PREDICTION OF NUCLEATE POOL BOILING HEAT TRANSFER COEFFICIENT

by

Alangar SATHYABHAMA * ***and Ramakrishna N. HEGDE***
Faculty, Department of Mechanical Engineering, M. S. Ramaiah Institute of Technology, Bangalore, India

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The correct prediction of the heat transfer performance of the boiling liquid within the evaporator of a refrigeration unit is one of the essential features for the successful operation of the whole unit. There are many correlations available in the literature for the prediction of boiling heat transfer coefficient of pure components. Eight heat transfer pool-boiling correlations that are well known in the literature have been selected and their prediction accuracy has been assessed against experimental data of ammonia available in the literature. The analysis concludes that within the investigated ranges of boiling conditions, the Kruzhilin, Kutateladze, Labuntsov, Mostinski nucleate pool-boiling correlations are the most accurate among those assessed.

Key words: *nucleate pool boiling, heat transfer coefficients, prediction, correlation, ammonia*

Introduction

With increased regulation being placed upon the use of chlorofluorocarbon (CFC), hydrochlorofluorocarbon (HCFC), and hydrofluorocarbon (HFC) based refrigerants, and the pending phase out of CFC and HCFC altogether, alternative refrigerants for use in existing refrigeration packages and systems are actively being investigated. These alternative refrigerants must have thermodynamic characteristics similar to those of CFC, HCFC, and HFC and be safe for humans and the environment. Ammonia is one such alternative refrigerant for new and existing refrigerating and air-conditioning systems. Ammonia has a low normal boiling point (–33 °C), an ozone depletion potential (ODP) of 0.00 when released to atmosphere, and a high latent heat of vaporization (9 times greater than R-12). In addition, ammonia in the atmosphere does not directly contribute to global warming. These characteristics result in a highly energy-efficient refrigerant with minimal environmental problems.

In the past few decades, extensive studies have been made on the boiling heat transfer performance of new alternative pure and mixed refrigerants [1, 2]. All these efforts were made to know heat transfer characteristics of the new CFC alternatives. Many generalized correla-

* Corresponding author; e-mail: sathyabhamaa@hotmail.com

tions for predicting the coefficients have been proposed, which can be applicable to various refrigerants. The objective of this paper is to identify the correlation that predicts the nucleate boiling heat transfer coefficient of ammonia with reasonable accuracy. A review of the existing nucleate boiling correlations for pure fluids is carried out. Heat transfer coefficients predicted using these correlations are compared with experimental data available in open literature.

Pool boiling heat transfer

Pool boiling is a condition where boiling occurs from a heated surface submerged in a large volume of stagnant liquid. Nucleate boiling region is characterized by the formation of vapor at preferred sites ("nucleation" sites) on a heating surface that is submerged in the liquid and maintained at a temperature above the saturation temperature of the liquid.

Nucleate pool boiling correlations for pure fluids

There are a number of empirical correlations to estimate the heat flux during saturated nucleate pool boiling of single component liquids. These are in effect extensions of the single phase forced and free convection correlations to pool boiling. In addition, a number of models are also available. These include mechanistic models, analogy models, and hydrodynamic models. The differences between these models lie mainly in the divergent opinions on how the heat energy is transferred from the surface to the fluid and the mode of heat transfer that is dominant. These models make use of observations like frequency of bubble departure, the number of nucleation sites, contact angle between surface and the liquid, surface roughness factor, *etc*. The accuracy of the database related to the parameters ultimately decides the success of the modeling analyses in correlating the experimental data. It can be seen that the models are selectively successful for certain ranges of pressure and system parameters. For predicting nucleate pool boiling curves, three different types of methods have emerged: physical property, reduced pressure and fluid specific. Different correlations of these three types are considered for comparison in the present analysis.

