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Investigation of the two-phase convective boiling of HFO-1234yf in a 3.9 mm diameter tube

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ABSTRACT

In this study, the influences of heat flux and mass flux on the two-phase convective boiling heat transfer performance are reported for refrigerants HFO-1234yf and HFC-134a in a 3.9 mm smooth diameter tube. Tests are performed with a saturation temperature of 10 °C. It is found that at lower vapor quality region the nucleate boiling is the dominant heat transfer mechanism while the convective evaporation mechanism takes control at the higher vapor quality region. Both HFC-134a and HFO-1234yf shows similar trend and the difference in heat transfer coefficient between HFO-1234 and HFC-134a is quite small. The comparable heat transfer performance between HFC-134a and HFO-1234yf is attributed to similar physical properties and nucleate boiling contribution. The present test results are in line with some existing reports but are inconsistent with one other study having a tube diameter of 1.1 mm. It is found that the departure of heat transfer coefficients between the available publications is mainly attributed to the different flow phenomena caused by the difference of the channel size and channel geometry. A noticeable deterioration of the heat transfer coefficient for HFO-1234yf is encountered in the microchannel. The pressure drops for HFC-134a is about 5–15% higher than that of HFO-1234yf.

1. Introduction

Concerns for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbans (HCFCs) refrigerants casting impact on environment lead to the advent of hydrofluorocarbans (HFCs). Despite HFC refrigerants have no ozone depletion potential (ODP), many of them have a relatively high global warming potential (GWP) which casts significant impact on the environment. For example, HFC-134a is the extensively used refrigerant in air-conditioning and automobile air conditioners (MACs), it has a GWP of 1300 (time horizon of 100 years). As a result, efforts were made to search for new refrigerants that are environmentally benign and can be used to in future air-conditioning and mobile air conditioning systems. Among the candidates, HFO-1234yf is regarded as one of the promising candidates for its GWP is as low as four. The thermophysical properties, cycle performance, and two-phase heat transfer performance of HFO-1234yf are the key parameters to assess the feasibility of using this new refrigerant in air conditioners. The thermophysical properties of refrigerant mixture were similar to those of HFC-134a (Arakawa et al. [1]), thereby offering an opportunity as a drop-in solution for current mobile air conditioners. Normally a drop-in solution yields a lower system performance for lacking optimization in the design process. For instance, Lee and Jung [2] had shown that the coefficient of performance and capacity of HFO-1234yf are up to 2.7% and 4.0% lower than those of HFC-134a, respectively during a typical drop-in experiment. The compressor discharge temperature and the amount of refrigerant charge of HFO-1234yf are 6.5 °C and 10% lower than those of HFC-134a. Analogous results were also reported by Zilio et al. [3] and Navarro-Esbri et al. [4], they also showed a slight decrease in COP for HFO-1234yf system at a same cooling capacity with HFC-134a.

For further optimizing the system performance, further details in designing the heat exchangers (condenser or evaporator) are imperative. As a consequence, information about the two-phase heat transfer convective performance in the evaporator plays a crucial role in optimizing the heat exchangers. However, the published results regarding to the convective evaporation performance of HFO-1234yf is still limited and inconsistent. For instance, Saitoh et al. [5] conducted study for boiling heat transfer of the refrigerant HFO-1234yf flowing in a smooth small-diameter horizontal tube (inner diameter (ID): 2 mm) and Li et al. [6] used similar test facility and identical test tube for comparing the HTC between HFC-32 and HFO-1234yf. Their test results showed that from the low to the high vapor quality region the difference between the heat transfer coefficients of HFO-1234yf and HFC-134a is small, Saitoh et al. [5] attributed this to the small differences in their thermodynamic properties. Recently, Col et al. [7] performed flow boiling of

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Nomenclature

A_o	outside heat transfer area of the tube, m^2
A_i	nominal inside heat transfer area of the tube, m^2
c_p	specific heat of water, J kg^{-1} K^{-1}
Co	confinement number, $Co = \frac{\left(\frac{\sigma}{g(\rho_L-\rho_G)}\right)^{0.5}}{d}$
D	hydraulic diameter at annulus side, m
D_i	inside diameter of the tube, m
D_o	outside diameter of the test tube, m
G	mass flux, kg m^{-2} s^{-1}
g	gravitation constant, N/m
h_i	inside heat transfer coefficient, W m^{-2} K^{-1}
h_o	heat transfer coefficient on the annulus side, W m^{-2} K^{-1}
i_{fg}	latent heat of evaporating vapor, J kg^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	effective heating length, m
$LMTD$	log mean temperature difference, K
$\dot{m}_{water}$	mass flow rate of the refrigerant, kg s^{-1}
$\dot{m}_{water}$	mass flow rate of coolant water, kg s^{-1}
Nu	Nusselt number, dimensionless
p	pressure, kPa
P_r	reduced pressure
Pr	Prandtl mumber, dimensionless
q	heat flux, W m^{-2}
$\dot{Q}$	heat transfer rate, W
Re	Reynolds number, dimensionless
R_w	wall resistance, K W^{-1}
$T_{water,in}$	inlet temperature of water at annulus side, K
$T_{water,out}$	outlet temperature of water at annulus side, K
T_{sat}	saturation temperature of the refrigerant, K
ΔT	temperature rise on the water coolant, K
ΔT_1	temperature difference, $\Delta T_1 = T_{sat,in} - T_{water,out}$, K
ΔT_2	temperature difference, $\Delta T_2 = T_{sat,out} - T_{water,in}$, K
U_o	overall heat transfer coefficient, W m^{-2} K^{-1}
v	velocity of water at annulus side, m s^{-1}
x	vapor quality

