Experimental Thermal and Fluid Science 66 (2015) 137–149

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Flow boiling heat transfer, pressure drop and dryout characteristics of R1234yf: Experimental results and predictions

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ARTICLE INFO

Article history:
Received 16 November 2014
Received in revised form 27 March 2015
Accepted 28 March 2015
Available online 2 April 2015

Keywords:
Heat flux
Dryout
Mini-channel
R1234yf
R134a
Correlation

ABSTRACT

Flow boiling heat transfer, pressure drop and dryout characteristics of R1234yf in a vertical stainless steel test section (1.60 mm inside diameter and 245 mm heated length) under upward flow conditions are reported in this article. The experiments were carried out at 27 and 32 °C saturation temperatures with five mass fluxes in the range of 100–500 kg/m^2 s while the applied heat flux was in the range of 5–130 kW/m^2. The experiments were carried out with gradual increase of the applied heat flux til completion of dryout. Under similar conditions, tests were repeated with R134a in the same test setup to compare thermal performance of these two refrigerants. The results showed that boiling heat transfer was strongly controlled by the applied heat flux and operating pressure with insignificant dependence on mass flux and vapor quality. The frictional pressure drop increased with mass flux and vapor quality and decreased with increasing saturation temperature as expected. Signs of dryout first appeared at vapor qualities of 85%, with the values generally increasing with increasing mass flux. The effect of varying system pressure was insignificant. The experimental results (boiling heat transfer, pressure drop and dryout heat flux) were compared with the predictions from well-known correlations (for macro and micro-scale channels) from the literature.

1. Introduction

Stratospheric ozone depletion forced legislative bodies to phase out some refrigerants (CFCs and HCFCs) and future European legislation will be affecting the widespread usage of most hydro fluoro carbons (HFCs) as well due to their contribution to global warming (European Union F-gas regulation to cut these emissions by 2/3 from their current value till 2030 [1]). The recently introduced R1234yf has favorable thermo-physical properties and good environmental footprint with a global warming potential (GWP) value of 4 (on 100 year time span). This fluid is considered a suitable candidate for replacing the conventionally used R134a (with GWP of 1430) for mobile applications [2], in spite of being "mildly" flammable. Other potential low GWP alternatives have their own limitations, for example R152a is more flammable while alteration in system design (transcritical operation) would be required with utilization of R744 [3]. When it comes to flammability, comparatively large ignition energy is required to ignite R1234yf, furthermore it is less flammable compared with hydrocarbons, R152a and R32 [4].

The boiling process has the capability to withstand high heat fluxes and gives fairly constant surface temperatures. Flow boiling is therefore an interesting alternative for cooling. There is a general agreement that the channel size influences the boiling process due to the fact that surface tension is more important in small channels. However, a literature review shows that there is no general consensus for distinguishing micro and macro channels. In general, utilization of compact channels with large surface area per unit volume of the fluid results in improved heat transfer, reduced refrigerant charge and less material used [5–7]. These compact channels find diverse applications including (but not limited to) electronic cooling, automotive industry, biomedical engineering and compact refrigeration systems.

Dryout refers the inability of the fluid stream to wet the heating surface. This happens at very high heat fluxes, but also at high vapor fractions, i.e. in the vicinity of the outlet of a heated channel. The point of dryout travels towards the inlet with increase of the applied heat flux mainly because of the fact that the vapor fraction at any point increases with increasing heat flux. The dryout region could be traced from the significantly higher wall superheat and associated deterioration in heat transfer compared to the two-

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http://dx.doi.org/10.1016/j.expthermflusci.2015.03.021
0894-1777/

Nomenclature

A_c	cross sectional area (m^2)
C_p	specific heat of liquid (kJ/kg K)
d_i	inside diameter of test section (m)
dp/dz	pressure gradient (Pa/m)
E	convective boiling enhancement factor (–)
f	fanning friction factor (–)
G	mass flux (kg/m^2 s)
h_{lg}	heat of evaporation (kJ/kg)
I	current (A)
k	thermal conductivity (W/mK)
l	heated length (m)
M	molecular weight (kg/kmol)
$\dot{m}$	mass flow rate (kg/s)
$p_R = p/p_{crit}$	reduced pressure (–)
Q	applied heat (W)
q''	heat flux (W/m^2)
Ra	average roughness value (μm)
S	nucleate boiling suppression factor (–)
v	specific volume (m^3/kg)
V	applied voltage (V)
x	vapor quality (–)
z	axial position (m)

