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A correlation to predict heat transfer coefficient in nucleate boiling on cylindrical heating elements

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Abstract

Nucleate boiling heat transfer from horizontal tubes has been analyzed using dimensional analysis and the postulations of different investigators. Inclusion of certain non-dimensional parameters in the analysis has resulted in closer approximation with the experimental data when compared with the regression equations of earlier investigators. The present correlation has been further tested with experimental data of Borishansky et al. [V.M. Borishansky, B.I. Bodrovich, F.P. Minchenko, Heat transfer during nucleate boiling of water and ethyl alcohol, in a volume of collection of articles, in: S.S. Kutateladze (Ed.), Aspects of Heat Transfer and Hydraulics of Two-Phase Mixtures, Govt. Energy Publishing House, Moscow, 1961, pp. 75–93] for water and ethyl alcohol obtained at different pressures on tubes with diameter varying between 5 to 7 mm. It is found that the correlation can predict the experimental values with a maximum deviation of ±16%.

Keywords: Nucleate boiling; Water and ethyl alcohol; Cylindrical heater elements; Heat transfer coefficients

1. Introduction

Numerous studies on nucleate boiling have been conducted and correlations developed to predict heat transfer coefficients. The pioneering works of Rohsenow [1], Mikic and Rohsenow [2], Mikic et al. [3] reported in textbooks and handbooks of heat transfer are widely used. It is well known that the correlation developed by Rohsenow [1] for estimating nucleate boiling heat flux depends on surface fluid combination. Certain other correlations offering computational ease and covering a wide range of system parameters have a large deviation when compared with the experimental data. Hence the problem is readdressed to tackle this issue.

Modeling of nucleate boiling is approached in different ways by various investigators which can be listed as:

- Turbulent convective regime around the nucleating bubble.
- Micro-convection of fluid surrounding dilating bubble in a thermal boundary layer adjacent to the heated wall.
- Natural convection of the fluid around the growing bubble.
- Vapor–liquid exchange in which the bubbles act as microscopic pumps drawing cold fluid from the ambient medium towards the wall at the time of release of the bubble from the surface.
- Inverted stagnation flow model in which the liquid is drawn towards the heating surface from the bulk.

Each of the above cited modeling techniques at one stage or the other makes use of observations like frequency of bubble departure, the number of nucleation sites, contact angle be-

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Nomenclature

A^*	constant in Borishansky's correlation	
A.D.	Average Deviation	
b	constant in Labunstov's correlation	
C	constant	
C_{sf}	variable constant in Rohsenow correlation	
C^*_{sf}	variable constant in Pioro correlation	
C_p	specific heat at constant pressure	J/kg K
D	outside diameter of the tube	m
g	acceleration due to gravity	m/s^2
h	heat transfer coefficient	W/m^2 K
h_{fg}	latent heat of vaporization	J/kg
k	thermal conductivity	W/m K
l^*	characteristic length, $= \sqrt{\frac{\sigma}{(\rho_l-\rho_v)g}}$	
L	length of the tube	m
m	variable constant in Pioro correlation	
Nu	Nusselt number, $= hl^*/k$	
P	pressure	N/m^2
P_r	a constant in Borishansky correlation	
P_{cr}	critical pressure	N/m^2
Pr	Prandtl number, $= \nu/\alpha$	
q	wall heat flux	W/m^2
r	variable constant in Rohsenow's correlation	
Re	modified Reynolds number, $= \frac{ql^*}{\upsilon_l \rho_v h_{fg}}$	
s	variable constant in Rohsenow's correlation	
S.D.	Standard Deviation	
T	temperature	°C
V	velocity of growth of the bubble	m/s
ΔP_{sat}	pressure difference corresponding to degree of superheat	
ΔT	temperature potential, $= T_w - T_S$	

Greek symbols

α	diffusivity	m^2/s
σ	surface tension	N/m
μ	absolute viscosity	kg/m s
ν	kinematic viscosity	m^2/s
ρ	density	kg/m^3
δ_t	thermal boundary layer thickness, $= \frac{k_l \Delta T}{q}$	
δ_B	bubble diameter, $= C\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}$	

Subscript

B	liquid bulk
cr	critical
Exp	experimental value
l	liquid
S	saturation
th	theory
v	vapor
w	wall

tween 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.

The models employed by investigators on nucleate boiling study can be found in [4–19]. One of the important modeling approaches to nucleate boiling is through dimensional analysis. There are many correlations existing in the literature which are obtained through dimensional analysis. For example, the correlation of Borishansky [20], Kutateladze [12], Kruzhilin [21,22], Borishansky et al. [23] and Stephan and Abdel Salem [24] are often referred to in the boiling literature and are frequently used in thermal design. Hence these correlations are considered for comparison in the present analysis.

