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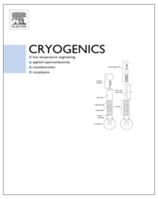

Flow boiling heat transfer coefficients at cryogenic temperatures for multi-component refrigerant mixtures of nitrogen–hydrocarbons

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ABSTRACT

The recuperative heat exchanger governs the overall performance of the mixed refrigerant Joule–Thomson cryocooler. In these heat exchangers, the non-azeotropic refrigerant mixture of nitrogen–hydrocarbons undergoes boiling and condensation simultaneously at cryogenic temperature. Hence, the design of such heat exchanger is crucial. However, due to lack of empirical correlations to predict two-phase heat transfer coefficients of multi-component mixtures at low temperature, the design of such heat exchanger is difficult.

The present study aims to assess the existing methods for prediction of flow boiling heat transfer coefficients. Many correlations are evaluated against available experimental data of flow boiling of refrigerant mixtures. Silver-Bell-Ghaly correlation and Granryd correlation are found to be more suitable to estimate local heat transfer coefficients. A modified Granryd correlation is recommended for further use.

1. Introduction

Joule–Thomson cryocooler (J–T) consists of compressor, an after-cooler, recuperative heat exchanger, an expansion device and an evaporator. The performance of these cryocoolers can be enhanced by using a mixture of nitrogen–hydrocarbons. Usually, a mixture of gases, such as methane, ethane, propane, iso-butane along with nitrogen or neon as a base component is used to form a non-azeotropic mixture. Use of refrigerant mixture enlarges the vapour dome as compared to the vapour dome of pure substance such as nitrogen. Therefore, the refrigerant mixture at high pressure gets condensed, while the return line low pressure stream from the evaporator gets evaporated in the heat exchanger. It increases the effectiveness of the heat exchanger, which governs the performance of the cryocooler.

There are many research articles related to mixed refrigerant Joule–Thomson (MR J–T) cryocoolers [1–4]; however, these describe mainly the use of flammable/non-flammable mixtures, optimization of mixture composition, and overall performance of the cryocooler. Little work [5–7] has been reported about the design of the heat exchanger for MR J–T cryocooler which is usually a multi tubes-in-tube helical coil heat exchanger. This is mainly due to lack of experimental data of forced convective boiling and condensation of multi-component mixtures in cryogenic temperature range. Recently, Nellis et al. [8] obtained experimental data of heat transfer coefficients for mixed refrigerants used in the cryocooler at various operating conditions. This is probably the only reported study on the flow boiling of nitrogen–hydrocarbons multi-component mixtures at cryogenic temperature.

Substantial work has been reported related to boiling of binary mixtures. Even a few studies related to boiling of ternary mixtures have also been compiled in recent review articles by Celata et al. [9] and Cheng and Mewes [10]. However, there is no generalized heat transfer correlation available in the open literature. The empirical or semi-empirical correlations available in the literature are mainly developed for the CFC, HCFC refrigerant mixtures and are useful for temperature close to ambient. The temperature glide for these mixtures is usually less than 10 K and variation in the thermo-physical properties is not significant compared to nitrogen–hydrocarbon mixtures used in the MR J–T cryocooler. The temperature glide, in case of nitrogen–hydrocarbon mixtures, is usually, more than 100 K. However, these studies on the mixtures, reported in the literature, give basic understanding of the heat transfer phenomenon in the mixtures. In the present work, an attempt is made to apply and assess the existing empirical correlations to predict the heat transfer coefficients for mixed refrigerants used in the J–T cryocooler. Thus, the objective of this work is to carry out a detailed study on the applicability of the existing correlations for such mixtures at cryogenic temperature and comparison against the available experimental data.

