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Empirical study of heterogeneous refrigerant condensation in pipe minichannels

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ABSTRACT

This paper concerns the experimental test results of homogeneous refrigerant R134a and zeotropic solutions R404A, R407C and R410A condensation in pipe minichannels with an internal diameter d = 0.90–3.30 mm. The paper presents experimental thermal and flow characteristics of condensation in comparable ranges. The experimental results were compared to the calculated results of other authors' correlations. It was found that the discrepancy between the results of tests and calculations is large, especially for zeotropic solutions, and in excess of the range of ±50%. The authors developed their own correlations, providing compatibility within ±25% for all of the tested refrigerants. Correlations are proposed for annular and annular-stratified two-phase flow structures.

Etude empirique de la condensation de frigorigène hétérogène dans les minicanaux d'une canalisation

Mots clés : Condenseur compact ; Condensation dans des minicanaux ; Transfert de chaleur ; Chute de pression durant ; Solution zéotropique

1. Introduction

The degradation of the ozone layer and increasing negative impact of the greenhouse effect were the primary reasons for the elimination of CFC (including R12) and HCFCs (R22) refrigerants. The search for new substitutes continue to this day, and there is no clear decision. The first to be introduced was the R134a refrigerant from the HFC group. For many years, it was a good replacement for the R12 refrigerant because its thermodynamic properties are similar to those of CFC refrigerants. There were several studies published in which R134a was the reference factor. However, its disadvantage is its high value of Global Warming Potential (GWP), which is approximately 1300. In the near future, this refrigerant will also be eliminated from use (it is already eliminated from car air-condition installations). Multiple companies are producing new, pro-ecological homogeneous and heterogeneous (two- and three component solutions) refrigerants. Currently, the greatest interest lies with the following refrigerants: R404A, R407C, R410A and R507.

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Nomenclature

A	heat transfer area (m^2)
d	minichannel inner diameter (m)
d_h	hydraulic diameter (m)
G	mass flux density (kg m^{-2} s^{-1})
J_G	dimensionless vapor velocity
L	length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
p	pressure (kPa)
Δp	pressure drop (kPa)
$(\Delta p/L)$	pressure drop per unit minitube length (kPa m^{-1})
Q	heat flux
T	temperature (°C)
x	quality
q	heat flux density (W m^{-2})
α	heat transfer coefficient (W m^{-2} K^{-1})
λ	thermal conductivity coefficient of refrigerants (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
μ	dynamic viscosity (kg m^{-1} s^{-1})
χ_{tt}	dimensionless two-phase flow multiplier Martinelli
Nu	$Nu_x = \frac{\alpha_x \cdot d}{\lambda_l}$ *Nusselt* number
Pr	*Prandtl* number
Re	$Re_l = \frac{G \cdot d}{\mu_l}$ *Reynolds* number

Subscripts

cr	critical value
i	further section *i* (I = 1,2,. . .. . ..9)
l	liquid
R	refrigerant
r	reduced pressure
s	dew point value
v	vapor
x	local value
z	outer surface

The listed solutions belong to the high-pressure refrigerant group and include in their composition: R404A (R125/R143a/R134a: 44/52/4% of mass), R407C (R32/R125/R134a: 23/25/52% mass), R410A (R32/R125: 50/50% of mass) and R507 (R143a/R125:50/50%). The R407C refrigerant is a typical zeotropic mixture, R404A and R410A are nearly azeotropic mixtures (NEARM), R507 refrigerant is an azeotropic mixture (Bohdal and Walczak, 2013; Mikielewicz and Matysko, 2013).

Problems with CFC implementation mainly concern steam compressor refrigeration systems, which include: compressors, evaporators, condensers, armatures and automatics. It is applicable to both conventional and compact devices. Compact systems with minimized dimensions, where small surfaces of heat exchange are used to exchange large heat flux densities, are of particular importance. In cases of very large heat fluxes, their reception is conducted by phase changes, especially during boiling and condensation. During the design of conventional and compact refrigeration devices, the size of the compressor, the heat transfer area and the flow resistance of the refrigerant flowing in the heat exchangers are defined. If the utilized refrigerant is heterogeneous, there is an increase in design and operational problems.

The condensation of solutions in refrigeration minicondensers can be used as an example. Obtaining the miniaturization effect of refrigeration condenser construction requires the use of channels with small and very small hydraulic diameters, e.g., $d_h < 3$ mm (including mini- and microchannels) (Kandlikar, 2003). The literature presents studies relating to the construction of such condensers, where they take into account the channel's dimensions, the cross-sectional shape of the channel and the condensation process parameters. For the design calculations, generally known and experimentally proven correlations are utilized to allow for the calculation of the heat transfer coefficient and flow resistance during refrigerant condensation. These correlations, which are generalized and recognized in the literature, are commonly used (Mikielewicz and Mikielewicz, 2011).

In cases where heterogeneous refrigerants (solutions) are used in minichannels during the flow condensation process, it must be noted that the condensation of the homogeneous refrigerant (e.g., R134a) and that of the solution (e.g., R407C) are significantly different (Kuczyński, 2012, 2013). Theoretically, a homogeneous refrigerant condensation occurs at a constant dew point temperature, T_s (which corresponds to the dew point pressure), and the state determination of the wet saturated vapor also requires entering a vapor quality, x. During the condensation phase transition, the dew point temperature of the solution changes. The concentration of solution components changes too. The real solutions generally show deviations from the ideal solution state, with is described by Raoult's law. The dew point pressure above the solution may be higher (a positive deviation) or lower (a negative deviation) from the dew point pressure described by Raoult's law. In practice, they are azeotropic or zeotropic solutions. An azeotropic mixture behaves similarly to the homogeneous refrigerant during the condensation process. Changing the dew point temperature in the condensation process of the zeotropic solution ΔT_{gD} is called temperature glide. Zeotropic solutions of low temperature glide values (e.g., R404A, for which $\Delta T_g \cong 0.5\,K$) are called nearly azeotropic refrigerant mixtures. The value of the temperature glide of the zeotropic solution R407C is $\Delta T_g = 7.2\,K$, which is significant. The analysis given above clearly shows that the homogeneous and heterogeneous refrigerant phase transition mechanisms are significantly different, which has an effect on the heat exchange calculation method utilized.

In this paper, particular attention is paid to the problems of R404A, R407C and R410A solutions and their condensation in pipe minichannels, compared with the condensation of homogeneous refrigerant R134a under comparable conditions. When selecting correlations to calculate the heat transfer coefficient and pressure drop during condensation in minichannels, two methods are typically used: (1) the correlations used for condensation in conventional channels are adopted, and (2) correlations obtained from experimental studies of refrigerant condensation in minichannels are used. Available publications regarding the condensation of the high pressure refrigerants R404A, R407C and R410A in channels with