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Flow boiling heat transfer of R1234yf inside a 3.4 mm ID microfin tube

A. Diani [a], S. Mancin [b], L. Rossetto [a,*]

[a] Dipartimento di Ingegneria Industriale, University of Padova, via Venezia 1, 35131 Padova, Italy
[b] Dipartimento di Tecnica e Gestione dei Sistemi Industriale, University of Padova, Stradella San Nicola 3, 36100 Vicenza, Italy

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ABSTRACT

This paper presents experimental results about the flow boiling of R1234yf inside a mini microfin tube. R1234yf is a Hydro Fluoro Olefin with a GWP < 1, and thus it has recently been proposed as one of the possible substitutes of the common R134a. This study was carried out in a facility located at the Dipartimento di Ingegneria Industriale of University of Padova. The microfin tube has an inner diameter at the fin tip of 3.4 mm, an outer diameter of 4.0 mm, it has 40 fins and each fin is 0.12 mm high. From the experimental measurements, it was possible to calculate the heat transfer coefficients, frictional pressure drops, and vapour qualities at the onset of the dryout phenomenon. The mass velocity was varied from 190 to 940 kg m^{-2} s^{-1}, the heat flux from 10 to 50 kW m^{-2}, the vapour quality from 0.10 to 0.99, and the saturation temperature at the inlet of the test section was kept constant and equal to 30 °C. The experimental results were also compared against the values predicted by empirical correlations available in the open literature.

1. Introduction

R1234yf is a new eco-friendly refrigerant, which has recently been proposed as a possible substitute of the common R134a in automotive air conditioning applications. It is a Hydro Fluoro Olefin (HFO) with a zero ozone depletion potential and its Global Warming Potential has recently been recalculated and found to be lower than 1 [1]. In addition, its thermodynamic properties are very similar to those of R134a, thus it has been suggested as a candidate for its replacement.

R1234yf has been matter of research since 2010, when the scientific community started to analyse its thermodynamic properties [2–5]. Compared to R134a, R1234yf has similar vapour pressure values below 330 K, then the vapour pressure values of R134a becomes slightly higher with increasing temperature. At the same temperatures, the saturated vapour densities of R1234yf are higher than those of R134a, whereas the saturated liquid densities are lower. The surface tension values are lower compared to the traditional R134a.

More recently, attention was also given to the two-phase heat transfer characteristics of this new low-GWP refrigerant. Flow boiling and condensation performance must be studied in order to design air conditioning and refrigeration equipment, which use R1234yf as working fluid. Correlations are also needed to evaluate its performance in a wide range of operating conditions.

Padilla et al. [6] visualized the flow regimes of R1234yf and R134a in a 6.70 mm inner diameter glass straight tube with a high-speed high resolution camera, and no major differences were observed among the two fluids. They also measured the pressure drops during two-phase flow of R1234yf, R134a, and R410A in horizontal straight tubes. The tube diameter varied from 7.90 mm to 10.85 mm, the mass velocity from 187 to 1702 kg m^{-2} s^{-1}, and the saturation temperature from 4.8 °C to 20.7 °C. R134a showed higher pressure drop than R1234yf, but the lowest pressure drops were those of R410A as a consequence of its thermophysical properties.

To date, most of the works in the open literature regarding R1234yf two-phase heat transfer are focused on flow boiling or condensation inside smooth tubes [7–12]. Saitoh et al. [7] experimentally studied the flow boiling heat transfer of R1234yf inside a smooth tube with an inner diameter of 2 mm. The local heat transfer coefficients were measured at heat fluxes of 6–24 kW m^{-2}, mass fluxes of 100–400 kg m^{-2} s^{-1}, at an evaporating temperature of 15 °C. The heat transfer coefficient of R1234yf was almost the same of that of R134a.

Wang et al. [8] carried out an experimental study on condensation heat transfer of R1234yf in a horizontal tube, having an inner diameter of 4 mm. The mass fluxes ranged from 100 to 400 kg m^{-2} s^{-1}, and different saturation temperatures were tested:

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* Corresponding author at: Dipartimento di Ingegneria Industriale, Università degli Studi di Padova, Via Venezia 1, 35131 Padova, Italy. Tel.: +39 049 8276869; fax: +39 049 8276896.

E-mail addresses: andrea.diani@unipd.it (A. Diani), simone.mancin@unipd.it (S. Mancin), luisa.rossetto@unipd.it (L. Rossetto).

