Experimental Thermal and Fluid Science 57 (2014) 293–300

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental assessment of the low GWP refrigerant HFO-1234ze(Z) for high temperature heat pumps

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ARTICLE INFO

Article history:
Received 23 April 2014
Received in revised form 13 May 2014
Accepted 13 May 2014
Available online 28 May 2014

Keywords:
GWP
HFO
Heat pump
Condensation
BPHE

ABSTRACT

This paper presents the experimental heat transfer coefficients and pressure drop measured during refrigerant HFO-1234ze(Z) saturated vapour condensation inside a commercial Brazed Plate Heat Exchanger (BPHE) and compares this data with similar measurements previously obtained for refrigerant HFC-236fa, HFC-134a, HC-600a, HFO-1234ze(E) in order to experimentally assess refrigerant HFO-1234ze(Z) for high temperature heat pumps. HFO-1234ze(Z) exhibits heat transfer coefficients much higher than those of all the refrigerants now used in heat pumps and frictional pressure drop similar to HC-600a at the same refrigerant mass flux. Therefore, considering also its thermodynamic properties, HFO-1234ze(Z) seems to be a very promising low GWP refrigerant for high temperature heat pumps with a potential capability similar to refrigerant CFC-114 that dominated this type of application before Montreal Protocol.

1. Introduction

High temperature heat pumps are widely used to deliver heat at temperatures up to 130 °C in several industrial and marine applications. This sector has been dominated for decades by the refrigerant CFC-114. Being an ozone depleting substance, it was banned by the Montreal Protocol and since then several studies investigated about the possible ozone-benign substitutes, suitable for evaporation temperatures even higher than 30 °C and condensation temperatures close to 150 °C, still avoiding transcritical operations.

Most of the available studies are based on thermodynamic screening of several possible fluids. Devotta and Rao Pendyala [1] analysed 30 different Hydro-Fluoro-Carbons (HFC) and Hydro-Fluoro-Ethers (HFE). Rakhesh et al. [2] compared the performance of CFC-114 with HFC-227ea. Among the HFC-s, the propane-based fluorinated molecules are the ones showing critical temperatures and working pressures more similar to CFC-114. Cortella et al. [3] studied both theoretically and experimentally several mixtures of HFC-236fa with HFC-134a, HFC-143a, HFC-32, HFC-125, HFE-170, HC-600a, HC-290. In an early study, Kazachki et al. [4] compared experimentally HFC-236fa and HFC-236ea and the first isomer was found to exploit the best performance. HFC-236fa was found to be a viable alternative to the CFC-114 in high temperature heat pumps, leading to a higher coefficient of performance and often a higher heating capacity. As a matter of fact, among the different options, HFC-236fa is the refrigerant that have encountered the greatest deal of interest in real applications both for industrial heat pumps and in marine uses (Toms et al. [5]). Its relatively long atmospheric lifetime (approximately 210 years) and its high GWP (6300) are the only concern from a global warming perspective. The increasing restrictions imposed by the Kyoto Protocol and by the European F-Gas Regulation (Regulation 842/2006 [6]) are driving the research towards the evaluation of new low GWP refrigerants. In this scenario there is a renewed interest for flammable natural refrigerants, Hydro-Carbon (HC), and for the recently proposed mildly flammable Hydro-Fluoro-Olefins (HFO).

In 2009, Brown et al. [7] proposed the use of HFO-1234ze(Z), a fluorinated olefin, as possible substitute of CFC-114 in high temperature heat pumps. They firstly implemented a calculation procedure for the estimation of the thermodynamic and thermophysical properties of the “not-so-well known” HFO-1234ze(Z). In fact, at the time of the publication, rather limited experimental data about thermodynamic and thermophysical properties of HFO-1234ze(Z) were available. Since then, limited sets of experimental data have been published and a full list of the related publications is reported in Fedele et al. [8]. Furthermore, Brown et al. [7] compared thermodynamic performance of HFO-1234ze(Z) and CFC-114 and concluded that HFO-1234ze(Z) deserved further consideration as a possible CFC-114 replacement. Fukuda et al. [9] compared thermodynamically, experimentally and numerically the two isomers

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http://dx.doi.org/10.1016/j.expthermflusci.2014.05.004
0894-1777/

