapor Compression Refrigeration Cycle using Al_2O_3-POE and CuO-POE Nanolubricants

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ABSTRACT

High power consumption of air conditioners and refrigerators is a big problem. Accordingly, many directions for achieving energy efficient air conditioning and refrigeration systems with environmentally friendly refrigerants need to be explored to face the depletion energy resources. Vapor compression refrigeration system is one of the many refrigeration cycles and is the most widespread method for refrigeration, air conditioning and heat pump. On the other hand, the rapid progress in technology of nanoparticles have led to combine a novel generation of heat transfer fluids called nanofluids in which addition of nanoparticles to base fluids changes their heat transfer characteristics. In the present study, the effect of using CuO-POE and Al_2O_3-POE nanolubricant on the flow boiling heat transfer coefficient (HTC) of R404a refrigerant is experimentally investigated. The experiments have been carried out at different nanoparticles concentration ranged from 0.20 vol.% to 0.70 vol.% for Al_2O_3 and from 0.05 vol.% to 0.25 vol.% for CuO, with nanoparticles size of 50-60 nm and at heat flux ranged from 10 to 12 kW/m^2. The results showe enhancement in flow boiling heat transfer coefficient (HTC) of R404a with using Al_2O_3-POE and CuO-POE nanolubricant. It is found that flow boiling HTC increases with increasing the heat flux for the tested range. Also, it is noticed that the flow boiling HTC increases with increasing the nanoparticles concentration in POE oil up to 0.60% by volume for Al_2O_3 and 0.2 vol.% for CuO then deteriorates.

Keywords: flow boiling, R404a, vapor compression refrigeration cycle, nanofluids, POE

NOMENCLATURE

c_w	Specific heat of water, J/kg. K
$\bar{h}$	Flow boiling heat transfer coefficient, W/m^2.K
k	Thermal conductivity, W/m. K
L	Length of test section, m
$\dot{m}_w$	Mass flow rate, kg/s
$\dot{Q}_w$	Heat transfer rate, W
q	Heat flux, W/m^2
r_i	Inner radius of the inner copper tube, m
r_o	Outer radius of the inner copper tube, m
$T_{w,in}$	Inlet water temperature, °C
$T_{w,out}$	Outlet water temperature, °C
$T_{wall,avg}$	Average wall temperature, °C
$T_{ref,avg}$	Average refrigerant temperature, °C
$\dot{V}_w$	Volume flow rate, m^3/s
ρ_w	Water density, kg/m^3

Subscripts

avg	Average
i	Inner
in	Inlet
o	Outer
out	Outlet
ref	Refrigerant
w	Water

1. INTRODUCTION

Due to the high amounts of energy consumption by thermal systems like refrigerators and air conditioners, it motivates studies 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. 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. Adding nanoparticles to the refrigeration system can increase the solubility between the lubricant and the refrigerant, improve the tribological properties of the lubricant and accordingly enhances the performance of the compressor (Wang and Xie, 2003). Moreover, they illustrated that 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 2% vol. concentration at temperature range 5-20ºC was investigated by Mahbubul et al. (2013b). Mahbubul et al. (2013c) showed that the density of Al_2O_3/R141b nanorefrigerant increased with the excess of volume concentrations and decrease with temperatures. 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) found no obvious 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 was observed. Also, they discovered large improvement of HTC between 50% and 101% and insufficient effect on the system pressure drop with the increase in the nanolubricant to 2%wt. 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 was proposed and the predictions agreed with 93% of the experiential data within a deviation of ±20%. Jwo et al. (2009) experimentally studied the replacement of refrigerant R-134a and polyolester lubricating oil with a hydrocarbon refrigerant and mineral oil lubricant in a domestic refrigeration unit. Al_2O_3 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 was 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. 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 was decreased using 1%wt. of Al_2O_3 nanoparticles compared with pure R134a. Li et al. (2015) studied experimentally the performance of heat pump with nanofluids prepared by dispersing 5wt% TiO_2 nanoparticles in R22. Their results showed small decrease of COP during the cooling mode and significant increase in COP of the heating mode. Dhamneya et al. (2018) carried out experiments for improving the performance of vapor compression refrigeration system coupled with evaporative cooling pad and nanorefrigerant in hot and dry weather. The results showed that the performance indices of the evaporative cooled condenser were significantly enhanced. Also, the system COP was highly increased in hot and dry climate condition compared with conventional system.

