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Prediction of pool boiling heat transfer coefficient for the refrigerant R141b and its solutions with surfactant and nanoparticles using limited set of experimental data

O. Khliyeva, A. Nikulin*, V. Zhelezny, N. Lukianov, Yu. Semenyuk and A.L.N. Moreira

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Prediction of pool boiling heat transfer coefficient for the refrigerant R141b and its solutions with surfactant and nanoparticles using limited set of experimental data

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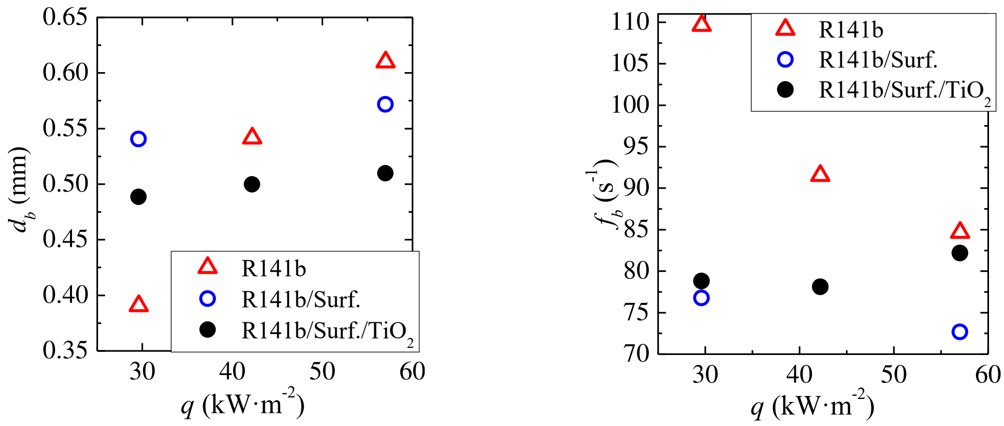
Abstract: The main purpose of this study is to evaluate the expediency of limited set of experimental data (LSED) to increase the accuracy of heat transfer coefficient (HTC) prediction under pool boiling conditions. The analysis was performed for the pure refrigerant R141b and its solutions with the surfactant Span-80 and TiO_2 nanoparticles. The results have shown, that the joint use of LSED and existing correlations for internal boiling characteristics (IBC) helps to improve HTC prediction.

Introduction/Background: Accurate prediction of heat transfer coefficient (HTC) under pool boiling conditions is still a challenge. It is known, that the HTC can be characterized using internal boiling characteristics (IBC) (bubble departure diameter, frequency and nucleation sites density) [1]. The models, such as Stephan-Abdelsalam [2] and Tolubinsky [3] which partially take into account the IBC are usually demonstrate unsatisfactory prediction of pool boiling HTC [3,4]. However, the models using all IBC, such as RPI (Rensselaer Polytechnic Institute) can predict boiling HTC at higher level of uncertainty [4,5]. It is worth to mention, that the IBC depend both on fluid and heating surface properties. This information is quite rare and is limited to a specific set of liquid/surface combinations. Moreover, high optical density of nanofluids, even at relatively low nanoparticles concentration, makes it difficult to use optical methods for experimental study of IBC.

Taking into account the aforementioned above, the aim of our study is to test a new approach to pool boiling HTC prediction. It requires a limited set of experimental data on HTC and IBC obtained in a narrow range of experimental parameters. Thereafter, those data can be extrapolated for a wider range of experimental parameters. We believe, that such approach is a compromise between a fully theoretical HTC prediction usually giving high uncertainty with fully experimental HTC characterization which has high time and costs consumption.

Discussion and Results: The experiments were performed with R141b and its solutions with the surfactant Span-80 (0.1 mass%) and surfactant Span-80/TiO_2 nanoparticles (0.1 mass%/0.1 mass%). The two-step method was used to prepare nanofluid. Spectral turbidimetry tests have shown that obtained nanofluid remains stable within three months with mean nanoparticle radius of 125 ± 7 nm.

The study of HTC during nucleate pool boiling was carried out using the original experimental setup [4] at 0.2, 0.3 and 0.4 MPa in the range of heat fluxes from 5 to 70 ($kW \cdot m^{-2}$). The obtained results were discussed elsewhere [3]. To study the IBC a simple experimental facility described in [3] was used at atmospheric pressure. As can be seen in Fig.1, the bubble departure diameter for R141b increase versus heat flux density, while theirs frequency demonstrate the inverse relationship. The bubble departure diameter and frequency do not change significantly versus heat flux density for R141b/Surf. and R141b/Surf./TiO_2 solutions.



