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Condensation heat transfer and pressure drop of refrigerants HFO-1234yf and HFC-134a in small circular tube

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ABSTRACT

HFO-1234yf has similar thermodynamic properties to HFC-134a but much lower GWP value. It is expected as a good candidate to replace the refrigerant HFC-134a in the near future. However, only very few papers have been published in the past years regarding to the flow condensation heat transfer performance of this new refrigerant. This study provides an experimental analysis of flow condensation heat transfer and pressure drops of refrigerants HFO-1234yf and HFC-134a in a small circular tube. The test results show that both pressure drop and condensation heat transfer performance depend on the fluid properties, flow conditions and flow patterns. The major controlling properties on pressure drops and heat transfer coefficients is strongly depending on their two-phase flow pattern at various flow conditions. At the lowest mass velocity, gravity is the major force that dominates the heat transfer mechanism and the flow pattern is slug. Higher liquid viscosity retarded the condensate flow but higher liquid conductivity provided better heat transfer through the liquid film. Both liquid viscosity and conductivity are the important controlling properties. While mass velocity and vapor quality increased, the effect of shear force increased and the flow pattern transferred to annular. Liquid thermal conductivity became the major controlling property at high vapor qualities. But at low vapor qualities, gravity is still important and therefore liquid viscosity is one the major controlling parameter. At the highest mass velocity conditions, gravity effect is negligible even though at very low vapor quality condition. Shear force dominated the condensation heat transfer mechanism and liquid conductivity is the most important controlling property. It can be concluded that the flow condensation heat transfer performance is strongly depending on the two-phase flow patterns at various flow conditions.

1. Introduction

Owing to the global warming effect consideration, the EU has banned the use of refrigerants with Global Warming Potential (GWP) value higher than 150 in all new passenger cars starting from 1 January 2017 (EU directive 2006/40/EC [1]). The study on the replacement of high GWP refrigerant such as HFC-134a is an important and urgent issue in the coming years. Recently, a new refrigerant, HFO-1234yf has been developed with similar thermodynamic properties to HFC-134a but much lower GWP value (GWP equals to 4 in comparing to 1,430 of HFC-134a). It is expected as a good candidate to replace the refrigerant HFC-134a in the near future. However, most of the heat transfer and flow performances of HFO-1234yf are still not very clear up-to-date especially for condensation heat transfer.

Only two papers have been found in the published literature for condensation heat transfer of HFO-1234yf in circular tubes. Del Col et al. [2] measured the condensation heat transfer coefficient of refrigerants HFO-1234yf and HFC-134a inside a circular channel with inner dimeter of 0.96 mm. Test section where cooled down by water circulation around the tube and local heat transfer coefficients were measured by several thermocouples along the test section. Condensation tests were carried out at mass fluxes ranging between 200 and 1,000 kg/m^2 s. Their results showed that HFO-1234yf displayed a lower pressure drop by 10–12% as compared to HFC-134a at the same operating conditions. They explained this result by the different reduced pressure of these two refrigerants which HFO-1234yf is greater by 20% than that of HFC-134a at tested saturation temperature. For condensation heat transfer, except for the lowest values of vapor quality, HFO-1234yf displayed a heat transfer coefficient lower than HFC-134a for all values of mass velocities. The condensation heat transfer coefficients of HFO-1234yf were from 15% at 200 kg/m^2 s and 0.4 vapor quality to 30% at 800 kg/m^2 s and 0.7 vapor quality lower than

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Nomenclature

A	heat transfer area, m^2
A_c	cross section area, m^2
c_p	specific heat capacity, J/kg·K
d	tube diameter, m^2
f	friction factor, dimensionless
G	mass flux, kg/m^2·s
h	heat transfer coefficient, W/m^2·K
i_{lv}	enthalpy of evaporation, kJ/kg
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, dimensionless
Pr	Prandtl number, dimensionless
Δp	pressure difference, Pa
q	heat transfer rate, W
q''	heat flux, W/m^2
R	thermal resistance, K/W
Re	Reynolds number, dimensionless
T	temperature, °C
ΔT_{lm}	logarithmic mean temperature difference, °C
U	overall heat transfer coefficient, W/m^2·K
u	superficial velocity m/s
x	vapor quality, kg/kg
x_{ave}	average vapor quality, kg/kg

Greek symbol

ρ	density, kg/m^3
μ	dynamic viscosity, N·s/m^2
σ	surface tension, N/m

Subscript

i	inlet
l	liquid
o	outlet
r	refrigerant
s	superficial velocity
v	vapor
w	water

those of HFC-134a. They explained this result by the reason of that the liquid thermal conductivity of HFO-1234yf is lower by 18% as compared to the one of HFC-134a.