2. EXPERIMENTAL SETUP

2.1 Experimental test rig

A test rig is established to conduct the experiments for studying the effect of using nanoparticles on the refrigeration cycle performance. Fig. 1 and 2 show a line diagram and a photograph of the test rig used in the present study and its components. It consists of two different cycles; refrigeration cycle and water cycle. The refrigeration cycle consists of compressor, condenser, expansion valve and evaporator (test section) in addition to the auxiliaries such as liquid receiver, accumulator, oil separator, filter drier and shut-off valves. Also, measuring devices such as pressure gauges and temperature sensors are installed in the cycle. The evaporator (test section) is a tube in tube heat exchanger type. The inner and outer tubes are made of copper. The refrigerant flows through the inner tube of 1400 mm length, 9.52 mm (3/8 inch) outer diameter and 7.72 mm inner diameter. The outer tube, with 19.05 mm (3/4 inch) outer diameter and 17.01 mm inner diameter, is divided into seven segments as shown in Fig. 3. Spacing of 30 mm is kept between the seven segments to enable temperature measurements along the outer surface of refrigerant tube. Moreover, each segment is provided with inlet and exit port at ends of its longitudinal surface to be connected using rubber hoses for allowing water flow. The water flows around the refrigerant tube through the annular space between outer and inner tubes of the test section where the heat is absorbed from water in counter flow manner. Water used in the present study represents the load and circulates through a closed cycle. The water cycle consists of 100 liters insulated tank, 0.5 HP centrifugal pump, 3 kW electric heater, flow meter, bypass line to control flow rate, temperature controller unit and valves.

Experimental runs are performed for various values of heat flux and nanoparticles concentration. Suitable measuring instruments are used for monitoring temperatures, water volume flow rate and refrigerant pressures. The temperatures are measured by using calibrated digital temperature sensors (embedded temperature panel meter TPM-30). The temperature sensors readings are in the range -50ºC to +70ºC with a resolution of 0.1ºC. They are used to measure the average wall temperature of the refrigerant tube by distributing them at six locations on the outer surface of the refrigerant tube as shown in Fig. 3. They are also used to measure the inlet and outlet water temperature of the test section. The water volume flow rate is monitored by using a calibrated rotameter, which have a range from 1 to 7 liters/min with a resolution 0.25 liters/min. During the experiments, the water volume flow rate is adjusted at 3 liters/min and a digital temperature controller (electronic thermostat) is used to control electric heater operation inside the water tank for adjusting the required inlet water temperature to the test section. Also, the pressures are measured at inlet and exit of the evaporator by using pressure gauges ranged from -30 to 150 psi.

2.2 Preparation of Al_2O_3-POE and CuO-POE Nanolubricants

Two types of nanoparticles, Al_2O_3 and CuO, are used in the present work to be mixed with polyolester oil (POE) to carry out the experiments on R404a refrigeration cycle. The nanoparticles are purchased from MKnano (M K Impex Corp.) with purity of 99% with average particle size of 50 nm as per manufacturer data sheet. The lubricating oil used in the present work is a synthetic polyolester oil and it is purchased from Emkarate RL 68H. This type of lubricating oil has viscosity and density values of $7.06\text{x}10^{-2}$ Pa.s and 0.977 g/ml respectively, and it is formulated specifically for use in air conditioning and refrigeration compressors. The low temperature and the thermal stability enable the use of Emkarate RL 68H over a wide operating temperature range.