The present work is aimed at obtaining a design correlation for immersion heaters operating under different system conditions with water as the surrounding fluid undergoing evaporation. The primary objective is to find experimental data under nucleate boiling regime valid for a wide range of system parameters. The next step is to check which of the correlations satisfy reasonably well the available data on cylindrical heater elements. The final objective is to propose a new correlation which satisfies the experimental data having better accuracy than the other correlations with the introduction of new non-dimensional, π-terms.

2. Correlations from available data set

The correlations related to nucleate boiling are taken from literature. Besides, a search is conducted to find out the availability of documented experimental data. In this regard the data of Borishansky et al. [23] covers wide range of system parameters. The material of the test section is 18–8 Cr–Ni cold drawn stainless steel tubes of diameter varying from 4.96 to 6.94 mm. The lengths of the test section varied in the range of 260 to 300 mm. The orientation of the test section is horizontal. The roughness factor of the surface is not considered as a parameter in the data regression done by Borishansky et al. [23].

The heating of the test section is accomplished by low voltage—alternating current and the wall heat flux is evaluated from $q_w = \frac{I^2 R}{\pi DL}$ where I is current in amps, R electrical resistance of the test section in ohms and D external diameter of the tube. The measurement of temperature of test section is recorded with the aid of chrome-alumel thermocouples preened to the surface at the upper and lower stagnations point of the cylindrical test section. An average of the two thermocouples is considered as the wall temperatures.

The bulk temperature is ascertained with the help of thermocouple located in the boiling medium midway from the heating surface and the free surface. The average convective heat transfer coefficient is estimated from equation $h = \frac{q_w}{\Delta T}$, where $\Delta T = (T_w - T_B)$, T_w is the external temperature of the surface of the tube wall and T_B is the bulk temperature of the boiling liquid.

The system is pressurized and controlled with the help of the condenser located in the free volume above the free surface of the fluid in the vessel. The vapors generated due to the boiling are re-condensed back by a condenser positioned above the free surface of the liquid bulk in the container. The system pressure is regulated by the rate of condensation of the vapors in the free volume. On every test section employed in the study, prolonged nucleate boiling is allowed before actual tests are commenced. Thus Borishansky's experimentation covered a wide range of system parameters with pressures varying from atmospheric conditions up to values close to critical pressures for ethyl alcohol [$1 \text{ bar} < P < 60 \text{ bar}$, $P_{cr} = 64 \text{ bar}$] and water [$1 \text{ bar} < P < 200 \text{ bar}$, $P_{cr} = 221 \text{ bar}$].

3. Comparison of various correlations with the data of Borishansky et al.

3.1. Rohsenow's correlation [1]

$$\frac{q}{\mu_l h_{fg}}\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2} = \left(\frac{1}{C_{sf}}\right)^{1/r} Pr^{-s/r}\left\{\frac{C_{pl}[T_w - T_S]}{h_{fg}}\right\}^{1/r} \tag{1}$$

The correlation of Rohsenow [1] is shown plotted in Fig. 1. Rohsenow correlation contains a variable coefficient depending on the choice of material and medium. As can be seen from Figs. 1 and 2 shown separately for water and ethyl alcohol data respectively, the deviations between the predictions and the data are quite considerable. The deviation between the data and the correlation is more than +30% from the predictions of Rohsenow.

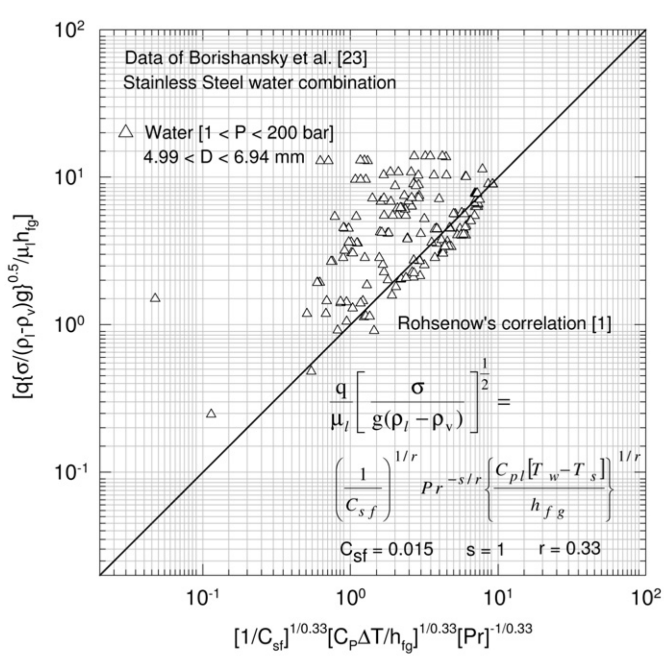

Fig. 1. Predictions from Rohsenow's correlation for stainless steel–water combination.

