# Comparative analysis of film boiling correlations for steam explosion problem

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**Abstract.** The article considers the existing models and correlations for describing heat transfer during film boiling. Film boiling is an important thermophysical process that determines the course of interaction of the melt of reactor core materials with the coolant, which can potentially occur during a severe accident at a nuclear power plant with a pressurized water-cooled reactor (VVER/PWR). The values of the Nusselt number predicted by these models are compared. A fairly significant dispersion of calculated parameters has been established, making it difficult to unambiguously choose one or another correlation. However, in the range of parameters typical for the interaction of a high-temperature melt of reactor core materials with a coolant, several correlations give quite close values, which allows them to be recommended for use in calculation codes for modeling thermal-hydraulic processes during a severe accident at a nuclear power plant with VVER/PWR type.

## 1 Introduction

With the development of a severe accident at nuclear power plants (NPPs) with light water reactors of the VVER/PWR type, direct contact of the melt of materials of the reactor core with the coolant can occur. When two liquids come into contact with significantly different temperatures, when the temperature of one of the liquids significantly exceeds the boiling point of the other, under certain conditions, a rapid boiling of a cold liquid occurs, accompanied by a rapid increase in pressure and expansion of the zones of their thermal interaction. This phenomenon, referred to as "steam explosion", represents a significant hazard as it can lead to significant dynamic forces on the reactor and containment structures and pose a threat to their integrity. In connection with the possible release of radioactive fission products, this phenomenon is being actively studied in the world's leading research centers specializing in the field of nuclear energy safety [1-2].

Since the temperature of the melt is much higher than the boiling point of the liquid, at the initial stage of a steam explosion, a vapor film is formed on the surface of the melt, separating the melt from the coolant. The presence of a vapor film on the surface of the melt significantly reduces the intensity of heat transfer between the melt and water and

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contributes to the creation of a quasi-equilibrium explosive mixture "melt-steam-liquid", which can exist for a relatively long time (1–10 s), allowing the melt to mix with a large amount of liquid. To date, quite a lot of experimental and theoretical studies of film boiling have been carried out and various semi-empirical correlations have been proposed to describe this phenomenon. Film boiling can be realized under various geometric conditions (boiling on a sphere, cylinder, horizontal/vertical plane, etc.) and under various thermophysical parameters (pressure, temperature, liquid velocity, etc.). Therefore, correlations obtained for some conditions may give incorrect results when applied in other conditions. This paper provides a comparative analysis of the available semi-empirical correlations for heat transfer during film boiling for conditions typical of steam explosions that occur during a severe accident at a nuclear power plant.

## 2 Materials and methods

Heat transfer correlations during film boiling, as a rule, represent a system of rather complex formulas, including the calculation of various quantities. Therefore, only brief information about the considered correlations is given here.

Frederking-Clark correlation [3]. These authors theoretically considered film boiling near a hot sphere immersed in a large volume of water at saturation temperature. An expression was obtained for the Nusselt number, which characterizes the heat transfer coefficient of the sphere and depends on the diameter of the sphere. However, the experimental data that they used to compare with the resulting formula showed no dependence on the diameter of the sphere (in the experimental range of parameters). Therefore, two formulas have been proposed:

$$Nu=C\left[ArPr_v\left(h'_{lv}/c_{pv}\Delta T_{sup}\right)\right]^n \tag{1}$$

Where $C=0.586$ and $n=0.25$ (theory) and $C=0.14$ and $n=0.33$ (experiment).

Here $Nu=\alpha_c D/\lambda_v$ – Nusselt number, $Ar=g(\rho_l-\rho_v)D^3/\left(\rho_v v_v^2\right)$ – Archimedes number, $Pr_v=c_{pv}\mu_v/\lambda_v$ – Prandtl number, $h'_{lv}=h_{lv}+0.5c_{pv}\Delta T_{sup}$ – latent heat of vaporization plus sensible heat; $\alpha_c$ – heat transfer coefficient, $D$ - diameter of sphere, $\rho$ – density, $h_{lv}$ – latent heat of vaporization; $\mu$ – viscosity, $v=\mu/\rho$ – kinematic viscosity, $\lambda$ – thermal conductivity, $c_p$ – heat capacity, indexes: $l$ – liquid, $v$ – vapor.