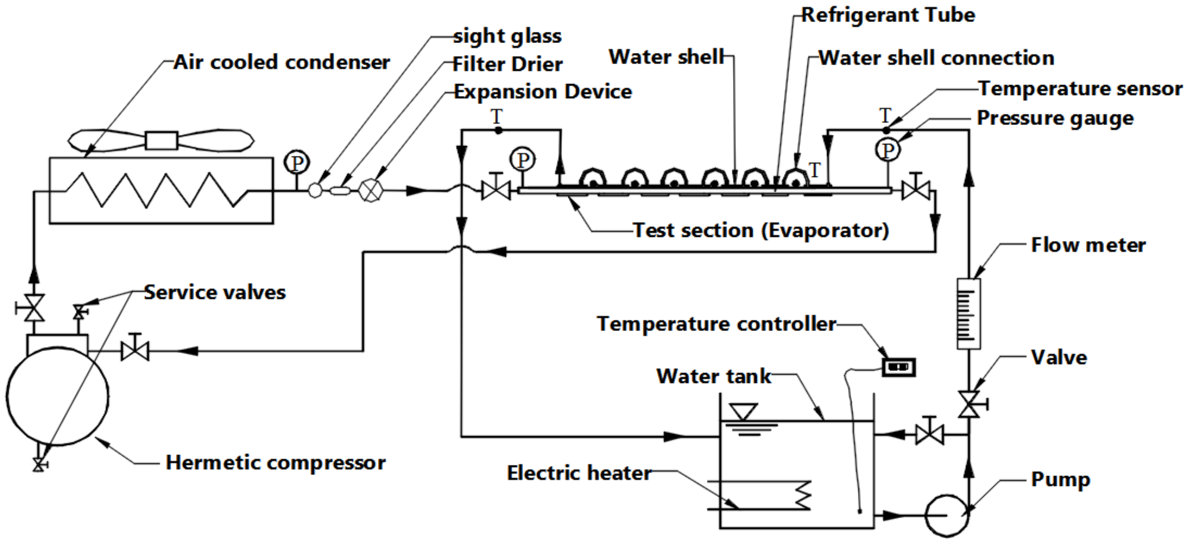

Fig. 1: Schematic diagram of the experimental test rig

Fig. 2: Photograph of the experimental test rig

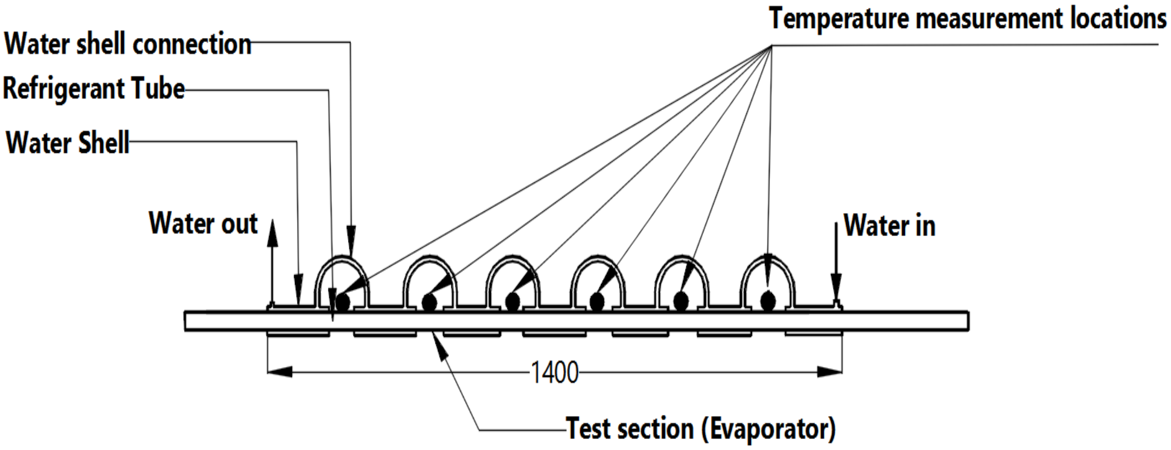

Fig. 3: Schematic diagram of the evaporator (test section)

In this study, the volume of polyolester oil POE is kept fixed at 782 cm^3, as recommended by compressor manufacturer. The mass of Al_2O_3 or CuO nanoparticles is calculated to achieve nanoparticles volume fraction values of 0.2%, 0.3%, 0.4%, 0.5%, 0.6% and 0.7% for Al_2O_3 and the values of 0.05%, 0.10%, 0.15%, 0.20% and 0.25% for CuO. 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 then sonicated using ultrasonic vibrator at room temperature for two hours to obtain good homogeneity of the mixture. This sonication time enhances the dispersion of nanoparticles within the fluid and consequently enhances the stability of nanofluid (Xie et al., 2010; Ahn et al., 2010).

