



# 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.

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## 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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**Table 1**  
Existing nucleate pool boiling correlations for mixtures.

Author(s)	Correlation
Thome [11]	$K = \frac{\Delta T_x}{\Delta T_{id}}$
Thome and Shakir [12]	$K = \frac{\Delta T_x}{\Delta T_{id}} \left[ 1 - \exp\left(\frac{-B_o q}{\beta \rho_l h_{lo}}\right) \right]$ $B_o = 1, \beta = 3.0 \times 10^{-4} \text{ m/s}$
Fujita and Tsutsui [13]	$K = \frac{\Delta T_x}{\Delta T_{id}} \left[ 1 - 0.8 \exp\left(\frac{-q}{10^5}\right) \right]$
Fujita and Tsutsui [14]	$K = \frac{\Delta T_x}{\Delta T_{id}} \left[ 1 - \exp\left\{ \frac{-60q}{\rho_l h_{lo}} \left( \frac{\rho_l^2}{\sigma g(\rho_l - \rho_v)} \right)^{1/4} \right\} \right]$
Inoue et al. [15]	$K = \frac{\Delta T_x}{\Delta T_{id}} \left[ 1 - 0.75 \exp\left(\frac{-0.75q}{10^5}\right) \right]$
Sun et al. [16]	$K = \frac{\Delta T_x}{\Delta T_{id}} \left[ 1 - 0.85 \exp\left(\frac{-q}{3 \times 10^5}\right) \right] (P/10^5)^{-0.01}$

multi-component mixtures with ‘n’ components, an ideal wall superheat,  $\Delta T_{id}$ , is determined using molar interpolation of the wall superheats for mixture components as given in Eq. (2).

$$\Delta T_{id} = \sum_{i=1}^n \hat{x}_i \Delta T_{s,i} \quad (2)$$

The ideal heat transfer coefficient,  $h_{id}$ , is given as

$$h_{id} = \frac{q}{\Delta T_{id}} = \frac{1}{\sum_{i=1}^n (\hat{x}_i / h_i)} \quad (3)$$

In the third approach, the ideal heat transfer coefficient is predicted by using any existing empirical nucleate boiling correlation for pure component with properties of the mixture. In the present work, this approach of evaluating nucleate boiling heat transfer coefficients for the multi-component mixture is preferred.

### 2.3. Flow boiling heat transfer coefficient of mixture

In comparison to the nucleate pool boiling heat transfer, there are few studies on evaluation of forced convective boiling heat transfer coefficients for mixtures. The empirical methods developed are mainly available for binary mixtures of refrigerants or common fluids boiling near room temperature. The commonly used empirical correlations for the forced convective boiling of mixtures are due to Bennett and Chen [19], Jung et al. [20], and Kandlikar [21]. Jung et al. [20] developed a flow boiling correlation for horizontal tubes for the binary mixtures of R22/R114 and R12/R152a. These predictive methods developed for mixtures are mostly based on the correlations used for pure components with certain modifications to account for the presence of a mixture. However, mostly these correlations are fluid specific and are applicable to limited operating conditions.

Chen correlation [18] is based upon the assumption that there are two active heat transfer mechanisms: nucleate boiling and convection. The nucleate boiling contribution is calculated using the Forster and Zuber correlation [18]. The convective component is determined using the Dittus–Boelter equation together with an enhancement factor  $F$ . Gungor and Winterton [22] developed a correlation for pure fluids, the form of which is similar to Chen correlation. The two-phase heat transfer coefficient,  $h_{tp}$ , for single component fluid is expressed as given in Eq. (4).

$$h_{tp} = E_o h_l + S h_{npb} \quad (4)$$

where  $h_l$  is the heat transfer coefficient for the liquid phase flowing alone,  $h_{npb}$  is pool boiling heat transfer coefficient,  $E_o$  is forced convection enhancement parameter,  $S$  is the forced convection suppression parameter and

$$h_l = 0.023 \frac{\lambda_l}{D} \text{Re}_l^{0.8} \text{Pr}_l^{0.4} \quad (5)$$

$$E_o = 1 + 24000 \text{Bo}^{1.16} + 1.37 \left( \frac{1}{X_{tt}} \right)^{0.86} \quad (6)$$

$$S = (1 + 1.15 \times 10^{-6} E_o^2 \text{Re}_l^{1.17})^{-1} \quad (7)$$

Gungor and Winterton [22] used Cooper (1984) correlation for the pool boiling heat transfer coefficient as given in Eq. (8).

$$h_{npb} = 55 p_r^{0.12} (-\log_{10} p_r)^{-0.55} M^{-0.5} q^{0.67} \quad (8)$$

Later, Gungor and Winterton [23] modified their correlation which is given as,

$$h_{tp} = E_{new} \cdot h_{lo} \quad (9)$$

where  $h_{lo}$  is liquid only heat transfer coefficient and their new two-phase convection multiplier,  $E_{new}$  is given in Eq. (10).

$$E_{new} = 1 + 3000 \cdot \text{Bo}^{0.86} + 1.12 \left( \frac{x}{1-x} \right)^{0.75} \left( \frac{\rho_l}{\rho_v} \right)^{0.41} \quad (10)$$