Wang et al. [3] observed two-phase flow pattern and measured condensation heat transfer of refrigerant HFO-1234yf in a horizontal tube with inner diameter of 4 mm at a mass flux range of 100–400 kg/m^2 s and compared the results with those of HFC-134a and HFC-32. They observed that the wavy flow was prevalent over most of the vapor quality range at a mass flux of 100 kg/m^2 s. The heat transfer is dominated mainly by intermediate flow region and gravity-dominated flow regime and increased slightly with increasing vapor quality. For a mass flux of 200 kg/m^2 s, approximately half of the vapor quality range is occupied by annular flow regimes. The heat transfer coefficients increase gradually with increasing vapor quality. For higher mass flux, 300 kg/m^2 s and 400 kg/m^2 s, annular flow was prevalent over most of the vapor quality range. There is a clear dependency of the heat transfer coefficient on the vapor quality and the mass flux. The heat transfer is primarily in the shear dominated flow regimes.

In comparing the condensation heat transfer between these three refrigerants, HFC-32 has the highest heat transfer coefficients while the heat transfer coefficients of HFO-1234yf are a little lower than that of HFC-134a at all test conditions. The largest difference of heat transfer coefficient between HFO-1234yf and HFC-134a is 23.8% at mass flux of 100 kg/m^2 s. Wang et al. [3] explained that this is because the thermal physical properties of HFO-1234yf (density ratio, viscosity ratio of liquid and vapor, the thermal conductivity) are all a little lower than that of HFC-134a.

Beside condensation in circular tubes, Illan-Gomez et al. [4] measured condensation heat transfer coefficient of HFO-1234yf and HFC-134a inside an aluminum multiport minichannel with hydraulic diameter of 1.16 mm. Similar and lower heat transfer coefficient of HFO-1234yf in compare to HFC-134a has been measured. The authors attributed it to the properties differences such as thermal conductivity, density and viscosity. Pressure drops of HFO-1234yf under the adiabatic and diabetic condition were reported as 5% to 7% lower than that of HFC-134a.

Longo and Zilio [5] measured the heat transfer coefficients and the pressure drop during condensation of HFO-1234yf and HFC-134a inside a brazed plate heat exchanger. Their test results showed that HFO-1234yf exhibited heat transfer coefficients 10–12% lower and frictional pressure drop 10–20% lower than those of HFC134a under the same operating conditions.

Another research regarding to the condensation of HFO-1234yf is that Park et al. [6] measured external condensation heat transfer coefficients of HFC-134a and HFO-1234yf on a plain, low fin, and Turbo-C tubes. Test results showed that the condensation heat transfer coefficients of HFO-1234yf are almost the same as those of HFC-134a for all three surfaces tested.

From the above literature review, it is found that very few experimental studied on condensation heat transfer of HFO-1234yf have been conducted in the past years. Most of them showed the condensation heat transfer coefficients of HFO-1234yf are lower than those of HFC-134a but all of them ignored the difference between these two refrigerants at certain test conditions. Table 1 summarizes the condensation heat transfer performance tested results in the published literatures. More study is necessary for clarifying the heat transfer mechanism of these two refrigerants.

2. Experimental method

2.1. Test section

This study provides an experimental measurement of condensation heat transfer and pressure drop of refrigerants

Table 1
Summary of the condensation heat transfer performance tested results.

Author/year	Test channel	T_{sat} °C	Diameter mm	Mass flux kg/m^2 s	Comparison
Del Col et al. [2]	Internal	40	1.0	200–1000	HFO-1234yf 15–30% < HFC-134a
Wang et al. [3]	Internal	40–50	4	100–400	HFO-1234yf up to 23.8% < HFC-134a
Illan-Gomez et al. [4]	Minichannel	30–50	1.6	350–940	HFO-1234yf 5–7% < HFC-134a
Longo and Zilio [5]	Plate heat exchanger	25–40	–	12–41	HFO-1234yf 10–12% < HFC-134a
Park et al. [6]	External	39	18.9	–	HFO-1234yf same as HFC-134a