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Modelling of Flow Boiling Process in Small Diameter Tubes

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Abstract

In the paper presented is application of a correlation describing flow boiling data, developed for conventional tubes, to small diameter tubes. Comparison between data from literature and calculated values has been made, which gives poor agreement and indicates that substantially more research is required to develop correlations with theoretical foundations to predict heat transfer in small diameter channels.

1. INTRODUCTION

Heat transfer during boiling is one of the most effective techniques for the removal of large heat fluxes from the heated wall. Its industrial applications are widespread, but originally applications can be found in energy conversion systems such as petrochemical industry, power engineering, chemical engineering, refrigeration and air-conditioning and other large-scale installations. With respect to such applications investigations into boiling heat transfer have been focused on large diameter tubes. Presently, a great progress in implementation of boiling heat transfer in mini or microscale can be observed, for example in compact heat exchangers, micro-heat pipes of large efficiency, cooling of electronic equipment and others. The increased interest is observed in better understanding of small-scale or micro-scale heat transport phenomena during intense heat transfer processes. For example, integrated computer processors can generate very high heat fluxes and therefore the accurate control of their temperature is of paramount importance with respect to their reliable operation. Single phase heat transfer proved to be insufficient in the removal of such high heat fluxes due to relatively smaller heat transfer coefficients. The last decade of the past century can confirm fast developments in the research into micro and nanoscale, which find applications in numerous technologies. According to Kandlikar [1], 3 mm tube hydraulic diameter can be regarded as a lower limit of the conventional evaporator tubes. Following his suggestions the minichannels fall into the range of hydraulic diameters between 600 μm and 3 mm, whereas the microchannels into the range between 50 μm and 600 μm, respectively.

Flow boiling in channels is probably the most complicated mechanism of convective heat transfer, which can be found in various applications. It has been the topic of significant interest for several years now, but the contributions into the subject are merely very specific and does not enable a more general analysis.

There is a considerable number of correlations that can be employed in determination of the heat transfer coefficient for flow boiling of freons in channels. Only very few of them, however, enable analysis within a full variation range of the quality, $x=0\div1$. Remarkably, none of the known correlations features theoretical foundations. This paper is aimed at presentation of a correlation developed some time ago, but yet to be published properly. The following issued should be considered in evaluation of applicability of correlations:

- theoretical foundations,
- high reliability of reproduction of heat transfer coefficients (considering experimental investigations for different freons, tube diameters and boiling parameters),
- generality to such an extent that it might be used to predict the heat transfer coefficient for new refrigerants or dimensions not considered hitherto, i.e. such that have not yet been applied in technical use or small diameter channels.

Nomenclature

C	- specific heat	w	- velocity
d	- channel inner diameter	α	- heat transfer coefficient
E	- dissipation energy	λ	- thermal conductivity
g	- gravity, exponent	μ	- dynamic viscosity
G	- mass flowrate	σ	- surface tension
l	- bubble characteristic length	ξ	- friction factor
p	- pressure		
q	- heat flux density	**Subscripts:**	
S	- limiting heat flux		
R_G	- two-phase flow resistance coefficient	PB	- pool boiling
R_{GM}	- modified two-phase flow resistance coefficient	TP	- two-phase flow
h_{fg}	- latent heat of evaporation	L	- saturated liquid
C	- specific heat at constant pressure	G	- saturated vapour
t	- temperature	TPB	- two-phase boiling
x	- quality	n	- saturated state, exponent