Dimensionless groups

Re	Reynolds No. $\left[\frac{Gd}{\mu}\right]$ (–)
We	Weber No. $\left[\frac{Gd}{\rho\sigma}\right]$ (–)
Bo	Boiling No. $\left[\frac{q''}{Gh_{lg}}\right]$ (–)
Xtt	Martinelli parameter $\left[\left(\frac{\mu_l}{\mu_g}\right)^{0.1}\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_l}\right)^{0.5}\right]$ (–)
Co	Confinement No. $\left[\sqrt{\frac{\sigma}{g(\rho_l-\rho_g)d^2}}\right]$ (–)
Fr	Froude's No. $\left[\frac{G^2}{gd\rho^2}\right]$ (–)

Abbreviations

CFC	chlorofluorocarbon
COP	coefficient of performance
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HTC	heat transfer coefficient
MAE	Mean Absolute Error

Greek letters

α	heat transfer coefficient (kW/m^2 K)
σ	surface tension (N/m)
ρ	density (kg/m^3)
μ	dynamic viscosity (N s/m^2)

Subscripts

Cooper	Cooper's pool boiling correlation
D–B	Dittus–Boelter correlation
exit	at outlet of test section
g	gas phase
h	heated section
in	refers to inlet of test section
l	liquid phase
lg	vaporization phase
lo	liquid only
sat	saturation condition
tp	two phase

phase (boiling) region. From safety and efficiency point of view dryout heat flux sets the upper operating limit for any practical system. It is therefore an important design parameter and requires reliable methods for its prediction.

A summary of recently reported experimental studies with R1234yf is described below. Some researchers also compared thermal performance of R1234yf with R134a, however different trends (higher, similar or lower HTCs with R1234yf) were reported, see details in following paragraphs.

An experimental study with R134a and R1234yf with a compact European automotive air conditioning system has been reported by Zilio et al. [3]. They reported lower thermodynamic performance (3–7% less cooling capacity and 1–3% lower COP) with R1234yf. However their numerical model (a modified system, with enhanced condenser and evaporator) showed higher performance compared with the base case of R134a.

Park et al. [8] reported an experimental study on external condensation heat transfer with R134a and R1234yf on plain (19.05 mm diameter), low fin and turbo-C tubes of 18.90 mm diameters each and 290 mm heat transfer length. They reported similar results with both refrigerants for each of the three selected surfaces. Another study conducted by the same authors was focused on nucleate boiling heat transfer with R134a and R1234yf on the outside of plain and low fin tubes [9], they reported similar heat transfer results with both refrigerants.

An experimental study with R134a and R1234yf in a small refrigeration cycle (with rotary compressor and plate type heat exchangers) was reported by Jarall [10]. Both the refrigerants were used in the same system without changing components or oil of the system. The results indicated lower cooling capacity, COP and compressor efficiency (3.4–13.7%, 0.35–11.8% and 0–6.3% respectively) with R1234yf.

Mortada et al. [11] reported an experimental study of boiling heat transfer with R134a and R1234yf in a rectangular multichannel test section (horizontal, hydraulic diameter 1.1 mm). This study was conducted at low mass fluxes (20–100 kg/m^2 s) and with heat flux of 2–15 kW/m^2 for vapor qualities till dryout. Convective boiling dominance (insignificant effect of heat flux while strong influence of mass flux and vapor quality) was observed in this study, furthermore higher heat transfer coefficient were found with R1234yf (maximum 40% difference in local values).

Another experimental study was reported by Del-Col et al. [12]; flow boiling of R1234yf in a 0.96 mm copper channel was the subject of this study. The experiments were conducted at 31 °C saturation temperature with 200–600 kg/m^2 s mass flux and 10–130 kW/m^2 heat flux. The test section was indirectly heated with hot water circulation. The experiments revealed that the heat transfer coefficients were strongly controlled by the heat flux with insignificant effects of the mass flux. The heat transfer coefficient initially decreased with quality (till $x = 0.3$, for all mass fluxes) and then became independent of vapor quality. Comparison with R134a showed similar heat transfer results for R1234yf.

Saitoh et al. [13] reported on an experimental study on flow boiling of R1234yf in a 2 mm diameter horizontal tube. Tests were done at 15 °C saturation temperature and with mass flux in the range 100–400 kg/m^2 s while heat flux was 6–24 kW/m^2. Results showed that at low vapor qualities ($x < 0.50$), the heat transfer coefficients were dependent on heat flux but less so on mass flux. This was interpreted as nucleate boiling being the dominating mechanism of heat transfer in this part of the test section. At