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A correlation to evaluate critical heat flux in small diameter tubes under subcooled conditions of the coolant

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Abstract

A correlation is generated by applying regression analysis to the data under subcooled conditions from the literature to determine the critical heat flux in small diameter tubes less than 3 mm at different pressures for a wide range of system parameters. The correlation is accomplished for the model of slug flow in the tube considering the determining criteria for the formation of the slugs as vapor locks in the tubes leading to departure from nucleate boiling [DNB] conditions. It is observed that the correlation satisfies a wide range of system parameters. Application of the correlation to the data of larger diameter tubes revealed satisfactory agreement. Besides for saturated flow conditions of the coolant ($x > 0$), another generalized correlation is also proposed with reasonably good accuracy. Comparison of the present correlations with some of the recent correlations indicated satisfactory agreement supporting the validity of the criteria employed in the regression.

Keywords: DNB; Small diameters; Subcooled conditions; Slow burnout ($x > 0$); Fast burnout ($x < 0$); Correlations

1. Introduction

The departure from nucleate boiling under severe thermal conditions leads to unpleasant conditions of failure of the tube due to degradation of thermal transport from the wall to the coolant. The classification of the failures is broadly done under two categories, viz., fast burnout and slow burnout depending upon the coolant conditions at the entrance. The fast burnout ($x < 0$) is a considered as a phenomenon occurring when the coolant is still under subcooled conditions i.e. when the coolant bulk has not attained the saturation temperature. In the slow burnt (i.e. $x > 0$) phenomenon the temperature excursions might not lead to the failure of the tube except for a rise in the temperature of the tube. The slow burn out occurs at the exit of the tube. In thermo-fusion nuclear reactors operating under high thermal loads the coolant will be under subcooled conditions. There are several studies [1–8] both experimental and theoretical delineating the effects of subcooling, mass flux of the coolant [6,7], the system pressure, channel heated length, channel orientation, thickness

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Nomenclature

A	cross-sectional area of the tube, m^2
Bo	boiling number
c	a constant in Tong's equation
c'	a constant in Celata's equation
C_1, C_2, C_5	constants in Mudawar's equation
C_p	specific heat, kJ/kg °k
D	diameter of the tube, m
D_B	bubble diameter, m
G	mass velocity, kg/m^2 s
h	enthalpy, kJ/kg
q	heat flux, W/m^2
L	length of the tube, m
P	system pressure, bar
P_{cr}	critical pressure, bar
q_{cr}	critical heat flux, W/m^2
Re	Reynolds number
T	temperature, °C
X	dryness fraction
V	velocity, m/s
We	Weber number

Greek symbols

α	contact angle
ρ	density, kg/m^3
μ	absolute viscosity, kg/m s
π	dimensionless group
σ	surface tension, N/m
ψ	a variable in Celata equation

Subscripts

e	exit
f	liquid phase
i	inlet
fg	phase change
l	liquid phase
s	saturated value
v	vapor phase
cr	critical value

of the wall, type of the heat flux distribution on critical heat flux. Celata and Mariani [9] vividly discussed some of the parametric effects such as mass velocity, pressure, diameter of the tube, type of heat flux variation around the tube etc. on the critical heat flux. There are several correlations related to subcooled conditions of the coolant. Some of the often-cited correlations are due to Gunther [17], Tong [31,32], Thom [30], Celata [13], Hall and Mudawar [19]. On set of DNB in the subcooled and very low quality region of convective tube flow conditions are frequently described under three mechanisms such as

- Initiation of dry patch conditions underneath a bubble due to rapid evaporation of the microlayer.
- Vapor crowding near the wall preventing radial flow of the liquid to wet the wall.
- Vapor slug formation with the thin peripheral liquid film in between the slug and the wall of the tube rapidly evaporating leading to dry wall conditions and further propagating into film boiling conditions.

The results are already documented in handbooks on two-phase flow heat transfer. Two-phase flow studies in certain electronic components due to miniaturization and high flux removal assume paramount importance in design. Hence, the objective of the article is to scan and cull the available data in the literature on critical flux in small diameter tubes (less than 3 mm) to establish a correlation for a wide range of system pressures and flow velocities. Further, the criteria are applied to larger diameter tubes and thus, the limits of applicability being extended further.

In addition the critical heat flux for saturated flow conditions of the coolant will be analyzed by introducing the Mozarov's [26] dimensionless parameter in correlating the data. It is generally attributed that onset of slow burnout in high quality region is associated with the tearing of the liquid film from the inner periphery of tube under combined action of thermal conditions at the wall with the shearing action of the free stream.