Hendricks-Baumeister correlation [4]. These authors found that the configuration of the interface and the dynamics of vapor removal are largely determined by the relative size of the sphere, characterized by the Bond number $Bo=(\rho_l-\rho_v)gR^2/\sigma$, $R=0.5D$ – radius of sphere. The mathematical model includes the Navier-Stokes equation for the vapor flow in the film, the continuity equation and the energy equation. The resulting correlation covers the entire range of sphere diameters from small to large:

$$Nu=2+0.2\left[-0.7\left(Ar/Sp'\right)G(Bo)\right]^{0.25}+\left\{0.2\left[\left(Ar/Sp'\right)G(Bo)\right]^{0.25}+\csc\theta'(Bo)\right\}\left[1+\cos\left(\theta'(Bo)\right)\right] \tag{2}$$

Where $Sp'$ – dimensionless superheat, $\theta'$ – the angle at which the thin film turns into the bubble, $\gamma$ – parameter characterizing the "thickness" of the bubble, $G(Bo)$ – dependence given by the authors in graphical form. $\theta'$ also depends on $Bo$ (the dependence is also given in graphical form).

Klimenko correlation [5]. An approach based on the division of spheres into small and large ones, which makes it possible to take into account various steam evacuation mechanisms, was used. Relations were obtained for film boiling near a sphere, in which the power law 1⁄4 is used for the laminar regime of vapor flow, and the law 1⁄3 for the turbulent regime:

$$Nu = 0.7 Ar^{0.25} Pr_v^{0.33} f_1(K) \ for \ Ar < 3\times10^7 \tag{3}$$

$$Nu = 0.175 Ar^{0.33} Pr_v^{0.33} f_2(K) \ for \ Ar \ge 3\times10^7 \tag{4}$$

$f_1(K)$, $f_2(K)$ – empirical functions on $K = h'_{lv}/c_{pv}\Delta T_{sup}$ .

Dhir-Purohit correlation [6]. Based on the results of experimental studies, these authors summarized the data in the form of empirical correlations:

Natural convection:

$$Nu = Nu_{sat} + C_r Nu_r + Nu_{nc}\left(Sc\mu_l\right)/\left(Sp\mu_v\right) \tag{5}$$

Where $Nu_{sat} = 0.8\left[Ar/Sp\right]^{0.25}$, $Nu_r = \alpha_r D/\lambda_v$, $Nu_{nc} = 0.9\left[GrPr_l\right]^{0.25}$, $C_r$ – parameter dependent on thermophysical properties and temperature values.

Forced convection:

$$Nu = Nu_{sat} + 0.8 Re_l^{0.5}\left[1+\left(Sc\mu_l\right)/\left(Sp\mu_v\right)\right] \tag{6}$$

Large subcooling:

$$Nu_{sub} = 0.977 Re_l^{0.5} Pr_l^{0.5}\left(Sc\mu_l\right)/\left(Sp\mu_v\right) \tag{8}$$

In the general case, the formula was provided:

$$Nu = \left(Nu_{sat}^4 + Nu_{sub}^4\right)^{0.25} \tag{9}$$

For practical application, the authors recommended introducing a correction factor of 2.04 into (9).

In the MC3D code, the Epstein-Hauser correlation is used in a slightly modified form [8]:

$$Nu = 2\left[\left(0.5 Nu_{sat}\right)^4 + Nu_{sub}^4\right]^{0.25} \tag{10}$$

Shih-El-Wakil correlation [9]. These authors carried out an investigation of film boiling of subcooled freon near small spheres under conditions of natural convection. Their mathematical model included the equations of continuity, momentum, and energy for a vapor film near a sphere and a liquid layer adjacent to the interface in the boundary layer approximation. Based on parametric calculations, the authors obtained the following expression:

$$Nu/Nu_{sat} = 1 + 13.91\left(Sc\,Gr/Ar\right)^{0.39} \tag{11}$$

Where $Sc$ - dimensionless subcooling, $Gr = g\beta_l(T_s - T_l)\left(D^3/\nu_l^2\right)$ – Grashof number.

The correlation of Michiyoshi et al. [10]. The relations were given for the heat transfer coefficient during film boiling of a subcooled liquid under conditions of natural convection, suitable for a vertical plate, a horizontal cylinder, and a sphere, obtained using an integral analysis of the problem of vapor film flow near a hot surface and liquid layer motion near the interface.

$$Nu = K\left(Ar/Sp^{'}\right)^{0.25} M_c^{0.25} \tag{12}$$

Where $M_c$ is a rather complex function of $Sc^{'}$, $Sc^{'}$, $Pr_l$.

