Critical heat flux calculation model for tubes with twisted tapes

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Abstract. A new method for calculating the heat transfer crisis in tubes with twisted tapes on the basis of the existing physical model of CHF for nucleate boiling is presented. The change of CHF in case of using twisted tapes is taken into account by introducing of correction factors to the existing model. Verification of the present model has been carried by checking out of existing experimental works with data on CHF with a total of 187 points. The model gives good agreement with the experiment in a wide range of parameters.

1. Introduction
One of the directions in the development of new methods of heat removal is using of heat transfer intensifiers including swirl promoters. The analysis of works devoted to modeling the crisis in flows with a swirl inserts has shown that the authors prefer modifications of existing physical models for smooth tubes.

In these works, there is no satisfactory physical description of critical heat flux (CHF) dependence on regime parameters. For example, it is impossible to find in results the maximums and minimums on the dependences of CHF by mass flux $q_{cr} = f(\rho \omega)$ at a constant values of vapour quality at the moment of crisis $x_{cr}$ that are clearly visible in CHF look-up table data [2].

It is proposed to modify the existing and proven in smooth tubes physical model of CHF burnout, developed by S. V. Zakharov and Yu. M. Pavlov in MPEI to make it suitable for the calculation of CHF in tubes with twisted tapes.

2. Base physical model

2.1. Physical justification of the base model
The physical model [1] is based on the assumption that steam conglomerates can form on the heat-exhausting surface as a result of individual bubbles merging. Between the steam conglomerate and the wall there is a thin liquid film with some thickness $\delta_{LF}$.

It can be assumed that the time of the conglomerate's presence on the wall or the time of existence of the liquid film under it is limited either by the period of intrusion into the wall layer of large-scale turbulent vortices, or by periodic renewal of the laminar layer due to its internal dynamic instability.
The onset of the crisis (burnout) is associated with the drying of the liquid film under the steam conglomerate during the period of conglomerate’s existence near the heat-transfer surface $\tau$. The CHF in this case can be expressed as:

$$q_{ct} = \frac{r' \rho' \delta_{LF}}{\tau}.$$  \hspace{1cm} (1)

An important assumption is the conditional division of the mass velocity range into «low» and «high» velocity ranges corresponding to $d_0 > \delta_{LF}$ and $d_0 < \delta_{LF}$, where $d_0$ is the bubble departure diameter and $\delta_{LF}$ is viscous layer thickness correspondingly. It was found that in the relative pressure range $p/p_{ct} > 0.5$ there is local minimum on the dependences $q_{ct} = f(p\rho_0)$ corresponds to constant value of mass velocity increasing with decreasing pressure and corresponding to equality $d_0 = \delta_{LF}$ with high accuracy. Criteria for transition between these velocity regions have been developed. Further calculations are based on investigation of expressions for flow dynamic velocity $u^*$ and for the period of turbulent vortexes intrusion into the wall area $\tau$:

$$\tau \approx \frac{d_h}{u_e},$$  \hspace{1cm} (2)

where $d_h$ is hydraulic diameter of the tube.

The question of the existence of such a temporal scale of turbulence has been studied previously, for example, in [3, 4].

2.2. Applicability of the base model

The discussed model is now the only explaining character of dependence of CHF on regime parameters in wide range of stream mass fluxes.

The range of applicability is limited by the range of the slug flow regime existence at relative pressures of $0.05 \leq p/p_{ct} < 0.5$ and the range of volume vapour quality of $0 < \varphi < 0.65$.

The final expression for the calculation $q_{ct}$ is:

$$q_{ct} = C_1 \frac{r \cdot \rho' \cdot \tau_{01,02}}{C_2 \cdot \rho\cdot \varphi \cdot \sigma \cdot T_s \cdot d_{01,02}^{1/2}},$$  \hspace{1cm} (3)

and allows iterative methods to quickly determine $q_{ct}$. In (3) $r$ is specific heat of evaporation, $J \cdot kg^{-1}$; $T_s$ is saturation temperature, $K$; $\lambda'$ is liquid thermal conductivity coefficient $W \cdot m^{-1} \cdot K^{-1}$; $\sigma$ is surface tension, $N \cdot m^{-1}$; $\tau_{01,02}$, $s$, and $d_{01,02}$, $m$, is period of turbulent vortexes intrusion and bubble departure diameter for «low» and «high» mass fluxes correspondingly «1» and «2»; $\rho'$ and $\rho''$ is liquid and vapour density, $kg \cdot m^{-3}$; $C_1$ and $C_2$ are constants.