2. Dimensionless criteria

It is essential to fix the probable mechanism that would lead to on set of burnout conditions in small diameter tubes. There are several analyses [26,27] related to the bubble dynamics and departure diameter of the bubble. The earlier analysis of Fritz [15] is shown plotted in Figs. 1 and 2 for possible values of the contact angles and system pressures. It can be seen that the order of magnitude of the departing bubble will be same as the diameter of the tube under consideration. Under such circumstances the bubble coalescence from the two neighboring activation cites in all likelihood will lead to vapor lock formation leading to a growth as slug flow conditions leading to further deterioration of thermal conditions adjacent to the wall in a small diameter. Formation of the vapor lock in the small diameter impedes

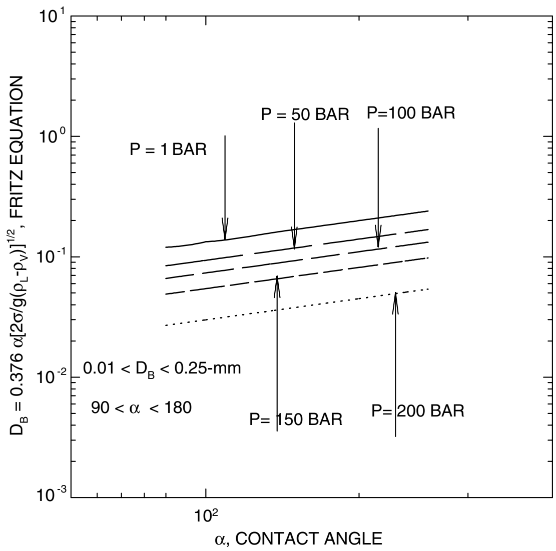

Fig. 1. Variation of the bubble diameter with contact angle, α.

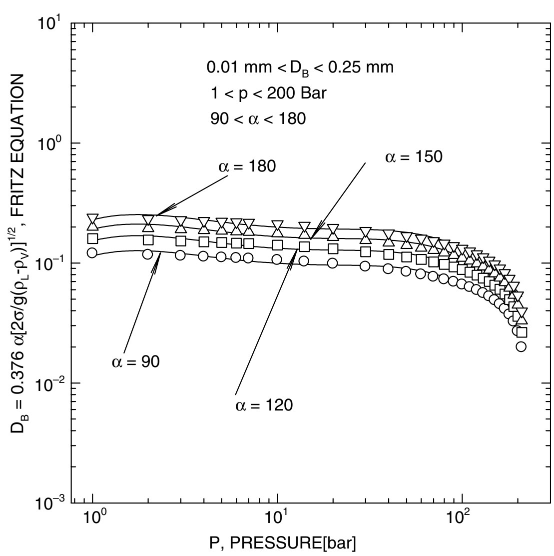

Fig. 2. Variation of bubble diameter with pressure.

momentarily the flow and essentially the movement of the slug is due to the buoyant forces against the shear resistance at the wall. When the thin liquid film between the slug and the wall totally evaporates due to further increase in heat flux, dry wall conditions set in. Hence thermal resistance at the wall substantially increases leading to burnout. Celata and Mariani [9] developed this model theoretically in the estimation of the critical heat flux and subcooled conditions of the coolant. The morphology of the two-phase flow of air–water systems in a tube under adiabatic conditions is fairly established [9]. Celata [10–13] in his data analysis found out that the empirical constant in his equation $q_{cr}/\mu_l h_{fg} = c' Re^{0.5}$, where $c' = 0.2164 + 4.74 \times 10^{-2} P$. Thus, the formation of the vapor lock leading to slug flow under diabatic conditions according to the existing literature is dependent on various governing parameters as listed:

$$q_{cr} = F[P, D, h_{fg}, \mu, G, L, (h_e - h_i)] \tag{1}$$

where

q_{cr}	critical heat flux
P	system pressure
h_{fg}	latent heat of vaporization
μ	absolute viscosity of the coolant
G	mass velocity of the flow
D	diameter of the tube
L	length
$h_e - h_i$	enthalpy rise of the coolant in the test section

The system of parameters can be converted into dimensionless π-groups as follows:

$$\frac{q_{cr} D}{\mu h_{fg}} = F\left[\frac{PD}{\mu h_{fg}^{1/2}}, \frac{h_e - h_i}{h_{fg}}, \frac{L}{D}, \frac{GD}{\mu}\right] \tag{2}$$

Thus, a brief description of the criteria in Eq. (2) leading to onset would be in order.

$$\pi_1 = \frac{q_{cr} D}{h_{fg}\mu_l} = \left[\frac{q_{cr}}{\rho_l h_{fg}}\right]\left[\frac{\rho_l D}{\mu}\right] = V_{cr}\frac{\rho_l D}{\mu}$$