$C = 0.5R^2 Sp^{'} Pr_l$, $Sc^{'} = c_{pl}\,\Delta T_{sup}/h_{lv}^{'}$, $K = 0.696$ for sphere.

Liu-Theofanous correlation [11]. These authors carried out a comprehensive experimental and computational study of film boiling on spheres and obtained a universal correlation describing heat transfer in a wide range of parameters - natural/forced convection and saturated/subcooled liquid. The authors considered the problem in a fairly complete formulation: a vapor film is described in the boundary layer approximation, a boundary layer is distinguished in the liquid near the interface, and the liquid flow outside the liquid boundary layer is considered potential. As a result, the following correlation was obtained:

$$Nu = \left\{Nu_p^5 + \left[f(Fr)Nu_{sat}\right]^5\right\}^{0.2} \tag{13}$$

Where $Nu_p$, $Nu_f$ are the Nusselt numbers for pool film boiling and forced convection conditions, respectively; empirical function $f(Fr)$ was introduced for smoothing the transition from the film boiling regime in a large volume to the forced convection regime; the Froude number is defined as $Fr = U_\infty^2/gD$. Relations for these parameters are presented in [11].

Kolev correlation [12]. He developed a model of film boiling on a vertical plate and then generalized it to a sphere. In the case of a vertical flat plate, Kolev obtained an analytical expression relating the various components of the heat flux from the plate surface:

$$q_{FB}/q_{FB,0} = \left[1 + \left(q_r - q_l - q_v\right)/q_{FB,0}\, q_{FB}/q_{FB,0}\right]^{-1/m} \tag{14}$$

Where $q_{FB}$ is the heat flux through the vapor film due to thermal conductivity (subcooled liquid), $q_{FB,0}$ is the heat flux through the vapor film due to thermal conductivity (saturated liquid), $q_r$ is the heat flux by radiation, $q_l$ is the heat flux from the interfacial surface of the liquid-vapor to subcooled liquid, $q_v$ – heat flow for steam heating, $m$ – parameter depending on film boiling conditions ($m$=2 - forced convection, $m$ = 4 - natural convection).

Kolev suggested that a similar relationship is also valid for film boiling on a sphere. Therefore, for $q_{FB,0}$, $q_r$, $q_l$ and $q_v$, he selected the appropriate correlations and determined the heat flux $q_{FB}$.

## 3 Results

The graphs below provide information on the similarities and differences between the film boiling models described above.

Figure 1a shows a comparison of correlations for film boiling on a sphere of saturated liquid in a pool. A dimensionless group is plotted along the ordinate axis, independent of the diameter of the sphere:

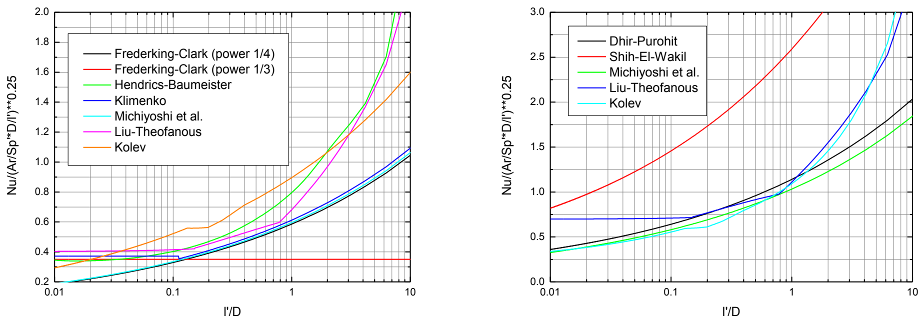
$$Nu/(Ar/Sp^{'} D/l^{'})^{0.25} = \alpha_c \left[ h_{lv}^{'} g \lambda_v \rho_v (\rho_l - \rho_v)/l^{'} \mu_v \Delta T_{sup} \right]^{-0.25} \qquad (15)$$

Along the abscissa axis is a dimensionless value $l^{'}/D$, inversely proportional to the diameter of the sphere. $l^{'} = \sqrt{\sigma/g(\rho_l - \rho_v)}$ – capillary length, $\sigma$ – surface tension, $g$ – gravity, $\Delta T_{sup} = T_w - T_s$ – superheat of solid wall.