So far the Chen's [2] correlation has quite commonly used in a variety of applications. He divided the heat transfer into two parts namely, the nucleate boiling contribution and non-boiling forced convection. There are numerous modifications of this correlation depending mainly on the employed in it formula to determine the "pool-boiling" coefficient. Shah [3] proposed a correlation in a graphical form introducing to it the convective number, Co, and the boiling number, Bo. Instead of taking the sum of two above mentioned contributions he recommends to pick the higher value of heat transfer coefficient. In the development of correlation approximately 800 experimental points have been used. In some later publications, [4], Shah supplemented his correlation with the relations enabling analytical calculation of constituent coefficients. Shah's correlation has been widely used in engineering practice. Kandlikar and Thakur [5] put forward another widely acknowledged correlation, which included both the bubble boiling and the convective evaporation process, taking advantage for its construction of the same data as Shah did. A later publication by Kandlikar [6] presented a correlation for a number of agents. In effect, the heat transfer coefficient is expressed in terms of the parameter dependent on the type of refrigerant. A large bank of data amounting to over 5000 testing points for water, R11, R12, R114, R13B1, R22, R113, R152a, nitrogen and neon has been used in development of correlation. As it follows from the construction of the Kandlikar's correlation, it does not provide accurate values for liquid-only or vapour-only flow of fluid in a channel. The correlation proposed by Gungor and Winterton [7] is a modification of Chen's correlation. The correlation is based on the same parameters used by Shah and Kandlikar. Bjorge [8] suggests superposition of heat flux as the base for elaborating the correlation. The constants of Bjorge's correlation depend also on the type of refrigerant. As can be deduced from the above survey none of the above correlations, despite their wide acceptance, does not feature theoretical foundations. They have been tuned to selected amount of experimental data and require constant validation against new flow parameters. Another difficulty is represented by the fact that flow boiling occurs in practice at small mass flowrate and small to moderate heat fluxes (refrigeration, air-conditioning) and large mass flowrates and moderate to high heat fluxes (power engineering). Capturing all these trends with one only correlation is a very difficult task. The research went in two directions to devise suitable tools for the first and the latter case. On the brink of application of boiling heat transfer to miniscale and microscale it seems that reliability of predictions must be sought in the correlations describing the moderate to small flowrates and small to moderate heat fluxes.

Since a few correlations are already available some justification would be desirable to propose a new one. First of all it would be desirable for a new correlation to lay some theoretical basis for the flow boiling process, secondly, be relatively simple to use without recourse to obscure functions, be applicable to subcooled and saturated flow conditions, be tested against a significant amount of data. In authors opinion the correlation due to J. Mikielewicz [9], with later modifications [10], tested in the present paper satisfies all these requirements.

2. A GENERAL CORRELATION DESCRIBING FLOW BOILING IN CHANNELS

J. Mikielewicz [9] has made use of a generalization of investigations by various authors as well as his own to devise a semi-empirical method of determining the heat transfer coefficient for boiling flow. The correlation is based on the knowledge of heat transfer coefficients for simpler cases of pool-boiling and convective single-phase flow, as well as on the knowledge of hydrodynamical resistance coefficients for two-phase vapour-liquid adiabatic flow conditions. Such conditions are acknowledged to be fairly well investigated and by means of them it was possible to determine the heat transfer for the complex problem of boiling flow. The correlation was further modified by Bilicki [11] and then further by Mikielewicz et al. [10,12]. The following issues were subject to additional analysis to obtain the latter form of correlation of higher accuracy:

- experimental flow conditions, the analysis was aimed at determination whether experimental data represents the boiling process or fluid convection, or flow beyond the critical heat flux.
- selection of the function describing the two-phase flow resistance; attempts have been made to search for the specific function which describes the flow resistance of two-phase freons.

The generalized correlation was worked out on the basis of the available data base for R12, R11 and R22. Selected data has been excluded from the analysis, where it was tested that the data correspond to a heat flux below which the boiling process does not occur, i.e. vapour bubbles are not generated on the channel wall. In such situation the heat exchange takes place between the overheated fluid and the channel wall. The correlation has been devised taking advantage of the linear regression theory fit to the experimental data using multiple regression theory. The details of the method can be found in [12], and here only the general outline is recalled.

2.1. Heat transfer in two-phase flow without bubble generation

Transformation of a two-phase flow onto an equivalent liquid flow enables to assume that heat transfer in the considered case can be described by means of relations applicable to equivalent single phase flow. The convective heat transfer coefficient is usually described with the aid of the Dittus-Boelter, which leads to the relation [12]:

$$\frac{\alpha_{TP}}{\alpha_O} = R^{0.4} \tag{1}$$

where α_O is the liquid- or vapour only heat transfer coefficient depending on the chosen two-phase flow resistance coefficient R. In the two-phase flow the following holds [12]: $Re_{TP}=R^{0.5}Re_0$. The result (1) allows to consider a more general case with bubble generation.