Thome and Shakir [12] proposed a method to account for mixture effect in predicting the heat transfer coefficient for forced convective boiling of mixture using pure component correlations. They suggested inclusion of a correction factor to account for mixture effect similar to the one used in nucleate pool boiling. Eq. (1) can be set as the correction factor, where the parameter,  $K$ , is calculated by any of the correlations given in Table 1. However, the ideal heat transfer coefficient,  $h_{id}$ , in Eq. (1), is calculated for flow boiling of the mixture. It should be determined by appropriate pure component flow boiling correlation utilizing the local mixture properties. The mixture correction factor,  $F_c$ , can be defined as

$$F_c = \frac{h_m}{h_{id}} \quad (11)$$

In order to predict flow boiling heat transfer coefficient for mixtures, any existing empirical correlation available for forced convective boiling of pure component can be modified using the correction factor,  $F_c$ . The Gungor–Winterton correlation (1987), i.e. Eq. (10), is modified as suggested by Thome [11] so that the parameter,  $E_{new}$ , includes the mixture correction factor applied to the boiling number as follows:

$$E_{new} = 1 + 3000 \cdot (\text{Bo} \cdot F_c)^{0.86} + 1.12 \left( \frac{x}{1-x} \right)^{0.75} \left( \frac{\rho_l}{\rho_v} \right)^{0.41} \quad (12)$$

Granryd [24] developed a correlation for convective boiling of non-azeotropic mixtures based on theoretical approach to two-phase heat transfer in evaporation in case of annular flow. It is based on the assumption that gas phase resistance is similar to that in Silver [25] and Bell-Ghaly [26] method. Granryd [24] tested the derived correlation for the experimental data of the mixtures, such as R22–R114 and R12–R152a from the literature. The local heat transfer coefficient ( $h_m$ ) in an evaporator with non-azeotropic refrigerant mixture is suggested by Granryd [24] to be estimated by Eqs. (13) and (14).

$$\frac{h_m}{h_{lo}} = f(X_{tt}) \quad (13)$$

$$\frac{h_m}{h_{lo}} = \frac{F_p}{(1+A)} = F_m \quad (14)$$

where  $h_{lo}$  is the liquid only heat transfer coefficient estimated from the relations for pure fluids (conventional Dittus–Boelter equation) with properties of the mixture.

$$h_{lo} = 0.023 \left( \frac{\lambda_l}{D} \right) \left[ (1-x) \frac{GD}{\mu} \right]^{0.8} \text{Pr}_l^{0.4} \quad (15)$$

$Pr_l$  is the Liquid Prandtl number,  $Pr_l = \frac{\mu_l C_{p_l}}{\lambda_l}$ ,  $G$  is the mass velocity,  $\text{kg/m}^2\text{s}$ . The parameter,  $F_p$ , is determined for flow boiling of pure refrigerants as given in Eq. (16).

$$F_p = 2.37 \left( 0.29 + \frac{1}{X_{tt}} \right)^{0.85} \quad (16)$$

The Martinelli parameter,  $X$  is used for the two-phase effect on convection. For laminar-liquid and turbulent-vapour flow, the Martinelli parameter,  $X_{vt}$ , is

$$X_{vt} = \left( \frac{f_l Re_v^{0.25}}{0.079} \right)^{0.5} \left( \frac{1-x}{x} \right) \left( \frac{\rho_v}{\rho_l} \right)^{0.5} \quad (17)$$

$$Re_v = \frac{GxD}{\mu_v} \quad (18)$$

For laminar flow ( $Re_l < 2000$ ) liquid friction factor,  $f_l$  is given as

$$f_l = \frac{16}{Re_l} \text{ where, } Re_l = \frac{G(1-x)D}{\mu_l}$$

For turbulent-liquid and turbulent-vapour flow, Martinelli parameter,  $X_{tt}$ , is

$$X_{tt} = \left( \frac{1-x}{x} \right)^{0.9} \left( \frac{\rho_v}{\rho_l} \right)^{0.5} \left( \frac{\mu_l}{\mu_v} \right)^{0.1} \quad (19)$$

$$A = \left( \frac{F_p}{C_{lg}} \right) x^2 \left[ \left( \frac{1-x}{x} \right) \left( \frac{\mu_v}{\mu_l} \right) \right]^{0.8} \left( \frac{Pr_l}{Pr_v} \right)^{0.4} \left( \frac{\lambda_l}{\lambda_v} \right) \left( \frac{Cp_v}{Cp_w} \right) \quad (20)$$

where  $C_{lg}$  is an enhancement factor to take into account the interface effects between gas and liquid. Granryd recommended the enhancement factor,  $C_{lg} = 2$  for evaporation of refrigerants.  $Cp_w$  is an 'apparent local specific heat' for the non-azeotropic mixture in the two-phase region at quality  $x$ , defined as

$$Cp_w = \left( \frac{\partial i}{\partial T} \right)_p \text{ where, } i \text{ is enthalpy.}$$

The method of Silver [25] and Bell-Ghaly [26] primarily developed in relation to condensation of multi-component mixtures can be applied to convective boiling of mixtures [27]. In forced convective boiling of mixtures, there is a concentration difference between vapour-liquid interface and bulk vapour, which is analogous to that in condensation of mixtures. The interfacial concentration difference leads to mass transfer resistance for evaporating fluid into bulk vapour. The heat transfer coefficient for the boiling/condensation of non-azeotropic refrigerant mixture is given by Eq. (21).

$$\frac{1}{h_m} = \frac{1}{h_c} + \frac{Z_g}{h_g} \quad (21)$$

where  $h_c$  is convective heat transfer coefficient for mixture calculated using correlations for pure component with properties of the mixture. The vapour heat transfer coefficient,  $h_g$  is calculated by Dittus-Boelter equation as given in Eq. (22).

$$h_g = 0.023 \left( \frac{\lambda_g}{D} \right) Re_g^{0.8} Pr_g^{0.4} \quad (22)$$

The parameter  $Z_g$ , in Eq. (21), is the ratio of the sensible cooling of the vapor to the total cooling rate, which can be written as

$$Z_g = x \cdot Cp_v \cdot \frac{dT_{dew}}{di} \quad (23)$$

where  $\frac{dT_{dew}}{di}$  is slope of the dew point temperature curve with respect to the enthalpy of the mixture as it condenses/evaporates.