Kruzhlin correlation

In 1947 Kruzhilin [3] proposed the following correlation where no special efforts have been made to account for the surface property:

$$\frac{h_{\mathrm{nb}} d}{k} \quad 0.082 \left(\frac{h_{\mathrm{fg}} q}{\mathrm{g} T_{\mathrm{s}} k} \frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{L}} \quad \rho_{\mathrm{v}}} \right)^{0.7} \left(\frac{T_{\mathrm{s}} c_{\mathrm{pL}} \sigma_{\mathrm{L}} \rho_{\mathrm{L}}}{h_{\mathrm{fg}}^2 \rho_{\mathrm{v}}^2 d} \right)^{0.33} \mathrm{Pr}^{\ 0.45} \tag{1}$$

where d is the pool boiling characteristic dimension:

$$d \quad \sqrt{\frac{\sigma}{\mathrm{g}(\rho_{\mathrm{L}} \quad \rho_{\mathrm{v}})}} \tag{2}$$

Rohsenow correlation

In 1952 Rohsenow [4] recognized the influence of liquid solid combination on boiling heat transfer and developed more general correlation:

$$\frac{c_{pL}\Delta T}{h_{fg}} \quad C_{sf}\ \frac{q}{\mu_L h_{fg}}\sqrt{\frac{\sigma_L}{g(\rho_L \quad \rho_v)}}^{n} \Pr^{m\ 1} \tag{3}$$

Heat transfer coefficient is obtained from the definition of heat transfer coefficient $h_{nb} =$ $= (q/\Delta T)$. The values of exponents are $m = 0.7$ and $n = 0.33$ for all fluids except water for which Rohsenow recommended setting $m = 0$. The values of surface-fluid factor (C_{sf}) for various surface-fluid combinations are proposed by Rohsenow with ±20% accuracy for the above correlation. This parameter apparently takes into account the contact angle, the surface microroughness, and their interaction in determining the nucleation site density.

Kutateladze correlation

Kutateladze [5] simplified Kruzhilin's correlation at the cost of its accuracy and developed an expression for Nusselt number in case of boiling:

$$\frac{h_{nb}d}{k} \quad 0.44\ \frac{10^{\ 4}qP}{gh_{fg}\rho_g\mu_L}\frac{\rho_L}{\rho_L \quad \rho_v}^{0.7} \Pr^{0.35} \tag{4}$$

He proposed another more accurate correlation:

$$h_{nb} \quad \sqrt[3]{3.37\ \ 10^{\ 9}\ \frac{k}{d}\ \frac{h_{fg}}{c_{pL}q}^{\ 2}\ \frac{\frac{P}{\rho_v}^{2}}{\frac{\sigma_L g}{\rho_L \quad \rho_v}}} \tag{5}$$

Labuntsov correlation

Labuntsov [6] derived the correlation that does not require an input of latent heat of vaporization:

$$h_{nb} \quad 0.075\ 1 \quad 10\ \frac{\rho_v}{\rho_L \quad \rho_v}^{0.67} \quad \frac{k^{\,2}}{\nu\sigma(T_s \quad 273.15)}^{0.33} q^{0.7} \tag{6}$$

Pioro correlation

Pioro [7] modified Rohsenow correlation

$$\frac{h_{nb}d}{k} \quad C_{sf}\sqrt[3]{\frac{q}{\rho_v^{0.5}h_{fg}[\sigma_L g(\rho_L \quad \rho_v)]^{0.25}}^{2}} \Pr^{m} \tag{7}$$

Foster-Zuber correlation

Foster, *et al.* [8] used bubble radius and the bubble growth velocity and obtained the following correlation:

$$q \quad 0.00122 \frac{k^{0.79} c_{pL}^{0.45} \rho_L^{0.49}}{\sigma^{0.5} \mu_L^{0.29} h_{fg}^{0.24} \rho_v^{024}} \Delta T^{1.24} \Delta P_{sat}^{0.75} \tag{8}$$

Mostinski correlation

Mostinski [9] neglected the surface effects and applied the principle of corresponding states to nucleate pool boiling heat transfer data, and correlated data as a function of the reduced pressure of the fluid and its critical pressure:

$$h_{nb} \quad 0.00417 q^{0.7} P_c^{0.69} F_{PF} \tag{9}$$

where P_c is the critical pressure of the fluid, F_{PF} – a non-dimensional pressure correction factor that characterizes pressure effects on nucleate boiling as:

$$F_{PF} \quad 1.8 p_r^{0.17} \quad 4 p_r^{1.2} \quad 10 p_r^{10} \tag{10}$$

This correlation gives reasonable results for wide range of fluids and reduced pressures.