2.2. Heat transfer in two-phase flow with bubble generation

It has been assumed that the heat transfer during flow boiling can be characterized by a sum of dissipation of a convective two-phase flow E_{TP} and bubble generation in the flow, E_{PB}, in the form:

$$E_{TPB} = E_{TP} + E_{PB} \tag{2}$$

The rate of energy dissipation in steady-state conditions can be approximated by dissipation in the laminar boundary layer. Similarly it can be assumed that there exists the friction factor for the bubble generation in the flow itself. In the same manner a total energy dissipation in the equivalent two-phase flow with bubble generation can be presented. Substitution of the above statements to (2) enables to obtain the following relation:

$$\xi_{TPB}^2 = \xi_{TP}^2 + \xi_{PB}^2 \tag{3}$$

The above result can be generalized using the analogy between the exchange of momentum and heat to obtain a similar relation linking the corresponding heat transfer coefficients:

$$\alpha_{TPB}^2 = \alpha_{TP}^2 + \alpha_{PB}^2 \tag{4}$$

Substituting (1) into (4) we arrive at a final form of correlation obtained by J. Mikielewicz [9]:

$$\frac{\alpha_{TPB}}{\alpha_{GO}} = \sqrt{R^{0.8} + \left(\frac{\alpha_{PB}}{\alpha_{GO}}\right)^2} \tag{5}$$

Further modification of J. Mikielewicz's correlation was based on devising an experimental correction, which provided a better fit to considered data points and enabled to extend the generality of correlation. The correlation form obtained after modification looks as follows:

$$\frac{\alpha_{TPB}}{\alpha_G} = \sqrt{R_{GM}^n + p\left(\frac{\alpha_{PB}}{\alpha_G}\right)^2} \tag{6}$$

where

$p = aCo^b \, Re_L^c \, Bo(l/d)^e \left(\frac{P_n \cdot l}{4\sigma 10^4}\right)^f Fr^g \, Pr_L^{1/3}$;

$R_G = [f_1 + 2(1-f_1)x] \cdot (1-x)^{1/3} + x^3$ is the Muller-Steinhagen and Heck relation [13] describing the flow resistance. Function f_l has a following definition $f_l = \left(\frac{\mu_L}{\mu_G}\right)^{0,25} \cdot \frac{\rho_G}{\rho_L}$ and finally the vapour-only heat transfer coefficient is calculated from the relation $\alpha_G = 0{,}023\frac{\lambda}{d} Re_G^{0,8} Pr_G^{1/3}$, where $Re_G = \frac{w_G \rho d}{\mu_G}$.

Much attention was paid to the right selection of the non-dimensional numbers present in the correction, namely the convective number, Co, and the flow resistance formulae, R_G. In the course of development of the correlation different variants of these numbers have been tested. Many of them did not meet the boundary conditions, i.e. for x=0 values of the heat transfer coefficient for liquid were not obtained, nor in the case of x=l it was possible to obtain the value of heat transfer coefficient for vapour. The data bank available to authors at the time did not include any heat transfer coefficients for flow quality approaching zero or unity. Therefore, only the values of heat transfer coefficients for fluid and vapour were known. The point was to find out a compatibility for boundary values of flow quality so as not to depreciate the simplicity of the analytical correlation. To determine the formulae describing the flow resistance coefficient R_G there was made use of an analogy between flux resistances and the heat transfer through application of the ratio of appropriate heat transfer coefficients in an equivalent power instead of the pressure ratio. The obtained result was named a modified coefficient R_{GM} describing the convection process of heat exchange in the boiling mixture flow:

$$R_{GM} = [f_{1z} + 2(1 - f_{1z})x] \cdot (1 - x)^{1/3} + x^3 \qquad (7)$$

where $f_{1z} = \frac{\mu_G}{\mu_L} \cdot \frac{C_L}{C_G} \cdot \left(\frac{\lambda_L}{\lambda_G}\right)^{1,5}$.

