Updating of the models for critical heat flux calculation in annular-dispersed flow

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Abstract. This study presents updating of two existing physical models of dryout in annular-dispersed flow regime according to the updated data of the experimental studies. Relations for critical heat flux at high mass vapour qualities, in two ranges of mass flow rates were considered. The calculation results were compared with the critical heat flux look-up tables at full range of mass flow rates. The comparing showed satisfactory agreement of results in the ranges of regime parameters $0.6 \leq x \leq 0.9$; $50 \leq \rho_\omega \leq 8000$ kg m$^{-2}$s$^{-1}$; $0.1 \leq p \leq 20$ MPa.

1. Introduction
Despite the complexity of the phenomenon of boiling crisis in forced flow, or dryout, there is some progress has been made over the last decades. This applies above all to the departure from nucleate boiling (DNB), due to the fact that mechanism of DNB has become clearer. The relations obtained on the basis of models [1, 2] allow calculation of CHF at both subcooled and saturated liquids in a wide range of pressures and mass flow rates with practical application accuracy.

Successes in studying the mechanism of critical heat flux (we will use «burnout» designation) in annular-dispersed flow regime, when mass vapour quality is high enough, do not seem so obvious to us today. This is primarily due to the most complicated processes of moisture exchange between the disperse core of the flow and a wave-shaped, boiling or smooth (depending on the regime parameters) liquid film on the wall accompanying the burnout.

Multiple attempts to propose a burnout mechanism [3, 4], including the variety of phenomena accompanying it (droplets entrainment from the ridges of the waves into the core of the flow, droplets deposition out of the core flow or their deposition by the opposite flow of steam formed during the evaporation of the film) to obtain a reliable calculation model, do not bring full understanding of the dryout phenomena.

This paper is proposed to verify the existing models [5, 6]. This necessity is caused by major changes in the work [7], which was published 11 years after the first publication of the CHF look-up tables [8]. Among the main differences, the authors have noted:
- Increased amount of experimental data (33 sets more);
- Introduction of «smoothing» of table values on the basis of a new statistical model, resulting in a change of CHF values up to 20%;
- new criteria for the selection of experimental points, which made it possible to remove from consideration 25% of the points considered in the first version of the CHF look-up tables.
Thus, the only available way to confirm the operability and relevance of existing models [5, 6] is to verify and re-analyse the results.

2. Critical heat flux models
Below is a brief description of the existing models, outlining the physical basis.

2.1. Case of «high» mass flow rates
The first of two considered special cases is the dryout in annular-dispersed flow at mass vapour quality $0.6 \leq x \leq 0.9$ and at high flow velocities, in the range $3000 \leq \rho \nu \leq 8000$ kg m$^{-2}$ s$^{-1}$ [5]. In this case, the liquid film on the wall is smooth, has a small thickness and does not boil, therefore we suggest there is no droplet entrainment from the film surface. The onset of the crisis in such conditions was often called a crisis of hydraulic resistance [6], because with increasing vapour quality friction pressure losses decreased. It is supposed that in pre-crisis mode the liquid film is forming by droplets falling on the wall from the dispersed core. Since at high flow velocities the droplets are less than the viscous sublayer thickness, their kinetic energy is insufficient to overcome the viscous sublayer (with liquid droplets moving along the wall) and reach the wall. Therefore, droplets can fall on the wall only at the moment of breaking down (renewal) of the viscous sublayer [9], which occurs periodically at intervals $\tau^*$, s:

$$\tau_* = 110 \nu^*/\left(u^*_f (\rho^*/\rho^f)^n\right),$$  \hspace{1cm} (1)

where $\rho^*$ and $\rho^f$ is liquid and vapour density, kg m$^{-3}$; $(\rho^*/\rho^f)^n$ is an empirical correction factor that takes into account additional dissipation of turbulent energy due to flow dispersion; $u^*_f$ friction (dynamic) velocity, m s$^{-1}$; $\nu^f$ is vapour kinematical viscosity, m$^2$ s.