Nishikawa- Fujita correlation

Nishikawa, *et al.* [10] have measured heat transfer in nucleate pool boiling of the refrigerants R21, R113, and R114 at horizontal flat plate heaters of different roughness. Assuming "thermodynamic similarity" they propose a common heat transfer correlation for these refrigerants. An essential feature of eq. (11) is that it is supposed to be common for different kinds of fluids. All the experimental data presented by the authors and by other authors were correlated well by this correlation within ±30% accuracy:

$$h_{nb} \quad \frac{31.4 P_c^{0.2}}{M^{0.1} T_c^{0.9}} (8R_p)^{0.2\ 1\ \frac{P}{P_c}} \quad \frac{\frac{P}{P_c}^{0.23}}{1 \quad 0.99 \frac{P}{P_c}^{0.9}} q^{0.8} \tag{11}$$

where $R_p = 0.125$ μm.

Stephan-Abdelsalam correlation

Stephan *et al.* [11] proposed four specific correlations applying a statistical multiple regression technique to water, refrigerants, organics, and cryogens. These correlations used the physical properties of the fluid evaluated at the saturation temperature and hence are said to be physical property based correlations. They proposed following correlation for refrigerants whose mean deviation was 10.6% in the reduced pressure range of 0.003-0.78:

$$\frac{h_{nb} d}{k} \quad 207 \frac{q d_b}{k T_s}^{0.745} \frac{\rho_v}{\rho_L}^{0.581} \mathrm{Pr}^{0.533} \tag{12}$$

where d_b is the bubble departure term and given by Fritz type of equation:

$$d \quad 0.00146\beta\sqrt{\frac{2\sigma}{g(\rho_L \quad \rho_v)}} \tag{13}$$

The contact angle β is assigned a fixed value of 35º for refrigerants and 45º for water.

Cooper correlation

Cooper [12] proposed a correlation, which earned the reputation for its accuracy in predicting nucleate pool boiling heat transfer coefficient. In his correlation, the heat transfer coefficient was presented as a function of the heat flux, reduced pressure, molecular weight of the liquid, and the surface roughness. For boiling on horizontal plane surfaces:

$$h_{nb} \quad 55(p_r)^{0.12 \quad 0.4343\ln R_p}(\quad 0.4343\ln p_r)^{\quad 0.55} M^{\quad 0.5} q^{0.67} \tag{14}$$

An increase in surface roughness has the effect of increasing the nucleate boiling heat transfer coefficient. Surface roughness may be affected by fouling, corrosion, and oxidation of the surface. When surface roughness is unknown, it is set to 1.0 μm. The author recommends multiplying the above heat transfer coefficient by a factor of 1.7 for horizontal copper cylinders; however, the correlation seems to be more accurate for boiling of refrigerants on copper tubes without this correction. Cooper correlation covers reduced pressure from about 0.001 to 0.9 and molecular weights from 2 to 200. Simplicity of Cooper's correlation is of special significance in cases where the physical properties of the boiling liquid are poorly defined.

Gorenflo correlation

Gorenflo [13] proposed a fluid specific reduced pressure correlation and included the effect of surface roughness. His method uses a reference heat transfer coefficient h_0, specified for each fluid at the following reference conditions of $p_{r0} = 0.1$, $R_{p0} = 0.4$ μm, and $q_0 = 20.000$ W/m^2. The nucleate boiling heat transfer coefficient at other conditions of pressure, roughness and heat flux is then calculated relative to the reference heat transfer coefficient using the following expression:

$$h_{nb} \quad h_0 F_{PF} \left(\frac{q}{q_0}\right)^{nf} \left(\frac{R_p}{R_{p0}}\right)^{0.133} \tag{15}$$

Pressure correction factor F_{PF} is:

$$F_{PF} \quad 1.2\,p_r^{0.27} \quad 2.5\left(\frac{1}{1 \quad p_r}\right)^{\quad p_r} \tag{16}$$