### 3. Experimentation

Nellis et al. [8] described an experimental test facility and procedure used for the measurement of horizontal, flow boiling heat transfer coefficient for nitrogen-hydrocarbon mixtures. They considered a test section length of 27 mm with an inner diameter of the tube being 0.835 mm. Experiments were conducted over a range of mixture compositions, temperatures, mass flow rates, and pressures. The mixture compositions and experimental test conditions are given in Table 2 [8]. The mixtures for Runs A and B contain four components, i.e. nitrogen, methane, ethane and propane. However, all other Runs C, D, E and F have mixtures of five components with addition of iso-butane to the above mentioned four components. It may be seen from Table 2 that the molar composition of nitrogen in the mixtures for Runs C and D is less than that for other runs. The operating pressure for Runs A, B and C is higher than that for Runs D, E, and F. Using these experimental data [8], the heat transfer coefficients are calculated using available correlations and are compared with the experimental values in the present work.

### 4. Results and discussion

#### 4.1. Assessment of existing empirical correlations

Several correlations are available in the literature to predict heat transfer coefficients for pure components. In order to predict heat transfer coefficients for the mixture of multi-component gases, single component correlations are tested using properties of mixture. This is a straightforward way to apply available empirical correlation to multi-component mixture. For this purpose, Chen correlation and Gungor-Winterton correlations are used. All the thermodynamic and the transport properties of the mixtures are determined using Peng-Robinson equation of state [28] in ASPEN [29].

Fig. 1 shows comparison of heat transfer coefficients obtained using the Chen correlation and the two correlations of Gungor and Winterton with the experimental values for Run E. The heat transfer coefficients are plotted with respect to saturation temperature of the mixture which is indicative of quality of the mixture too. It can be noted from Fig. 1 that none of the available correlations predict heat transfer coefficients anywhere close to experimental data. It is observed from Fig. 1 that the Chen correlation and Gungor-Winterton (1987) correlation give steady increase in heat transfer coefficient up to a temperature of 240 K. Even the predicted trends obtained using these correlations do not match with the experimental data. However, predictions given by Gungor and Winterton (1987) are in better agreement in comparison to the Chen correlation, particularly in the high quality region of convection i.e. in the temperature range of 160–240 K. On the other hand, predictions given by Gungor and Winterton (1986) correlation [22] follow the trend shown by experimental data although the predictions are on higher side as compared to experimental values. One of the reasons for such deviations could be application of pure component correlations to the mixture of gases.

#### 4.2. Modifications in correlations

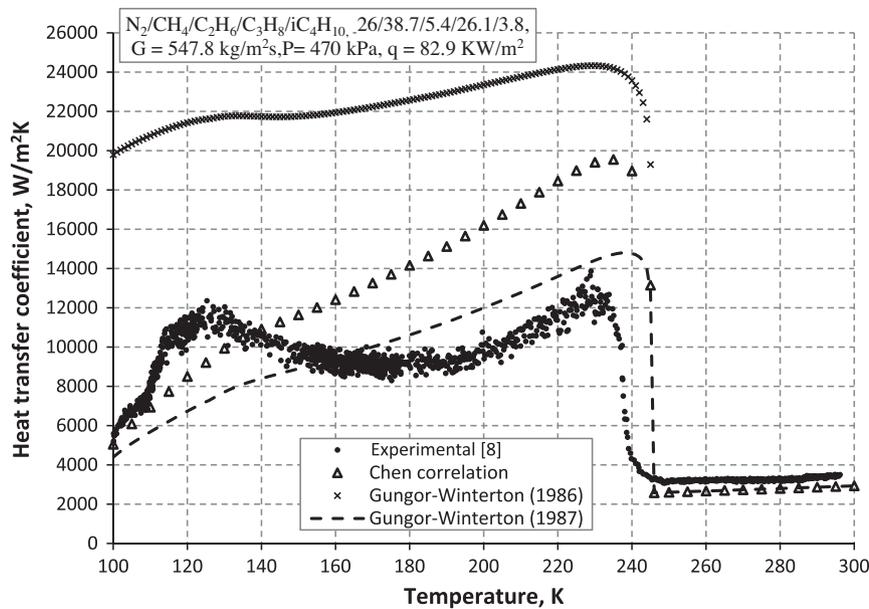
The available empirical correlations which take into account the correction factors towards the mixture effect can be modified suitably for calculation of two-phase heat transfer coefficients for the multi-component mixtures of nitrogen-hydrocarbons. The modifications in the existing empirical correlations for flow boiling of mixtures are carried out in such a way that the predicted results match the experimental data.