3.2. Correlation of Pioro et al. [26,27]

$$\frac{h}{k}\left(\frac{\sigma}{(\rho_l - \rho_v)g}\right)^{0.5} = C^*_{sf}\left(\frac{q}{h_{fg}\rho_v^2[\sigma g(\rho_l - \rho_v)]^{0.25}}\right)^{1/3} Pr^m \tag{2}$$

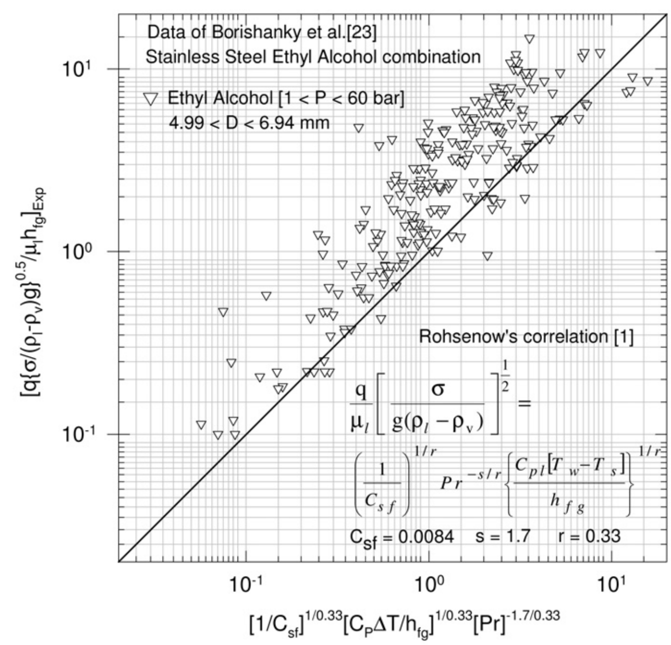

Fig. 2. Predictions from Rohsenow's equation for stainless steel–ethyl alcohol combination.

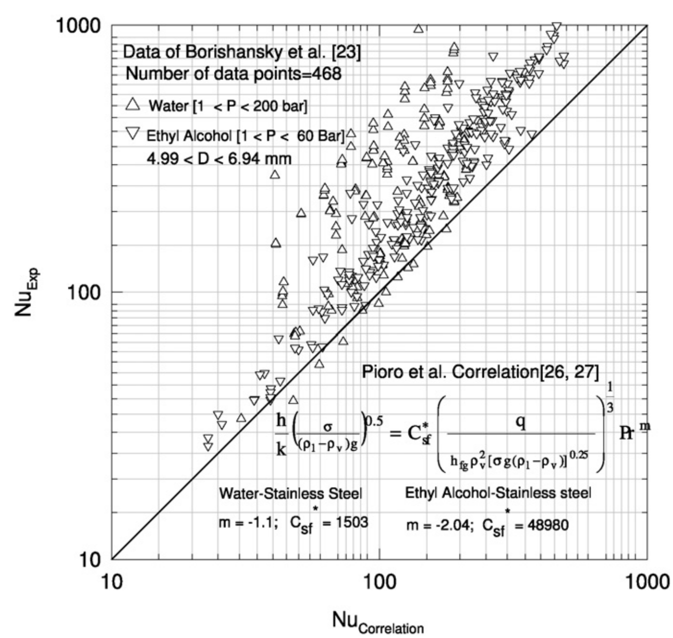

Fig. 3. Validation of Pioro correlation with experimental data.

