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Heat transfer and pressure drop in the main heat exchanger of a cryogenic mixed refrigerant cycle

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Abstract. Mixed refrigerant cycles (MRCs) offer a cost- and energy-efficient cooling method for the temperature range between 80 and 200 K. The performance of MRCs is substantially influenced by entropy production in the main heat exchanger. Due to the wide-boiling refrigerant mixtures applied in MRCs, a reliable design of the heat exchangers is challenging as two-phase heat transfer and pressure drop in both fluid streams must be considered simultaneously.

This contribution presents a literature review on the boiling/condensation heat transfer and pressure drop of zeotropic mixtures at low temperatures. Based on this survey, suitable correlations for the design of MRC heat exchangers are identified.

1. Introduction

MRCs consist of a Linde-Hampson refrigeration cycle operated with zeotropic refrigerant mixtures, e.g. nitrogen-hydrocarbon mixtures. The use of such wide-boiling mixtures yields increased process efficiencies at relatively low operating pressures in comparison to pure gases. For a detailed description of MRCs and their applications the reader is referred to Venkatarathnam [1]. In recent years, the application of MRCs as a reliable and efficient refrigeration method for current-leads, high-temperature superconductors, etc. has been reviewed by several researchers [2–4]. Especially the cooling of current-leads benefits from the capability of absorbing heat loads continuously over a wide temperature range [5]. The overall process efficiency is governed by the mixture composition and the performance of the main heat exchanger. A reliable design of this heat exchanger is challenging though, since boiling and condensation of wide-boiling mixtures have to be considered.

In general, experimental data suitable for MRCs is scarce, since most studies focus on binary mixtures and near ambient temperatures [6, 7]. Nonetheless, some studies on the overall heat transfer and the pressure drop for MRC heat exchangers are available in literature [8–12]. Additionally, experimental data on the boiling and condensation characteristics of wide-boiling mixtures at cryogenic temperatures have been published [13–19].

In this paper, we identify correlations suitable for the heat exchanger design process, based on a literature survey on the boiling and condensation characteristics of zeotropic mixtures at low temperatures. Novel correlations for boiling and condensation heat transfer coefficients are presented in section 2 and compared to experimental data from literature in section 3. Finally, we summarise our findings in section 4.

2. Derivation of new correlations

Numerous studies have shown that the influence of mass transfer on heat transfer of zeotropic mixtures has to be accounted for, even for mixtures with a relatively low temperature glide [6, 7]. This influence can either be considered by calculating the coupled heat and mass transfer [20] or by applying so-called equilibrium models, e.g. the Granryd, Little or Silver-Bell-Ghaly (SBG) methods [21–24]. Since this study focuses on correlations for use in the heat exchanger design process, only the simpler equilibrium models are considered.

According to Little [22, 25] the boiling heat transfer of zeotropic mixtures in the annular flow regime can be derived as

$$\alpha_{\mathrm{tp}} = \left(\frac{1}{\alpha_{\mathrm{l,film}}} + \frac{x^2\, c_{p,\mathrm{v}}^2}{\left((1-x)\, c_{p,\mathrm{l}} + x\, c_{p,\mathrm{v}}\right)\left(\frac{\partial h}{\partial T}\right)_p} \frac{1}{\alpha_{\mathrm{v}}} \right)^{-1} \tag{1}$$

where α is the heat transfer coefficient, x the quality, c_p the specific heat capacity, h the specific enthalpy, T the temperature and p the pressure. The heat transfer coefficients are calculated from the Dittus-Boelter equation [26] under consideration of the void fraction ϵ as recommended by Little [22]:

$$\alpha_{\mathrm{l,film}} = 0.023 \left(\frac{Re_{\mathrm{l}}}{1+\sqrt{\epsilon}} \right)^{0.8} Pr_{\mathrm{l}}^{0.4} \frac{\lambda_{\mathrm{l}}}{d_h(1-\sqrt{\epsilon})} \tag{2}$$

$$\alpha_{\mathrm{v}} = 0.023 \left(\frac{Re_{\mathrm{v}}}{\sqrt{\epsilon}} \right)^{0.8} Pr_{\mathrm{v}}^{0.4} \frac{\lambda_{\mathrm{v}}}{d_h\sqrt{\epsilon}} \tag{3}$$

Here Re denotes the Reynolds number, Pr the Prandtl number, d_{h} the hydraulic diameter and λ the thermal conductivity.