**Table 2**  
Mixture compositions and test conditions [8].

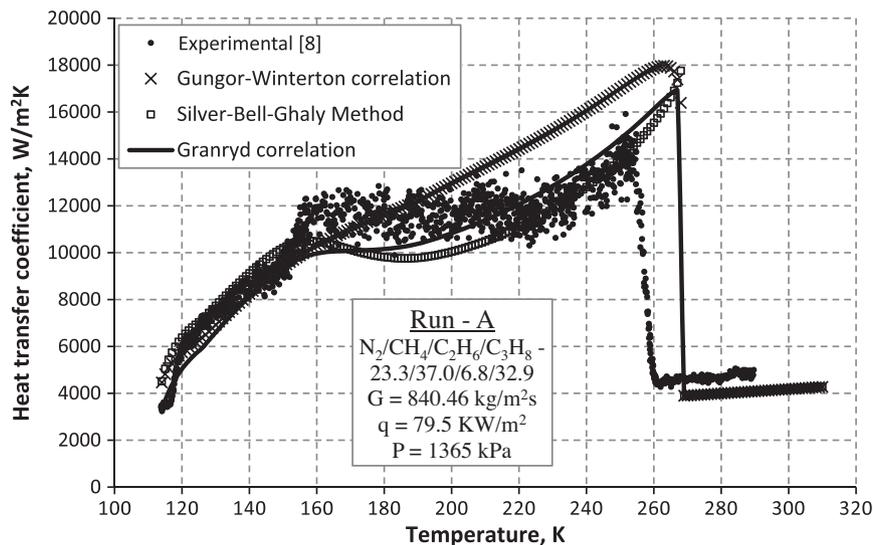
Run	Mixture composition $N_2/CH_4/C_2H_6/C_3H_8/iC_4H_{10}$	Mass flow rate (g/s)	Mass flux, $G$ ( $kg/m^2 s$ )	Heat flux ( $kW/m^2$ )	Pressure (kPa)
Run A	23.3/37.0/6.8/32.9/0	0.46	840.5	79.5	1365
Run B	20.4/38.3/5.4/35.8/0	0.44	803.9	79.4	1439
Run C	7.4/49.4/18.4/17.8/7.0	0.42	767.4	82.7	1424
Run D	6.9/50.9/19.1/16.8/6.4	0.29	529.9	83.4	394
Run E	26.0/38.7/5.4/26.1/3.8	0.30	547.8	82.9	470
Run F	24.1/40.1/5.7/26.3/4.0	0.14	255.8	82.9	434

Three different approaches have been identified in the present work to calculate heat transfer coefficients. In the first approach, Gungor–Winterton (1987) correlation [23], as given in Eq. (10), along with correction suggested by Thome [11] is used. The correction takes mixture effect into account. For this, Gungor–Winterton correlation for pure component is selected to evaluate the ideal heat transfer coefficients.

In the second approach, the flow boiling heat transfer coefficients are predicted using Silver-Bell-Ghaly (SBG) [25] method. In this method, convective heat transfer coefficient,  $h_c$ , is calculated using pure component correlation. For this purpose, Gungor–Winterton correlation [23] is modified as given in Eq. (24) using a correction factor. The correction factor for mixture effect is obtained using Thome and Shakir correlation [12] as given in Table 1.



**Fig. 1.** Heat transfer coefficients for Run E predicted using single component correlations.



**Fig. 2.** Heat transfer coefficients for Run A.

$$E_{new} = 1 + 3000 \cdot (Bo \cdot F_c)^{0.86} + 1.12 \left( \frac{x}{1-x} \right)^{0.85} \left( \frac{\rho_l}{\rho_v} \right)^{0.7} \quad (24)$$

In the third approach, Granryd correlation [24] is modified for its use to predict heat transfer coefficients of boiling nitrogen-hydrocarbon mixtures. The enhancement factor,  $C_{ig}$  in the Granryd correlation is modified depending on the mass flow rate of the refrigerant mixture. In the present work, different values of the enhancement factor are tried to study the applicability of the present form of Granryd correlation for the mixtures of nitrogen-hydrocarbons. The reduced enhancement factor ( $C_{ig} < 2$ ) leads to better fit of the experimental data, particularly for the mixtures boiling with higher mass velocity.

Figs. 2–7 show the comparison of the predicted heat transfer coefficients using above three approaches with the experimental data for Run A, B, C, D, E and F respectively. It may be emphatically stated that the predictions based on modified correlations are closer to the experimental results. It is observed from these figures that the heat transfer coefficients obtained using Silver-Bell-Ghaly

method and modified Granryd correlation show a better match with the experimental values as compared to that using modified Gungor–Winterton correlation.

The local values of heat transfer coefficients strongly depend on composition of the mixture in addition to process parameters such as mass flow rate and pressure of the mixture. It is noted from the experimental data for Run A, B, E and F that the variation in heat transfer coefficients is a characteristic M-shape variation, while it is not observed in the case of Run C and D. This is mainly due to composition of the various gases in the mixtures used. The molar percentage of middle boiling point component i.e. ethane, in the overall composition of the mixtures for Run A, B, E and F is lower as compared to that for Run C and D, as shown in Table 2. The trends in variation of heat transfer coefficients predicted using Silver-Bell-Ghaly method and modified Granryd correlations are similar to those of the experimental values for all the runs. On the contrary, modified Gungor–Winterton correlation does not follow the specific variation found in the measured heat transfer coefficients with respect to temperatures. It is evident from Figs. 2 to