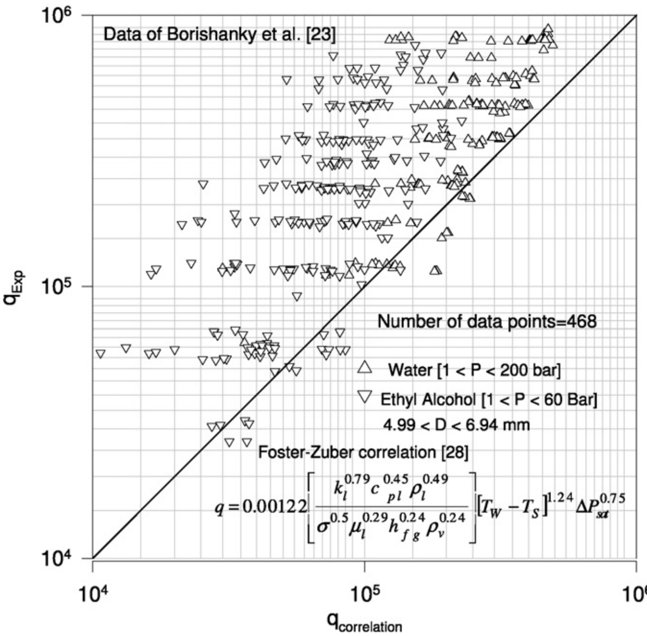

Fig. 4. Validation of Foster–Zuber correlation with experimental data.

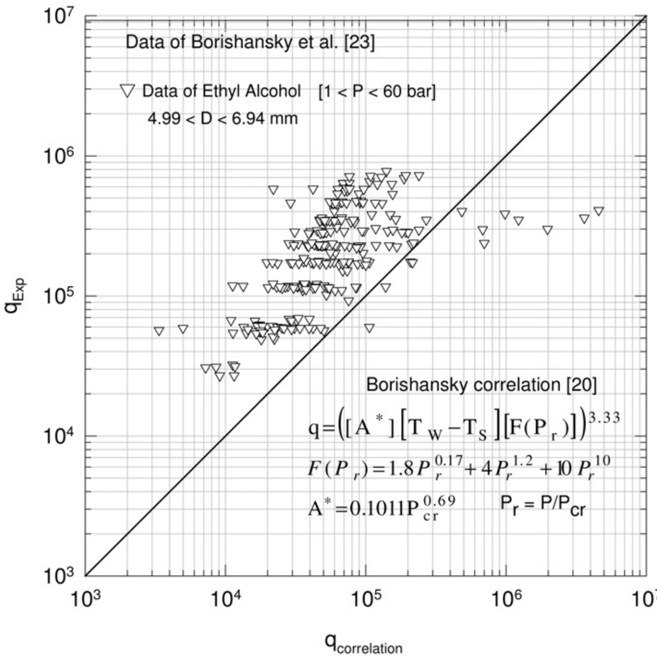

Fig. 5. Validation of Borishansky correlation with data for ethyl alcohol.

Pioro et al. [25–27] conducted exhaustive survey and concluded in their analysis that Rohsenow's correlation is the best among the correlations. However certain corrections in the coefficients for the surface-medium combination were incorporated by them. Eq. (2) of Pioro et al. [25,26] under predicts the experimental values as can be seen from Fig. 3. Thus the corrections introduced into the correlation of Rohsenow do not seem to justify the claim of Pioro et al. [25,26] especially with regard to the data under consideration.

3.3. Foster–Zuber correlation [28]

$$q = 0.00122\left[\frac{k_l^{0.79} c_{pl}^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} h_{fg}^{0.24} \rho_v^{0.24}}\right][T_w - T_S]^{1.24} \Delta P_{sat}^{0.75} \tag{3}$$

A plot is drawn between the predictions from Eq. (3) of Foster–Zuber [28] and the experimental data both for water and ethyl alcohol in Fig. 4. There is a systematic deviation with very wide scatter in the data predictions and does not predict closely for water and ethyl alcohol.

3.4. Borishansky correlation [20]

The correlation of Borishansky et al. is as follows

$$q = \left(A^*\right)^{3.33} [T_w - T_S]^{3.33} \left[F(P_r)\right]^{3.33} \tag{4}$$

where $A^* = 0.1011 P_{cr}^{0.69}$; $F(P_r) = 1.8 P_r^{0.17} + 4 P_r^{1.2} + 10 P_r^{10}$ where $P_r = P/P_{cr}$ and the pressure is in bar.

The correlation equation (4) of Borishansky [20] makes use of (P/P_{cr}) as one of the dominant criteria in the regression of the data. It can be seen from Fig. 5 that the correlation of Borishansky underpredicts the heat flux for all ranges of system parameters for ethyl alcohol. However from Fig. 6 it can be seen that the data of water fairly agrees with the predictions. The

