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Saturated vapour condensation of HFC404A inside a 4 mm ID horizontal smooth tube: Comparison with the long-term low GWP substitutes HC290 (Propane) and HC1270 (Propylene)

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ABSTRACT

This paper presents the comparative analysis of HFC404A and its low GWP substitutes HC290, and HC1270 in saturated vapour condensation inside a 4 mm ID horizontal smooth tube. The experimental tests were carried out at 30, 35, and 40 °C of saturation temperatures, with refrigerant mass flux in the range 75–800 kg m^{-2} s^{-1} at decreasing vapour quality. A transition point from gravity-dominated and forced convection condensation was found for an equivalent Reynolds number around 10,000. The experimental heat transfer coefficients in the forced convection condensation regime were very well predicted by the Akers et al. (1959) model, whereas the Friedel (1979) correlation was able to reproduce the frictional pressure drop data in the whole experimental range. HC290 and HC1270 exhibit heat transfer coefficients higher and frictional pressure drops lower than those of HFC404A; therefore both the HC refrigerants seem to be very promising as long-term low GWP substitutes for HFC404A.

1. Introduction

HFC404A and HFC507A, the worldwide leading refrigerants in commercial and industrial refrigeration in the past two decades, are now subjected to a progressive phase-out due to their high Global Warming Potential (GWP), 3922 and 3985 respectively. In 2013 Japan approved the revision of its fluorocarbon regulations [1] that fundamentally changed the way HFCs are produced, used and disposed defining specific measures at each step of the life-cycle. This act led to a progressive phase-out of high GWP HFC refrigerants requiring the transition to either HFC-free refrigerants or to low GWP HFC refrigerants by certain target years. In particular HFC404A must be replaced with refrigerants having a GWP < 100 in cold storage warehouses within 2019 and with refrigerants having a GWP < 1500 in condensing and refrigerating units within 2025. The European Union in 2014 published a new release of the EU F-gas regulation [2] that established January 1st, 2020 and January 1st, 2022 as the limit date for the HFC507A and HFC404A substitution with mid-term replacements (GWP < 2500) and long-term replacements (GWP < 150), respectively. In 2015 the status of HFC507A and HFC404A was changed by the US Environmental Protection Agency [3] from acceptable to unacceptable starting from July 20th, 2016 to January 1st, 2020 according to the application and the type and size of refrigerating unit.

Therefore the long-term substitution of HFC507A and HFC404A with low GWP alternatives becomes one of the most critical item for industrial and commercial refrigeration. This topic was investigated by Mota-Babiloni et al. [4] who identified six different solutions, none of which can be considered as long-term substitutes (GWP < 150). Moreover the HFC404A and HFC507A alternatives found were HFC or HFC/HFO zeotropic mixtures with a large temperature glide (5.0–7.7 °C) and therefore poor two-phase heat transfer performance. At present HC1270 (Propylene) and HC290 (Propane) seem to be the unique pure refrigerants applicable as long-term low GWP (around 2–3) replacements for HFC507A and HFC404A with similar volumetric and pressure properties. However both the HC refrigerants considered are highly flammable, being classified in Class A3 of ANSI/ASHRAE Standard 34, 2013 [5], and their use is subjected to several restrictions. In general the application of flammable refrigerants requires a specific design of the refrigerant circuit aimed at reducing effectively the refrigerant charge or based on a secondary fluid configuration. The use of tubes of small-diameter (ID < 6 mm) for manufacturing the evaporators and the condensers offers an opportunity to increase the heat transfer coefficients and to reduce, at the same time, the refrigerant charge [6] with positive effects both on performance and safety of the refrigerating machines. Most of the European manufactures have recently extended their heat exchangers

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Nomenclature

A	heat transfer area of the measurement section, m^2
c_p	specific heat capacity, J kg^{-1} K^{-1}
d	tube diameter, m
f.s.	full scale
G	refrigerant mass flux, kg m^{-2} s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
ID	inside diameter
j	specific enthalpy, J kg^{-1}
J_H	Colburn factor
k	coverage factor
L	length of the measurement section, m
m	mass flow rate, kg s^{-1}
MAPE	mean absolute percentage deviation, $MAPE = \left(\frac{100}{n}\right)\sum_{i=1}^{n}\frac{\lvert V_{\exp,i}-V_{clc,i}\rvert}{V_{\exp,i}}$
OD	outside diameter
p	pressure, Pa
q	heat flux, $q = \frac{Q}{A}$, Wm^{-2}
Q	heat flow rate, W
R_a	arithmetic mean roughness (ISO4271/1), μm
R_p	roughness (DIN 4762/1), μm
T	temperature, K (°C)
v	specific volume, m^3 kg^{-1}
V	variable
X	vapour quality, $X = \frac{j-j_L}{\Delta j_{LG}}$

Greek symbol

Δ	difference
Δj_{LG}	latent heat of condensation, J kg^{-1}
ρ	density, kg m^{-3}

Subscript

a	momentum
c	local
clc	calculated
exp	experimental
f	frictional
g	gravity
in	inlet
LG	liquid vapour phase change
m	mean value
m.w	mean value on the whole test section
out	outlet
pb	pre-evaporator
ps	pre-section
r	refrigerant
t	total
sat	saturation
w	water
wall	tube wall

production range to include 4 and 5 mm ID copper tubes, especially in finned coil condensers and evaporators.