The proposal about the influence of period $\tau$ is the main assumption adopted for model development. Low deviations from experimental values confirm the correctness of this assumption.

About 90% of the data of CHF look-up tables, which do not belong to the slug flow, at calculation on [1] have a RMS of 0.200. The discussed model gives convincing results including comparison with experimental data at boiling of nitrogen, helium, various freons and on various geometries of the channel.

3. Amendments to the physical model

3.1. Review of existing practices

From the beginning of the study of the boiling crisis near 1960 to the present day, attention has been paid to various mechanisms for intensifying the heat transfer and pull away dryout, including the use of twisted tapes. The most complete lists of such works are given in [5, 6].
3. The main reason why the tape insert increases the CHF value compared to smooth tubes with the same mass flux $\rho \omega$ and channel diameter $d_h$ is a change in the flow structure: the centrifugal acceleration caused by channel twisting and the increased axial velocity compared to smooth tubes contribute to a more intensive phase mixing and irrigation of the channel wall.

The tape insert into the channel acts as a displacement, reducing the cross-sectional area of the channel, which leads to increased velocity, as well as reducing the hydraulic diameter of the channel. Therefore, in order to make the base model correspond to conditions of using the twisted tape in the round tube, it is proposed to introduce the most obvious corrections here: correction of the tube hydraulic diameter $d_h$ and correction for mass flux $\rho \omega$.

3.2. Hydraulic diameter correction factor

In available CHF studies in a tube with a twisted tape, the hydraulic diameter was calculated identically, without taking into account the twisting, assuming that a straight tape was inserted into the tube:

$$d_h = \frac{4 \cdot F}{P} = \frac{4 \cdot (\pi \cdot d^2 / 4 - \delta \cdot d)}{\pi \cdot d + 2 \cdot d - 28},$$

(4)

where $F$ is tube cross sectional area, $m^2$; $P$ is tube wetted perimeter, m; $d$ is inner diameter of tube, m; $\delta$ is tape thickness, m.

It is suggested to write down the expression for hydraulic diameter in «volumetric» form, which allows taking into account the tape twisting:

$$d_{h,\text{vol}} = \frac{4 \cdot V}{F} = \frac{4 \cdot \left( \frac{\pi \cdot d^2}{4} \cdot t - S \cdot \delta \right)}{\pi \cdot d \cdot t + 2 \cdot S - 2 \cdot \delta \cdot L_{TT}},$$

(5)

where $V$ is volume, $m^3$; $L_{TT}$ and $S$ is the length and the surface area of the twisted tape, calculated for the helicoid screw figure:

$$S = 2 \cdot \pi \left[ \sqrt{r^2 + b^2} \ln \frac{r + \sqrt{r^2 + b^2}}{b} \right], \quad b = \frac{t}{2 \pi} = \frac{d \cdot y}{\pi}.$$

The twist ratio $y = H_{180^\circ} / d_h$ is length for $180^\circ$ turning divided by inner diameter of the channel.

![Figure 1](image)

**Figure 1.** Dependence of the hydraulic diameter on the twist ratio for a screw insert with a thickness of $\delta = 1$ mm for $d_h = 8$ mm.

Dependence $d_{h,\text{vol}}(y)$ on figure 1 shows that in the range $y < 2$ ratio of tape area to the volume it closes is large. It is to be expected that the effect of twisting is not linear in this range; this is taken into account by using the $d_{h,\text{vol}}(y)$ in the new model.
3.3. Correction factor for flow rate

From a general understanding of the processes occurring during nucleate boiling in the channel, it is clear that the increase in heat dissipation when the flow is swirled by means of tape is due to the following factors:

- by increasing near-wall velocity;
- by rearranging the flow and the appearance of secondary currents and vortices;
- by increasing the turbulence of the flow.

The basic model used in this study already takes into account the influence of the axial flow velocity on its structure in the form of dependencies of dynamic velocity \( u^* \), hydraulic resistance coefficient \( \xi (\rho, \omega) \) and frequency of steam conglomerates outlet \( \tau (\rho, \omega, u^*) \). Assuming about the effect of secondary currents generated by twisting does not violate the physical assumptions of the base model, it is expected that the correction factor for flow rate will be sufficient to correctly describe the physical phenomena at twisting.