Nomenclature

A	nominal area of a plate (m^2)
b	height of the corrugation (m)
c_p	specific heat capacity (J kg^{-1} K^{-1})
d_h	hydraulic diameter, $d_h = 2\ b$ (m)
f.s.	full scale
g	gravity acceleration (m s^{-2})
G	mass flux, $G = \frac{m}{n_{ch} W b}$ (kg m^{-2} s^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
J	specific enthalpy (J kg^{-1})
k	coverage factor
$\frac{KE}{V}$	kinetic energy per unit volume (J m^{-3})
L	flow length of the plate (m)
m	mass flow rate (kg s^{-1})
N	number of effective plates
n_{ch}	number of channels
p	pressure (Pa)
P	corrugation pitch (m)
Pr	Prandtl number, $\mathrm{Pr} = \frac{\mu c_p}{\lambda}$
q	heat flux, $q = \frac{Q}{S}$ (W m^{-2})
Q	heat flow rate (W)
Re	Reynolds number, $\mathrm{Re} = \frac{G d_h}{\mu}$
Re_{eq}	equivalent Reynolds number, $\mathrm{Re}_{eq} = G[(1-X)+X\sqrt{\frac{\rho_L}{\rho_G}}]\frac{d_h}{\mu_L}$
S	nominal heat transfer area (m^2)
s	plate wall thickness (m)
T	temperature (K)
U	overall heat transfer coefficient (W m^{-2} K^{-1})
v	specific volume (m^3 kg^{-1})
V	volume (m^3)
VHC	Volumetric Heating Capacity (J m^{-3})
W	width of the plate (m)
X	vapour quality, $X = \frac{J - J_L}{\Delta J_{LG}}$

Greek symbols

β	inclination angle of the corrugation
Δ	difference
ΔJ_{LG}	latent heat of vaporisation (J kg^{-1})
ϕ	enlargement factor
λ	thermal conductivity (W m^{-1} K^{-1})
μ	viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})

Subscripts

a	momentum
ave	average
AKERS	Akers et al. (1959)
c	manifold and port
e	evaporator
eq	equivalent
f	frictional
g	gravity
G	vapour phase
in	inlet
L	liquid phase
LG	liquid vapour phase change
ln	logarithmic
m	average value
NUSSELT	Nusselt (1916)
out	outlet
p	plate
pb	pre-evaporator
r	refrigerant
t	total
sat	saturation

HFO-1234ze(E) and HFO-1234ze(Z) in a high temperature heat pump equipped with tube-in-tube condenser and evaporator, with condensation temperatures higher than 75 °C. They proposed an assessment that considered the irreversible losses generated by the main components (the compressor, the condenser, the expansion valve, and the evaporator) and included pressure drop effects. The conclusion of the assessment was that HFO-1234ze(E) and HFO-1234ze(Z) are suitable for high temperature heat pump rather than air conditioning or refrigeration application.

Among the more widely used HC refrigerants, i.e. propane (HC-290), propylene (HC-1270) and isobutane (HC-600a), HC-600a is the only one having critical temperature and normal boiling point close to CFC-114 values. Recently two heat pumps operating with HC-600a, with a total heating capacity of about 450 kW and a cooling capacity of about 325 kW, capable to deliver hot water up to 80 °C were installed in an hospital in Denmark (Pachai and Harraghy [10]). The heat pumps operate with Brazed Plates Heat Exchangers (BPHE) as the condenser. BPHEs offer the unique opportunity of markedly reducing the heat pump charge, in comparison to tubular heat exchangers. This feature is extremely interesting to assess the sustainable use of flammable or mildly flammable refrigerants in heat pumps for industrial applications.

A first simple thermodynamic benchmark for screening refrigerants in heat pump applications can be based on the properties reported in Table 1. This table reports thermodynamic properties, including the Volumetric Heating Capacity (VHC) defined as the product of latent heat of condensation evaluated at a constant saturation temperature of 90 °C and the vapour density at compression suction (assuming saturation temperature 20 °C and vapour superheating 18 °C, that is the minimum to avoid wet isentropic compression with CFC-114). Environmental and safety data like the GWP on 100-year basis and the ASHRAE safety classification [11] are reported too. Table 1 considers the already mentioned HFC-236fa, HFC-134a that is largely used in domestic tap water heaters, the hydrocarbon HC-600a that has been recently applied in heat pumps and the hydrofluoroolefins HFO-1234ze(E) and HFO-1234ze(Z). For comparison CFC-114 properties are also reported. According to Table 1, HFC-134a and HFO-1234ze(E) have a relatively lower critical temperature in comparison to CFC-114, that could limit the use of these fluids at condensation temperature higher than about 90 °C. The reader may also appreciate that HFC-236fa and HFO-1234ze(Z) are the only fluids with a VHC similar to CFC-114, whereas the other display higher values. This would require a change in the compressor design and so they cannot be considered as candidates for drop-in replacement of CFC-114. Moreover, HFO-1234ze(Z) exhibits the highest critical temperature. Therefore, HFO-1234ze(Z) seems to be very promising for high temperature heat pumps under a thermodynamic point of view.

This paper presents the experimental heat transfer coefficients and pressure drop measured during HFO-1234ze(Z) saturated vapour condensation inside a commercial BPHE and compares this data with similar measurements previously obtained by present authors for HFC-236fa, HFC-134a, HC-600a, HFO-1234ze(E) in order to experimentally assess refrigerant HFO-1234ze(Z) for high