= critical Reynolds number signifying on set of DNB

$$\frac{PD}{\mu h_{fg}^{1/2}} = \left[\frac{P}{G h_{fg}^{1/2}}\right]\left[\frac{GD}{\mu}\right] \equiv \pi_2 \pi_3$$

π_2 = morphological parameter associated with two-phase flow structure under diabatic conditions

π_3 = flow Reynolds number governing hydrodynamics of two-phase flow

$$\pi_4 = \frac{h_e - h_i}{h_{fg}} = \frac{\text{rise in enthalpy of the coolant}}{\text{latent heat of vaporization}}$$

$$\pi_5 = \frac{L}{D} = \frac{\text{length}}{\text{diameter}}$$

= geometric dimensionless ratio of the test section

Under subcooled conditions onset of DNB is found to occur at the exit of the tube. Hence L/D seems to be a significant parameter as well.

Further, the energy balance must hold good till $q \to q_{cr}$, i.e.

$$\frac{h_e - h_i}{h_{fg}} = 4\left[\frac{qD}{\mu h_{fg}}\right]\left[\frac{L}{D}\right]\left[\frac{\mu}{GD}\right] \tag{3}$$

When $q = q_{cr}$, Eq. (3) the energy balance will get mathematically restructured differently as follows with the indices having different magnitudes other than unity.

$$\frac{h_e - h_i}{h_{fg}} = \text{const}\left[\frac{q_{cr}D}{\mu h_{fg}}\right]^{a_1}\left[\frac{L}{D}\right]^{a_2}\left[\frac{\mu}{GD}\right]^{a_3} \tag{4}$$

Combining Eqs. (2) and (4)

$$\frac{q_{cr}D}{\mu h_{fg}} = \text{const}\left[\frac{PD}{\mu h_{fg}^{1/2}}\right]^{b_1}\left[\frac{L}{D}\right]^{b_2}\left[\frac{GD}{\mu}\right]^{b_3} \tag{5}$$

where b_1, b_2, b_3 are the unknown indices, which are to be determined from the data.

Thus, the phenomenon of DNB under subcooled conditions is found to be described by four π groups. Subsequently, the available data in the literature will be subjected to regression analysis subject to the criteria shown in Eq. (5). In the group one might find the absence of the degree of subcooling. Its effect can be reflected in the regression by choosing the physical properties at the temperature corresponding to the inlet temperature of the coolant. If the process is truthfully described by the system of criteria i.e., Eq. (5) the data can be correlated reasonably with the aid of these π terms under consideration.

3. Selection of data

The various sources chosen for the collection of the data for regression are shown in Table 1.

Out of the total number of 3050 requisitioned for the purpose of correlation, 1265 correspond to tubes with diameter less than 3 mm as given in Tables 4–6.

In Fig. 3 the data subjected to the regression are shown plotted and the following correlation is obtained with an average deviation of 20%.

$$\frac{q_{cr}D}{\mu h_{fg}} = 0.239Re^{0.657}\left[\frac{PD}{\mu h_{fg}^{1/2}}\right]^{0.123}\left[\frac{D}{L}\right]^{0.48} \tag{6}$$

Subsequently, an attempt is made in the regression by replacing the π-parameter $\left[\frac{PD}{\mu h_{fg}^{1/2}}\right]$ with $\left[\frac{P}{P_{cr}}\right]$ where P_{cr} is the thermodynamic critical pressure of the coolant under consideration. The correlation

$$\frac{q_{cr}D}{\mu h_{fg}} = 0.154Re^{0.7}\left[\frac{P}{P_{cr}}\right]^{0.17}\left[\frac{D}{L}\right]^{0.5} \tag{7}$$

is shown plotted in Fig. 4, which depicts the reliability of the correlation with an average deviation of 18%.

Further, to check whether any improvement in the correlation can be achieved by choosing the characteristic length as the diameter of the bubble, D_B, correlations are attempted with the following groups of criteria.

$$\frac{q_{cr}D_B}{\mu h_{fg}} = F\left\{\left[\frac{PD}{\mu h_{fg}^{1/2}}\right],\left[\frac{L}{D}\right],\left[\frac{GD}{\mu}\right],\left[\frac{D_B}{D}\right]\right\} \tag{8}$$

$$\frac{q_{cr}D_B}{\mu h_{fg}} = F\left\{\left[\frac{P}{P_{cr}}\right],\left[\frac{L}{D}\right],\left[\frac{GD}{\mu}\right],\left[\frac{D_B}{D}\right]\right\} \tag{9}$$

