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Condensation of nano-refrigerant inside a horizontal tube

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ABSTRACT

In this paper, condensing pressure drop of refrigerant-based nanofluid inside a tube is studied. Isobutene was selected as the base fluid while CuO nanoparticles were utilized to prepare nano-refrigerant. However, for the feasibility of nanoparticle dispersion into the refrigerant, Polyester oil (POE) was utilized as lubricant oil and added to the pure refrigerant by 1% mass fraction. Various values of mass flux, vapor quality, concentration of nanoparticle are investigated. Results indicate that adding nanoparticles leads to enhance frictional pressure drop. Nanoparticles caused larger pressure drop penalty at relatively lower vapor qualities which may be attributed to the existing condensation flow pattern such that annular flow is less influenced by nanoparticles compared to intermittent flow regime.

1. Introduction

Homogenized dispersions of nano-scale (less than 100 μm) solid particles in a base fluid are called nanofluid and were firstly proposed by Choi and Eastman in 1995 [1]. As a special type of nanofluids, refrigerant-based nanofluids (nano-refrigerants) have been introduced [2]. The potential advantageous of thermal characteristics of nano-refrigerants in refrigeration systems has been reported by scientists [3]. However, nanoparticles may cause pressure drop penalty which in turn affect the overall efficiency of the heat exchangers. Therefore, nano-refrigerants could be recognized as a really promising method to improve the performance of refrigeration systems if both heat transfer and pressure drop characteristics of such medium are well understood.

Investigations on the pressure drop characteristics of nanofluids has been mainly dedicated on single phase flows [4,5] whereas there are very few studies in the literature that focused on phase change pressure drop of nanofluid flow. Bartel et al. [6] and Henderson [7] reported an insignificant effect of nanoparticles on the pressure drop of R-134a/POE/CuO nano-refrigerant flow boiling inside a horizontal tube, however, no experimental result of the pressure drop were presented. Peng et al. [8], provided the experimental data of the frictional pressure drop of R113/CuO nano-refrigerant flow boiling inside a horizontal tube. Frictional pressure drop of nano-refrigerants were larger than those for pure refrigerant and increased with nanoparticle concentration. Their results showed the higher nanoparticle impact factor at low and high vapor quality ($x < 0.5$ and $x > 0.7$) compared to intermediate vapor quality ($0.5 < x < 0.7$). Also, the nanoparticle impact factor decreased with increasing mass flux. A correlation was proposed to predict the frictional pressure drop of nano-refrigerant flow boiling. Alawi et al. [9] measured the frictional pressure drop of TiO2/R123 flow boiling in a horizontal tube. Significant increase in pressure drops were reported for higher nanoparticle concentration. Zhang et al. [10] carried out an experimental investigation on pressure drop of nano-refrigerant flow boiling in a horizontal tube using multiwalled carbon nanotube (MWCNT) as nanoparticle to create MWCNT-R123 nano-refrigerant. Larger frictional pressure drops were achieved for nano-refrigerant in comparison to that of pure refrigerant. They mentioned that frictional pressure drop for flow boiling of nanofluids could be reasonably estimated by substituting the thermophysical properties of nanofluids into the Muller-Steinhagen and Heck's [11] correlation.

Despite the recent works, our current understanding of phase change pressure drop characteristics of nano-refrigerant is still limited. To the best knowledge of the authors, there is no study in open literature to address the pressure drop for condensing flow of nanofluid inside a channel. In this study, the hydrocarbon refrigerant isobutene (R600a) is selected due to its appropriate thermophysical features, high energy efficiency, negligible ozone depletion and global warming potentials. Nanofluid has been utilized in several applications in recent years [12–22].

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Nomenclature

C_p	Specific heat [J kg^{-1} K^{-1}]
D	inner diameter of the tube [m]
d	diameter of nanoparticle [m]
G	mass flux [kg m^{-2}s^{-1}]
h	enthalphy [kJ kg^{-1}]
m	mass flow rate [kg s^{-1}]
Q	heat transfer rate [W]
Δp	Pressure drop [pa]
T	temperature [°C]
x	vapor quality [−]
w	mass fraction of nanoparticles [−]

Greek symbols

ε	void fraction [−]
ρ	density [kg m^{-3}]
σ	Surface tension [N m^{-1}]
φ	volume fraction of nanoparticles [−]

Subscripts

b	baseline
cw	cooling water
e	evaporator
f	frictional
h	homogenous
in	inlet of the test section
mom	momentum
s	static
tot	total
l	liquid
n	nanoparticle
no	nominal
o	oil
out	outlet of the test section
r	refrigerant
ra	Rouhani-Axelsson
$test$	test section
v	vapor