(a) (b)

Figure 1. Bubble departure diameter (a) and frequency (b) versus heat flux density for R141b, R141b/Surf. and R141b/Surf./TiO_2

The models of Tolubinsky [3] and RPI [4] were firstly used to compare the experimental results on HTC. The following equations describe the dependence of bubble departure diameter and frequency versus pressure and rough estimate for nucleation sites density

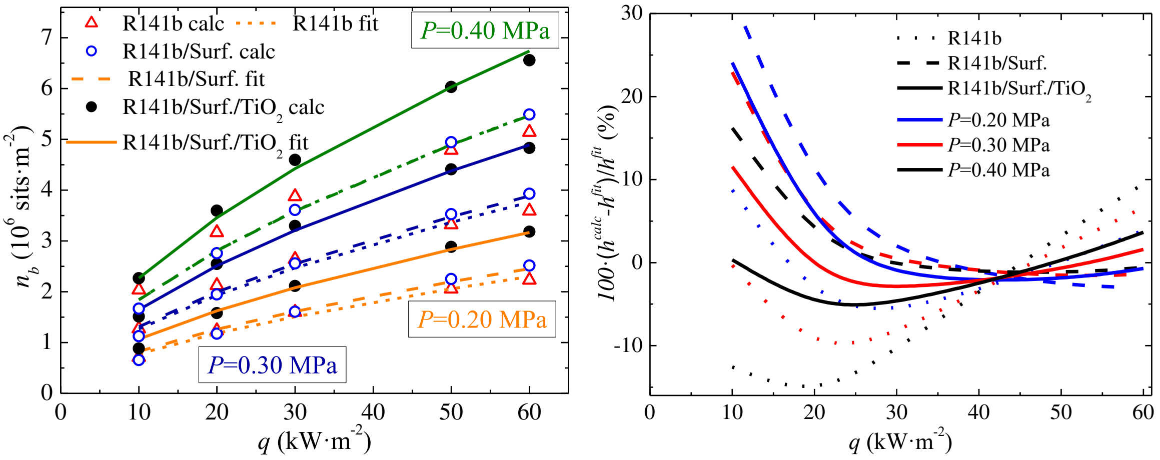
$$\bar{d}_b = \bar{d}_{b\,0.1}\left(\frac{\sigma\left(\rho'_{0.1}-\rho''_{0.1}\right)}{\sigma_{0.1}\left(\rho'_{0.1}-\rho''_{0.1}\right)}\right)^{0.5} \qquad (1)$$

$$\bar{w}_b/\bar{w}_{b\,0.1} = \left(\rho''_{0.1}/\rho''\right)^{2.3+0.5\,lg\,\pi} \qquad (2)$$

$$\sqrt{n_b} = 25\cdot 10^{-8}\left(\frac{\Delta h\cdot\rho''\cdot\Delta T}{T_S\cdot\sigma}\right)^{1.5} \qquad (3)$$

where $\bar{d}_b$, ρ', ρ'', σ, $\bar{w}_b = \bar{d}_b \bar{f}_b$ are the mean bubble departure diameter, density of the liquid and vapour, surface tension, mean velocity of bubble growth at certain pressure; $\bar{d}_{b\,0.1}$, $\rho'_{0.1}$, $\rho''_{0.1}$, $\sigma_{0.1}$, $\bar{w}_{b\,0.1}$ are the mean bubble departure diameter, density of the liquid and vapour, surface tension, mean velocity of bubble growth at $P_{0.1}$ =0.1013 (MPa) respectively; $\pi = P_{0.1}/P_C$ is the reduced pressure; n_b is and nucleation sites density; Δh is heat of vaporization; ΔT is wall superheat; T_S is saturation temperature.

The results of comparison indicated to significant deviations of experimental values from calculated ones. Moreover, the models give the opposite results for the surfactant and nanoparticles effect on HTC. Such results could be explained by the effect of nanoparticles on nucleation sites density, which can increase or decrease as compared to base liquid [4].



(a) (b)

Figure 2. Experimental and calculated by Eq.(4) values of nucleation sites density (a) and relative deviations of experimental and calculated values of HTC using RPI model [4,5] and Eq.(4) (b).

At the next stage, a method using RPI model to calculate a nucleation sites density was utilised [4]. The results of calculation for all studied boiling pressures are shown in Fig.2(a). Nucleation sites density for nanofluid is much higher than for pure liquid.

Nevertheless, the additive of surfactant does not change significantly the nucleation sites density. The performed analysis has shown, that the dependence of nucleation sites density versus heat flux density and pressure for all studied samples in all range of parameters is the following

$$n_b = n_{b\,0.1}\left(\frac{\Delta h \cdot \rho''}{T_S \cdot \sigma} \cdot \frac{T_{S\,0.1} \cdot \sigma_{0.1}}{\Delta h_{0.1} \cdot \rho''_{0.1}}\right)^C \tag{4}$$

where C=1.093 is an exponent.

In the Fig.2(b) the relative deviations of experimental and calculated data on HTC within RPI model [4] and using Eq.(4) are shown. As can be seen, the deviations do not exceed 10% from 20 to 60 (kW·m^{-2}). The increased deviations for heat flux density below 20 (kW·m^{-2}) are probably gathered with the stochastic nature of the boiling process onset and termination.

Summary/Conclusions: For more accurate HTC prediction during boiling of pure liquids and nanofluids, it is necessary to have data on IBC. The information on IBC obtained using a limited set of experimental data at one value of pressure and two or several values of heat flux density allow to predict HTC during boiling with sufficient accuracy for many applications.

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