In the original publication, Little proposed the use of the Chisholm [27] void fraction model. As noted by Barraza et al. [15], this correlation performs well in the range of $x = 0.1 - 0.8$, while its relatively poor performance at high qualities is associated with partial dry-out. We propose the use of the Baroczy [28] void fraction model to achieve better performance at low qualities. To improve the prediction at high quality, the pure fluid dry-out correlation proposed by Del Col et al. [29] is implemented and modified by the mixture boiling correction factor F_{c} as suggested by Thome and Shakir [30]:

$$x_{\mathrm{d}} = 0.4695 \left(\frac{4\, F_{\mathrm{c}}\, \dot{q}\, RLL}{\dot{m}\, d_{\mathrm{h}}\, \Delta h_{\mathrm{lv}}} \right)^{1.472} \left(\frac{\dot{m}^2\, d_{\mathrm{h}}}{\rho_{\mathrm{l}}\, \sigma} \right)^{0.3024} \left(\frac{d_{\mathrm{h}}}{0.001} \right)^{0.1836} (1-p_{\mathrm{R}})^{1.239} \tag{4}$$

$$RLL = \left(0.437 \left(\frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{l}}} \right)^{0.073} \left(\frac{\rho_{\mathrm{l}}\, \sigma}{\dot{m}^2} \right)^{0.24} d_{\mathrm{h}}^{0.72} \left(\frac{\dot{m}\, \Delta h_{\mathrm{lv}}}{F_{\mathrm{c}}\, \dot{q}} \right) \right)^{1/0.96} \tag{5}$$

where x_{d} is the dry-out quality, $\dot{q}$ the heat flux, $\dot{m}$ the mass velocity, Δh_{lv} the heat of vaporisation, ρ the density, σ the surface tension and p_{R} the reduced pressure. F_{c} is usually applied to consider the effect of mass diffusion on the nucleate boiling contribution of pure fluid flow boiling correlations and is defined as

$$F_{\mathrm{c}} = \frac{1}{1 + \frac{\alpha_{\mathrm{id}}\, \Delta T_{\mathrm{glide}}}{\dot{q}} \left(1 - \exp\left(\frac{-\dot{q}}{\beta\, \rho_{\mathrm{l}}\, \Delta h_{\mathrm{lv}}} \right) \right)} \tag{6}$$

where $\Delta T_{\mathrm{glide}}$ is the difference between dew and bubble point temperature of the refrigerant mixture and the mass transfer coefficient β is assumed to be $0.0003\,\mathrm{m\,s^{-1}}$ following the

Table 1. Summary of the database on mixed refrigerant two-phase flow (HC = hydrocarbon mixtures, SR = synthetic refrigerant mixtures, N = number of data points).

Boiling			Condensation			Pressure drop		
Reference	Fluids	N	Reference	Fluids	N	Reference	Fluids	N
Nellis [13]	HC	7410	Maråk [17]	HC	271	Maråk [17]	HC	287
Chen [14]	HC	247	Yu [18]	HC	66	Barraza [16]	HC&SR	9253
Barraza [15]	HC&SR	9268	Zhuang [19]	HC	200			
Total		16925	Total		537	Total		9540

Table 2. Predictive capabilities for the presented database (AAD = average absolute deviation, ARD = average relative deviation).