Though, the data could be successful correlated there is not much improvement in the average deviation. The resulting correlation is as follows for the criteria given in Eqs. (8) and (9)

$$\frac{q_{cr}D_B}{\mu h_{fg}} = 0.095\left[\frac{P}{P_{cr}}\right]^{0.176}\left[\frac{L}{D}\right]^{-0.5}\left[\frac{GD}{\mu}\right]^{0.7}\left[\frac{D_B}{D}\right]^{0.9} \tag{10}$$

Further, the usefulness of the criteria listed in Eq. (5) for all data points 3050 from various sources as per the Tables 1–6 is tested. The system of criteria could successfully correlate covering a wide range of mass velocities,

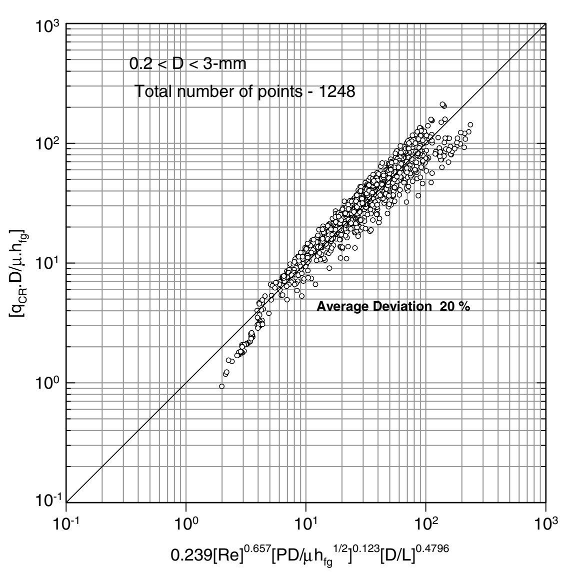

Fig. 3. Validation of correlation ($D < 3$ mm).

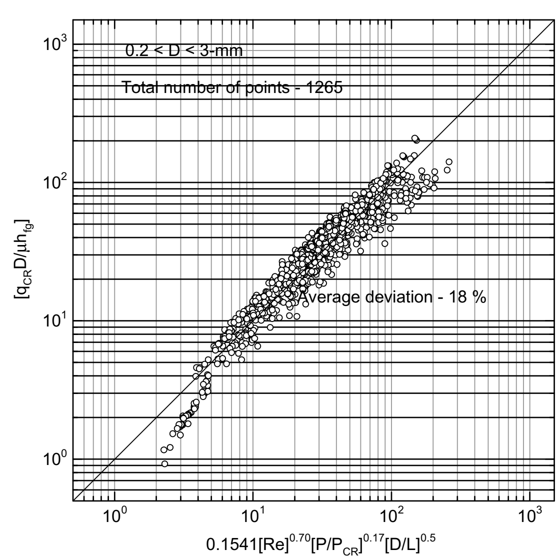

Fig. 4. Correlation for small diameter tubes.

Table 1
General data of all authors

S. no.	Data	Pressure (bar)	Mass flux, G (kg/m^2 s)	q_{cr} (MW/m^2)	Temp, T (°C)	Diameter, D (mm)	L (m)	Count
1	ENEA	1.019–85	9.1673E2 to 4.3139E4	3.8896–60.579	1.14–242	0.584–25.4	6.34e−3 to 6.096E−1	756
2	Boyd [4]	4.5–16.6	7.579e2 to 4.0563e4	1.3959–41.5	18–20	3–10.2	2.897e−1 to 1.17	36
3	Bergles [1]	1.31–22.77	8.438e3 to 4.181E4	18.7–123.8	6–85	0.33–2.67	1.77e−3 to 6.64e−2	210
4	Ornatskii [29]	9–32	5.004e3 to 9e4	6.37–227.95	1–205	0.4–2	1.12e−2 to 5.6e−2	310
5	Knoebel [36]	1.88–7.37	3.9149e−3 to 1.3657e4	3.3327–11.425	0.3–104.8	9.52–9.53	6.096e−1	376
6	Gambill [16]	0.92–85	7.0576e3 to 1.2285e4	7.025–54.338	5–35.85	3.18–7.75	1.91e−2 to 5.842e−1	33
7	Thorgerson [36]	4.458	4.1752e3 to 1.342e4	4.2084–12.383	1–80	3.05–11.7	6.096e−1	42
8	Nariai [28]	1–15	4.3e3 to 2.99e4	4.65–69.89	15–78	1–6	1e−2 to 1e−1	147
9	Zeigarnik [38]	5–30	2.5e3 to 2.06e4	3.478–32.6	0.5–134	3.15–4	8.05e−2 to 2.5e−1	60

system pressures, subcooloing and diameters of the tubes in the range 1–10 mm. The resulting correlation is as follows:

$$\frac{q_{cr}D}{\mu h_{fg}} = 0.483Re^{0.62}\left[\frac{PD}{\mu h_{fg}^{1/2}}\right]^{0.17}\left[\frac{D}{L}\right]^{0.5} \tag{11}$$

Eq. (11) correlated the data with an average deviation of 17%. Eq. (11) is shown plotted in Fig. 5 with all the data points from various sources.