The effect of reduced pressure on the exponent nf for the heat flux term is given by:

$$nf = 0.9 - 0.3\,p_r^{0.3} \tag{17}$$

The surface roughness R_p is set to 0.4 μm when unknown. The correction factors are valid for all fluids except water and helium; for water the corresponding correction factors are:

$$F_{PF} \quad 1.73\,p_r^{0.27} \quad 6.1\left(\frac{0.68}{1 \quad p_r}\right)^{\quad p_r^2} \tag{18}$$

and

$$nf \quad 0.9 \quad 0.3\,p_r^{0.15} \tag{19}$$

This method is applicable over the reduced pressure ranges from 0.0005 to 0.95.

Jung correlation

Jung *et al.* [14] developed a new correlation (eq. 20) based upon the measured data of eight pure refrigerants following both Cooper's and Stephan-Abdelsalam's approaches. Some dimensionless groups affecting nucleate boiling heat transfer were identified and they were correlated by a regression analysis to yield a new correlation valid for all halogenated refrigerants. Their correlation takes into account that the exponent to the heat flux term varies significantly among fluids and also is a strong function of reduced pressure:

$$h_{\mathrm{nb}} \quad 10\frac{k}{d}\left(\frac{\frac{q}{A}d}{kT_{\mathrm{s}}}\right)^{c_1} p_{\mathrm{r}}^{0.1}(1 \quad T_{\mathrm{r}})^{1.4}\left(\frac{\vartheta}{\alpha}\right)^{0.25} \tag{20}$$

where

$$c_1 \quad 0.855\left(\frac{\rho_{\mathrm{v}}}{\rho_{\mathrm{L}}}\right)^{0.309} p_r^{0.437} \tag{21}$$

All the properties needed in the correlation development were calculated by REPPROP program. Mean deviation of the correlation was less than 7% for all the refrigerants tested.

Leiner correlation

Leiner [15] modified the general equation for nucleate boiling heat transfer valid for various fluids by taking into account fluid specific parameters (eq. 22).The physical quantities are nondimensionalized in the new type of equation by fluid-specific scaling units being critical data or power products of critical data of the fluid. The equation and the fluid specific reference values ho of the heat transfer coefficient presented by Gorenflo for nearly 50 fluids are the empirical basis, to which the new equation is fitted. The correlation is supposed to allow for estimating nucleate boiling heat transfer coefficients in poorly known fluids. Fluid properties at the actual boiling condition or specific reference values of the heat transfer coefficient are not required to apply the new type of correlation. This "general" heat transfer correlation for nucleate boiling represents the reference values ho of Gorenflo with a mean deviation of about 14% depending on the number of fluid specific parameters taken into account for.

$$\frac{h_{\mathrm{nb}}}{h_0}\left(\frac{h_0 T_{00}}{q_0^{n_0} q_{00}^{1\ n_0}}\right)^{2/15}\left(\frac{L_{00}}{R_{\mathrm{p0}}}\right)^{nf\ n_0}\left(\frac{q_{00}}{q_0}\right)^{nf} F_{\mathrm{pF}}\left(\frac{q}{q_{00}}\right)^{nf}\left(\frac{R_p}{L_{00}}\right)^{2/15} \tag{22}$$

with

$$\left(\frac{h_0 T_{00}}{q_0^{n_0} q_{00}^{1\ n_0}}\right)^{2/15}\left(\frac{L_{00}}{R_{p0}}\right) \quad A \quad 0.4368C^{0.2113}K^{\ 0.0521}Z_c^{\ 0.9166} \tag{23}$$

where

$$C \quad \frac{c_{\mathrm{pL}}}{R} \tag{24}$$

$$K = 5.37(1 + \omega) \tag{25}$$

$$\omega \quad \log_{10}(p^*_{T\ 0.7}) \quad 1 \tag{26}$$

$$Z_c \quad \frac{p_c}{\rho_c R T_c} \tag{27}$$

Fluid-specific scaling units used in eqs. (22)-(27) are given in tab. 1.