In the open literature it is possible to find some experimental work on HFC404A, HC290, and HC1270 in-tube condensation, however the major part of the data refers to traditional 3/8″ and 1/2″ OD smooth or microfin tubes and only a few data considers small-diameter tubes.

Boissieux et al. [7] investigated the heat transfer performance of three HFC refrigerant mixtures, HFC404A, HFC407C, and R417A, in condensation inside a 3/8″ OD smooth tube and compared the experimental results with existing correlations.

Sami and Fontaine [8] carried out an experimental study on condensation of four refrigerant mixtures, HFC404A, HFC407B, HFC408A, and HFC507, inside a 3/8″ OD microfin tube as alternative for traditional refrigerant CFC502 in air conditioning applications. HFC408A and HFC507 exhibited the best heat transfer and pressure drop performances, respectively.

Infante Ferreira et al. [9] analysed HFC404A–lubricant oil mixture forced convection condensation inside smooth, microfin, and cross-hatched 3/8″ OD horizontal tubes. The heat transfer enhancement for the microfin and the cross-hatched tubes ranged between 80 and 140%; the enhancement increased up to oil concentrations of 2%, and then, for higher oil concentrations, it decreased especially at high mass fluxes.

Jiang et al. [10] measured HFC404A and HFC410A condensation heat transfer coefficient at near-critical pressures inside a 6.2 mm and a 9.4 mm ID smooth tube. The heat transfer coefficients increased with vapour quality, mass flux and with the decrease in tube diameter, while the effect of reduced pressure was less significant.

Sapali and Patil [11] experimentally investigated HFC404A condensation inside smooth and microfin 3/8″ OD horizontal tubes finding a 30–100% enhancement in heat transfer coefficient for microfin tube with respect to plane tube.

Charun [12] studied heat exchange and pressure drop during HFC404A condensation inside 1.4–3.3 mm ID stainless steel smooth tubes and provided an insightful review concerning HFC404A condensation inside conventional and small-diameter tubes. At a refrigerant mass flux of 300 kg m^{-2} s^{-1} the increase of the tube ID from 1.4 to 3.3 mm results in a 40–50% decrease of the condensation heat transfer coefficient.

Andresen et al. [13] measured HFC404A and HFC410A condensation pressure drop at near-critical pressures inside smooth tubes with an ID in the range 0.76–9.4 mm and proposed a new correlation for high reduced pressures.

Chang et al. [14] investigated condensation of pure hydrocarbons, HC290 (Propane), HC600 (Butane), HC600a (Isobutane), and HC1270 (Propylene) and also their binary mixtures inside a 3/8″ mm OD smooth tube as alternative for HCFC22 refrigerant. Pure hydrocarbons performed better than binary mixtures and, in particular, HC1270 and HC290 showed heat transfer performance slightly higher (+5%) and slightly lower (−5%) than HCFC22, respectively.

Lee et al. [15] measured heat transfer coefficients and pressure drops of HC290 (Propane), HC600a (Isobutane), HC1270 (Propylene), and HCFC22 condensing inside a 3/8″ and a 1/2″ OD smooth tube. HC refrigerants exhibited heat transfer coefficients higher than those of HCFC22, and the experimental data agreed with traditional correlation for condensation inside smooth tubes.

Park et al. [16] carried out heat transfer and pressure drop measurement on HC290 (Propane), HC600a (Isobutane), HC1270 (Propylene), DME (Dimethyl Ether), and HCFC22 condensation inside a 3/8″ OD smooth tube. HC refrigerants and DME shown heat transfer coefficients higher than HCFC22 and, in particular, HC1270 shown the best performance within HC refrigerants.

Garimella and his co-workers [17–20] carried out an extensive experimental and theoretical analysis on HC refrigerants condensation inside smooth tubes. The analysis included the measurement of heat transfer coefficients and pressure drops during condensation of HC290 (Propane) and two HC refrigerant mixtures (33% Propane/67% Ethane and 67% Propane/33% Ethane) inside a 7.75 mm and a 14.45 mm ID horizontal smooth tubes. Garimella