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Proposal for a correlation raising the impact of the external diameter of a horizontal tube during pool boiling

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ABSTRACT

In this study, an exhaustive research of the correlations integrating the effect of the diameter have been made; the results obtained with these correlations are compared with data of the recent literature relating to pool boiling outside a horizontal tube. The same data are analyzed and it was noted that the heat transfer coefficient increases when the diameter varies from 4 to 6.5 mm, then decreases from 6.5 to 51 mm.

In this second interval, we propose a new correlation for the calculation of the heat transfer coefficient depending in addition to the diameter, the pressure and the roughness; satisfactory results are predicted, applied in the case of water, hydrocarbon and refrigerant. Then, simplified forms of correlations have been deduced for water and the R134a.

1. Introduction

Boiling is a very effective method for transferring a huge amount of heat at low temperature gradients. The transfer of heat generated by boiling of the liquid vapor finds wide application in the food industry, chemical, petrochemical and refrigeration.

The heat transfer equipment for boiling such as boilers and evaporators generally consists of a bundle of tubes in which the process fluid often remains outside of the tube. Under certain critical conditions, the steam generated forms a thermal barrier resulting in a sudden rise in temperature and the critical heat flux causes a sudden deterioration of the heat transfer coefficient can result in fusion of the heating wall. This phenomenon is called "boiling crisis", noted that the boiling crisis is a brutal and destructive phenomenon that must be avoided in steam systems.

The importance of this study is from a constant need to evaluate the heat transfer coefficient as a function of the energy released during the boiling of liquid and characteristics of the two-phase flow that regulates heat exchange. Knowing that the design of these devices mentioned above is made from the results incorporating an empirical correction factor.

Generally, the understanding of heat transfer in boiling remains a problem tackled and mechanisms of heat transfer are discussed, namely that correlations are used to predict the heat flux are based on experience and are difficult to extrapolate to other experimental conditions: type of fluid, pressure, geometry.

For several decades, the boiling heat transfer has been studied in detail, starting with the work of Nukiyama who got the first boiling curve for over half a century. Several publications are published annually as a still strong interest shown for this mode of transfer knowing that nucleate pool boiling remains a phenomenon extremely complex, imperceptible and dependent on several parameters like the saturated vapor pressure and the thermo-physical properties of the fluid, the characteristics of surface, the thermo-physical properties of material, dimensions, orientation, thickness, surface quality, and the microstructure according to Dhir [1] and Pioro [2].

It must be recalled that many correlations were developed to predict the heat transfer coefficient and is used in a general context whatever the type of heating element; plate, wire or tube. Cornwell [3] was the first who studied the effect of the diameter on pool boiling outside a horizontal tube, It was concluded that the heat transfer coefficient decreases as the diameter increases; later on Cornwell and Houston [4] studied the effect of the tube diameter by using a correlation based on the convection, applicable for the diameters of the range industrial, and checked for water, the refrigerants and the organic matters. Chun and Kang [5] obtained

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starting from several experiments a correlation showing the effect of the diameter of the tube and roughness in pool boiling, and Sarma et al. [6] found a correlation which predicts the heat transfer coefficient outside a horizontal tube.

During the nucleate boiling outside of a horizontal tube heated electrically, a temperature distribution around the circumference of the tube is observed, and then reached maximum and minimum values, respectively top downwards. The values of the heat transfer coefficient reach maximum values on the level of the tube bottom, when the heat flux is uniform, as mentioned by Cornwell [7].

In the following work, we try to analyze the main correlations that could be used to evaluate the coefficient of heat transfer between the fluid and the tube wall during nucleate pool boiling by including the effect of tube diameter. We also present the most recent experimental work on the boil outside a horizontal tube. The correlations studied are validated with these experimental data.

In this context, our study aims to propose a correlation which may be used to evaluate the heat transfer coefficient; depending on a set of thermo-physical parameters of the fluid, diameter, roughness and pressure. From this correlation, we have drawn simplified forms of equations applicable for two different fluids.

2. State of the art of the empirical correlations

A whole of empirical correlations are proposed to be able to evaluate the rate of heat transfer during nucleate pool boiling. The phenomena of heat transfer are studied under various modes and it is raised that the principal parameters which influence pool boiling are: the heat flux, the saturated vapor pressure, the thermo-physical properties and the characteristics of the surface of boiling. Among these correlations we retained four [3–6], of which the effect of the diameter is apparent for smooth horizontal tubes and whose boiling appears outside, as Table 1 shows it.

