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Research Paper

Prediction of heat transfer during condensation of carbon dioxide in channels

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HIGHLIGHTS

- Database of all published data for CO_2 condensation inside plain tubes was prepared.
- Database compared with general and CO_2 specific correlations.
- A correlation was identified which gives good agreement for mass flux up to 300 kg/m^2 s.
- All other correlations were found to have large deviations at all mass flow rates.

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ABSTRACT

There is currently great interest in the use of CO_2 as a refrigerant and hence a reliable method for predicting heat transfer during condensation in channels is needed. This research was done to evaluate the applicability of available predictive techniques. A number of correlations, including three very recently published correlations, were compared with a database that included all test data that could be found. These include single tubes and multichannels with diameters of 0.15–22.1 mm, evaporation temperatures of –25 °C to 29 °C, mass flux of 50–1000 kg/m^{2}s, and vapor qualities of 0.02–0.97. One of the general correlations gave good agreement for mass flux up to 300 kg/m^2 s. None of the other correlations gave good agreement with data at any flow rate.

1. Introduction

Due to concerns about ozone layer depletion and global warming, the CFC and HCFC refrigerants have been phased out. Alternative refrigerants are therefore needed which have low GWP (Global Warming Potential) and ODP (Ozone Depletion Potential). One of the alternative refrigerants is carbon dioxide which has zero ODP and its GWP is one. Further, it is completely non-flammable and non-toxic, and is compatible with most materials of construction. While CO_2 is already being used to some extent, its wider use is hampered by the lack of a thoroughly reliable method for calculation of heat transfer during condensation in tubes/channels. A number of researchers have reported that widely used correlations gave large deviations with their test data. In a recent study, Heo and Yun [1] compared a number of correlations to a wide ranging database and found all of them to give large deviations. They proposed a new correlation which gave better agreement with data but its mean absolute deviation was 44.8%. This is far from being satisfactory.

The present research was undertaken in an effort to identify reliable predictive techniques. A database consisting of all known published data was developed and was compared to a number of correlations including three very recent ones. One of the published correlations, Shah [2], was found reliable up to a mass flux of 300 kg/m^2 s. This result is of considerable value for designs. None of the correlations gave consistent performance at higher mass fluxes.

In the following, the results of this research are presented and discussed.

2. Previous work

Research on condensation in tubes of all sizes has been reviewed by Dalkilic and Wongwises [3]and that on condensation in minichannels by Awad et al. [4].

2.1. Experimental studies

Schmidt [5] performed measurements in a 22.1 mm diameter vertical tube at pressures of 60–70 bar. Only his mean heat transfer data at 70 bar are analyzable. Kondou and Hrnjak [6], Jang and Hrnjak [7], Iqbal and Bansal [8], Zilly et al. [9], Kim et al. [10], Kang et al.

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[11] and Son and Oh [12] performed measurements in single horizontal tubes of 3.5–6.5 mm diameters. Park and Hrnjak [13], Heo et al. [14,15], Huai and Koyama [16], Fronk and Garimella [17], Jige et al. [18], and Zhang et al. [19] performed tests on multichannels with hydraulic equivalent diameters of 0.15–1.5 mm. Table 1 gives the range of parameters covered by these studies.

In the tests of Schmidt, refrigerant was circulated with a compressor. Though an oil separator was used, carbon dioxide may have contained some oil. Oil was not present in any of the other tests mentioned above. All test sections were horizontal except that of Schmidt which was vertical.

Most of the above mentioned researchers have indicated large uncertainties in their reported heat transfer coefficients. For example, the estimate by Zhang et al. is ±35%.

2.2. Comparison with correlations

A number of researchers compared their test data with various correlations. Kim et al. [10] compared their data with the correlations of Dobson and Chato [25], Cavallini et al. [26] and Thome et al. [27]. They found the first two unsatisfactory. Kang et al. [11] found the correlations of Shah [28], Cavallini and Zecchin [29], and Thome et al. [27] to greatly overpredict their data. Park and Hrnjak [13] found large deviations with the correlations of Dobson and Chato [25] and Cavallini et al. [26]. Heo and Yun [1] compared the correlations of Thome et al. [27], Bandhauer et al. [30], Kim and Mudawar [21] and Cavallini et al. [26] with their own data as well as data from several other sources and found them to give very large deviations.