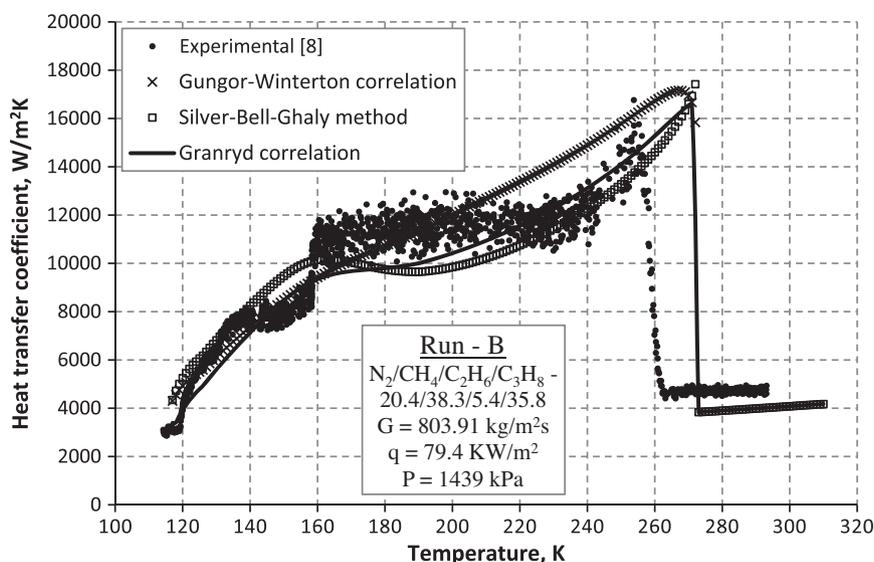


Fig. 3. Heat transfer coefficients for Run B.

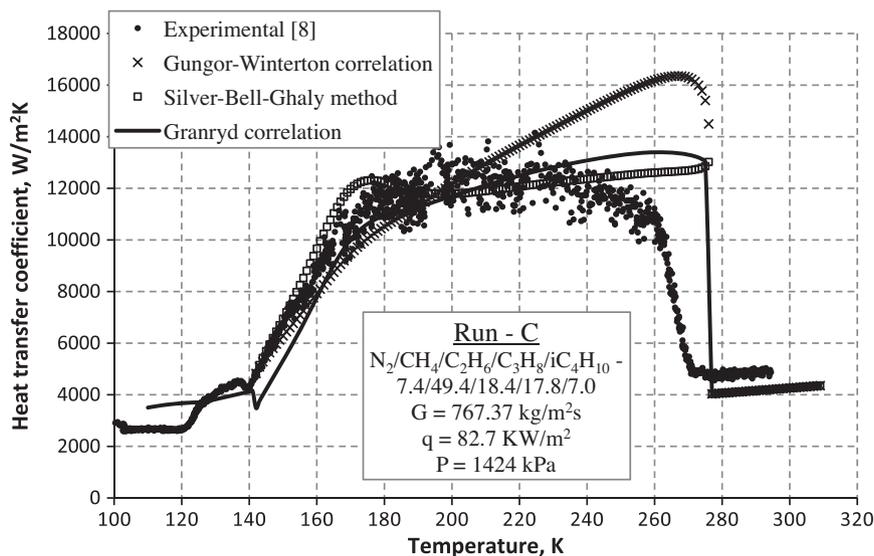


Fig. 4. Heat transfer coefficients for Run C.

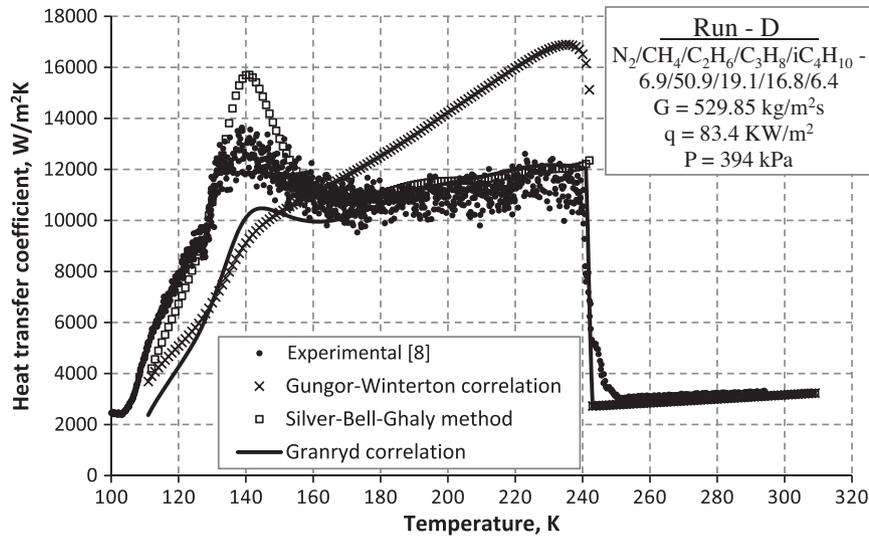


Fig. 5. Heat transfer coefficients for Run D.