For $l^{'}/D > 0.15$, the dependence of the dimensionless group on the diameter disappears for all models except for Frederking-Clark and Michiyoshi et al., in which the Nusselt number is determined proportionally to $Ar^{0.25}$. In the range $0.1 < l^{'}/D < 1.0$, most of the dependencies are close to each other, the Kolev correlation is located noticeably higher. At $l^{'}/D > 1.0$, the Liu-Theofanous, Hendricks-Baumeister and Kolev models rise quite sharply.

Figure 1b shows a similar comparison of correlations for film boiling of a subcooled liquid on a sphere in a pool. The Shih-El-Wakil correlation lies much higher than the others. In the range $0.1 < l^{'}/D < 2.0$, all other correlations lie quite close to each other. At $l^{'}/D > 2.0$, the Liu-Theofanous and Kolev dependencies deviate upward from the rest of the correlations.

Figure 2 compares the correlations for film boiling of a liquid on a sphere under conditions of forced convection at various degrees of subcooling of the liquid to the saturation temperature. The behavior of the Dhir-Purohit dependence differs markedly from other correlations, which are relatively close to each other. The Epstein-Hauser correlation is given in its original form (9), multiplied by 2.04, and in a modified form (10).



(a) (b)

**Fig. 1.** Comparison of pool film boiling correlations. Pressure 1 bar, $\Delta T_{sup}$ =1000 K, $D$ =10 mm. (a) saturated liquid, (b) subcooled liquid ( $\Delta T_{sup}$ =40 K).

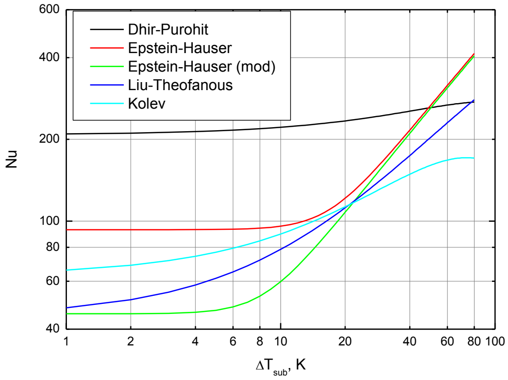


**Fig. 2.** Comparison of pool film boiling correlations. Pressure 1 bar, $\Delta T_{sup}$ =1000 K, $D$ =10 mm, $U_l$ =1.5 m/s.

## 4 Discussion

Qualitative coincidence in behavior is observed for all considered correlations. As can be seen from Figure 1, all correlations predict that the heat transfer characterized by a dimensionless group, which includes the Nusselt number, increases as the diameter of the sphere decreases (the parameter $l^{'}/D$ increases). Similarly, Figure 2 shows that an increase in subcooling contributes to an increase in the Nusselt number, which characterizes heat exchange during film boiling. Consider the quantitative discrepancies. The value of $l^{'}$ in the pressure range 1-50 bar varies from 2.5 mm to 1.8 mm. The characteristic sizes of droplets formed by the interaction of a high-temperature melt with water are ~ 1 - 30 mm, which approximately corresponds to the range $0.1 < l^{'}/D < 1.0$. If we discard the correlations of Kolev, Shin-El-Wakil and Frederking-Clarck (power 1/3), then in this parameter range all other correlations predict the values of the Nusselt number with an accuracy of ± 25%, which corresponds to the accuracy of experimental measuring instruments. From our point of view, it is preferable to use the Liu-Theofanous correlation, which gives "median" values. However, the correlations of Frederking-Clark (power 1/4), Hendrics-Baumeister, Klimenko, Michiyoshi et al. and Epstein-Hauser also give quite acceptable results.

## 5 Conclusion

Film boiling has been studied for a long time both theoretically and experimentally. Quite a lot of models/correlations have been proposed to describe heat transfer. The comparison carried out in this paper shows a very significant dispersion of data obtained from these correlations. However, in the range of parameters typical for the interaction of the melt with the coolant, a number of correlations can be identified that allow for fairly accurate prediction of the values of the heat transfer coefficient. It is most preferable to use the Liu-Theofanous correlation, which gives "median" values.

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