Table 1. Fluid-specific scaling units defined by T_c and P_c

Physical quantity	SI-unit	Fluid-specific unit
Temperature difference, ΔT	K	$T_{00} = T_c$
Heai flux, q	Wm^{-2}	$q_{00} \quad P_c\sqrt{RT_c}$
Heat transfer coefficient, h	$Wm^{-2}K^{-1}$	$h_{00} \quad P_c\sqrt{RT_c}$
Size of roughness or any length L	m	$L_{00} \quad \sqrt[3]{\frac{kT_c}{P_c}}$ $k \quad \frac{R_{mol}}{N_{mol}}, R \quad \frac{R_{mol}}{M_{mol}}$ with $n_0 \quad 0.75$

Assessment of pool-boiling correlations

To achieve the objective of this paper it was decided to select eight well-known nucleate pool-boiling correlations and compare their prediction accuracy against the reliable experimental databases. Three experimental papers reporting data on nucleate pool boiling were chosen to serve as basis for comparison of the selected heat transfer correlations. Inoue *et al.* [16], measured the pool boiling heat transfer coefficients of ammonia/water mixture and its pure components on a horizontal platinum wire (diameter of 0.3 mm, 37 mm length) at pressure of 0.4 and 0.7 MPa. The wire was heated using a direct electric current. Arima *et al*. [17], obtained data using an experimental device where the heating surface was a horizontal flat circular surface of silver with a diameter of 10 mm. The flat surface was polished with No. 800 emery paper and had a mean surface roughness of 1 mm. With this surface the authors obtained the boiling curve for ammonia/water mixture and its pure components at a pressure level from 1 to 15 bar. Zeng *et al.* [18] conducted a spray evaporation experiment using commercial nozzles distributing liquid ammonia on a horizontal, plain stainless steel tube with ¾-in diameter. The average local spray flow rate was varied from 0.0138 to 0.0777 kg/sm, the saturation temperature was varied from –23.3°C to 10 °C, and the heat flux was tested from 8 to 60 kW/m^2. The thermophysical properties of ammonia are taken from ASHRAE Fundamentals 2005 [19].

Prediction accuracy of nucleate pool-boiling correlations

For the purpose of this analysis, eight nucleate pool boiling correlations have been selected, which were developed by Kruzhilin, Kutateladze (old), Labuntsov, Mostinski, Nishikawa-Fujita, Stephan-Abdelsalam, Cooper, and Gorenflo. These correlations are often re-

ferred to in the boiling literature and frequently used in the thermal design. The classic Rohsenow correlation and other correlations that use constants depending on the interaction between the fluid and the surface have not been selected because the surface-fluid factor (C_{sf}) is an unknown constant for ammonia. The prediction accuracy of the correlations was assessed and compared. The results of this comparison are presented in tab. 2. The prediction errors were evaluated using the following definitions:

$$Error \quad \frac{HTC_{\text{pred}} \quad HTC_{\text{exp}}}{HTC_{\text{exp}}} \tag{28}$$

$$Mean\ error \quad \sum_{i\ 1}^{n} \frac{Error_i}{n} \tag{29}$$

$$RMS\ error \quad \sqrt{\sum_{i\ 1}^{n} \frac{Error_i^2}{n}} \tag{30}$$

Table 2. Accuracy of correlations

Authors	Experimental condition	Correlation	Mean error [%]	RMS error [%]
Inoue *et al.*	P = 0.7 MPa q = 72 to 1000 kW/m^2 No. of data points = 11	Kruzhilin	7.54	30.5
		Kutateladze (old)	22.3	40.4
		Labuntsov	–13.1	29.7
		Mostinski	–21	30
		Nishikawa-Fujita	29.4	37.4
		Stephan-Abdelsalam	–57.4	58.3
		Cooper	103	117
		Gorenflo	244	254
Arima *et al.*	P = 0.7 MPa q =72 to 2800 kW/m^2 No. of data points = 20	Kruzhilin	32.3	153
		Kutateladze (old)	50.5	233
		Labuntsov	6.02	42.5
		Mostinski	–3.16	8.75
		Nishikawa-Fujita	64.21	71.11
		Stephan-Abdelsalam	–46.9	212
		Cooper	149.83	151.31
		Gorenflo	332.26	338.68
Zeng *et al.*	P = 0.4 MPa q = 8 to 60 kW/m^2 No. of data points = 7	Kruzhilin	94.75	95.2
		Kutateladze (old)	98	98.4
		Labuntsov	58.7	58.9
		Mostinski	29.8	29.63
		Nishikawa-Fujita	64.33	66.46
		Stephan-Abdelsalam	–42.24	42.4
		Cooper	225.46	225.98
		Gorenflo	340.93	343.55

Figure 1 shows prediction errors between the experimental data and the corresponding results predicted by the selected correlations. The experimental data refer to those of Inoue *et al*.

