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Research paper

Effect of lubricating oil on flow boiling characteristics of R-600a/oil inside a horizontal smooth tube

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ABSTRACT

The aim of the present study is to experimentally investigate the effect of oil on flow boiling of R-600a as a hydrocarbon refrigerant inside a horizontal smooth tube. In order to study the effect of oil on the flow boiling of R-600a, a well instrumented apparatus was designed, fabricated and installed. The experimental conditions of this study include nominal oil concentrations from 0% to 2.5%, mass velocities in range of 130–380 kg/m^{2}s, inlet vapor qualities from 0.05 to 0.77 and heat fluxes from 10 to 28 kW/m^{2}which were conducted in a copper test tube with the inner diameter of 8.7 mm. Several parameters affecting the heat transfer coefficient and pressure drop of refrigerant–oil mixture, such as oil concentration, mass flux and vapor quality were investigated. The comparison between two-phase pressure drop for pure refrigerant and the refrigerant oil mixture reveals that pressure drop increases with the increase of oil concentration in all ranges of vapor quality and mass velocities. However, heat transfer coefficients tend to increase at low vapor qualities and decrease at the middle and high vapor qualities due to presence of oil.

1. Introduction

The presence of oil inside refrigerant systems is unavoidable since the oil is required to lubricate the moving parts of the compressor. Oil can affect the flow boiling of the refrigerant by its changing thermal conductivity, surface tension, flow pattern and other properties of refrigerant during flow boiling. Therefore, the effect of oil on the flow boiling heat transfer is important to be investigated. In the open literature, a great number of papers including refrigerant–oil mixture can be found for different test condition and refrigerants.

Cho and Tae [1] reported a 20% increase in pressure drop and a 10% reduction in heat transfer compared with the pure refrigerant during evaporation of refrigerants (R22 and R-407C) with the presence of 5.0% oil. Gao and Honda [2] Conducted an experimental study on flow boiling heat transfer of CO_2 (R-744) and oil (PAG) mixtures inside a horizontal tube with an inner diameter of 3 mm. According to their study when the concentration of the lubricant oil in weight was more than 1%, the local heat transfer coefficient was much lower than that without the lubricant oil.

Zheng et al. [3] studied the flow boiling of an ammonia–lubricant oil mixture inside horizontal plain tube and they concluded that the heat transfer increased with evaporation temperature and applied heat flux. Dang et al. [4] conducted a study on flow boiling of CO_2–lubricant oil mixtures in smooth tubes. They used synthetic PAG lubricant oil and their results showed that for a small quantity of this oil in the system, 0.5% in weight, the heat transfer coefficient reduced significantly, less than 50% in comparison with pure CO_2. When the oil concentration was increased to 1.0 or 5.0%, the heat transfer coefficient remained similar to the results obtained for 0.5%.

Hu et al. [5] performed a study on heat transfer and pressure drop in flow boiling of R-410a–oil mixture inside horizontal smooth tube and they reported that the presence of oil enhanced the heat transfer at low and intermediate vapor qualities. Their pressure drop results showed an increase in all vapor qualities. Bandarra Filho et al. [6] presented a comprehensive review of flow boiling characteristics of refrigerant–lubricant oil mixtures. They summarize that there is no clear agreement on the effect of oil. According to their report, an increase in surface tension and foam formation (especially at lower mass fluxes) may lead to a better wetting of the tube wall and thus enhancing heat transfer. On the other hand, frictional pressure drop in general increases with the oil concentration due to an increase in liquid viscosity.

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Nomenclature

D	diameter (mm)
G	mass velocity (kg/m^{2}s)
h	specific enthalpy (kJ/kg)
K	thermal conductivity (W/m K)
L	length (mm)
m	mass flow rate (kg/s)
P	pressure (kPa)
Q	rate of heat transfer (W)
q	heat flux (W/m^2)
Re	Reynolds number
T	temperature (K)
x	vapor quality
X_{tt}	Martinelli parameter
Greek symbols	
α	heat transfer coefficient (W/m^{2}K)
ω	oil concentration
ε	void fraction
μ	dynamic viscosity (Pa s)
Subscripts	
in	inlet
L	liquid phase
loc	local
no	nominal
O	lubricant oil
out	outlet
pre	preheater
R	refrigerant
sat	saturate
test	test section
tp	two phase
V	vapor phase
W	wall