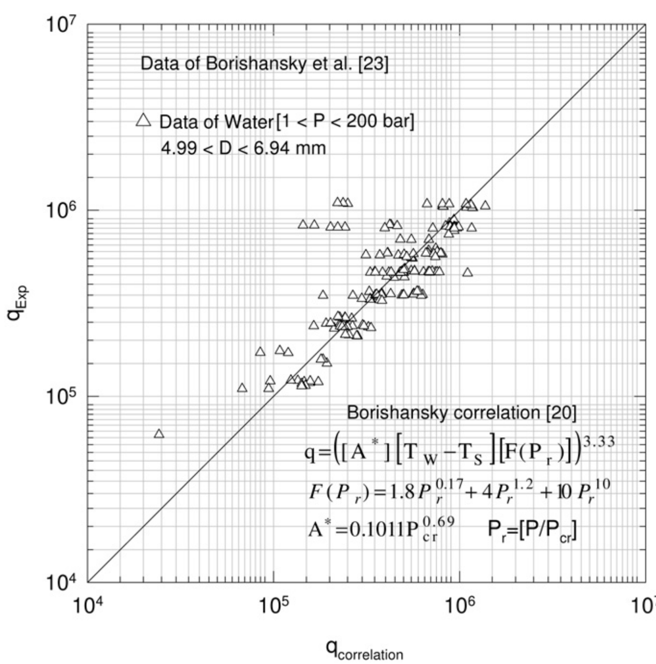

Fig. 6. Validation of Borishansky correlation with data for water.

correlation has been developed based on dimensional analysis applied to the law of corresponding thermodynamic states.

3.5. Correlation of Kichigin and Tobilevich [23]

$$Nu = \frac{hl^*}{k} = \frac{h\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}}{k}$$
$$= 3.25 \times 10^{-4} Re^{0.6} Pr^{0.6} \left(\frac{gl^*}{\nu^2}\right)^{0.125}$$

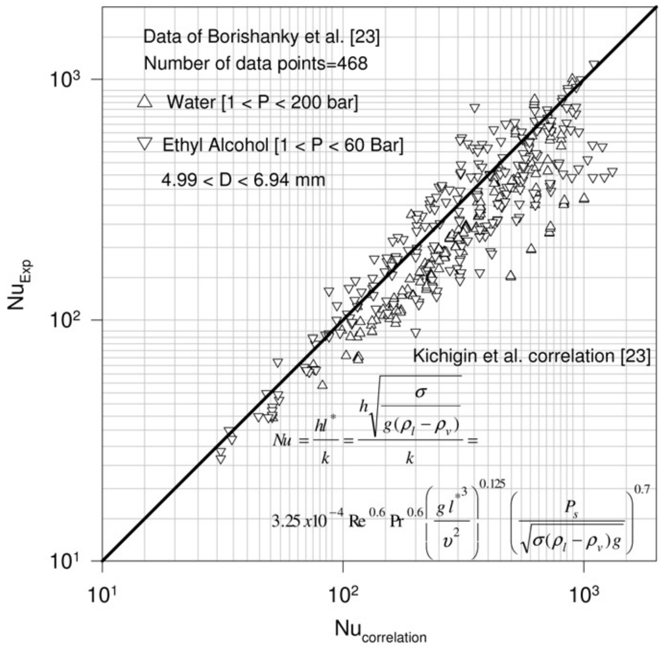

Fig. 7. Comparison of Kichigin et al. correlation with the data of Borishansky.

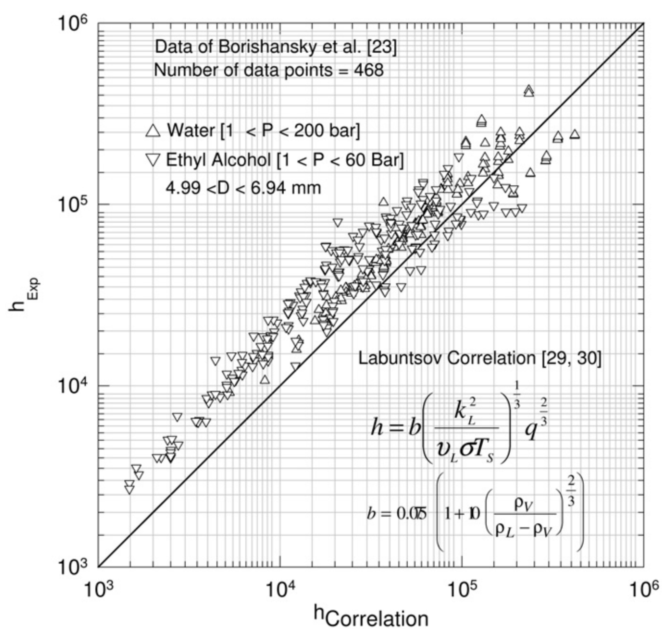

Fig. 8. Comparison of correlation of Labuntsov with experimental data of Borishansky et al.