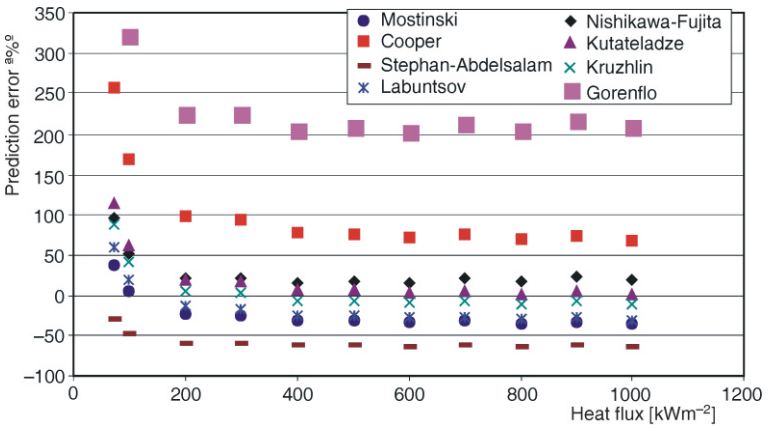

Figure 1. Accuracy of correlations

[16] at 0.7 MPa. It is clearly seen that the prediction errors are the lowest for Kutateladze (old) and Kruzhilin correlations within the investigated range of heat flux. In general, prediction error increases with decreasing heat flux for all the correlations. The maximum prediction error can be seen as high as +320% for Gorenflo correlation (eq. 15). The reason for this large deviation is the absolute value of heat transfer coefficient h_0 = 7000 W/m^2 for ammonia given by Gorenflo derived using experimental data with copper tubes at heat flux q_0 = 20000 kW/m^2. Ammonia is extremely corrosive against copper and copper alloys. Therefore the heating elements for experiments with ammonia mostly consist of mild steel or stainless steel and h_o obtained with copper tubes cannot be used to compare these experimental results. Also the experimental heat flux range in ref. [16] does not include the heat flux for h_o (q_0 = 20000 kW/m^2).

Figure 2 shows the comparison between the experimental data of Zeng *et al*. and Inoue *et al*. at 0.4 MPa and those predicted by the eight selected correlations. It is seen from the figure that Lubuntsov correlation fits the experimental data of Inoue *et. al* very well. Mostinski correlation predicts similar results. The large deviations observed between the experimental data for ammonia and the predictions of Cooper correlations are reduced if a lower surface roughness is considered. The Cooper correlation considering a surface roughness of R_p = 0.7 μm gives similar results to the Kruzhilin correlation. Stephan-Abdelsalam correlation under predicts the data of Inoue *et al*. The reason for this large deviation might be that the database upon which

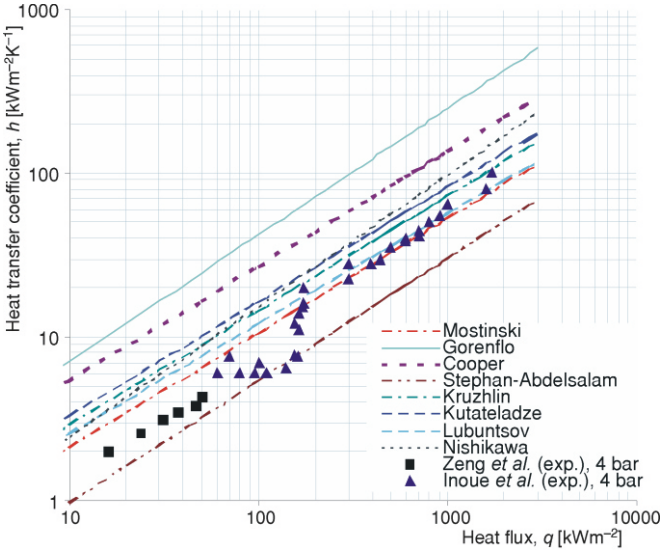

Figure 2. Comparison between the experimental data of Inoue *et al.*, Zeng *et al.*, and pool boiling correlations at 0.4 MPa