Thus none of the existing correlations has been found satisfactory. The correlations of Thome et al. [27], Cavallini et al. [26] and Dobson and Chato [25] were found unsatisfactory by several researchers.

3. Published predictive techniques

A large number of correlations have been proposed. Most of them are based on data from a single source or from a few sources and do not perform well outside the range of those data. There are some correlations which were originally based on a limited amount of data but have been compared by others with more data for many fluids with good results. Among such correlations are those of Ananiev et al. [23] and Akers et al. [24]. There are a very few correlations which were based on a wide range of data covering extremes of parameters and a variety of fluids. Among these are Thome et al. [27], Dobson and Chato [25], Cavallini et al. [22], and Shah [2,20]. The first two of these are flow pattern based. As noted in the previous section, these two have been found to perform poorly for carbon dioxide and are therefore not discussed any further. A correlation which has been verified with a wide range of data for small channels is that by Kim and Mudawar [21]. The correlations applicable to many fluids mentioned above are called general correlations in the following.

Most recently, Heo and Yun [1] have presented a correlation specifically for CO_2 which was compared to data from several sources.

Details of various correlations are given below.

3.1. The Shah correlation

The original Shah correlation [28] published in 1979 has been widely used but is limited to moderate pressures and higher flow rates. In Shah [20] a modified version was presented which was shown to apply to pressures up to near critical and flow rates from very high to extremely low. It has three heat transfer regimes, namely I, II, and III. The boundary between regimes II and III for horizontal tubes could not be identified in Shah [20] and was given later in Shah [2].

The correlation uses the following two heat transfer equations:

$$h_I = h_{LO}\left(1+\frac{3.8}{Z^{0.95}}\right)\left(\frac{\mu_l}{14\mu_g}\right)^{(0.0058+0.557p_r)} \tag{1}$$

$$h_{Nu} = 1.32\mathrm{Re}_{LO}^{-1/3}\left[\frac{\rho_l(\rho_l-\rho_g)gk_l^3}{\mu_l^2}\right]^{1/3} \tag{2}$$

Eq. (1) is the same as that in the Shah [28] correlation except that it did not have the viscosity ratio factor. Eq. (2) is the Nusselt equation for laminar film condensation in vertical tubes; the constant has been increased by 20% as recommended by McAdams [31] on the basis of comparison with test data. These equations are used according to the heat transfer regime as below:

In Regime I,

$$h_{TP} = h_I \tag{3}$$

In Regime II,

$$h_{TP} = h_I + h_{Nu} \tag{4}$$

In Regime III:

$$h_{TP} = h_{Nu} \tag{5}$$

h_{LO} in Eq. (1) is the heat transfer coefficient of the liquid phase flowing alone in the tube. It is calculated by the following equation:

$$h_{LO} = 0.023\mathrm{Re}_{LO}^{0.8}\mathrm{Pr}_l^{0.4}k_l/D \tag{6}$$

Z is the correlating parameter introduced by Shah [28] defined as:

$$Z = (1/x-1)^{0.8}p_r^{0.4} \tag{7}$$

3.1.1. Heat transfer regimes for horizontal tubes

The boundaries between were determined by data analysis described in Shah [2,20]. Regime I occurs when:

$$J_g \geq 0.98(Z+0.263)^{-0.62} \tag{8}$$

Regime III occurs when:

$$J_g \leq 0.95\left(1.254+2.27Z^{1.249}\right)^{-1} \tag{9}$$

If neither of the above conditions is satisfied, it is Regime II.

J_g is the dimensionless vapor velocity defined as:

$$J_g = \frac{xG}{(gD\rho_g(\rho_l-\rho_g))^{0.5}} \tag{10}$$

3.1.2. Heat transfer regimes for vertical tubes

The boundary between Regimes I and II is given by the following relation. Regime I occurs when

$$J_g \geq \frac{1}{2.4Z+0.73} \tag{11}$$

The boundary between Regimes II and III is given by the following relation: Regime III prevails when

$$J_g \leq 0.89-0.93\exp\left(-0.087Z^{-1.17}\right) \tag{12}$$