$$\times\left(\frac{P_\mathrm{s}}{\sqrt{\sigma(\rho_\mathrm{l}-\rho_\mathrm{v})g}}\right)^{0.7} \tag{5}$$

where

$$Re=\frac{ql^*}{h_\mathrm{fg}\nu_\mathrm{l}\rho_\mathrm{v}} \quad \text{and} \quad l^*=\sqrt{\frac{\sigma}{(\rho_\mathrm{l}-\rho_\mathrm{v})g}}$$

Amongst the correlations tested, Eq. (5) of Tobilevich et al. [23] is found to give reasonably good agreement with the data both for water and ethyl alcohol as can be seen from Fig. 7. However, the deviation seems to be on the high side with magnitudes of accuracy varying more than ±30%.

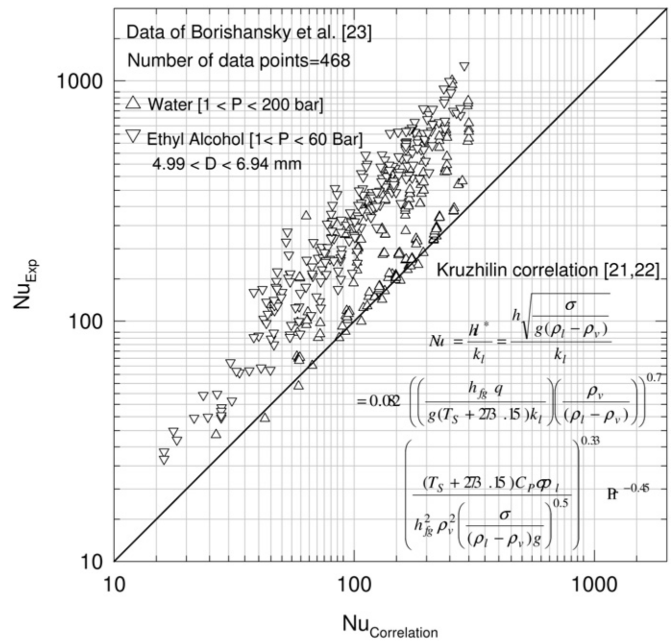

Fig. 9. Comparison of Kruzhilin correlation with data of Borishansky.

3.6. *Labuntsov's correlation [29,30]*

$$h=b\left(\frac{k_\mathrm{l}^2}{\nu_\mathrm{l}\sigma T_\mathrm{S}}\right)^{1/3}q^{2/3}$$

$$\text{where } b=0.075\left(1+10\left(\frac{\rho_\mathrm{v}}{(\rho_\mathrm{l}-\rho_\mathrm{v})}\right)^{2/3}\right) \tag{6}$$

In Fig. 8, the whole range of data is found to systematically lie on the benchmark thick line. However, it can be seen that the scatter of the data is minimum and the parameters in the correlation are found to be inadequate to give satisfactory agreement with the experimental data.

3.7. *Kruzhilin's correlation [21,22]*

$$\begin{aligned} Nu&=\frac{hl^*}{k_\mathrm{l}} \\ &=\frac{h\sqrt{\frac{\sigma}{g(\rho_\mathrm{l}-\rho_\mathrm{v})}}}{k_\mathrm{l}} \\ &=0.082\left(\left(\frac{h_\mathrm{fg}q}{g(T_\mathrm{S}+273.15)k_\mathrm{l}}\right)\left(\frac{\rho_\mathrm{v}}{(\rho_\mathrm{l}-\rho_\mathrm{v})}\right)\right)^{0.7} \\ &\quad\times\left(\frac{(T_\mathrm{S}+273.15)C_\mathrm{P}\sigma\rho_\mathrm{l}}{h_\mathrm{fg}^2\rho_\mathrm{v}^2(\frac{\sigma}{(\rho_\mathrm{l}-\rho_\mathrm{v})g})^{0.5}}\right)^{0.33}Pr^{-0.45} \end{aligned} \tag{7}$$

One of the earliest correlations in nucleate boiling is due to Kruzhlin et al. [21,22]. Fig. 9 also indicates that the correlation underpredicts the experimental data.

Thus, a review of several correlations has been organized and in the light of lack of efficacy to predict values close to the experimental data related to water and ethyl alcohol for wide pressure range, it is felt that the problem to be readdressed making use of the information available.