Compressors are commonly lubricated with oil in commercial systems and a small portion of the oil might leak into the working fluid. In most previous works, however, nanoparticles were directly added to refrigerants without presence of oil. To address such deficiency, in this study, nanoparticles are dispersed into the lubricant oil and then were mixed with the refrigerant as the baseline. The primarily objective of this study is to first introduce experimental findings of condensation pressure drops of refrigerant-based nanofluid inside a horizontal tube and the second goal is to explore the influence of major parameters such as mass flux, vapor quality and concentration of nanoparticles on the frictional pressure drop.

2. Experimental approach and method

2.1. Experimental apparatus

Fig. 1 shows the schematic diagram of the experimental set-up consists of gear pump, heater, evaporator, test condenser, post condenser, receiver, bypass path and flow meter. A magnetically gear pump drives the liquid phase of nano-refrigerant in the system and flows through a Fischer rotameter with the accuracy of ±1% of full scale to measure the flow rate. An inventor was connected to the gear pump to adjust the mass velocity of the working fluid. Then, the fluid flows to the heater to be heated up and evaporates in the evaporator to reach the desired inlet vapor quality to the test condenser. The test condenser is a shell and tube counter flow heat exchanger where the working fluid flows inside the inner tube (8.7 mm I.D.) and the cooled-water flows in the annulus. Pressures at the inlet and outlet of the test section were measured by pressure gauges (EN 837-1 Wika model), with the accuracy of 10 kPa, and the pressure drop along the test section was measured by a differential pressure transducer (PDM-75 model), which was calibrated by the factory (Endress Hauser) for up to 150 kPa. A counter flow heat exchanger with a 12 m coiled tube was installed after the test section as a post-condenser and a cylindrical shell was also placed downstream of the post-condenser as a receiver to ensure that the working fluid is liquid before it enters the pump.

Isobutene (R600a, 99.5% purity) and Polyolester oil (POE) were chosen as the pure refrigerant and the lubricant respectively. A by-pass line was utilized in the system to inject the oil or the homogenized mixture of oil/nanoparticles in the system to form baseline mixture (R600a/POE) or nano-refrigerant (R600a/POE/CuO) flows. Then, the pump worked for 4 h to homogenize the mixture.

2.2. Working fluids

Isobutene (R600a) is widely used as a refrigerant in low capacity (household and small commercial) refrigeration applications due to its low Global Warming Potential (GWP), zero Ozone Depletion Potential (ODP), low cost and enhanced cycle efficiency at high condensing temperatures [23]. In order to create the baseline mixture, Polyolester oil (POE) with commercial name of RL68H is applied as the lubricant added to the pure R600a by 1% mass fraction. POE is completely soluble in R600a and has the nominal kinematic viscosity of 72.3 μm^2 s^{-1} at 40$^{\circ C}$, as reported by the manufacturer. Copper oxide (CuO) was used as nanoparticles with approximate scale of 40 nm in diameter. The characteristics of these nanoparticles are presented in Table 1. Different mass fractions of 0.5%, 1% and 1.5% were dispersed in POE (by a digital electronic balance with the maximum error of 0.1 mg). By using the ultrasonic device (UP400S, Hielscher GmbH) the blend of oil and nanoparticles are vibrated for 1 h, at 400 W and 20 KHz to achieve the uniform dispersed mixture. Then the mixture of oil/nanoparticles is injected to the pure refrigerant. The dispersion of the nanofluid was monitored for 12 h and no significant sedimentation was occurred. Since surfactant influences the condensation process, it was not used for stabilization. Deposition of the nanofluid in the system was monitored through the sight glass section. Negligible amount of deposition was observed during the operation process. The nano-refrigerants were detected to be stable for more than 12 h. Therefore, each experiment was conducted for less than 8 h.

3. Data reduction

3.1. Frictional pressure drop

The frictional pressure drop ΔP_f can be calculated from Eq. (1):

$$\Delta p_f = \Delta p_{tot} - \Delta p_{static} - \Delta p_{mom} \tag{1}$$

Table 1
Nanoparticle specifications as specified by the manufacturer EPRUI Nanoparticles.

Isobaric specific heat [J kg^{-1} k^{-1}]	Purity (%)	Density [g cm^{-3}]	Diameter [nm]	Thermal conductivity [Wm^{-1} K^{-}1]
550.5	99.8	6.32	40	32.9