4. Correlation for q_{cr} in the region $x > 0$

When $x > 0$, the hydrodynamics of two-phase flow transits to annular flow regime and the break down of the liquid film can be due to the combined action of the vapor generation due to vapor bubble nucleation on the wall and the shearing action of the lighter phase on the liquid film. Mozarov [26] investigated under adiabatic conditions the critical velocity of the lighter phase that would lead to total entrainment of the liquid from the annular film. It is thought of that a modification of Eq. (5) with some more governing parameters included would respond to the evaluation of critical heat flux when $x > 0$ (Figs. 6 and 7, Table 7).

The governing parameters are listed as follows:

$$\frac{q_{cr}D}{\mu h_{fg}} = F\left\{\left[\frac{PD}{\mu h_{fg}^{1/2}}\right], \left[\frac{L}{D}\right], \left[\frac{GD}{\mu}\right], x, (1-x)\right\} \tag{12}$$

The experimental data (250 points) of Russian investigators, Peskov et al. [27] for a wide range of system conditions have been chosen for obtaining a correlation. The ranges of the data employed are: $100\ \text{ata} < P < 200\ \text{ata}: 0.003 < x < 0.431 : 492 < G < 5545\quad [\text{kg/m}^2\ \text{s}] : 8\ \text{mm} < D < 12\ \text{mm}$. The correlation with an average deviation of ±18% is as follows:

$$\frac{q_{cr}D}{\mu h_{fg}} = 0.000537\left[\frac{PD}{\mu h_{fg}^{1/2}}\right]^{0.48}\left[\frac{L}{D}\right]^{-0.4} \times \left[\frac{GD}{\mu}(1-x)\right]^{0.287}\left[\frac{1-x}{x}\right]^{0.177} \tag{13}$$

Or alternatively with the inclusion of dimensionless number of Mozarov's $\left[\frac{\sigma D\rho_v}{\mu_L^2}\right]$ [26] for the break down of liquid film as on of the determining criteria the following correlation is found to agree with the experimental data with an improvement in average deviation of ±17% and standard deviation of 22%

$$\frac{q_{cr}D}{\mu h_{fg}} = 0.2383\times 10^5\left[\frac{PD}{\mu h_{fg}^{1/2}}\right]^{0.26}\left[\frac{L}{D}\right]^{-0.41}\left[\frac{GD}{\mu}\right]^{0.25} \times [1-x]^{1.831}\left[\frac{\sigma D\rho_v}{\mu_L^2}\right]^{0.46} \tag{14}$$

Table 2
ENEA data for water in vertical channel

S. no	Data	Pressure (bar)	Mass flux, G (kg/m^2 s)	q_{cr} (MW/m^2)	Temp, T (°C)	Diameter, D (mm)	Length, L (m)	Count
1	Data of water in vertical channel	0.953–51	2018.6–49673.8	3.988–67.593	18–80	0.25–8	1e−2–1.6e−1	320
2	Data of R-12 in vertical tubes	6.6–29.27	385.3–1558.2	2.8e−2 to 92.592	26–90	7.72	1.18–2.3	115

Table 3
Data of water in light water reactors

S. no.	Data	Pressure (bar)	Mass flux, G (kg/m^2 s)	q_{cr} (MW/m^2)	Temp, T (°C)	Diameter, D (mm)	Length, L (m)	Count
1	HTFS	140–152	741.2–4311.2	1.5586–4.8114	72.5–280	10–17	1.0008–1.999	85
2	Thompson [35]	33.92–103.24	3808–10,390.4	3.3538–10.1591	199.56–250	10.262	0.762–0.7938	64
3	Lee [25]	38.53–111.24	2040–4161.6	3.9296–7.7225	178.69–252.93	5.588–10.77	0.2159–0.8636	16
4	ENEA	33.46–206.69	512.7–18362	1.1043–14.7654	20–354.03	1.905–37.465	0.0351–1.9717	190