Boiling			Condensation			Pressure drop		
Correlation	AAD %	ARD %	Correlation α_{pure} from [32]	AAD %	ARD %	Correlation $\zeta_{\text{l,v}}$ from [34]	AAD %	ARD %
Little [22]	25.8	-20.5	Shao [39]	30.1	23.6	Cicchitti [40]	27.6	22.0
Granryd [21]	23.6	-13.0	SBG [23, 24]	27.6	21.9	MSH [41]	36.4	31.5
this study	16.8	-3.4	this study	21.1	0.8	Friedel [42]	33.5	2.8

recommendation by Thome [31]. The post-dry-out heat transfer is approximated with a sigmoid function between α_{tp} at $x = x_{\text{d}}$ and α_{v} at $x = 1$:

$$\alpha_{\text{d}} = \alpha_{\text{tp}} - (\alpha_{\text{tp}} - \alpha_{\text{v}})\left(1 - \exp\left[4\pi\left(\frac{1-x}{1-x_{\text{d}}} - \frac{1}{2}\right)\right]\right)^{-1} \tag{7}$$

Although the Little correlation was originally validated for boiling heat transfer, the resemblance with the SBG equation suggests that it can also be used for condensation. We propose the use of equation 1 with $\alpha_{\text{l,film}}$ calculated with the condensation correlation from Cavallini et al. [32].

Previous studies have shown that the two-phase pressure drop of refrigerant mixtures can be estimated with pure fluid correlations [9, 16, 33]. The Friedel [34] correlation is used to calculate the single phase pressure drop, as it avoids a discontinuity at the laminar-turbulent transition.

3. Comparison with literature

Table 1 lists all datasets on mixed refrigerant two-phase flow utilized in this work. The original data from Nellis et al. [13] and Barraza et al. [15, 16] was supplied by the authors, all other data points were taken from diagrams in the respective publications.

The properties of the hydrocarbon mixtures were calculated with the Peng-Robinson equation of state [35] in Aspen Plus [36]. The authors have chosen to use Peng-Robinson for all hydrocarbon mixtures in spite of the inferior accuracy in comparison to REFPROP [37], because REFPROP encountered convergence issues with some hydrocarbon mixture compositions. The fluid properties of the synthetic refrigerants were predicted as described by Kochenburger [38], where the unavailable binary interaction parameters for R134a were assumed to be $k_{ij} = 0$.

Bearing in mind the simplicity of the presented correlation, the boiling heat transfer database is predicted very well, particularly in the annular flow regime (cf. figure 1). Slightly over 80 %

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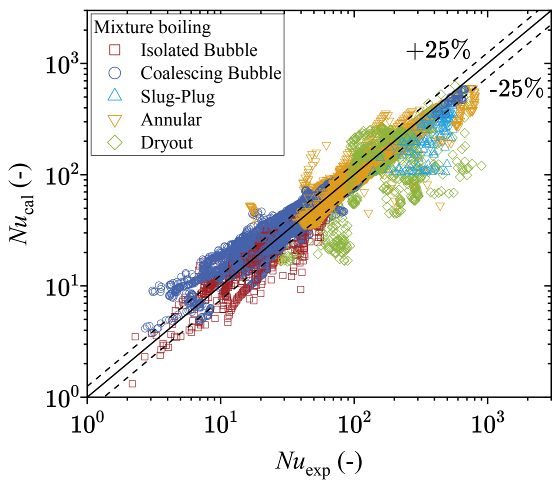

Figure 1. Comparison of experimental and calculated Nusselt numbers.

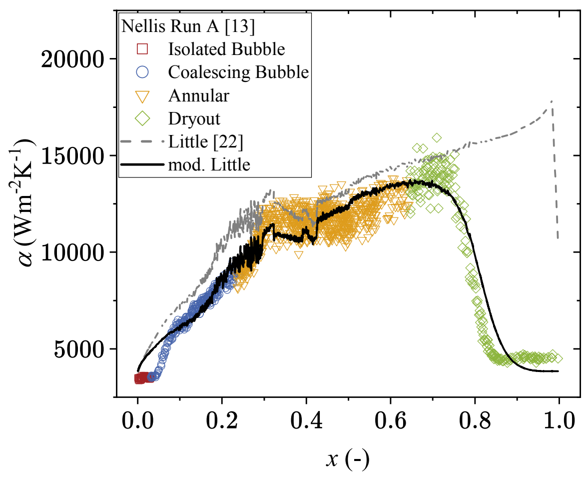

Figure 2. Comparison of modified Litte correlation with Run A from Nellis [13].

