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Research paper

A method for predicting heat transfer during boiling of mixtures in plain tubes

Mirza M. Shah *

Engineering Research Associates, 10 Dahlia Lane, Redding, CT 06896, USA

HIGHLIGHTS

- Presents new method for calculating heat transfer of mixtures boiling in tubes.
- Verified with data for 45 mixtures from 21 studies in tubes 0.19–14 mm diameter.
- Flow 50–930 kg/m^{2}s, reduced pressures from 0.05 to 0.63, glides upto 156 °C.
- No other method has been verified over such a wide range.
- Applications in refrigeration, air conditioning, cryogenics, LNG, chemical industry.

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ABSTRACT

Methods for predicting heat transfer during boiling of mixtures inside tubes are needed for refrigeration, cryocoolers, and LNG vaporizers but published methods have been verified only with limited data. The method evaluated here consists of modifying the predictions of pure fluid correlations by applying a well-known correction factor for pool boiling in the nucleate boiling region and applying a correction factor used for condensation heat transfer to the region in which nucleate boiling has been completely suppressed. For comparison, calculations were also done using only the pool boiling correction factor. These correction factors were used together with five well-known correlations for pure fluids. These were compared to a data base consisting of 878 data points for 45 mixtures of 19 fluids from 21 independent studies. The fluids included halocarbons, hydrocarbons, nitrogen, and carbon dioxide. The data included tube diameters 0.19–14 mm, horizontal and vertical orientations, flow rates 50–930 kg/m^{2}s, reduced pressures from 0.05 to 0.63, and temperature glides upto 156 °C. The proposed method worked well for all mixtures except LNG. LNG data were in agreement with two correlations for pure fluids without any correction.

1. Introduction

Heat transfer during boiling of mixtures needs to be calculated for many applications that include evaporators for refrigeration and air conditioning, heat exchangers for cryocoolers, LNG (Liquefied Natural Gas) vaporizers, reboilers for chemical processes, etc. As is well-known, heat transfer coefficients of non-azeotropic mixtures are lower than those of the components due to the resistances caused by sensible heat transfer and mass transfer and therefore cannot be calculated by using mixture mean properties in formulas for pure fluids. While there have been many experimental studies and many methods for calculating heat transfer of mixtures have been proposed, none has been sufficiently verified to give confidence in its use. Thus there is a need for a well-verified method which can be used with confidence. This need has become more acute in recent years due to phasing out of many popular refrigerants due to concerns about ozone layer depletion and global warming. A variety of mixtures are being evaluated as substitutes and it requires estimation of boiling heat transfer. As use of mixtures instead of pure gases greatly improves the efficiency of cryocoolers, a variety of mixtures are being considered. To perform measurements on each proposed mixture is a very expensive and time consuming task. Hence there is a need for a reliable method of calculation.

The present research effort was made to try to fulfill this need. A method is proposed in which predictions of pure fluid correlations

* Tel.: +1 860 869 1328.
E-mail address: mshah.erc@gmail.com.

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Nomenclature

Bo	boiling number = $q/(G\ h_{lg})$, (−)
C_{pg}	specific heat of vapor at constant pressure, J/kg K
Co	convection number = $(1/x - 1)^{0.8} (\rho_g/\rho_l)^{0.5}$, (−)
D	inside diameter of tube, (m)
Fr_l	Froude number for all mass flowing as liquid = $G^2/(\rho_l^2 gD)$, (−)
G	total mass flux (liquid + vapor), (kg/m^2s)
g	acceleration due to gravity, (m/s^2)
H	enthalpy, (J/kg)
h	heat transfer coefficient, (W/m^2K)
h_{cb}	heat transfer coefficient during convective boiling, (W/m^2K)
h_{GS}	heat transfer coefficient assuming vapor is flowing alone in the tube, (W/m^2K)
h_I	pool boiling heat transfer coefficient with mixture mean properties, W/m^2K)
h_{lg}	latent heat of vaporization, (J/kg)
h_{LS}	heat transfer coefficient with liquid phase flowing alone in the tube, (W/m^2K)
h_{nb}	heat transfer coefficient during nucleate boiling, (W/m^2K)
h_{TP}	two-phase heat transfer coefficient, (W/m^2K)
J	=Co, except where Eq. (14) is applicable, (−)
k	thermal conductivity, (W/m K)
M	molecular weight, (−)
N	number of data points, (−)
p_r	reduced pressure, (−)
Pr	Prandtl number, (−)
q	heat flux, (W/m^2)
T_{BUB}	bubble point temperature of mixture, (K)
T_{DEW}	dew point temperature of mixture, (K)
T_{SAT}	saturation temperature, (K)
x	vapor quality, (−)
Y	factor in Bell-Ghaly method, defined by Eq. 3, (−)
Greek	
μ	dynamic viscosity, (kg/m s)
ρ	density, (kg/m^3)
Subscripts	
l	of liquid
g	of vapor
mix	of mixture