Table 4
Small diameter general data

S. no.	Data	Pressure (bar)	Mass flux, G (kg/m^2 s)	q_{cr} (MW/m^2)	Temp, T (°C)	Diameter, D (mm)	Length, L (m)	Count
1	ENEA	1–23	4.032e3 to 4.3139e4	6–56.808	3–130	0.584–3.07	1e−1 to 2.897e−1	311
2	Nariai [28]	1.01–10.5	4.3e3 to 2.9911e4	4.656–69.89	15–78	1–3	1e−2 to 1.01e−1	124
3	Bergles [1]	1.31–22.77	8.438e6 to 4.181e4	18.7–123.8	6–85	0.33–2.67	1.77e−3 to 6.64e−2	210
4	Ornatskii [29]	9.81–32.54	5.004e3 to 9e4	6.37–227.95	1.5–205	0.4–2	1.12e−2 to 5.6e−2	310

Table 5
ENEA data for small diameter vertical channel

S. no.	Data	Pressure (bar)	Mass flux, G (kg/m^2 s)	q_{cr} (MW/m^2)	Temp, T (°C)	Diameter, D (mm)	Length, L (m)	Count
1	ENEA	1–23	2.923e3 to 4.96738e4	6.8695–67.593	18.6–45	0.25–3	1e−1	90

Table 6
Light water reactor data of various authors for small diameter tubes [37]

S. no.	Data	Pressure (bar)	Mass flux, G (kg/m^2 s)	q_{cr} (MW/m^2)	Temp, T (°C)	Diameter, D (mm)	Length, L (m)	Count
1	ENEA	13.78–190	818.7 to 1.5776e4	1.104–21.4225	52–354	1.14–3	1.143e−2 to 6.96e−1	220

5. Comparison with other correlations

Thus the present regression yielded correlations (7) and (11) for small diameter tubes $D < 3$ mm and for whole range of tubes $0.584\text{ mm} < D < 37.5\text{ mm}$ respectively. These equations are compared in Figs. 8–10 with correlations of authors often referred to in the literature. Fig. 8 indicates that the modified equation of Tong [13] agreed reasonably well with Eqs. (7) and (11) of the present study. Figs. 9 and 10 bring out the analysis of Hall and Mudawar [19] with our Eqs. (7) and (11). One can infer from the close agreement of the present analyses with the correlation of Hall and Mudawar [19] the right choice of system of criteria employed in the regression. However for $D < 3$ mm the present analysis (see Fig. 10) gives very close estimates as can be computed from the correlations of Hall and Mudawar [19]. In the case of slow burnout, the Russian data of Peskov et al. [27] are compared with correlations of Katto et al. [22], Bowring [3] and present equation [14]. With

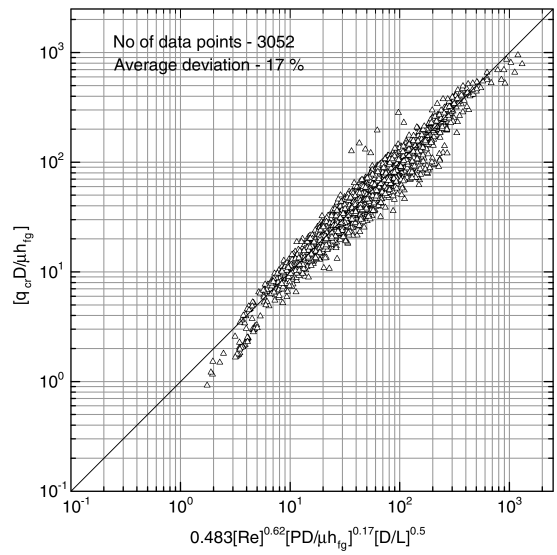

Fig. 5. Validation of correlation of all data (3050 points).

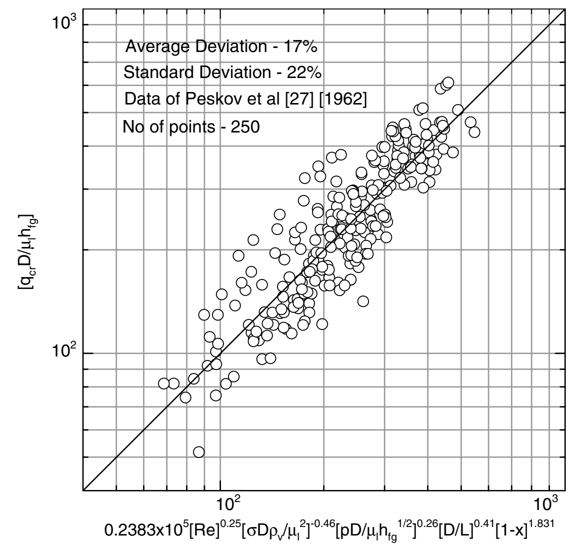

Fig. 7. Correlation for saturated flow boiling.

