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# Measured and predicted heat transfer coefficients for boiling zeotropic mixed refrigerants in horizontal tubes

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ABSTRACT

The use of mixed gas working fluids has become common in Joule–Thomson type cryocoolers for a variety of applications. However, there is a scarcity of data currently available with supporting theory capable of predicting the heat transfer coefficients associated with two-phase, multi-component mixtures at cryogenic temperatures. This paper aims to fill this void by providing experimental data for the heat transfer coefficient associated with of multicomponent zeotropic mixtures boiling in small channels over temperatures ranging from 100 K to room temperature. The sensitivity of the measured heat transfer coefficient to parameters such as heat flux, mass flux, pressure, tube diameter, and mixture composition is also presented. The results indicate that the heat transfer process is driven, principally, by convective boiling; however, composition, diameter, and surface roughness affect the measured heat transfer coefficient. Evaporating pressure has less relevance compared to the other parameters.

The actual experimental data collected as part of this effort and additional data from Nellis et al. (2005) are used to evaluate models to characterize the heat transfer process for boiling zeotropic mixtures in horizontal tubes. The heat transfer coefficient data is predicted well using correlations described by Granryd (1991) and Little (2008). The Granryd correlation is the recommended correlation to predict heat transfer coefficient of zeotropic mixtures because it shows the best accuracy with an Absolute Average Deviation (AAD) of 16% and predicts 83% of the data with a relative error lower than 25%. The Little correlation exhibits greater accuracy at high Reynolds number, high thermodynamic quality, or both; however, its accuracy is substantially reduced for low qualities and low Reynolds number.

## 1. Introduction

This research studies the heat transfer process of evaporating zeotropic multi-component mixtures in small diameter horizontal tubes between cryogenic and room temperatures. There are few data or theories available in the open literature that can reliably predict heat transfer coefficients for the studied zeotropic mixtures operating over the wide temperature range considered here. Nellis et al. [1] provides six sets of data for the local heat transfer coefficient during boiling of nitrogen–hydrocarbon gas zeotropic mixtures evaporating in a horizontal test section with an inner diameter of 0.835 mm over a range of composition, temperatures, mass fluxes, and pressures. The zeotropic mixtures are formed by different compositions of nitrogen, methane, ethane, propane and isobutane. The test conditions include variation of the mass flux between 200 and 900 kg/m$^2$-s, the evaporating pressures between 400 and 1400 kPa using a constant heat flux of 80 kW/m$^2$ for all test conditions. These data are included in the comparisons with correlations presented in this paper.

According to the results of Nellis et al. [1], the heat transfer coefficient for mixtures under single-phase conditions is well predicted by standard correlations for single-phase flow, such as the Dittus–Boelter [4]. Also, they observe a minimal effect on the heat transfer coefficient due to composition and pressure but a substantial effect related to the mass flux. Other authors such as Boiarski et al. [5], Gong et al. [6], and Ardhapurkar et al. [7] have reported measurements of the overall heat transfer coefficient for a heat exchanger operating with mixtures at cryogenic temperatures. However, these data have limited utility because the overall heat transfer coefficient data cannot be extrapolated to other systems with system geometries differing from those for which the data were obtained.

No other studies were found that provide experimental data for heat transfer coefficients with the number of components and the

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**Nomenclature**

| | |
|---|---|
| AAD | average absolute deviation |
| $Bo$ | Boiling number |
| $C$ | constant Mishra correlation |
| $C_{lv}$ | enhancement factor |
| $Co$ | Convective number |
| $Cp$ | specific heat |
| $D$ | diffusion coefficient |
| $Fr$ | Froude number |
| $g$ | gravitational acceleration |
| $G$ | mass flux |
| $h$ | enthalpy |
| $htc$ | heat transfer coefficient |
| $ID$ | inner diameter |
| $k$ | thermal conductivity |
| $M$ | molar mass |
| $Nu$ | Nusselt number |
| $P$ | pressure |
| Pr | Prandtl number |
| $\dot{Q}''$ | heat flux |
| $R$ | surface roughness |
| Re | Reynolds number |
| $relrough$ | relative roughness |
| RMS | root mean square |
| $S$ | suppression factor |
| $T$ | temperature |
| $x$ | liquid mass fraction |
| $x$ | thermodynamic quality |
| $X$ | Lockhart–Martinelli coefficient |
| $We$ | Weber number |
| $y$ | vapor mass fraction |