3. EXPERIMENTAL PROCEDURES

The following test procedures are conducted to perform the required experiment. A sample of Al_2O_3-POE or CuO-POE nanolubricant with the specified volume fraction is prepared. The prepared sample is charged into the refrigeration cycle via the service port in 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 required temperature, the water is then pumped from the tank to the test section (evaporator) then 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 other concentrations of nanofluids.

4. DATA REDUCTION

The flow boiling HTC ($\bar{h}$) is calculated using:

$$\bar{h} = k\dot{Q}_w / [2\pi r_i kL(T_{wall,avg} - T_{ref,avg}) - \dot{Q}_w r_i \ln\left(\frac{r_o}{r_i}\right)] \qquad (1)$$

Where k is the copper tube thermal conductivity; r_o and r_i are inside and outside radii of the inner copper tube in the test section, respectively; L is the test section length; $T_{ref,avg}$ is the refrigerant temperature which is estimated at the average pressure in the test section, $P = (P_{in} + P_{exit})/2$, and $T_{wall,avg}$ is the wall temperature of refrigerant tube which represent average of six thermocouple readings at its outer surface between the seven segments of outer water shell as clarified in Fig. 3.

Also, $\dot{Q}_w$ is the heat transfer and it is calculated using the following equation:

$$\dot{Q}_w = \dot{m}_w \, c_w \, (T_{w,in} - T_{w,out}) \qquad (2)$$

where c_w is specific heat of water, $T_{w,in}$ and $T_{w,out}$ are the measured inlet and outlet water temperature water temperature of the test section and $\dot{m}_w$ is the water flow rate and it is calculated using the following equation:

$$\dot{m}_w = \rho_w \dot{V}_w \qquad (3)$$

where ρ_w is the water density and $\dot{V}_w$ is the measured water volume flow rate.

Heat flux, q, is calculated using following equation:

$$q = \frac{\dot{Q}_w}{2\pi r_o L} \qquad (4)$$

For all experimental runs, the average uncertainties in main parameters are summarized in Table (1).

Table 1: Average uncertainties in main parameters.

Parameter	**Uncertainty (ω)**
$\dot{m}_w$	±2.5%
$\dot{Q}_w$	±6.4%
q	±12.4%
$T_{wall,avg}$	±0.7%
$\bar{h}$	±13.7%

5. RESULET AND DISCUSSION

5.1 Effect of Heat Flux on the flow boiling HTC

Fig. 4 depicts the variation of the flow boiling HTC of R404a with heat flux for pure POE and different volumetric nanoparticles concentration of Al_2O_3-POE nanolubricant. It is illustrated from the figure that as the heat flux increases the flow boiling HTC increases. Also, it is observed that the use of nanofluid enhances the heat transfer process in case of using Al_2O_3-POE with nanoparticles concentration up to 0.60% by volume, whereas the increase of the nanoparticles concentration to 0.70% by volume leads to deterioration of heat transfer process. The flow boiling HTC with using pure POE shows the lowest value and then increases.