The liquid film formed on the wall evaporates up to the next renewal of the viscous layer. Therefore, the film thickness varies periodically from some maximum to minimum value. This should lead to periodic changes in the wall temperature, which has been repeatedly observed in experiments to study CHF in annular-dispersed flow regimes. If liquid film evaporates completely during the period $\tau^*$, it will lead to burnout. The CHF in this case can be determined as:

$$q_{cr} = \rho^f \frac{\delta_{LF}}{\tau_*},$$  \hspace{1cm} (2)

where $\delta_{LF}$, m, is the maximum thickness of the film formed by droplets deposited on the wall when the viscous substrate is renewed. It is determined by the size of droplets $d_h$ and the number $N_{dep}$ of droplets deposited on the wall in a certain section of the channel at the moment of viscous layer renewal:

$$\delta_{LF} = N_{dep} \frac{d_h^2}{4d_{dr}},$$  \hspace{1cm} (3)

where $d_h$ is tube hydraulic diameter, m; $d_{dr}$ is droplet mean diameter, m.

It is assumed that the number of droplets falling on the wall is proportional to the total number of droplets in the flow $N_{dr}$ at some section of the channel. It can be determined by the expression:

$$N_{dr} = F_h - F_{LF} - \phi F_h = \left(\frac{d_h}{d_{dr}}\right)^2 (1-\phi) - \frac{4 F_{LF}}{\pi d_{dr}},$$ \hspace{1cm} (4)

where $F_h$ and $F_{LF}$ are respectively the channel cross-sectional area and the part of the channel cross-sectional area occupied by the liquid film before droplets deposited from the flow; $\phi$ is volume vapour quality.
Since droplet deposition to the wall occurs at the moment of the next viscous layer renewal, when the evaporating film is the thinnest, the second component in (4) can be neglected and (3) can be converted to form with constant $C_1$:

$$\delta_{LF} = C_1 N_{de} \frac{d_t^2}{d_h} = C_1 d_h (1 - \varphi) .$$

(5)

Since the hydraulic resistance coefficient is calculated as for a turbulent flow in a tube with smooth walls ($\xi = 0.25 \times 0.316 \text{Re}^{-0.25}$), the dynamic gas velocity in (1) can be calculated with the expression:

$$u_* = w^* \sqrt{\frac{2}{8}} = 0.2 \frac{w^*}{v^*} \frac{d_t^2}{d_i^2} .$$

(6)

The volume vapour quality can be calculated with:

$$\varphi = \left(1 + \frac{1 - x \rho^*}{x \rho^*} \right)^{-1} .$$

(7)

Expression (7) does not take into account phase slippage. That may be acceptable assumption in the conditions when the droplets are small, their shape is close to spherical, and their mass velocity is high.

Taking into account (1), (5) and (6), expression (2) is converted to form:

$$q_{dp} = C_1 \tau \left( \frac{d_t}{v^*/\rho^*} \right)^{0.75} \left( \frac{\rho^*}{\rho} \right)^{0.8} \rho w^{1.75} (1 - \varphi) .$$

(8)

2.2. A case of «low» mass flow rates

The second of the special cases presented in [6] is discussed below.

Conditions are considered when annular-dispersed regime with a high vapour quality is formed in the channel ($x = 0.6 \pm 0.9$) and low mass fluxes $50 \leq \rho_0 \leq 3000 \text{ kg m}^{-2} \text{ s}^{-1}$. In this case it can be assumed that there is a thin, smooth, unboiling liquid film on the wall, which is formed by droplets deposited out of the core flow. Liquid droplets move in the turbulent core and their size determined by the flow velocity. When large droplets fall out of the film, spatter (secondary droplets) may be knocked out, some of which are carried back into the flow core. This process is accompanied by reduction in film thickness.

The "massive" droplets under consideration should exceed the thickness of the viscous layer, which plays the role of a layer separating the steam turbulent core of the flow and the thin liquid film on the wall. The thickness of the viscous layer can be estimated as: $\delta_v = 10 v^*/u_*$ where $u_*$ is dynamic velocity for the steam core of the flow; $v^*$ is kinematic viscosity of the steam. In this case, at the moment of intrusion of large turbulent vortex into the wall layer, droplets of liquid will fall out on the surface of the channel, forming a liquid film. The invasion period of such vortexes is determined by the channel diameter $d_t$ and average flow velocity $\omega$, m s$^{-1}$ [9]:

$$\tau = \frac{d_t}{\omega} (1 - \varphi)^n ,$$

(9)

where $(1 - \varphi)^n$ is the correction factor taking into account laminarization of the dispersed flow due to the presence of liquid droplets in its vapour core.