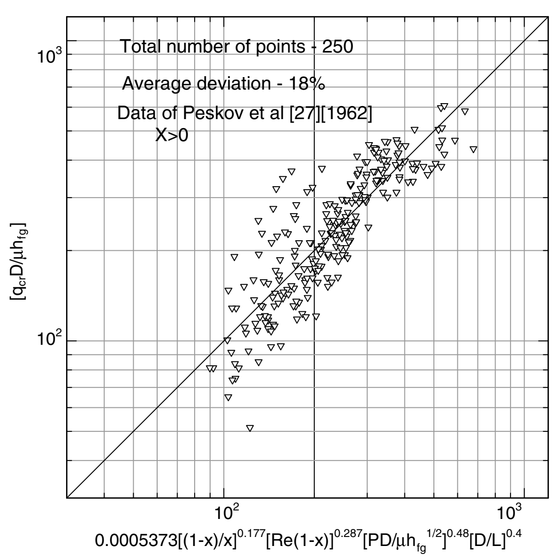

Fig. 6. Correlation for saturated flow boiling.

in the inherent limits of scatter of the experimental data, the line from the present analysis is in the proximate range of the line of predictions from the Katto's correlation (Fig. 11).

6. Conclusions

Thus, from the study the following conclusions can be arrived at

1. The fast burnout data under subcooled conditions of the coolant can be successfully correlated by Eqs. (7) and (11). However, the physical properties are to be evaluated at the inlet temperature of the coolant. Thus the effect of the subcooling of the coolant on critical heat flux is camouflaged and it is implicitly present in the analysis through the physical parameters selected for regression.
2. Correlation equation obtained for small diameter (0.8 mm $< D <$ 3 mm) tubes is found to be applicable to the larger diameters up to 37.5 mm and the same equation holds good.
3. The correlation i.e. Eq. (13) is found applicable to the two-phase annular flow systems i.e. $x > 0$. Introduction of the surface tension parameter of Mozarov gave an improved correlation i.e. Eq. (14) purporting the model that the onset of critical conditions might be due to the combined effect of heat flux and high velocity vapor leading to physical destruction of the liquid film.

Table 7
Data of water for saturated flow boiling ($x > 0$)

S. no.	Data	Pressure (ata)	Mass flux, G (KG/m^2 s)	q_{cr} (MW/m^2)	Dryness fraction, X	Diameter, D (mm)	Length, L (m)	Count
1	Peskov et al. [27] For water in horizontal tubes	100–200	491.67–5541.67	0.58–4.923	0.003–0.431	8–10	0.25–2.1	250

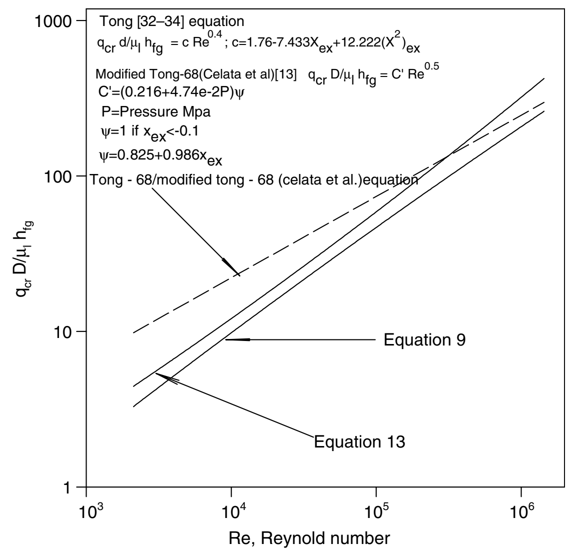

Fig. 8. Comparison of present analysis with Tong analysis [13,32–34].

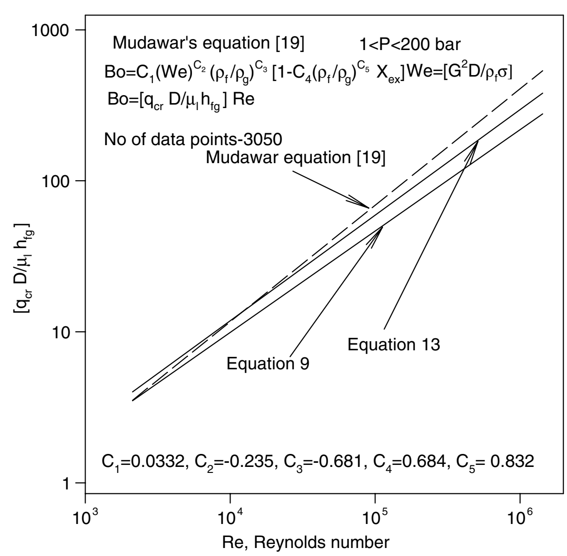

Fig. 9. Comparison of present analysis with Mudawar analysis.