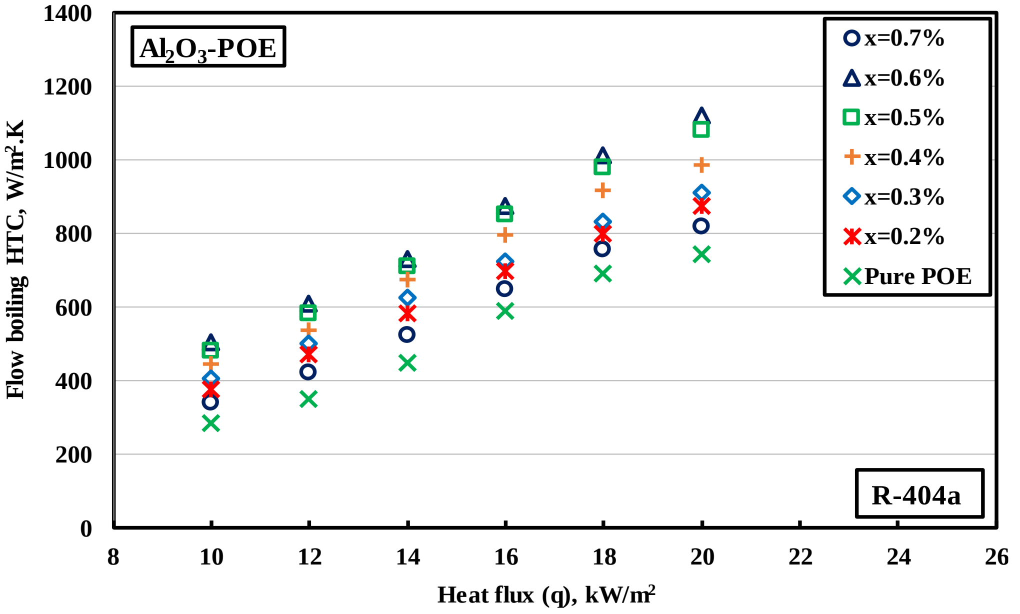

Fig. 4: Variation of flow boiling HTC with heat flux for different Al_2O_3 concentrations in Al_2O_3-POE nanolubricant

The variation of the flow boiling HTC of R404a with heat flux for pure POE and different volumetric nanoparticles concentration of CuO-POE nanolubricant is shown in Fig. 5. The same effect of heat flux on the flow boiling HTC is observed. It is illustrated from the figure that as the heat flux increases the flow boiling HTC increases. Also, it is noticed that the using of CuO-POE nanolubricant enhances the heat transfer process with nanoparticles concentration up to 0.20% by volume, whereas the increase of the nanoparticles concentration to 0.25% by volume leads to deterioration of heat transfer process. The flow boiling HTC with using pure POE shows the lowest value and then increases.

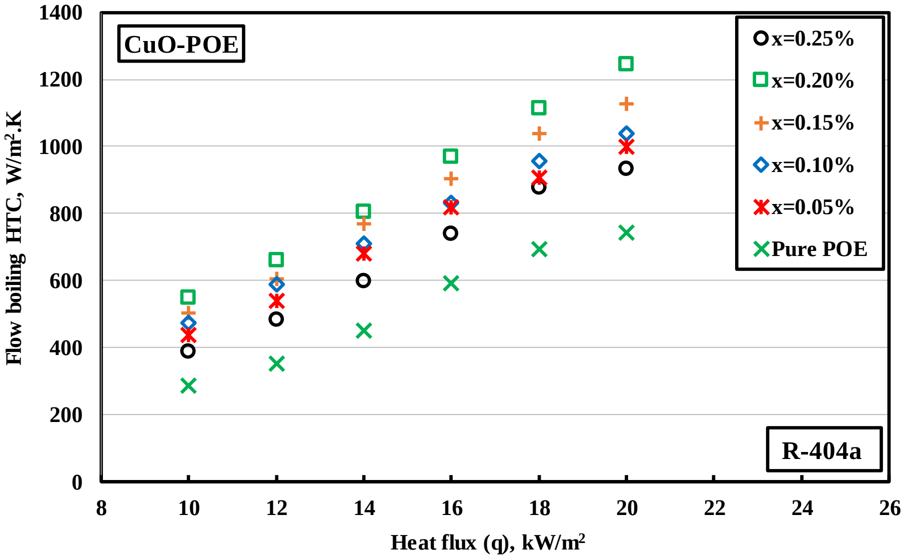

Fig. 5: Variation of flow boiling HTC with heat flux for different CuO concentrations in CuO-POE nanolubricant

5.2 Effect of Nanoparticles Concentrations on the flow boiling HTC

Fig. 6 shows the variation of the flow boiling HTC with Al_2O_3 nanoparticles concentrations for different values of heat flux. It is noticed that at any concentration, increasing the heat flux increases flow boiling HTC. Also, at any heat flux, the flow boiling HTC increases with nanoparticles concentration up to 0.60% then decreases.