Boiling outside the horizontal tubes finds its application in varied fields of industry such as the evaporators and the steam generators, and in this purpose that we are interested in the evaluation of the heat transfer in order to quantify it, by using the important parameters which affect pool boiling.

The equation of Cornwell (1) gives us the heat transfer coefficient according to the thermo-physical characteristics of the fluid, the tube diameter, and of the heat flux. It uses a coefficient C_{tb} which is equal to 100 in the case of water and 150 for the other fluids when the pressure is lower than 0.1 of the critical pressure; this equation is valid for going diameter from 6 to 32 mm, applicable for all fluids and with a commercial surface quality, the results are obtained with a margin of ±33%.

The equation of Cornwell and Houston (2) allows determining the heat transfer coefficient according to the thermo-physical characteristics of the fluid, the critical pressure of the fluid, the function $F(P) = (1,8P_r^{0,17} + 4P_r^{1,2} + 10P_r^{10})$ which describes well the dependence to the pressure, and the tube diameter, as well as heat flux. The results obtained starting from experiments made on molded or machined tubes with diameters varying from 8 to 50 mm, the heat flux is limited from 0.1 to 0.8 of the critical heat flux, and the pressure lay between 0.001 and 0.8 of the critical pressure.

The equation of Chung and Kang (3) determines the heat flux according to roughness, the temperature difference between the wall and the fluid, and the tube diameter; the results obtained with a margin of ±25%, for a diameter tube which varies from 9.7 to 25.4 mm, a heat flux from 0 to 160 kW/m ^{2}, and a pressure equal to 0.1 MPa, the roughness of surface was of 15.1–60.9 nm.

The equation of Sarma et al. (4) connects the heat flux and the temperature difference between the wall and the fluid, by including the thermo-physical parameters of the fluid, the pressure, the critical pressure, the capillary length, and the diameter; the correlation was obtained starting from results of experiment made on horizontal tubes of varying diameter from 5 to 7 mm, used for water and ethanol with an error margin of ±16%.

The experimental results of nucleate boiling far from the points of beginning of boiling and critical flux, give us a relation between the heat flux and the temperature difference exponential form of the type $q \propto \Delta T^3$, it can be presented in the form $h \propto \Delta T^2$, but the most practical form is given by the relation of the heat transfer coefficient according to the surface heat flux, i.e. the relation of the type $h \propto q^n$ with $n = 0.67$ in general; We then refitted the four correlations quoted know-top in Table 2, by using the equation of Newton $q = h\Delta T$.

3. Comparison of the correlations

3.1. Experimental data analysis

Most of the recent experimental data dating from the year 2000 up to date wave been recovered from literature [8–27], gathered in Table 3; totaling more than 1000 points, and relating to the boiling of fluids outside horizontal smooth tube, three substances are concerned, water [8–20], the hydrocarbons [13,21–23] and refrigerant [24–27]; through this study we widened the range of the diameters from 4 to 51 mm, and the absolute pressure varying

Table 1
Nucleate boiling correlations.

Author	Correlations	
Cornwell [3] (1982)	$\frac{hD}{\lambda_l} = C_{tb}\left(\frac{qD}{\mu_l L}\right)^{2/3}$	(1)
Cornwell and Houston [4] (1994)	$\frac{hD}{\lambda_l} = 9.7P_c^{0.5}\left(1.8P_r^{0.17} + 4P_r^{1.2} + 10P_r^{10}\right)\left(\frac{qD}{\mu_l L}\right)^{0.67}\left(\frac{c_{pl}\mu_l}{\lambda_l}\right)^{0.4}$	(2)
Chun and Kang [5] (1998)	$q = \frac{0.015\varepsilon^{0.084}\Delta T^{5.508}}{D^{1.318}}$	(3)
Sarma et al. [6] (2007)	$\frac{q}{\mu_l L}\sqrt{\frac{\sigma}{(\rho_l - \rho_v)g}} = 3.8\times10^{-6}\left(\frac{qD}{\lambda_l \Delta T}\right)^{1.22}\left(\frac{P}{P_c}\right)^{0.72}\left(\frac{PD}{\mu_l L^{1/2}}\right)^{0.55}\left(\sqrt{\frac{\sigma}{(\rho_l - \rho_v)gD^2}}\right)^{1.65}$	(4)