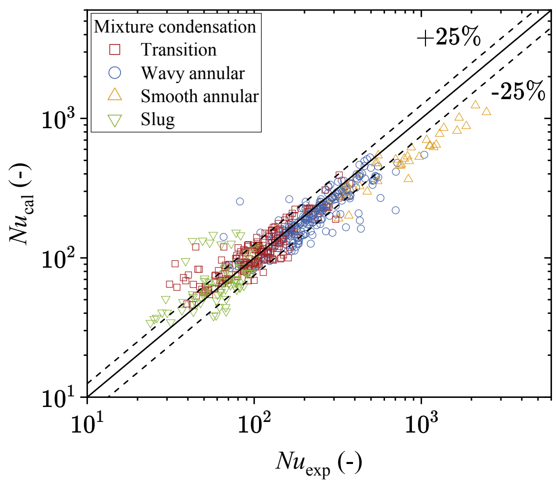

Figure 3. Comparison of experimental and calculated Nusselt numbers.

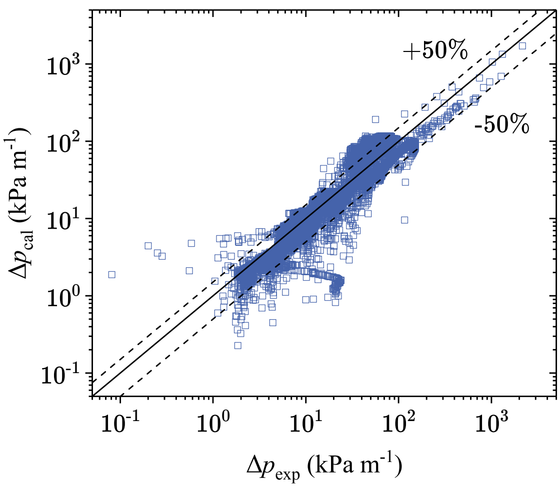

Figure 4. Comparison of experimental database with the Friedel [42] correlation.

of the data points are predicted within the $\pm 25\,\%$ error band. The depicted flow patterns were identified with the flow pattern map presented by Ong et al. [43], where F_c [30] was applied to the boiling number. The metrics presented in table 2 indicate that the new boiling correlation predicts the database significantly better than established correlations from literature. The exemplary comparison between the original and the modified Little correlation depicted in figure 2 illustrates the significant improvement particularly in the dryout region.

A comparison of the experimental data with the condensation heat transfer model is presented in figure 3. Here, the Kim et al. [44] flow pattern map was applied. Again, the database is predicted well with 70 % of the data points within $\pm 25\,\%$. It should be noted, though, that the heat transfer is slightly under-predicted at high Nu and over-predicted at low Nu. Still the prediction is considerably better than the widely-used SBG method, when both correlations are combined with the Cavallini et al. [32] pure fluid correlation (cf. table 2).

The predictive performance of pure fluid two-phase pressure drop correlations is listed in table 2. While the absolute deviation is comparable for all correlations, the relative deviation of the Friedel [42] correlation is significantly lower. On average, the Cicchitti [40] and Müller-Steinhagen & Heck (MSH) [41] correlations under-predict the pressure drop, which is problematic in a heat exchanger design process. Therefore, the authors recommend the use of the Friedel [42] correlation despite the slightly higher AAD. As illustrated in figure 4, the experimental pressure drop data is predicted reasonably well, with 85 % of the data points within a ±50 % error band.

4. Summary and conclusions

In this study, experimental heat transfer and pressure drop data of multi-component zeotropic refrigerant mixtures from literature are compared with different correlations. Modifications to existing correlations for boiling and condensation heat transfer are suggested to improve the prediction of the database. The modified heat transfer correlations predict the boiling data with an AAD of 16.8 % and the condensation data with an AAD of 21.1 %. The two-phase pressure drop data is best predicted with the Friedel [42] correlation (AAD = 33.5 %). The proposed correlations will be implemented in a numerical heat exchanger model introduced in [45] and the predictions will be compared to experimental data of a tubes-in-tube heat exchanger in a MRC test stand at KIT in a future publication.

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