The variation of the flow boiling HTC with CuO nanoparticles concentrations for different values of heat flux is illustrated in Fig. 7. The same behavior occurs for increasing the flow boiling HTC with heat flux at any nanoparticle concentration. Also, it is observed that the flow boiling HTC increases with the increase in CuO concentration up to 0.2% then deteriorates.

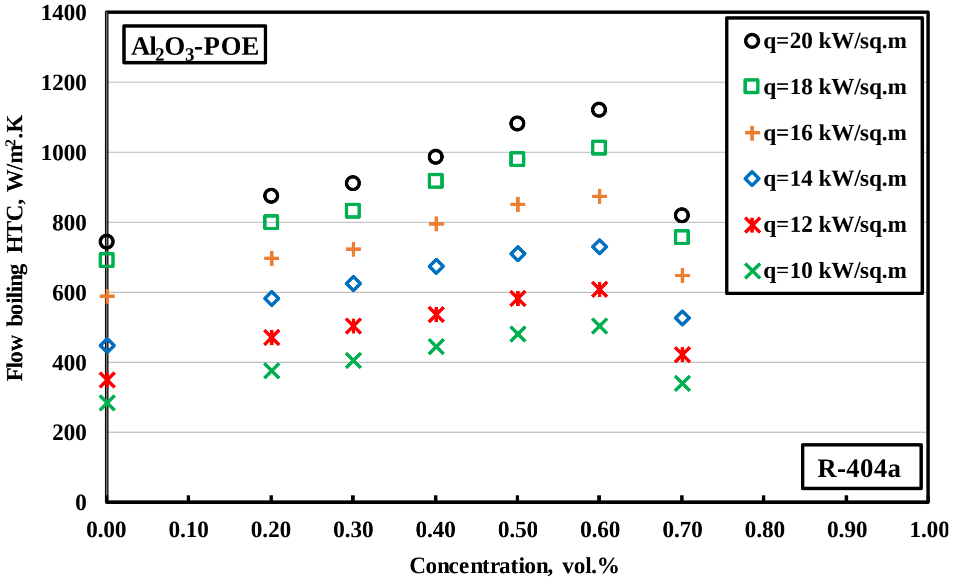

Fig. 6: Variation of flow boiling HTC with Al_2O_3 concentrations in Al_2O_3-POE nanolubricant for different values of heat flux.

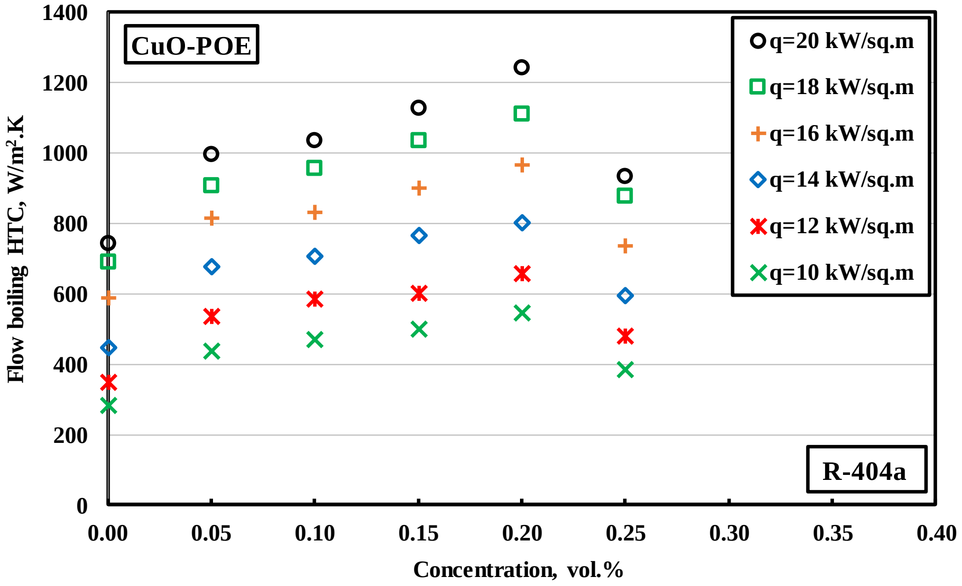

Fig. 7: Variation of flow boiling HTC with CuO concentrations in CuO-POE nanolubricant for different values of heat flux.

