Determinant of local heat transfer coefficient during boiling in annular channels of small diameters

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Abstract. The presented work considers various methods for calculating the local heat transfer coefficient during boiling in annular channels of small diameters. The specificity of two different boiling modes, convective and nucleate, is analysed. The described calculation methods are compared.

1. Introduction

The main task in the calculation of convective heat transfer during boiling is to determine the heat transfer coefficient $\alpha$. The main approach to determine heat transfer coefficients at present is the use of correlation dependences obtained experimentally. Due to the great scientific interest in studying the process of heat transfer during boiling, many experimental studies have been carried out. Unfortunately, numerous papers led to various confusions inadvertently. Currently, there are different correlations for calculating the heat transfer coefficient during boiling, but many of them have not been tested and verified in sufficient quantities. The aim of this study is to develop a reliable method for determining the local heat transfer coefficient during boiling in annular channels of small diameters.

The study of boiling processes is complicated by the presence of several boiling modes, the variety of structures of the two-phase flow during boiling, which determines the effect of the degree of dryness on the overall efficiency of the heat exchange circuit. It is necessary to note the problem of studying processes in the initial boiling regimes at low dryness degrees. In this case, the dominant mechanism of heat transfer intensification is the nucleate boiling mechanism, which leads to a sharp increase in the heat transfer coefficient. Such a change in the heat transfer coefficient has a significant effect on the heat transfer processes of two-phase cooling systems [1, 4].

For the boiling process with the directional movement of the coolant in pipes and channels, based on the research analysis of Russian and foreign authors, two main approaches based on different boiling models can be noted: convective boiling (CB) [5] and nucleate boiling (NB) [6].

2. Materials and research techniques

This study considers the applied technical problem of the heat transfer coefficient determining during boiling in annular channels of small diameters. This case is typical for evaporative heat exchangers that are part of various two-phase cooling systems. For a numerical assessment of the correlation dependences, we will take the following initial data as a test case: working fluid – R718 (water), pressure 47.622 kPa, boiling point 353,15 K, flow rate 0.010 kg / s, pipe with a diameter of 0.008 m.
As the theoretical basis of the study, an approach was chosen that defines the total heat transfer coefficient during boiling as the sum of two components: these are the components of the heat transfer coefficient for convective boiling $\alpha_{cb}$ and nucleate boiling $\alpha_{nb}$. The summation is carried out taking into account the coefficients $F$ and $S$:

$$\alpha = F \cdot \alpha_{cb} + S \cdot \alpha_{nb}$$  \hspace{1cm} (1)

In turn, the parameters are determined by changing the Martinelli parameter. For the theory most common for boiling in a channel, Chen's theory, let us evaluate for the test case the dynamics of change and the interconnection of parameters: the Martinelli parameter; $S$ parameter; $F$ parameter; as well as the components of the heat transfer coefficient in convective boiling $\alpha_{cb}$ and nucleate boiling $\alpha_{nb}$.

The Martinelli parameter for given boundary conditions will be determined by the equation:

$$X_m = \left( \frac{1-x}{x} \right)^{0.9} \left( \frac{\rho_v}{\rho_l} \right)^{0.5} \left( \frac{\mu_v}{\mu_l} \right)^{0.1} = 0.024 \left( \frac{1-x}{x} \right)^{0.9}$$  \hspace{1cm} (2)

where $x$ – the dryness degree, $\rho$ – the density, $\mu$ – the viscosity, $v$ – the vapour phase, $l$ – the liquid phase.

The $F$ parameter for the given boundary conditions will be determined as:

$$F = 2.35 \left( \frac{1}{X_m} + 0.213 \right)^{0.736} = 2.35 \left( 41.66 \cdot \left( \frac{x}{1-x} \right)^{0.9} + 0.213 \right)^{0.736}$$  \hspace{1cm} (3)

The $F$ parameter characterizes the contribution of the heat transfer coefficient during convective boiling to the total value. This parameter for small values of $x$ varies slightly, its most significant increase is observed at $x > 0.5$ (figure 1).

![Figure 1](image)

Figure 1. Change in $F$ parameter depending on the dryness degree.

Therefore, the $F$ parameter reflects the predominance of the convective boiling mechanism in areas at $x > 0.5$. 

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For given boundary conditions, we obtain the S parameter:

\[
S = \left( \frac{1}{1 + 0.00000253 \left[ \text{Re}_L F^{1.25} \right]^{0.17}} \right) \quad \text{Re}_L = \frac{G(1-x)d}{\mu_L} \tag{4}
\]

where \( \text{Re}_L \) – Reynolds coefficient for the liquid phase, \( G \) – mass flow rate, \( d \) – channel diameter, \( \mu_L \) – liquid viscosity.

The S parameter reflects the nucleate boiling contribution to the total heat transfer coefficient graphically (figure 2): in accordance with its change, the mode of nucleate boiling prevails in the initial stages of boiling, which is then levelled.