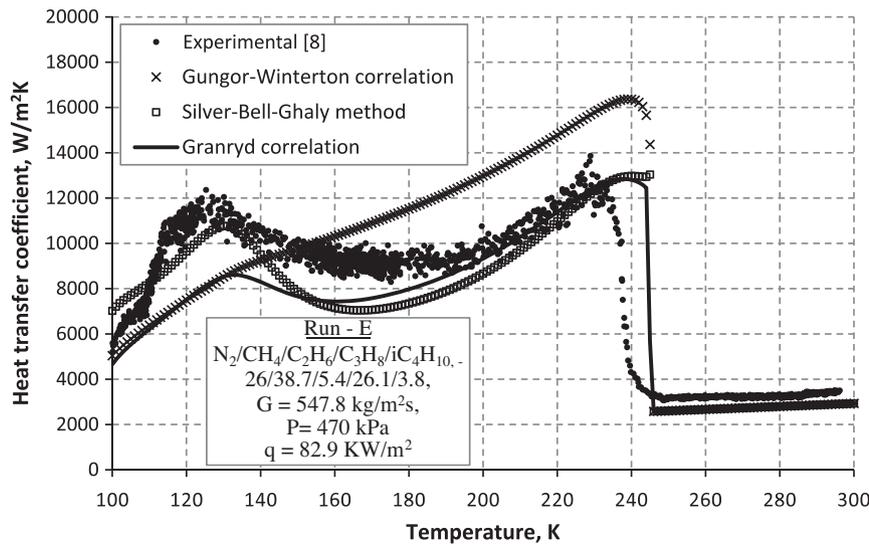


Fig. 6. Heat transfer coefficients for Run E.

7 that modified Gungor–Winterton correlation shows steady increase in the heat transfer coefficients with increase in quality.

The average absolute deviations (AAD) are obtained for the predicted results in order to understand applicability of the correlations. The AAD is obtained by calculating the normalized percentage difference between the experimental heat transfer coefficient values and the predicted values using different empirical methods according to Eq. (25).

$$AAD = \frac{1}{N} \sum \frac{|h_{\text{exp}} - h_{\text{predicted}}|}{h_{\text{exp}}} \quad (25)$$

The AAD for all the correlations tested is compared in Table 3. The AAD of the heat transfer coefficients predicted using Silver-Bell-Ghaly method for Run A, is 24.37%, which is lower than that of modified Gungor–Winterton correlation. AAD for modified Granryd correlation ( $C_{1g} = 1.4$ ) is also compared with that for original Granryd correlation ( $C_{1g} = 2$ ) in Table 3. It is found that the reduced value of the constant ( $C_{1g} = 1.4$ ) in the Granryd equation, improves prediction of heat transfer coefficients as compared to that predicted using  $C_{1g} = 2$  for all the runs excluding Run F.

From Table 2, it can be observed that Run A through E have significantly higher mass flux compared to Run F. For these high mass flux runs (A–E), value of  $C_{1g} = 1.4$  leads to a reasonable prediction of heat transfer coefficients. However, for Run F, with a significant lower mass flux (nearly 50% lower than mass flux value for Run E), use of  $C_{1g} = 1.4$  results in increase in deviation between predicted and experimental values of heat transfer coefficients. Therefore, for Run F (or in general for mixtures with lower mass flux) value of  $C_{1g}$  can be taken as 2. Since experimental data is available only for these six runs, for mixtures with different compositions, operating pressure and mass flux, it would be inappropriate to make a definitive statement on the predictability of the correlation. This analysis is a step in the direction of providing a detailed understanding of correlation use for multi-component mixtures. A more complete experimental data set with varying conditions for same composition is required to understand behaviour of each parameter on heat transfer coefficient values.

It is also clear from Table 3 that the Silver-Bell-Ghaly method and modified Granryd correlation predict heat transfer coefficients more accurately. The maximum AAD for modified Granryd correla-

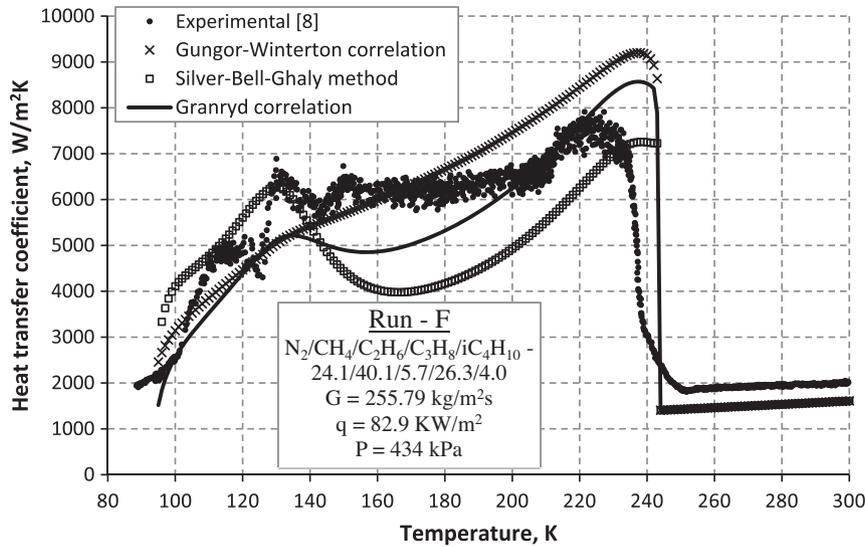


Fig. 7. Heat transfer coefficients for Run F.

Table 3  
Average absolute deviation.