As the first approximation, we can assume that the number of droplets falling on the wall $N_{dep}$ is proportional to the total number of droplets in the flow ($C_1 N_{de}$) in a certain channel section. We can define $N_{de}$ similarly to the previous case from (4).
When deposited droplets collide with the surface of the film, secondary droplets (splashes) are formed, some of which can be entrained away by the flow. Their quantity can be estimated as:

\[ N_{\text{ent}} = \frac{N_{\text{dep}} \rho' u_{\text{dr}}^2 \delta_{\text{LF}}}{\sigma (1 - \phi)}, \quad (10) \]

where \( u_{\text{dr}} \) is the velocity of droplets deposited on the film from the core of the flow, m s\(^{-1}\); \( \delta_{\text{LF}} \) is the thickness of the liquid film, m; \( (1 - \phi) \) takes into account the resistance to droplets (splashes) carried by droplets falling on the film.

The thickness of the film formed by droplets deposited on the wall at the moment of intrusion into the wall layer of the turbulent vortex excluding secondary droplets (splashes) carried away by the flow is determined from the expression:

\[ \delta_{\text{LF}} = \left( N_{\text{dep}} - N_{\text{ent}} \right) \frac{d_{\text{dr}}^2}{d_{\text{h}}} - \left( N_{\text{dep}} - C_2 N_{\text{dep}} \rho' u_{\text{dr}}^2 \delta_{\text{LF}} \right) \frac{d_{\text{dr}}^2}{d_{\text{h}}} \]

or

\[ \delta_{\text{LF}} = C_1 \left[ \frac{d_{\text{h}}}{d_{\text{dr}}} \right]^2 \left( 1 - \phi \right) - \frac{4 F_{\text{LF}}^0}{\pi d_{\text{dr}}} \left( 1 - C_2 \rho' u_{\text{dr}}^2 \delta_{\text{LF}} \right) \frac{d_{\text{dr}}^2}{d_{\text{h}}} \cdot \]

Assuming that the droplets deposited on the wall form a film with thickness \( \delta_{\text{LF}} \) that is much thicker than the initial one \( \delta_{\text{LF}}^0 \), the component \( \frac{4 F_{\text{LF}}^0}{\pi d_{\text{dr}}} = 4 \delta_{\text{LF}}^0 \frac{d_{\text{h}}}{d_{\text{dr}}} \) can be neglected and the expression for \( \delta_{\text{LF}} \) converted to:

\[ \delta_{\text{LF}} = C_1 \frac{d_{\text{h}} (1 - \phi)}{1 + C_1 ' d_{\text{h}} \rho' u_{\text{dr}}^2 \sigma}, \quad (11) \]

where \( C_1 ' = C_1 C_2 \).

If the liquid film evaporates completely during the period \( \tau \), it will lead to burnout. The CHF in this case can be determined from the expression:

\[ q_{\text{cr}} = \rho \tau \delta_{\text{LF}}. \quad (12) \]

Using (9) and (12), assuming \( \rho \approx u_{\text{dr}} \approx \rho_{\text{v}} \), and neglecting «1» we get expression for CHF:

\[ q_{\text{cr}} = C_1 \rho \tau \frac{(1 - \phi)^{1 - \phi}}{d_{\text{h}} \rho_{\text{v}}}. \quad (13) \]

3. Comparison with experimental data

3.1. Matching conditions

The case of high mass velocities was compared with the experiment by calculating using (8) 660 values \( q_{\text{cr}} \) for pressures \( p = 0.1 \div 21 \text{ MPa} \), vapour qualities in range \( x_{\text{cr}} = 0.6 \div 0.9 \) and the mass velocities \( \rho_{\text{v}} = 3000 \div 8000 \text{ kg m}^{-2}\text{s}^{-1} \). The structure of the annular-dispersed flow represented in the CHF model meet the case of these regime parameters with best corresponding.
The case of «low» mass velocities was compared with the experiment by calculating with (13) of 280 experimental values \( q_{cr} \) for the pressures \( p = 10 \div 21 \text{ MPa}, \ x_{cr} = 0.6 \div 0.9 \) and \( \rho_0 = 50 \div 3000 \text{ kg m}^{-2}\text{s}^{-1} \).