Having introduced R_{GM} to the correlation we obtain the compatibility of heat transfer coefficient for limiting boundary cases. To obtain compatibility also for boiling with vapour generation in flow it was necessary to assume such a form of the correction function which assumes zero values for limiting boundary conditions. This requirement was found to best met by the convective number Co. It has been constructed in the following form:

$$Co = R_G - (1 - f_1)x - f_1 \qquad (8)$$

3. COMPARISION OF CORRELATION WITH EXPERIMENTAL DATA

Physical properties of considered fluids have been determined by means of application of spline approximation to the physical property data provided by Hirschberg [14]. The pool-boiling heat transfer coefficient has been obtained from the fluid-specific relations of the heat flux – temperature form. The Dittus-Boelter equations was used to compute the liquid-only and gas-only heat transfer coefficients. The input data for the computing program were: mass flow rate G (kg/m^{2}s), saturation temperature - t_s (°C), flow quality - x(-), flow boiling heat transfer coefficient - α_{TPB} (W/m^{2}K) and the tube diameter - d(m). Using the method of multiple regression calculated have been coefficients a, b, c, d, e, f, g and n which were compared with the experimental values taken from the data base. The acquired data bank consisted of over 2000 points and the entire data were utilized in elaborating of the correlation. As a result of the calculations for the whole data bank, i.e. for over 2000 points it was possible to obtain the coefficients which appear in the correlation. These are: a=0.024, b=0.639, c=1.524, d=-0.907, e=2.727, f=-1.339, g=0.029 and n=0.76. The experimental data correlate with the coefficient r=0.97. The obtained result, should be regarded as a very good, taking into account that the correlation is of a general character and its coefficients do not. depend on the kind of fluid. From the histogram in Figure 1 it is evident, that 49.3% of the predictions fall in the range within ±20% of deviations, while 63.3% of predictions within ±30% of deviations. It must be borne in mind that considered data come from a variety of authors and each containing its own statistical error.

4. APPLICATION OF CORRELATION TO SMALL DIAMETER TUBES

Recent developments in heat transfer in small diameter passages bring about the question how good are the correlations developed for conventional tubes in predicting heat transfer coefficient and friction coefficient in small diameter passages.

Flow boiling in small diameter passages raises few questions, namely:

1. How does the small passage dimension affect the bubble dynamics and the two-phase flow?
2. How is the heat transfer and pressure drop affected in these channels?
3. What is the performance of best flow boiling models in predicting heat transfer and pressure drop in small diameter passages?
4. Are there any other additional effects influencing heat transfer, which are more pronounced in small diameter channels, such as for example axial heat conduction (small Peclet numbers), conjugate heat walls (relatively thick walls), temperature dependent properties (large axial temperature gradients), pressure dependent properties (large axial pressure gradients) or the wall roughness, Herwig & Hausner [15].

A very good review has appeared recently by Bergles et al. [18], where the recommendations for further research include development of experimental data and correlations for the hydraulic diameters smaller than 300 μm to predict heat transfer, pressure drop and critical heat transfer.

In order to perform comparisons some selected data from literature has been collected and the presented earlier correlation run to predict such cases. In Figures 2-4 presented are the results of calculation for three different refrigerants. The results show a good qualitative character, however quantitatively they require more accuracy of predictions. This means that the correlations developed earlier for larger diameters cannot be blindly used in predictions of data for smaller diameters, even in the light of the fact that the phenomena should only be scaled down in the considered cases.

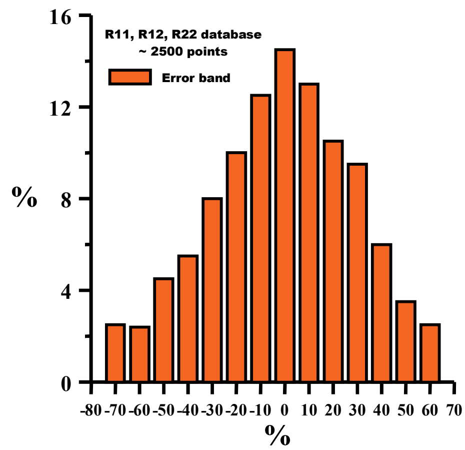

FIG. 1. Histogram of deviations for the entire data bank [12].