are modified by published correction factors for pool boiling and condensation heat transfer of mixtures. This method was evaluated by comparison with an extensive database consisting of 878 data points for 45 mixtures of 19 fluids from 21 independent studies. The fluids included halocarbons, hydrocarbons, nitrogen, and carbon dioxide. The data include tube diameters 0.19–14 mm, horizontal and vertical orientations, flow rates 50–930 kg/m^2s, reduced pressures from 0.05 to 0.63, saturation temperatures down to −180 °C, and temperature glides upto 156 °C. The proposed method worked well for all mixtures except LNG. The LNG data showed agreement with two general correlations for pure fluids without any correction.

So that the results may be viewed in perspective, the entire database was also compared with a method proposed by Thome [1] in which only the nucleate boiling term of pure fluid correlations is modified by a pool boiling correction factor.

In the following, the proposed method is presented and its physical bases are described. The results of data analyses are presented in tabular and graphical forms.

2. Previous research

There have been many experimental studies on boiling of mixtures in tubes. The review paper by Thome [1] lists studies done till then on boiling of mixtures in plain tubes. Numerous experimental studies have been published since then. Many of these papers do not give data in an analyzable form.

Numerous correlations, empirical and analytical, have been proposed but none of them has been verified with more than a few data sets. Many of them involve constants which are designed to fit a particular data set. Hence their general applicability is unknown.

Most of the proposed predictive methods modify the nucleate boiling contribution to heat transfer in correlations for single-component fluids. Examples are Palen and Small [2] and Kandlikar [3]. Thome [1] had also suggested the same approach, using the Thome & Shakir [4] correlation for pool boiling of mixtures for this purpose. There have been a few comparisons of this method with data, some showing good agreement and some showing poor agreement. For example Grauso et al. [5] found this method unsatisfactory while Zurcher et al. [6] showed that this method worked well for their R–407C data. Barbosa and Hewitt [7] pointed out that there is also a mass transfer resistance at the liquid–vapor interface in flow without nucleation due to the difference in composition between the liquid and the bulk vapor. Jung et al. [10] have proposed an empirical correction factor for this mass transfer resistance based on their own data.

The correlation given by Kandlikar [3] was verified with data from five sources but it is applicable only to binary mixtures. Many of the refrigerants presently being used, considered, or developed, have three or more components. Mixtures for cryocoolers also have more than two components. Further, it involves experimentally determined fluid specific factors which are given only for a few fluids. The Kandlikar method does not include correction for mass transfer resistance at interface during evaporation with suppressed nucleation.

Thus at the present, there is no well-verified method for the prediction of heat transfer during boiling of mixtures in tubes and there is a need for one.

3. Basis of the proposed calculation method

The calculation method proposed here is to modify the predictions of correlations for pure fluids by the Thome–Shakir [4] correction factor in the nucleate boiling region and the Bell–-Ghaly [8] method in the convective boiling region. This methodology is based on the physical phenomena that occur in the process. To explain the basis of this method, the physical phenomena are first discussed. Then the Thome–Shakir and Bell-Ghaly methods are described.

3.1. Physical phenomena

As is well known, nucleate boiling dominates at low qualities and high heat fluxes. This is called the nucleate boiling region. At