5.3 Effect of Nanoparticle Type on the flow boiling HTC

Fig. 8 illustrates the variation of the flow boiling HTC with the Nanoparticle type for different values of heat flux at certain value of concentration 0.20% by volume. It is noticed that flow boiling HTC increases with the increase in values of heat flux at the same concentration 0.20% by volume for both types of nanoparticles. At 0.20% concentration, the flow boiling HTC for CuO has higher values when compared with Al_2O_3. But, as clarified in Fig. 7, the flow boiling HTC deteriorates with the increase in CuO concentration above value of 0.2% by volume. On the other hand, the flow boiling HTC in case of using Al_2O_3 increases with concentration up to 0.6% then deteriorates.

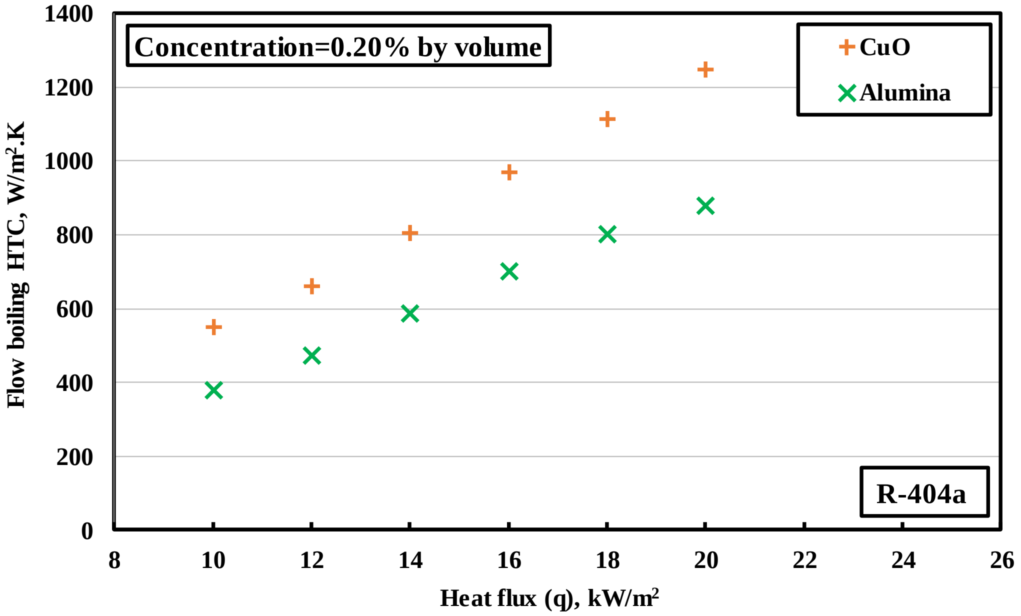

Fig. 8: Variation of flow boiling HTC with heat flux for different types of nanoparticles at volumetric concentrations of 0.20%.

6. CONCLUSIONS

From the previous discussion the following conclusions can be extracted.

- The nanolubricant of poloyster oil, Al_2O_3-POE and CuO-POE, have been successfully prepared and showed perfect working with R404a refrigerant.
- The flow boiling HTC increases with the increase of heat flux.

- The flow boiling HTC increases with the increase of Al_2O_3 nanoparticles concentration in Al_2O_3-POE up to 0.60% by volume then deteriorates.
- The flow boiling HTC increases with the increase of CuO nanoparticles concentration in CuO-POE up to 0.20% by volume then deteriorates.
- At nanoparticles volumetric concentration of 0.20%, The flow boiling HTC in case of using CuO-POE shows better values than Al_2O_3-POE but above this concentration the flow boiling HTC deteriorates with using CuO-POE and increases with using Al_2O_3-POE.

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