3.8. Present analysis

In the choice of determining the required criteria for π-grouping, considerations of the earlier investigators are made use wherever necessary. Rohsenow's [1] turbulent convective analogy suggests that velocity of vapor generation can be of importance in nucleate boiling studies. Hence, taking one from his approach, it is assumed that modified Reynolds number $\frac{q_w l^*}{\mu_l h_{fg}}$ is a significant π-parameter where l^* can be the characteristic length. The choice of l^* may be the diameter of the emerging bubble i.e. $C\sqrt{\frac{\sigma}{(\rho_l-\rho_v)g}}$, where the value of C can be included in the constant of multiplication to be finally evaluated in the dimensionless correlation.

Besides, Mostinski [7] and Borishansky [20] suggested that a better correlation can be achieved by introducing P/P_{cr} as an important thermodynamic consideration. Hence, weightage is given to this group in the choice.

Tien et al. [6] considered nucleate boiling heat transfer as inverted stagnation flow normal and towards the wall. Hence, δ_t/D is considered as an important π group. δ_t is the thickness of thermal boundary layer, which can be of the same order of magnitude given by

$$\delta_t = \left(\frac{\Delta T k_l}{q_w}\right) \tag{8}$$

Thus the present analysis pivots around the choice of the three dimensionless π groups. It follows that

$$\frac{q_w D}{\mu_l h_{fg}} = F\left[\frac{P}{P_{cr}}, \frac{\delta_t}{D}, \frac{\delta_B}{D}\right] \tag{9}$$

Or the system can be rearranged as

$$\frac{q_w}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{(\rho_l-\rho_v)g}} = F\left[\frac{P}{P_{cr}}, \frac{\delta_t}{D}, \frac{1}{D}\sqrt{\frac{\sigma}{(\rho_l-\rho_v)g}}\right] \tag{10}$$

The parameter δ_t/D takes into account the effects of diameter D, the cylindrical heater element. Thus, the experimental data (468 points) are subjected to regression analysis to obtain a correlation as follows:

$$\frac{q_w}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{(\rho_l-\rho_v)h_{fg}}} = 0.0312\left(\frac{D}{\delta_t}\right)^{1.15}\left(\sqrt{\frac{\sigma}{(\rho_l-\rho_v)gD^2}}\right)^{-1.99}\left(\frac{P}{P_{cr}}\right)^{0.208} \tag{11}$$

Fig. 10 shows the experimental data along with the correlation together for water and ethyl alcohol at different pressures. The figure shows the data points cluster along the solid line with uniform scatter on either side of the thick line. Nevertheless the average deviation is $\pm 37\%$ with a standard deviation of $\pm 46\%$. Hence, such a scatter is to be minimized by introducing another π-term of significance. In this regard, a new π-term ($\frac{PD}{\mu_l h_{fg}^{1/2}}$) is introduced into the existing system to change the scenario drastically reducing the average deviation to $\pm 16\%$ and standard deviation to $\pm 20\%$. The validation of the correlation is shown in Fig. 11 along with the data. The proposed correlation is as follows:

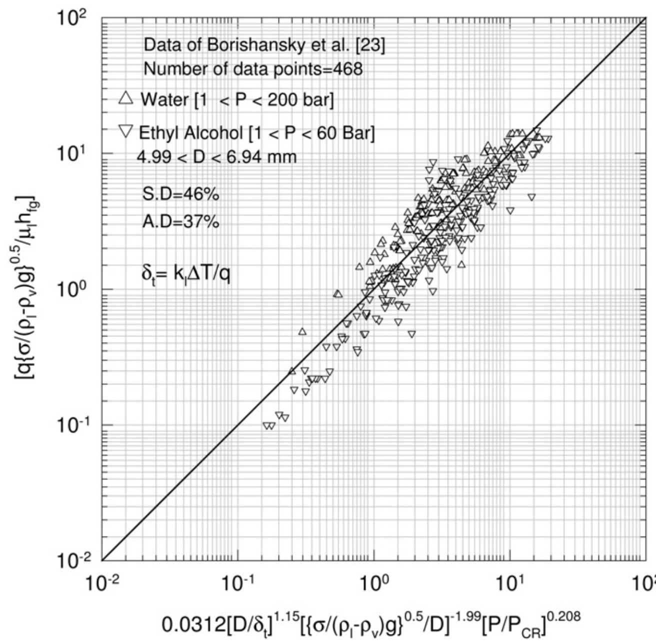

Fig. 10. A correlation with the system of criteria as given in Eq. (11).