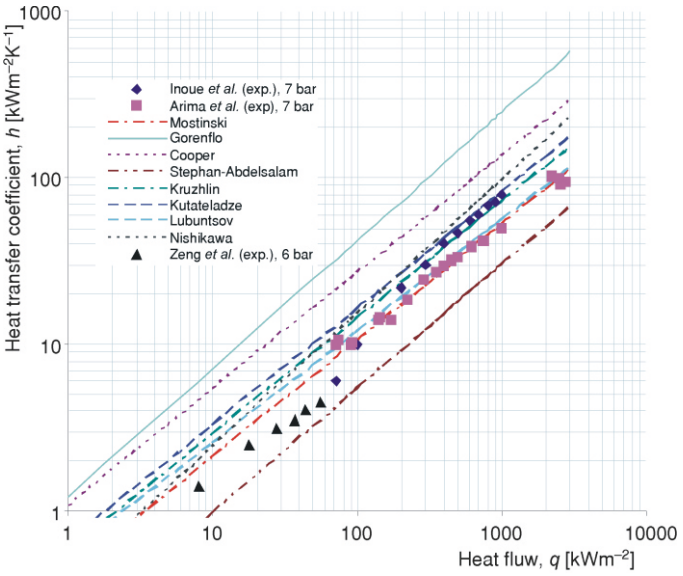

Figure 3. Comparison between the experimental data of Inoue *et al.*, Zeng *et al.*, and Arima *et al.*, and pool boiling correlations at 0.7

the correlation was developed was not consistent. In fact, Stephan and Abdelsalam used pool boiling data obtained from various geometries including a tube, cylinder, and wire in their correlation development. Data of Zeng *et al.* are predicted fairly by Stephan and Abdelsalam correlations.

Figure 3 compares experimental data of Zeng *et al.*, and Inoue *et al.*, and Arima *et al.* at 0.7 MPa with those predicted using the selected correlations. It can be seen that the experimental heat transfer coefficients measured by Inoue *et al.* are higher than those of Arima *et al.* This variation may be due to the variation in heating surface material and geometry. Kruzhilin and Kutateladze correlations still fit the experimental data of Inoue *et al.* very well. Labuntsov and Mostinski correlations fit the data of Arima *et al.* over all range of heat flux. Gorenflo and Cooper correlations still over-predict the data and Stephan-Abdelsalam correlation under-predicts the data. Stephan-Abdelsalam correlation gives better approximation of data obtained by Zeng *et al.*

Experimental data of Arima *et al.* at 1.0 and 1.5 MPa are given in figs. 4. and 5, respectively. As can be observed Labuntsov and Mostinski correlations fit the data very well at 1.0 MPa. Gorenflo and Cooper correlations still over-predict the data and Stephan-Abdelsalam cor-

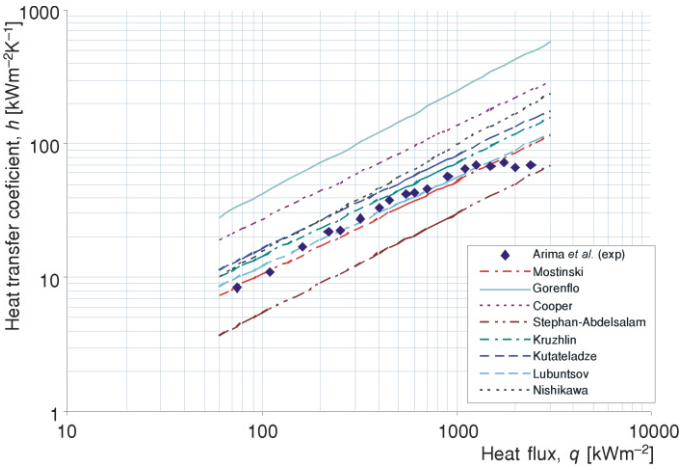

Figure 4. Comparison between the experimental data of Arima *et al.* and pool boiling correlation at 1.0 MPa