Run	Average absolute deviation (AAD) (%)			
	Modified Gungor–Winterton	Silver–Bell Ghaly	Granryd (C <sub>lg</sub> = 2.0)	Modified Granryd correlation (C <sub>lg</sub> = 1.4)
Run A	29.52	24.37	29.40	23.40
Run B	28.98	27.45	31.23	25.78
Run C	29.14	17.56	29.44	20.47
Run D	23.38	8.61	18.80	12.95
Run E	31.93	23.24	23.77	21.83
Run F	21.04	26.22	20.87	24.52

tion observed to be 25.78% for Run B, whereas it gives minimum deviations of 12.95% for Run D. However, the Silver-Bell-Ghaly method predicts the heat transfer coefficients with the maximum AAD of 27.45% for Run B and with the minimum AAD of 8.6% only, for Run D. The AAD for modified Gungor–Winterton correlation is more as compared to other correlations, for all the experimental data except for Run F.

The temperature glides for the various mixtures are given in Table 4. It is found that the temperature glide is lowest, i.e. 131.8 K for the mixture of Run D, whereas it is highest, i.e. 156 K for the mixture of Run B. The mixture effect is predominant for the mixtures with higher temperature glides. Therefore, the deviation of the predicted heat transfer coefficients is more for the mixture having higher temperature glide and it is minimum for the mixture with low temperature glide.

It is also noted that the predictions based on the above correlations are more accurate particularly for quality in the range of 0.1–0.75. For example, in the case of Run A, AAD for modified

Table 4  
Temperature glide for mixtures.

Run	Bubble point temperature, T <sub>b</sub> (K)	Dew point temperature, T <sub>d</sub> (K)	Temperature glide, ΔT <sub>g</sub> (K)
A	113.596	268.37	154.774
B	116.463	272.469	156.006
C	141.894	276.405	134.511
D	110.506	242.32	131.814
E	94.51	245.196	150.686
F	94.02	243.88	149.86

Table 5  
The modified empirical correlations for mixtures.

Author(s)	Correlations
Modified Gungor–Winterton	$h_m = E_{new} \cdot h_{l0}$ $E_{new} = 1 + 3000 \cdot (Bo \cdot F_c)^{0.86} + 1.12 \left(\frac{x}{1-x}\right)^{0.75} \left(\frac{\rho_l}{\rho_v}\right)^{0.41}$ $\frac{h}{h_{id}} = \frac{1}{1+K}$ $K = \frac{\Delta T_g}{\Delta T_{id}} \left[ 1 - \exp\left(\frac{-B_g q}{\beta \rho_l h_{lv}}\right) \right]$
Silver–Bell Ghaly method	$\frac{1}{h_m} = \frac{1}{h_c} + \frac{Z_g}{h_g}$ $h_c = E_{new} h_{l0}$ $E_{new} = 1 + 3000 \cdot (Bo \cdot F_c)^{0.86} + 1.12 \left(\frac{x}{1-x}\right)^{0.85} \left(\frac{\rho_l}{\rho_v}\right)^{0.7}$
Modified Granryd	$\frac{h_m}{h_b} = \frac{F_p}{(1+A)} = F_m$ $F_p = 2.37 \left(0.29 + \frac{1}{x}\right)^{0.85}$ $A = \left(\frac{F_p}{C_{lg}}\right) x^2 \left[\frac{(1-x)}{x}\right] \left(\frac{\mu_w}{\mu_l}\right)^{0.8} \left(\frac{Pr_l}{Pr_w}\right)^{0.4} \left(\frac{z_l}{z_w}\right) \left(\frac{C_{p,l}}{C_{p,w}}\right)$ $C_{lg} = 1.4 \text{ if } G > 500 \text{ kg/m}^2 \text{ s}$ $C_{lg} = 2 \text{ if } G < 300 \text{ kg/m}^2 \text{ s}$

Gungor–Winterton and modified Granryd correlation for quality in the range of 0.1–0.75 are 12.5% and 8.44% respectively, while AAD for Silver-Bell-Ghaly method is 7.96% only. The saturation temperature corresponding to quality 0.1 is 121 K, while it is 255 K corresponding to 0.75. However, these correlations over predict the experimental data in the region of quality higher than 0.75.

Overall, the results of the Silver-Bell-Ghaly method and modified Granryd correlations are in good agreement with the experimental data for all the runs, A–F. Therefore, these empirical methods with suggested modifications can be used for prediction of flow boiling heat transfer coefficients of multi-component mixtures. The modified forms of these empirical correlations are summarized in Table 5. The knowledge of heat transfer coefficients will be very useful to design the heat exchanger for mixed refrigerant J–T cryocooler.

### 5. Conclusions

The existing correlations are assessed to predict the flow boiling heat transfer coefficients of multi-component non-azeotropic

refrigerant mixtures of nitrogen and hydrocarbons. The predicted values of heat transfer coefficients are compared with the available experimental data from the literature. The modifications in the existing correlations are suggested to make them suitable to estimate the local heat transfer coefficient. Following conclusions are drawn from the present study.

1. The existing flow boiling correlations of pure substance are not suitable for the non-azeotropic mixtures of nitrogen–hydrocarbons.
2. The modified Granryd correlation and Silver-Bell-Ghaly method can be used to predict the local heat transfer coefficients of boiling refrigerants mixtures used in MR J-T cryocooler. The maximum average absolute deviation for Silver-Bell-Ghaly method found to be 27.4% whereas it is 25.8% for modified Granryd correlation.
3. The average deviation for the suggested correlations is found to be more for the mixtures having higher temperature glide.