There are several options to make changes to the near-wall (parietal) velocity due to the presence of twisted tape in the channel. Gambill and Jaehwan [10, 11], as well as Tong [12] calculate the velocity near the tube wall using:

\[
\omega_{sw} = \omega \cdot \left( \frac{4y^2 + \pi^2}{2y} \right)^{\frac{1}{2}},
\]

where \( \omega_{sw} \) and \( \omega \) is near-wall velocity in swirled and smooth flow, m s\(^{-1}\).

Authors Hata, Masuzaki [13] introduce the correction factor for value of \( q_{cr} \) in a smooth tube based on a single correction for velocity in the parietal area:

\[
\omega_{sw} = \omega \cdot \frac{\pi d^2}{\pi d^2 - 4w\delta} \cdot \left( \frac{4y^2 + \pi^2}{2y} \right)^{\frac{1}{2}}.
\]

In [14] the expression for the \( \omega_{sw} \) is obtained by analysis of the law of conservation of momentum in the tube with a swirl tape. Omitting theoretical calculations, the result is recorded as:

\[
\omega_{sw} = \omega \cdot \frac{1}{\pi + 2} \left[ \pi \cdot \sqrt{1 + A^2} + A \left( \sqrt{1 + A^2} + A^2 \cdot \ln \left( A + \sqrt{1 + A^2} \right) \right) \right],
\]

where \( A = \frac{2\pi R_h}{H} = \frac{\pi}{2y} \).

The calculation for each of options above gives a value \( \omega_{sw} / \omega \) in the range of 1.34-1.72 at \( y = 1 \) and in the range of 1.06-1.28 at \( y = 4 \), refer to figure 2.

![Figure 2](image_url)  
**Figure 2.** Velocity correction factors given by (6) – (8) in a tube with \( d_h = 8 \) mm with tape thickness \( \delta = 1 \) mm.
Expression (8), in opposition to the above, takes into account tape thickness and width as known parameters. Comparing expressions (6) – (8) to determine the flow velocity and with further CHF calculation using (3), this correction factor showed the best agreement with the experimental data. It was accepted in new model for CHF calculation in tubes with swirl tapes.

4. Comparing the calculations with experimental data

4.1. CHF data sampling in twisted-tape tubes

The initial review involved all data of CHF in round tubes with twisted tapes regularly heating along the tube length. Since the range of regime parameters that meet the previously accepted assumptions of the base model is limited, only points that meet the criteria are accepted for the verification calculation: \( p \geq 1 \) MPa and \( 0 < \varphi < 0.65 \).

The collected array of experimental data is divided into two: with uniform heating of tubes around the circumference of the circle (heating angle 360°, 95 points) and with partial heating (heating angles 90, 180, 270 degrees, 92 points in total). Thus, to verify the proposed model, a database of experimental values \( q_{cr,sw} \) included in total 187 points from 7 studies was prepared.

Table 1 shows the list of data sets and the boundary values of parameters in sets.

| Source                      | \( p_{cr} \) (MPa) | \( \rho_{oo} \) (kg m\(^{-2}\) s\(^{-1}\)) | \( x_{cr} \) | \( d_{h} \) (mm) | \( q_{cr} \) (MW m\(^{-2}\)) | \( \varphi \) (%) | Number of points |
|-----------------------------|--------------------|------------------------------------------|-----------|----------------|-----------------|----------------|-----------------|
| Data for subcooled liquid   |                    |                                          |           |                |                 |                |                 |
| Viskanta [15]               | 13.8               | 680...1360                               | -0.06...-0.0 | 8              | 4.0...4.9      | 16...34        | 10/0            |
| Araki [16]                  | 1.0...1.49         | 4060...1398                              | -0.36...-0.28 | 7              | 19.8...39.6   | 0...27         | 0/7             |
| Euroatom [17]               | 1.0...3.6          | 3000...16000                             | -0.13...-0.46 | 10,14,18      | 16.8...68.6   | 0...61         | 0/42            |
| Kinoshita [18]              | 1.1...1.5          | 4600...9000                              | -0.16...-0.24 | 6              | 14.3...28.9   | 1...5          | 7/31            |
| Inasaka [12]                | 0.10               | 6400...11500                             | -0.06...-0.08 | 6              | 7.3...14.1    | 1...4          |                 |
| Malakhovsky [19]            | 1.0                | 1100...9900                              | -0.22...-0.31 | 4              | 11.4...51.0   | 0...10         | 0/12            |
| Data for saturated liquid   |                    |                                          |           |                |                 |                |                 |
| Kisina [20]                 | 14.7...20.1        | 2030...2800                              | 0.22...0.44        | 11,14         | 0.8...1.7     | 59...63        | 11/0            |
| Viskanta [15]               | 13.8               | 680...2700                               | 0.01...0.25       | 8              | 2.2...5.0     | 27...64        | 35/0            |
| Mayinger [21]               | 6.8...9.8          | 2340...3590                              | 0...0.15         | 7              | 3.5...6.2     | 43...65        | 32/0            |
| Data for subcooled and saturated liquid |         |                                          |           |                |                 |                |                 |
| All                         | 1.0...20.1         | 680...16000                              | -0.36...0.44      | 4...18        | 2.2...68.6    | 0...65         | 110/93          |