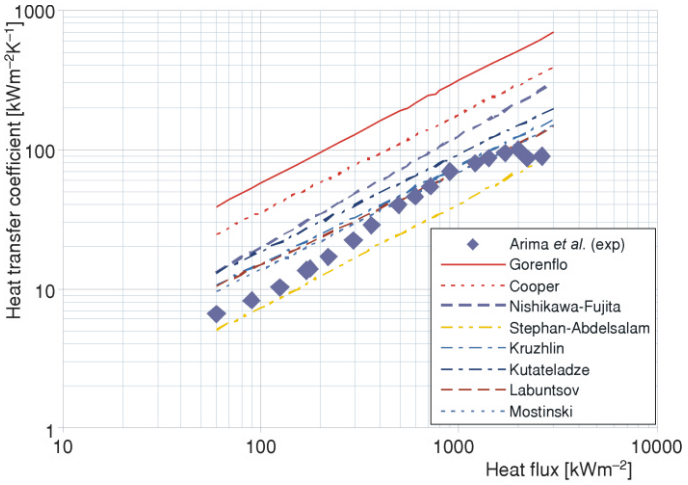

Figure 5. Comparison between the experimental data of Arima *et al.* and pool boiling correlation at 1.5 MPa

relation under-predicts the data. At 1.5 MPa Stephan-Abdelsalam correlation predicts the data with reasonable accuracy at low heat flux and at high heat flux Labuntsov and Mostinski correlations fit the data very well.

Conclusions

Three different types of nucleate pool boiling correlations are assessed here: physical property, reduced pressure, and fluid specific. Many authors found that the best general physical-property-based method is that of Stephan and Abdelsalam for refrigerants. However, this analysis concludes that Kruzhilin, Kutateladze, and Labuntsov, which use constant values for the coefficients and powers are the best for ammonia. The Cooper correlation, with a lower surface roughness effect is the best of the reduced pressure type correlations. The fluid specific Gorenflo correlation over-predicts the data for ammonia. One reason for the wide variation is that nucleate boiling is very sensitive to the precise condition of the surface on which boiling occurs. The variability exhibited by the calculated values actually reflects the variability observed among the sets of experimental data upon which the various correlations are based.

Nomenclature

C_{sf} – coefficient in eq. (3)
c_p – specific heat capacity, [Jkg^{-1}K^{-1}]
d – pool boiling characteristic dimension, $[\sigma/g(\rho_L - \rho_v)]^{1/2}$, [m]
d_b – bubble departure diameter, [m]
F_{PF} – pressure function
g – gravitational acceleration, [ms^{-2}]
h_{fg} – latent heat of vaporization, [Jkg^{-1}]
h_{nb} – nucleate boiling heat transfer coefficient, [Wm^{-2}K^{-1}]
k – thermal conductivity, [Wm^{-1}K^{-1}]
M – molecular weight, [kgkmol^{-1}]
nf – exponent in Gorenflo correlation
P – pressure, [kPa]
P_c – critical pressure, [kPa]
Pr – Prandtl number,$(=\mu c_p/k)$
p_r – reduced pressure, [–]
q – heat flux [Wm^{-2}K^{-1}]
R – specific gas constant, [Jkg^{-1}K^{-1}]
R_p – roughness, [mm]
T – temperature, [K]
ΔT – temperature difference, [K]

Greek letters

α – thermal diffusivity, [m^{2}s^{-1}]
β – contact angle, [deg.]

ν – kinematic viscosity, [m^2s^{-1}]
ρ – density, [kgm^{-3}]
σ – surface tension, [Nm^{-1}]
μ – viscosity, [Pa·s]
ω – accentric factor

Subscripts

c – critical
id – ideal
L – liquid
sat – saturation
v – vapour
0 – reference value
00 – fluid specific scaling unit

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