Dang et al. [7] addressed experimental studies on the flow boiling heat transfer of carbon dioxide with PAG-type lubricating oil entrained from 0% to 5% in horizontal smooth tubes with inner diameter of 2–6 mm. Their experiments were conducted at mass fluxes of 360–1440 kg/m^{2}s, heat fluxes of 4.5–36 kW/m^2 and the saturation temperature of 15 °C. They founded that the heat transfer coefficient declined by less than half compared to pure refrigerant at low oil concentrations of 0.5–1%, while it did not decrease with increasing oil concentration. Also they reported that presence of oil caused the mass flux to significantly influence the heat transfer coefficient at a low heat flux till dryout, and the dryout quality decreased at a large mass flux. The measured pressure drops increased monotonously thanks to the formation of an oil layer along the tube's inner wall and an increase in viscosity due to the entrainment of lubricating oil in CO_2.

Wetzel et al. [8] investigated the flow boiling heat transfer and pressure drop of CO_2–oil mixtures at low temperatures inside a 14 mm smooth tube under near isothermal wall condition. In their test conditions, the nominal concentration of oil (0–3 wt%), saturation pressure (14.3–26.4 bar), mass flux (75–300 kg/m^{2}s), inlet vapor quality (0.1–0.9) and heat flux (0–100 kW/m^2) were varied. They observed a decline in heat transfer coefficients and a considerable increase in pressure drop with increasing local oil concentration (i.e. nominal oil concentration and vapor quality) relative to measurements with oil-free conditions. Only for low oil concentrations (1 wt%) and medium vapor qualities ($0.5 < x < 0.7$) a slight improvement in average heat transfer were seen. Regarding their local measurements, the addition of oil can lead to a significant decrease in liquid heat transfer coefficient (i.e. bottom tube segments). On the other hand an increase in tube wetting induced by foam formation resulted in a growth of local heat transfer coefficients at the top of the tube. By using refrigerant mixture properties, the heat transfer correlations could not describe the experimental data satisfactorily.

Recently, Li et al. [9] have proposed a correlation for flow boiling heat transfer based on experimental data for mixtures of CO_2 and partial miscible PAG oil by Dang et al. [7]. The correlation is based on cubic superposition of convective and nucleate boiling contribution terms as proposed by Steiner and Taborek [10].

Different studies published in the open literature shows different results about the effect of oil on the heat transfer performance under flow boiling condition of refrigerant–oil mixture. Some researchers reported decrease of heat transfer with oil concentration and some investigators observed an increase of heat transfer at low oil concentration and low vapor qualities. One possible explanation for the discrepancy with results may be explained by the fact that, the heat transfer characteristics of refrigerant–oil mixture highly depends on the type of refrigerant, type of the oil, oil concentration and the test conditions. Miscibility, surface tension and viscosity are main properties of oil which can change the properties of refrigerant.

R-600a as a hydrocarbon refrigerant was chosen in this study. Due to environmental issues like ozone depleting and global warming, natural refrigerants such as ammonia (R-717), carbon dioxide (R-744) and hydrocarbons such as isobutane (R-600a) have been studied to replace CFCs, HCFCs and HFCs in refrigeration, air-conditioning and heat pump systems. Comparing the Ozone Depletion Potential of R-600a (0) as a hydrocarbon refrigerant with R-12 (1) as a CFC refrigerant and 100 years Global Warming Potential of R-600a (20) with R-134a (1370) as an HFC refrigerant shows that R-600a has a better environmentally performance [Molina and Rowland [11]–Kurylo [12]].

Hydrocarbons present great advantages such as thermodynamic and transport properties, small molecular weight, and appropriate compatibility with lubricants, compared to the disadvantage of low limit of flammability. Moreover, some recent studies show that R-600a has also better energy performance comparing with other refrigerant. Calm [13] addressed that R-600a have taken the place of R-12 and later R-134a and nowadays dominates in the domestic refrigerators in Europe. Therefore, environmentally advantages and different properties of hydrocarbons refrigerants compared with conventional refrigerants make it necessary to investigate the effect of oil on flow boiling hydrocarbons refrigerants.

As noted above none of the mentioned studies have investigated the oil effect on flow boiling of hydrocarbons refrigerants. The aim of this study is to investigate the convective boiling characteristics of R-600a–oil mixture and the results of this paper could be used in design of evaporators in refrigerators with R-600a–oil mixture as a working fluid.

2. Experimental apparatus

2.1. Description

The schematic of the experimental apparatus, for testing the heat transfer coefficient and the pressure drop of refrigerant–oil mixture, including variable frequency gear pump, coriolis-effect mass flow meter, preheaters, test evaporator, by-pass section,