4.2. Analysis of calculation results

The proposed method tends to underestimate the values in \( q_{cr,sw} \) in relation to the experimental data \( q_{cr,sw} \). The single largest deviations from experimental values were +37% and -65% in the direction of excess and undervallation respectively.

Comparison of calculation results with experimental data is shown in figure 3 and figure 4. It shows almost all points with non-uniform heating were to the right of the equality line of calculated and experimental values, i.e. they were underestimated. This can be explained by the data [18]: the CHF value is greater with uneven heating around the tube circumference than with uniform heating. At the same time the authors could not reveal dependencies \( q_{cr,sw} = f(\beta) \). Known models and calculation methods for \( q_{cr,sw} \) do not introduce special corrective factors depending on the angle \( \beta \). Figure 4 is similar to the previous one except for the scale of the axes.
The RMS and arithmetic mean errors of the calculation are summarized in Table 2.

| Set of points                        | Quantity of points | RMS error | Ar. mean error |
|--------------------------------------|--------------------|-----------|----------------|
| Separation of the array of points on the basis of unheated / saturated liquids |                    |           |                |
| Low mass fluxes – 1995               | 0.50               | 1.0·10^{-2} | 8.0·10^{-4}   |
| High mass fluxes – 2006              | 0.18               | 2.4·10^{-9} | -              |
| Division of an array of points by heating method |                    |           |                |
| Uniform heating of the tube (360°)   | 110                | 0.335     | -0.125         |
| Uneven heating (90, 180, 270°)       | 93                 | 0.315     | -0.171         |
| All points                           | 203                | 0.33      | -0.15          |

According to Table 2, the method shows good accuracy of calculation \( q_{cr,sw} \) in the conditions ranges mentioned above. The dependence from the heating angle and liquid state is almost imperceptible.

The ratio \( q_{cr,sw} / q_{cr} \) indicating the «delay» of CHF onset in tubes with a twisted tape in comparison with smooth tubes at the same mode parameters, according to the results of calculations by [1] and by the present method was from 1.1 to 1.4. These data are in agreement with the majority results of studies on boiling in tubes with swirl promoters, for example [22]. However, some researchers extend the range \( q_{cr,sw} / q_{cr} \) to 1.7 at high mass velocities.

5. Comparison with existing models

In order to assess the calculation quality of the developed model, calculations were made using other known models designed to assess the CHF in tubes with swirl promoters. Due to the large amount of scientific literature on this issue, this section cannot claim to be a complete review of existing methods and approaches. The results of calculations based on the data of the most cited works or giving the smallest error in calculation are presented.

The list of sources is presented in Table 3.

The value of arithmetic and RMS errors, number of calculation points (according to corresponding limitations in the table 3) are shown in Table 4.
The data of table 4 allow to make the conclusion about proposed model provides the greatest accuracy of calculation within the limits of pressure and vapour quality, competing in the value of error only with Inasaka work or with the generalizing formula of Krug, Kuzma-Kichta.

6. Conclusions
A new model for calculating the CHF in tubes with twisted tapes based on the existing CHF calculation model for nucleate boiling is presented.

The low RMS error of the calculation results confirms the reliability of the physical model accepted as the basis and the physical justifications of the adopted correction factors. The pattern of deviations from the experimental values indicates the possibility of making clarifications associated with the details of hydro- and thermodynamic conditions at boiling in a channel with a twisted tape. Especially it concerns the behavior of the model at high heat and mass fluxes.

The model gives a quite satisfactory result in a wide pressures range for water \( p = 1 \div 22 \) MPa, with no restrictions on other regime parameters, except for the volume vapour quality \( \varphi = 0 \div 65\% \), so have a significant advantage over other considered methods.

Further development of theoretical research devoted to the development of reliable physical models on this issue largely depends on the appearance of new experimental work on the heat transfer crisis.

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