*Subscripts*

| | |
|---|---|
| $avg$ | average |
| $c$ | convective boiling |
| $l$ | liquid |
| $lo$ | liquid only |
| $lv$ | latent or vaporization |
| $mixt$ | mixture |
| $n$ | nucleate boiling |
| $nb$ | nucleate boiling |
| $p$ | constant pressure |
| RMS | root mean square |
| $tt$ | turbulent liquid/turbulent vapor |
| $v$ | vapor |
| $vo$ | vapor only |
| $2ph$ | two-phase |

*Superscripts*

| | |
|---|---|
| $m$ | constant Mishra correlation |
| $n$ | constant Mishra correlation |

*Greek letters*

| | |
|---|---|
| $\alpha$ | void fraction |
| $\Delta$ | difference |
| $\Delta$ | delta |
| $\kappa$ | thermal diffusivity |
| $\mu$ | viscosity |
| $\rho$ | density |
| $\sigma$ | surface tension |

range of temperatures provided in this research. There are some studies that provide limited data for ternary mixtures, e.g., Zhang et al. [8], but the temperature glides of the studied mixtures are less than 10 K. In general, the existing empirical data are focused on measurements of the heat transfer coefficient for boiling of binary mixtures operating at near room temperature conditions with small temperature glides. Even though these data are not directly related to the present study, the heat transfer coefficient data obtained for binary mixtures are relevant because they provide some insight in understanding the heat transfer behavior of two-phase mixtures.

Several studies of binary mixtures have shown that mixtures behave differently than pure fluids during a phase change. Stephan [9] indicates that heat transfer coefficients for mixtures can be lower than those of pure fluids at the same flow conditions. The deterioration of the heat transfer coefficients is explained because the difference in composition of the liquid and vapor, which may cause a mass transfer that inhibits heat transfer [10]. The experimental work performed by Jung et al. [11] suggests a suppression of nucleate boiling for mixed refrigerants; measured heat transfer coefficients for mixtures in this region are as much as 36% lower than the pure fluid values under the same flow conditions. Sardesai et al. [12] explained that the mixture affects nucleate boiling because diffusion of constituents adds a thermal resistance; thereby, degrading the heat transfer coefficient. This degradation effect is substantially reduced in the convection-dominated region. Another reason for the variation in heat transfer coefficients of mixtures is the nonlinear and strong variation in thermodynamic and transport properties with composition and temperature. Shin et al. [13] concluded that heat transfer coefficient depend strongly on heat flux in the low quality region but become independent of heat flux as quality increases. The pool boiling heat transfer coefficient in the binary mixture of ammonia/water was studied by Inoue [14]. Inoue shows that the heat transfer coefficients in ammonia/water mixtures become dramatically smaller than those expected for either of the pure components independently.

The boiling process that occurs as a fluid flows through a horizontal tube is complicated, even for a pure fluid. Steiner and Taborek [15] claim that different flow regimes drive different heat transfer coefficients during boiling. Collier and Thome [16] describe a typical flow boiling process in a horizontal tube, including the flow regimes that the fluid experiences during evaporation. As sub-cooled liquid flows through a tube while heat is applied at the tube wall, the liquid is heated and its temperature increases until it reaches its saturation temperature condition ($x = 0$). As evaporation proceeds, the flow may experience different regimes or patterns including bubbly flow, plug flow, slug flow, stratified-wavy flow, annular flow and partial dry out before reaching a saturated vapor state ($x = 1$). There are two phenomena that may drive boiling: nucleate and convective boiling. Nucleate boiling occurs at the wall–liquid interphase and, in general, it is the phenomenon that dominates at low qualities. The vapor bubbles produced by nucleation tend to accumulate in the center of the tube, occupying a significant proportion of the cross sectional area due to the large specific volume of the vapor even at low quality. This situation increases the liquid velocity and forces to the liquid to flow near the walls (annular flow) forming a thin layer that continues to evaporate due to nucleation. At the liquid vapor interface, the convective boiling process carries out the evaporation and dominates the boiling process at higher qualities. When the quality