Appendix A

As per the suggestion of the reviewers, regression analysis is carried out at the time of submission of revision including the subcooling parameter $[C_p(T_s - T_i)/h_{fg}]$ as one of the determining criteria in the system. The following correlation with a marginal improvement in average deviation of 17% could be achieved with subcooling parameter included in the system. Hence, the

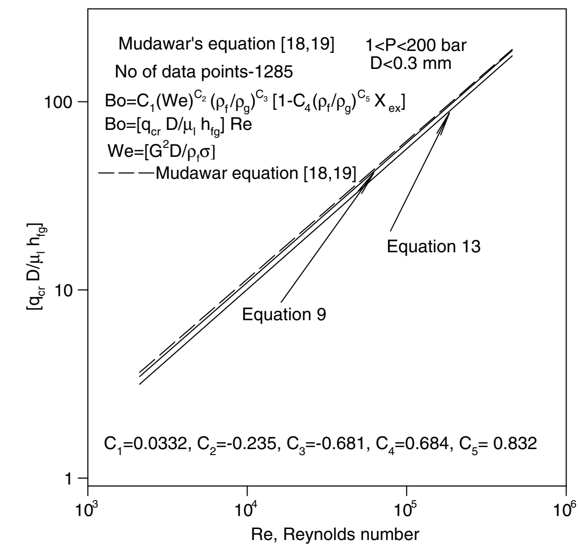

Fig. 10. Comparison of present analysis for small diameter with Mudawar analysis [18,19].

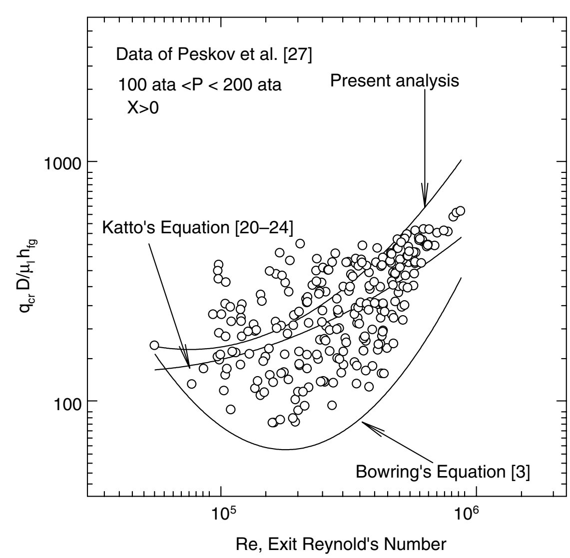

Fig. 11. Comparison of present equation for saturated flow with equations of Katto and Bowring [3,20–24,27].

physical properties evaluated at T_i might take into account effectively the subcooling effects of the coolant on critical heat flux.

$$\frac{q_{cr}D}{\mu_l h_{fg}} = 0.118Re^{0.77}\left[\frac{P}{P_{cr}}\right]^{0.2}\left[\frac{D}{L}\right]^{0.45}\left[\frac{C_p(T_s - T_i)}{h_{fg}}\right]^{0.216} \tag{9A}$$

The validation of correlation (9A) is shown in the Fig. 12 depicting the deviations as indicated in the figure.

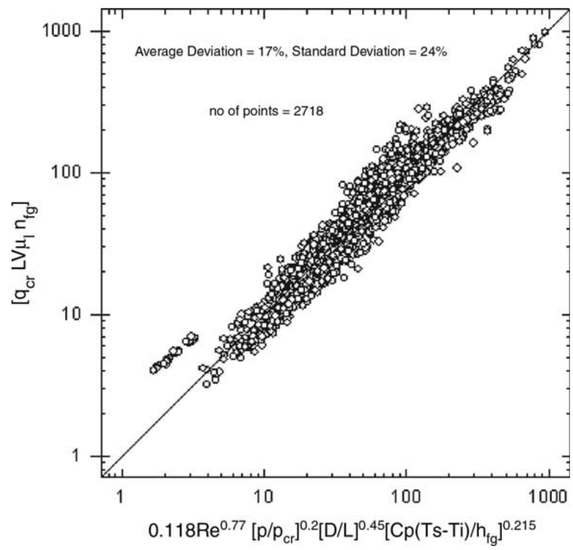

Fig. 12. Validation of correlation with data.

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