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Nomenclature

AAD	average absolute deviation
Bo	boiling number, dimensionless
B_o	an empirical scaling factor in Thome and Shakir equation [12]
Cp	specific heat, J/kg K
C_{lg}	correction factor in Eq. (20), dimensionless
Cp_w	apparent local specific heat, J/kg K
D	diameter, m
Eo	forced convection enhancement parameter
F_c	mixture correction factor, dimensionless
f	friction factor, dimensionless
G	mass flux, kg/m^2 s
g	acceleration due to gravity, m/s^2
h	heat transfer coefficient, W/m^2 K
h_{lv}	differential latent heat of vaporization, J/kg
i	enthalpy, J/kg
K	heat transfer reduction factor in Eq. (1), dimensionless
M	molecular weight, kg/kmol
n	components
P	pressure, kPa
p_r	reduced pressure, dimensionless
Pr	Prandtl number, dimensionless
q	heat flux, W/m^2
Re	Reynolds number, dimensionless
S	forced convection suppression parameter
T	temperature, K
T_b	bubble point temperature, K
T_d	dew point temperature, K
x	quality
X	Martinelli parameter

Greek symbols

ΔT	wall superheat, K
ΔT_g	temperature glide, K
ΔT_s	wall superheat for individual components, K
β	liquid mass transfer coefficient, m/s
λ	thermal conductivity, W/mK
μ	dynamic viscosity, Ns/m^2
ρ	mass density, kg/m^3
σ	surface Tension, N/m
$\hat{x}$	mole fraction of component

Subscripts

c	convective
dew	dew point
exp	experimental
g	gas
i	component – i
id	ideal
l	liquid
lo	liquid only
m	mixture
npb	nucleate pool boiling
tp	two-phase
tt	turbulent–turbulent
v	vapour
vt	laminar-turbulent

2. Background

2.1. Study of heat transfer mechanism of mixtures

Numerous studies have been reported in the literature [11–17] regarding prediction of the nucleate pool boiling heat transfer coefficients of binary mixtures. The heat transfer mechanism for nucleate boiling of mixtures is different than that for pure substance. In case of mixtures, the saturation temperature increases during boiling due to boiling-off of low boiling component progressively. Additionally, there is a mass transfer effect at the liquid–vapour interface due to concentration difference between liquid and vapour. The low boiling point component evaporates preferentially in the mixture, which results in change in the composition of the mixture in the liquid and the vapour phases. The vapour phase gets enriched with low boiling point component, while the liquid phase gets depleted in low boiling point component. It is known from the literature [11–16] that the heat transfer coefficients for boiling of mixtures are substantially lower than those for the pure components due to simultaneous heat and mass transfer effects. This degradation in heat transfer coefficient is severe if the difference in composition of liquid and vapour is more or difference in dew point and bubble point temperatures (temperature glide) is more. The deterioration in boiling heat transfer coefficient increases with the increase in heat flux. Moreover, the decrease in heat transfer with the difference in concentration is more at high pressures than at low pressures [17]. It means that the multi-component mixtures with higher temperature glide (more than 100 K), such as nitrogen–hydrocarbons, have more reduction in heat transfer coefficients. The wide boiling range of multi-component mixture also causes significant variation in thermo-physical properties.

2.2. Empirical methods for nucleate boiling of mixtures

Many heat transfer correlations are proposed for nucleate boiling of mixtures. These are functions of either temperature glide or concentration difference, i.e. difference of the mass fraction in liquid and vapour phase. The correlations, expressed in terms of concentration difference, need the knowledge of vapour–liquid equilibrium data. This makes it difficult to apply them for multi-component mixtures. Therefore, in the present case of multi-component mixtures, correlations expressed in terms of temperature glide only are considered to evaluate heat transfer coefficients.

These correlations for mixtures are usually expressed in terms of the ideal heat transfer coefficient, h_{id}, defined using an ideal wall superheat, ΔT_{id}, along with the reduction factor towards mixture effect as given in Eq. (1).

$$\frac{h}{h_{id}} = \frac{1}{1+K} \tag{1}$$

where K is heat transfer reduction factor. The ideal heat transfer coefficient, h_{id}, is the heat transfer coefficient without any mass transfer effects. The nucleate pool boiling correlations, which include only temperature glide parameter, are listed in Table 1. Three different approaches have been suggested in the literature to calculate ideal nucleate boiling heat transfer coefficient for mixture [18].

In the simple approach, h_{id}, is defined as mole fraction weighted average of single component nucleate boiling heat transfer coefficients for the pure components at the same pressure and heat flux.

In the second approach, it is defined as an average ideal heat transfer coefficient based on a mole fraction weighted average of the wall superheats for the pure component fluids at the specified heat flux and at the same system pressure or temperature. For

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