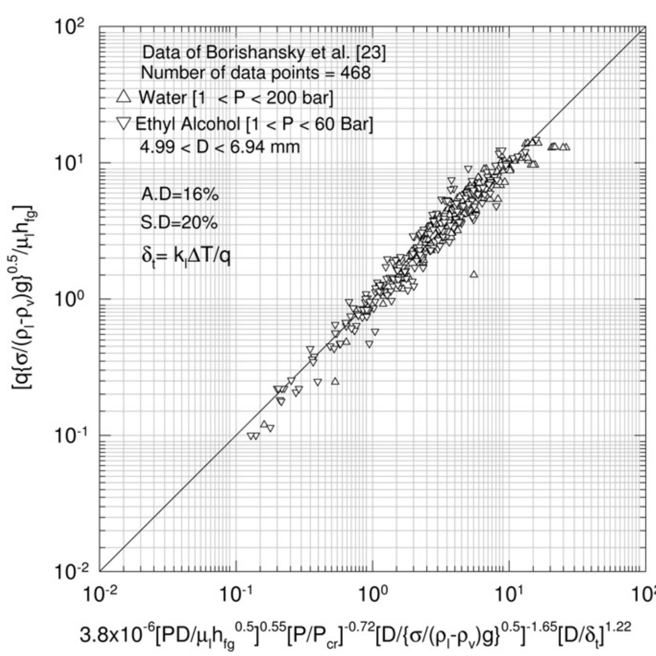

Fig. 11. Validation of experimental data with present correlation.

$$\frac{q_w}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{(\rho_l-\rho_v)g}} = 3.8\times 10^{-6}\left(\frac{D}{\delta_t}\right)^{1..22}\left(\frac{P}{P_{cr}}\right)^{0.72} \times\left(\frac{PD}{\mu_l h_{fg}^{1/2}}\right)^{0.55}\left(\sqrt{\frac{\sigma}{(\rho_l-\rho_v)gD^2}}\right)^{1.65} \tag{12}$$

The significance of the π-term ($\frac{PD}{\mu_l h_{fg}^{1/2}}$) can be well understood by expanding it as a product of 3-π groups.

$$\frac{PD}{\mu_l h_{fg}^{1/2}} = \left(\frac{PD^2}{\rho_l D^2 V^2}\right)\left(\frac{\rho_l V D}{\mu_l}\right)\left(\frac{V^2}{h_{fg}}\right)^{1/2} = \pi_1\pi_2\pi_3 \qquad (13)$$

where, V can be viewed as the velocity of growth of the bubble. The physical significance of various π parameters is as follows.

$$\pi_1 = \frac{PD^2}{\rho_l D^2 V^2}\text{[modified Euler's number]: } \left[\frac{\text{pressure force}}{\text{inertia force of the bubble}}\right] \qquad (14)$$

π_1 denotes the dynamics of bubble growth

$$\pi_2 = \frac{VD\rho_l}{\mu_l}\text{[modified Reynolds number]: } \left[\frac{\text{inertia force}}{\text{viscous force}}\right] \qquad (15)$$

π_2 denotes the dynamics of flow of the surrounding fluid during the bubble dilatation

$$\pi_3 = \frac{V^2}{h_{fg}} = \left[\frac{\text{energy associated with dilatation of the bubble interface}}{\text{latent heat of vaporization}}\right] \qquad (16)$$

π_3 denotes the influence of the thermal aspects associated with liquid vaporization responsible for the growth of the bubble.

Hence the π-term $\frac{PD}{\mu_l h_{fg}^{1/2}}$ give the combined influence of dynamics of the bubble growth with the thermal effects in the thermal boundary layer adjacent to the wall. Inclusion of such a dimensionless group led to a correlation with better accuracy as evident in Fig. 11.

4. Conclusions

The following conclusions can be arrived at:

1. The proposed correlation of the present investigation favourably predicts experimental data related to water and ethyl alcohol over a wide range of pressures with reasonable accuracy of $\pm 16\%$. However, it is to be tested for other systems to acclaim universality.
2. The analysis yielded a correlation with introduction of a new π-term $\frac{PD}{\mu_l h_{fg}^{1/2}}$ into the system. It indirectly takes into account the dynamics of the growing nucleating bubble on the wall. It proved to be a significant π-parameter in predicting the experimental data closely.
3. The correlation can be made use of in the design of immersion heaters with net vaporization at least for the media of water and ethyl alcohol over a wide pressure range and tube configurations as indicated. The correlation has the merit of predicting the data with a constant of multiplication factor of finite magnitude irrespective of surface-fluid combination. The study resulted in a new correlation giving better agreement with the experimental data compared to earlier correlations cited in the study.

Acknowledgements

The article is submitted in honor of Professor Sadik Kakac on his 75th birthday. The dimensionless parameter $\frac{PD}{\mu_l h_{fg}^{1/2}}$ is named as KAKAC number in view of his learned contributions in two-phase flow dynamics and heat transfer.

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