**Figure 2.** Change in S parameter depending on the dryness degree.

This coefficient has a maximum at the initial boiling points, and then decreases to zero at \( x > 0.8 \).

The heat transfer coefficient for convective boiling (F.W. Dittus) is determined by the equation [5].

\[
\alpha_{cb} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \frac{\lambda}{d} \tag{5}
\]

where \( \text{Re} \) – Reynolds criterion, \( \text{Pr} \) – Prandtl criterion, \( \lambda \) – liquid heat transfer coefficient, \( d \) – channel diameter.

Let us estimate the coefficient for given boundary conditions. The adjusted Reynolds criterion for the liquid phase according to the second formula:

\[
\text{Re} = \frac{Gd(1-x)}{\mu} \tag{6}
\]

Taking into account \( m = \rho F \nu \quad \mu = \rho \eta \quad G = \frac{m}{F} \)

\[
\text{Re} = \frac{\rho \nu d(1-x)}{\mu} = \frac{\nu d(1-x)}{\eta} \tag{7}
\]

As can be seen from the above,

\[
\alpha_{cb} = 0.023 \left( \frac{\nu d(1-x)}{\eta} \right)^{0.8} \frac{\lambda}{d} \text{Pr}^{0.4} \tag{9}
\]

The dependence of the heat transfer coefficient \( \alpha_{cb} \) in the initial boiling sections is moderately decreasing depending on the dryness degree \( x \) character.
Further the heat transfer coefficient contribution at convective boiling to the total value of the heat transfer coefficient using the F parameter \( F \times \alpha_c \) is estimated (figure 3). This parameter has a significantly increasing character, which is associated with an increase in the dryness degree \( x \).

![Graph](image)

**Figure 3.** Convective component contribution to the heat transfer coefficient during boiling.

In general, the determination of the heat transfer coefficient for convective boiling from the dependences of J.C. Chen and F.W. Dittus does not cause significant difficulties and shows a graphic representation of the flow. This dependence can be used for the purposes of this study.

The possibility of using the M.G. Cooper dependence for nucleate boiling of heat transfer for the purposes of this study can be estimated as follows [3].

\[
\alpha_{nb} = 55 \cdot P_{red}^{0.12} \left(-\log_{10} P_{red}\right)^{-0.55} \cdot M^{-0.5} \cdot q^{0.67}
\]  

(10)

where Bo - Boiling number, \( P_{red} \) - reduced pressure.

Using the data of the test calculation task, it was obtained \( \alpha_{nb} = 13600 \left[W / m^2 K\right] \)

It should be noted that when using the M.G. Cooper method, the definition of the S parameter will differ from the J.C. Chen method [2]. In this case, the S parameter is recalculated:

\[
E = 1 + 24000 \cdot Bo^{1.16} + 1.37 \left(\frac{1}{X_n}\right)^{0.86}
\]

(11)

\[
S = \left[1 + 1.15 \cdot 10^{-6} \cdot E^2 \cdot Re^{1.17}\right]^{-1}
\]

(12)

A graph of the heat transfer coefficient distribution for the nucleate component of boiling by dryness degree \( x \) can be constructed taking into account the specified boundary conditions for the problem (figure 4).
Figure 4. The effect of the nucleate component on the heat transfer coefficient during boiling.

3. Results and Discussion

For the test problem in this study, we determine the total contribution of the components from nucleate and convective boiling to the value of the heat transfer coefficient during boiling in the heat flow. The figure 5 presents the result of data comparison.

Figure 5. Total heat transfer coefficient depending on the dryness degree x.

In the range under consideration and according to the graph, it is observed: for nucleate boiling, at the beginning there is a sharp jump at the initial section \(x = 0\), then a proportional decrease down to zero; for convective boiling - proportional growth, starting with the base value of the heat transfer
coefficient for the pure liquid flow. The overall pattern for the heat transfer coefficient distribution depending on the dryness degree \( x \) is as follows: at the beginning of the boiling section, there is a sharp increase due to the beginning of the nucleate boiling process. Then there is an insignificant reduction with a decrease in the heat transfer from nucleate boiling for dryness degree \( x = 0.05 \). After that, starting from \( x = 0.1 \), there is growth due to increase in convective boiling component.

To verify the obtained method a comparison of the calculated data with the experimental data in the test case was made. The figure 6 presents the result of this data comparison.

![Figure 6. Calculated and experimental data comparison.](image)

The resulting pattern is in good agreement with the experimental data obtained by the authors.

4. Conclusion
As a result of the present study, methods for determining the local heat transfer coefficients during boiling in annular channels of small diameters were obtained. The methodology is based on the convective and nucleate boiling modes components calculations. The main approaches to the calculation of these parameters were analysed and the most suitable methods for the problem under consideration were determined. The method was confirmed by experimental data for the test case.

References
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