Greek symbols

ρ_l	density of refrigerant, kg m^{-3}
μ	dynamic viscosity of refrigerant, N s m^{-2}
σ	surface tension of refrigerant, N m^{-1}

Subscript

L	liquid phase
G	gas phase
f	water fluid at annulus side
i	inside
in	inlet
o	outside
out	outlet
w	wall
$water$	water

HFO-1234yf in a 1mm diameter circular microchannel and compared to R134a with a saturation temperature of 31 °C. They found that there were no significant differences between the flow boiling performance of R1234yf and R134a. On the other hand, Mortada et al. [8] performed an experiment for HFO-1234yf and HFC-134a in a 1.1 mm rectangular channel with rather small mass flux of 20–100 kg m^{-2} s^{-1} and heat flux from 2 to 15 kW m^{-2}. However, their results showed that the HTC for HFO-1234yf is lower than that of HFC-134a as much as 40%. The results are contradictory to the findings of Saitoh et al. [4] and Col et al. [7]. A recent overview about the general two-phase heat transfer characteristics for HFO-1234yf by Wang [9] also reported some inconsistent data in condensation.

In view of the relatively few data associated with the connective boiling performance of HFO-1234yf, it is the objective of this study to report some newly tested data concerning the two-phase convective heat transfer performance. Moreover, there are some contradictory results about the HFO-1234yf and HFC-134a. The present study also aims to elaborate some possible causes about the differences of the existing data.

2. Experimental setup

The schematic of the experimental apparatus is depicted in Fig. 1(a). The test rig is composed of three independent flow loops. Namely, a refrigerant loop, a heating water flow loop and a glycol flow loop. The refrigerant flow loop consists of a variable speed gear pump which delivers subcooled refrigerant to the preheater. The refrigerant pump can provide refrigerant mass fluxes ranging from 100 to 500 kg m^{-2} s^{-1}. A very accurate mass flowmeter is installed between the refrigerant pump and the preheater. Note that the accuracy of the mass flowmeter is generally 0.3% of the test span. The subcooled refrigerant liquid was heated in the preheater to achieve a prescribed evaporator inlet quality before entering the test section. Then, the refrigerant went into the test section to vaporize. Finally, the two-phase refrigerant was condensed in a shell-and-coil condenser. The horizontal test section is a double-pipe heat exchanger with effective heat transfer length of 0.6 m. Its detailed configuration can be seen from Fig. 1(b). Note that an electrically heated preheater is installed at the upstream of the test section, and the generated two-phase mixtures from the preheater flows into the test section. A 50-mm-thick rubber insulation is wrapped around the double-pipe test section to ensure heat loss to the ambient to be less than 10 W (less than 2% of the heat input) for the test tube. As seen from Fig. 1(b), inside the double-pipe heat exchanger, water flows countercurrently in the test section annulus, while refrigerant is evaporated inside the test tube. The pressure drop of the refrigerant across the test tube was measured by a differential pressure transducer with 10 Pa precision. A magnetic flowmeter was used to record the flowrates of water in the annulus of the test section. The magnetic flowmeter was calibrated in advance with a calibrated accuracy of 0.002 L/s. An absolute pressure transducer was installed at the inlet and exit of the test section with resolution up to 0.1 kPa. During each experiment, the heat flux in the test section is maintained at a desired constant value. Experiments were conducted using a smooth copper tube having an internal diameter of 3.9 mm. Tests were conducted at an evaporation temperature of 10 °C. All of the water and refrigerant temperatures, were measured by RTDs (Pt 100 Ω) having a calibrated accuracy of 0.05 °C. The refrigerant leaving the test section was condensed and subcooled by a glycol circuit. The inlet temperature of the glycol is controlled by a 3 kW low-temperature thermostat. All of the data signals were collected and converted by a data acquisition system (Hybrid recorder). The data acquisition system then transmits the converted signals through USB interface to a host computer for further operation. Uncertainties of the heat transfer coefficients and reported in the present investigation, following the single-sample analysis proposed by Moffat [10], are within ±7.1% of the measured values. The working fluids in this study are HFO-1234yf and HFC-134a.