For definition of constants \( n, C_1 \) in (8) and (13) the data of CHF look-up tables [7] have been used.

### 3.2. Comparison results

Numerical results are the values of constants in the formulas for \( q_{cr} \), as well as arithmetic-mean and root-mean-square errors \( \sigma_{rms} \) and \( \sigma_{am} \) given in table 1. More of 90% of the CHF look-up table data for each flow variant deviate from the calculated ones by no more than 36%.

**Table 1. Results of comparison of calculation models by look-up tables 1995 [8].**

| Flow variant                  | \( n \)  | \( C_1 \)  | \( \sigma_{rms} \) | \( \sigma_{am} \) |
|-------------------------------|---------|------------|-------------------|------------------|
| High mass fluxes – 1995       | 0.20    | 3.2 \times 10^{-9} | -0.024            | 0.26             |
| Low mass fluxes – 1995        | 0.50    | 1.0 \times 10^{-2}  | 0.190             | 0.53             |
| High mass fluxes – 2006       | 0.18    | 2.4 \times 10^{-9}  | 0.340             | -0.10            |
| Low mass fluxes – 2006        | 0.05    | 6.0 \times 10^{-3}  | 0.354             | -0.12            |

At a choice between various variants of constants with similar sums of \( \sigma_{rms} \) and \( \sigma_{am} \) distribution of quantity of the relative deviations by their values \( \Delta = q_{cr}/q_{exp} - 1 \) where \( q_{exp} \) is value by CHF look-up tables [7]. These distributions submit as histograms are shown in figures 1 and 2.

![Figure 1. «High» mass speeds. Distribution of quantity \( n \) deviations \( \Delta = q_{cr}/q_{exp} - 1 \) by their values (total 660 points).](image1)

![Figure 2. «Low» mass speeds. Distribution of quantity \( n \) deviations \( \Delta = q_{cr}/q_{exp} - 1 \) by their values (total 280 points).](image2)

The character of the obtained data, namely, the form of histograms closes to the normal distribution form and having a maximum in the adjacency of the zero error, suggests that the statistical significance of experimental values is important, and the choice of such constants \( n \) and \( C_1 \) provides the greatest accuracy new points will be calculating.
Figure 3. Comparison of data [7] with calculations by (8) at $p = 0.5$ MPa and $\rho_0 = 8000$ kg m$^{-2}$ s$^{-1}$.

The analysis of the comparison results was carried out separately for each of the flow variants («high» and «low» mass velocities).

In figure 3 in coordinates $q_{cr} - x$ the comparison of 2006 look-up tables data for water [7] with the calculation results for (8) for annular-dispersed flow is shown. Example of «high» mass fluxes is given. The results of the comparison suggest that the ratios (8) and (13) at the range of vapour qualities $x = 0.6 \div 0.9$ and at relative pressures over the $p/p_{cr} \geq 0.5$ work for the full range of mass velocities. According to the figure, for some regime parameters the model works for mass vapour qualities up to $x = 0.2$.

Figures 4 — 6 show as an example the results of comparing the data of 2006 CHF look-up tables [7] with the calculations for (8) and (13) over the full range of mass velocities for different pressures.

Figure 4. Comparison of data [7] with the calculation by (8) at $p = 0.5$ MPa and $x = 0.6 \div 0.9$.

Figure 5. Comparison of data [7] with the calculation by (8) and (13) at $p = 12$ MPa and $x = 0.6 \div 0.9$.

Figure 6. Comparison of data [7] with the calculation by (8) and (13) at $p = 16$ MPa and $x = 0.6 \div 0.9$. 
As can be seen from the figures 5 and 6, the character of the CHF dependence on $p$, $x$ and $\rho_w$ is correctly described within the regime parameters specified in subsections 2.1 and 2.2. This indicates fundamentally correct physical basis inherent in the model.

4. Conclusion
The presented quantitative and qualitative results of models verification give satisfactory results in the wide range of pressures and mass fluxes of water: $p = 0.1 \div 20$ MPa, $\rho_\omega = 50 \div 8000$ kg m$^{-2}$ s$^{-1}$.

In the study the data of CHF look-up tables for high vapour quality in the area of annular-dispersed regimes are analyzed. Relevance of the calculation methodology for new experimental data is shown. New values of constants for model correlations as well as deviations from experimental data are calculated.

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