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### References

- [1] Longworth RC, Boiarski MJ, Klusmier LA. 80 K closed cycle throttle refrigerator. *Cryocoolers* 1995;8:537–41.
- [2] Boiarski M, Khatri A, Kovalenko V. Design optimization of the throttle-cycle cooler with mixed refrigerant. *Cryocoolers* 1999;10:457–65. R.G. Ross, Jr. ed., Plenum Press, New York.
- [3] Gong MQ, Luo EC, Zhou Y, Liang JT, Zhang L. Optimum composition calculation for multicomponent cryogenic mixture used in Joule–Thomson refrigerators. *Adv Cryogenic Eng* 2000;45:283–90.
- [4] Walimbe NS, Narayankhedkar KG, Atrey MD. Experimental investigation on mixed refrigerant Joule–Thomson cryocooler with flammable and non-flammable refrigerant mixtures. *Cryogenics* 2010;50(10):653–9.
- [5] Alexeev A, Thiel A, Haberstroh Ch, Quack H. Study of behaviour in the heat exchanger of a mixed gas Joule–Thomson cooler. *Adv Cryogenic Eng* 2000;45:307–15.
- [6] Gong MQ, Wu JF, Luo EC, Qi YF, Hu QG, Zhou Y. Study on the overall heat transfer coefficient for the tube-in-tube heat exchanger used in mixed-gases coolers. *Adv Cryogenic Eng* 2002;47B:1483–90.
- [7] Ardhapurkar PM, Sridharan A, Atrey MD. Investigations on two-phase heat exchanger for mixed refrigerant Joule–Thomson cryocooler. *Adv Cryogenic Eng* 2012;57A:706–13.
- [8] Nellis G, Hughes C, Pfothenauer J. Heat transfer coefficient measurements for mixed gas working fluids at cryogenic temperatures. *Cryogenics* 2005;45(8):546–56.
- [9] Celata GP, Cumo M, Setaro T. A review of pool and forced convective boiling of binary mixtures. *Exp Thermal Fluid Sci* 1994;9:367–81.
- [10] Cheng Lixin, Mewes Dieter. Review of two-phase flow and flow boiling of mixtures in small and mini channels. *Int J Multiph Flow* 2006;32:183–207.
- [11] Thome JR. Boiling of new refrigerants: a state-of-the-art review. *Int J Refrigeration* 1996;19(7):435–57.
- [12] Thome JR, Shakir S. A new correlation for nucleate pool boiling of aqueous mixtures. *AIChE Symp Ser* 1987;83(257):46–51.
- [13] Fujita Y, Tsutsui M. Heat transfer in nucleate pool boiling of binary mixtures. *Int J Heat Mass Transfer* 1994;37:291–302.
- [14] Fujita Y, Tsutsui M. Nucleate boiling of two and three-component mixtures. *Int J Heat Mass Transfer* 2004;47:4637–48.
- [15] Inoue T, Kawae N, Monde M. Characteristics of heat transfer coefficient during nucleate pool boiling of binary mixtures: improvement of correlation and its physical meaning. *Heat Mass Transfer* 1998;33(4):337–44.
- [16] Sun Zhaohu, Gong M, Li Zhijian, Wu Jianfeng. Nucleate pool boiling heat transfer coefficients of pure HFC134a, HC290, HC600a and their binary and ternary mixtures. *Heat Mass Transfer* 2007;50:94–104.
- [17] Stephan K. Two-phase heat exchange for new refrigerants and their mixtures. *Int J Refrigeration* 1995;18(3):198–209.
- [18] Cary Van P. *Liquid–vapor phase-change phenomena*. 2nd ed. Taylor & Francis; 2008.
- [19] Bennett DL, Chen JC. Forced convective boiling in vertical tubes for saturated pure components and binary mixtures. *AIChE J* 1980;26:454–61.
- [20] Jung DS, McLinden M, Radermacher R, Didion D. A Study of flow boiling heat transfer with refrigerant mixtures. *Int J Heat Mass Transfer* 1989;32(9):1751–64.
- [21] Kandlikar SG. Boiling heat transfer with binary mixtures: part II – flow boiling in plain tubes. *ASME J Heat Transfer* 1998;120(2):388–94.
- [22] Gungor KE, Winterton RHS. A general correlation for flow boiling in tubes and annuli. *Int J Heat Mass Transfer* 1986;29(3):351–8.
- [23] Gungor KE, Winterton RHS. Simplified general correlation for saturated flow boiling and comparisons with data. *Chem Eng Res Des* 1987;65:148–56.
- [24] Granryd E. Heat transfer in flow evaporation of non-azeotropic refrigerant mixtures – A theoretical approach. In: *Proc. 18th Int. Congress of Refrigeration, Montreal, vol. 3, 1991. pp. 1330–1334.*
- [25] Silver L. Gas cooling with aqueous condensation. *Trans Inst Chem Eng* 1947;25:30–42.
- [26] Bell KJ, Ghaly MA. An approximate generalized design method for multicomponent/partial condenser. *AIChE Symp Ser* 1973;69:72–9.
- [27] Collier John G, Thome John R. *Convective boiling and condensation*. Oxford University Press; 1996.
- [28] Peng D, Robinson DB. A new two constant equation of state. *Ind Eng Chem Fundam* 1976;15(1):59–64.
- [29] ASPEN, version 2004.1, AspenTech India Pvt. Ltd.