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Nomenclature

c	specific heat (J kg^{-1} K^{-1})
$\left(-\frac{dp}{dz}\right)$	pressure gradient (Pa m^{-1})
G	mass velocity (kg s^{-1} m^{-2})
h	specific enthalpy (J kg^{-1}), fin height (m)
HF	heat flux (W m^{-2})
HTC	heat transfer coefficient (W m^{-2} K^{-1})
I	electric current (A)
L	sample length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
n	fin number (–)
p	pressure (Pa)
P	power (W)
q	heat flow rate (W)
t	temperature (°C)
x	quality (–)
z	coordinate along the flow direction (m)

Greek symbols

β	helix angle (°)
Δp	pressure drop (Pa)
ΔT	temperature difference (K)
ΔV	electric potential (V)
γ	apex angle (°)

Subscripts

a	momentum term
A	absolute
cr	critical
D	at the fin tip
EL	electric
f	frictional
in	inlet
L	saturated liquid
loss	losses
out	outlet
p	at constant pressure
pc	precondenser
ref	refrigerant
red	reduced
sat	saturation
tot	total
TS	test section
V	saturated vapour
vs	superheated gas
w	water

40, 45, and 50 °C. Heat transfer coefficients were also compared to those of R134a and R32: R32 had the highest heat transfer coefficients, whereas those of R1234yf were slightly lower than those of R134a, at the same operating test conditions.

Few works can be found in the open literature regarding R1234yf two-phase heat transfer inside microfin tubes. Han et al. [13] investigated the boiling heat transfer characteristics of refrigerant R1234yf in a 7 mm OD microfin tube at mass fluxes from 100 to 400 kg m^{-2} s^{-1}, heat fluxes of 4, 8, and 12 kW m^{-2}, saturation temperatures of 5 °C and 15 °C, with four different oil concentrations: 0%, 1.5%, 3.0%, and 5.0%. Generally speaking, at constant operating conditions, the average heat transfer coefficient decreases with the oil concentration.

No works can be found about R1234yf two-phase heat transfer inside small microfin tubes, i.e. with an outer diameter lower than 5 mm. Small microfin tubes were initially used for CO_2 applications, due to its high working pressures [14,15]. Recently, mini microfin tubes have also been proposed for traditional refrigeration and air conditioning equipment, because they can achieve high heat transfer coefficients, and thus, leading to more efficient and compact heat exchangers, with a consequent refrigerant charge reduction. Few investigators experimentally studied the flow boiling of HFOs inside small microfin tubes, but none studied R1234yf.

Kondou et al. [16] investigated the flow boiling of R32, R1234ze(E), and R32/R1234ze(E) non-azeotropic mixtures in a horizontal microfin tube with an inner diameter of 5.2 mm. Tests were run at a saturation temperature of 10 °C, heat fluxes of 10 and 15 kW m^{-2}, and mass velocities from 150 to 400 kg m^{-2} s^{-1}. The R32/R1234ze(E) mixtures revealed lower heat transfer coefficient than both the pure base fluids. Based on correlations available in the open literature, they proposed a correlation that considers the thermal resistance in the vapour phase due to the temperature glide and the boiling heat transfer degradation caused by the decrease in the effective superheat; a good agreement was found with the experimental values.

Diani et al. [17] experimentally studied the flow boiling of R1234ze(E) inside a microfin tube with an internal diameter at the fin tip of 3.4 mm. Different operating test conditions permitted to highlight the effects of vapour quality, mass flux, and heat flux on the heat transfer coefficient, pressure drop, and vapour quality at the onset of the dryout phenomenon. In addition, the same authors [17] proposed two correlations to estimate the heat transfer coefficient in the region pre-dryout and the frictional pressure drop.

Wu et al. [18] performed experiments during flow boiling of R22 and R410A inside one smooth tube and five different microfin tubes with the same outer diameter of 5 mm. Data were for mass velocities from 100 to 600 kg m^{-2} s^{-1}, heat fluxes from 5 to 31 kW m^{-2}, at a saturation temperature of 279 K. They also developed a new general semi-empirical model based on their data and data from literature, which can be applied for intermittent and annular flow patterns.

This paper reports some results about R1234yf flow boiling heat transfer and pressure drop inside a mini microfin tube having an internal diameter at the fin tip of 3.4 mm. The results permit to highlight the effects of the operating conditions, i.e. vapour quality, mass velocity, and heat flux, on the two phase heat transfer and fluid flow behaviors of the microfin tube. The results are also compared with heat transfer coefficients and frictional pressure drops estimated by semi-empirical correlations available in the open literature.

2. Experimental facility

The experimental tests were run in an experimental facility located at the Heat Transfer in Micro-geometries Lab (HTMg-Lab) of the Dipartimento di Ingegneria Industriale of Università degli Studi di Padova. This experimental test rig permits pressure drop and either condensation or flow boiling heat transfer measurements to be performed. It has a maximum working pressure of 3 MPa and the refrigerant mass flow rate can be varied up to 72 kg h^{-1}.

A schematic of the facility is reported in Fig. 1. It consists of three main loops: the refrigerant loop, the hot water loop, and the cold water loop. In the refrigerant loop, the refrigerant is