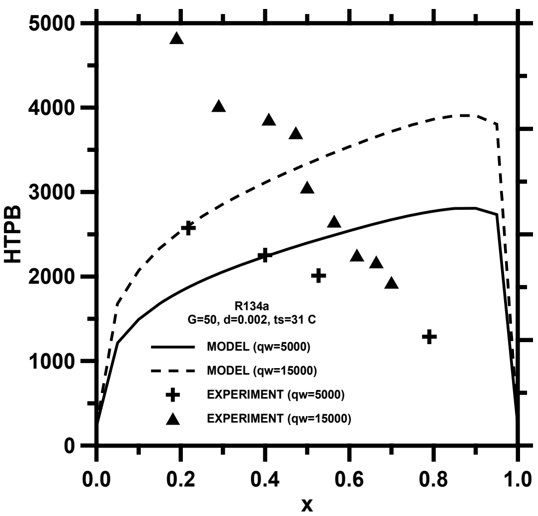

FIG. 2. Dependence of heat transfer coefficient with quality for R134a. Data due to Yan and Lin [16]. G=50 kg/m^{2}s, d=2mm.

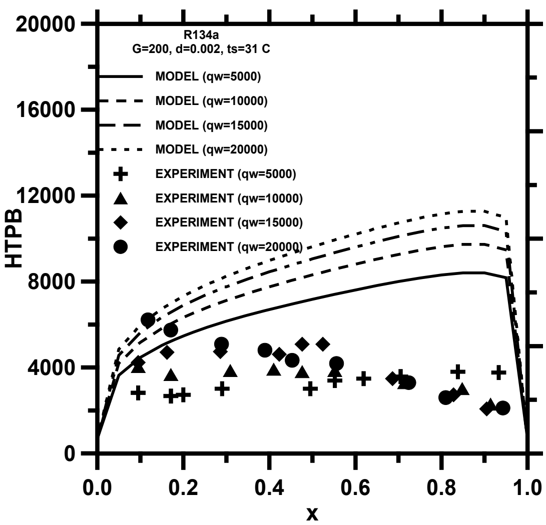

FIG. 3. Dependence of heat transfer coefficient with quality for R134a. Data due to Yan and Lin [16]. G=200 kg/m^{2}s, d=2mm.

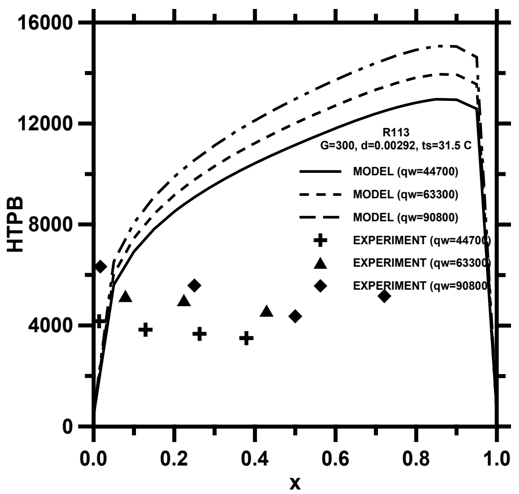

FIG. 4. Dependence of heat transfer coefficient with quality for R113. Data due to Wambsganss et al. [17]. G=300 kg/m^{2}s, d=2.92mm.

5. CONCLUSIONS

According to the theory of similarity the presented correlation can also be applied to new refrigerants as far as the investigated range of the similarity numbers is concerned. The use of correlation is very simple on account of its analytical form which is its fundamental advantage. Moreover it satisfies the requirements of the experimental correlation accuracies describing the boiling flow process. In view of the latest investigation by Kandlikar [1], it may occur that the heat transfer coefficient deteriorates with the flow quality in some cases. Such a case cannot be described by the majority of correlations known from literature on account, of their structure. The correlation under investigation possesses; such a capability which raises its quality. It is coded within the relationship of the flow resistance coefficient and the correction p. The mutual relationship between these functions makes it. possible to obtain a rising or falling dependence of heat transfer coefficient, during the boiling flow upon flow quality x. The accuracy of the proposed correlation, in the common range of parameters, is comparable with the best correlations known today. The presented correlation is of general character, and its coefficients do not depend on the type of freon. Further work on fitting of that correlation into a larger database including the small passages is required.

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