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Thermal state of a heating element under impulse heating

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The paper describes the calculation procedure of heating element thermal state based on the experimental study of heating element thermal processes under impulse heating in a subcooled pool. This procedure can be used to analyze the thermal state of the reactor fuel element in case of accidents with unauthorized introduction of excessive reactivity in process of core loading and accidents in pool-type reactors.

1. Introduction
Nuclear reactors accidents related to unauthorized introduction of excessive reactivity leading to a self-sustaining fission chain reaction are characterized by rapid increasing of core power rate. Despite the following sharp decrease of the reactor power because of negative feedback the amount of the energy stored in the heating elements can be sufficient to fully or partially melting of the core. As a result of accidents with a self-sustaining fission chain reaction that took place on reactors and critical assemblies different states of heating elements were observed: complete destruction and melting or preservation of tightness [1]. Therefore, for consequence analysis of reactivity accidents are necessary to describe correctly the process of heat transfer from heating element to coolant.

2. Experimental study of the thermal state of the heating element with a pulse increase in power

2.1. The design of the experimental facility
An experimental study of thermal state of heating element under impulse heating was carried out in the experimental facility "Impulse" [2, 3]. The schematic of the experimental facility is shown in figure 1.

![Figure 1. Schematic of the experimental facility "IMPULSE."](image-url)
The experimental facility includes an electrically heated stainless steel rod (heating element) with a diameter of 6 mm and a length of 0.22 m. Two electrically insulated thermocouples are mounted on the heating element outer surface at a distance of 0.02 m from each end and 2 potential wires which are used to determine the average temperature of the heating element by the electrical resistance between two points. Correspondently, during the experiment are measured electric power rate, surface and average rod temperatures. These parameters were measured both during heating element warming and 10 seconds after the power was switched off. The recording of the measured parameters synchronized with the power-on signal.

The experimental facility was filled with water at a temperature of 20 °C.

Power density in the heating element being 3-7.2 kW/cm$^3$ with impulse duration 0.5 – 2 s.

2.2. Results of the experimental study

The main factor determining the temperature state of the heating element is the presence (see figure 5) or absence (see figure 6) of the burn up effect. In case of the burn up take place a sharp increase in the surface temperature of the heating element which occurs after transient from nucleate boiling to film boiling stage (transient to post-CHF heat transfer stage).

Approximately 1 second after the power switch off, heat transfer significantly exceeds the values corresponding to film boiling stage. Such a rapid changing of boiling stages is associated with the instability of film boiling along the heating element with the disappearance of internal heat release.

3. Calculation procedure of the heating element temperature state

The calculation procedure is based on a one-dimensional heat conductivity equation describing heat transfer inside the heating element which is solved through numerical finite-difference method and relationships defining heat transfer on the outer surface of the heating element (see figure 2). The relationships consider all heat transfer modes on the heating element outer surface under impulse warming in cold water, heat transfer to the one-phase coolant, nucleate boiling, transition and film boiling at post-CHF stage. The calculation procedure also considers instable film boiling after of internal heating release.

**Convection [4]**

$$\text{Nu}_{\text{conv}} = CRa_m$$

where $Nu$ - Nusselt number, $Ra$ – Rayleigh number

**Nucleate boiling [5]**

$$\text{Nu}_{\text{NB}} = C Re^a Pr^2$$

where $Nu_{\text{NB}} = \frac{q_{\text{NB}} L_s}{\Delta T_0}$, $Re = \frac{\varphi \rho \Delta L}{\eta}$, $L_s = \frac{c_p \rho' \sigma T_0}{(\alpha + \rho')^2}$

$Re$ – Reynolds number, $Pr$ – Prandtl number

**Transient boiling**

$$\lg q_w = \lg q_{cr1} - \lg \left( \frac{T_w}{T_{cr1}} \right) \lg \left( \frac{q_{cr1}}{q_1} \right) \left( \lg \left( \frac{T_{np}}{T_{cr1}} \right) \right)^{-1}$$

where $q_{cr1} = q_{cr10} \left( 1 + 0.1 \left( \frac{\rho'}{\rho} \right)^{1/4} \right)$

$$q_{cr10} = 0.16 \sqrt{\rho'} \left( \frac{\sigma g (\rho' - \rho)}{\rho} \right)^{1/4}$$

**Film boiling [6]**

$$\alpha_{FB1} = 0.39 \left( \frac{\rho_m (\rho' - \rho_m)}{\rho_m (T_{W} - T_0)} \right)^{1/4} L_s$$

where

$$L_s = \frac{c_p \rho' \sigma T_0}{(\alpha + \rho')^{1/2}}$$

**Instable film boiling [7]**

$$\text{Nu}_{\text{f}} = 0.545 Re^{0.28} A_{\text{f}}^{-0.042} - 0.07$$

Figure 2. Logic chart for wall heat transfer regime.
It should be especially noted that the use of the traditional approach to the description of heat transfer which does not take into account the instability of film boiling when the internal energy releases does not allow to reduce the heating element surface temperature for the time interval observed in the experiment (see figure 5).

The existence of film boiling on the surface of the heating element depends on the value of the heat flux that is supplied to the outer surface from inside the heated body. This effect explains the instability of the film boiling regime when internal heating in the element ceases [8, 13].

At present, there are two approaches to the consideration of unstable film boiling (analyzing the evolution of a vapor wave film take into consideration the periodic contact a heating surface by a liquid [8,9-13] or not one[7]). For practically significant values of heat fluxes, the condition of the periodic contact the heating surface by liquid is always satisfied (see figure 3).

The results of experimental studies [9-11] of burn up effect and film boiling show the anomalously high heat fluxes (up to 10 MW/m²) at the heating surface in the case of subcooling water more than 30 degrees. Apparently, this phenomenon is explained by the contact of a highly heated surface with a liquid followed by explosive boiling. In this case, there is a periodic change of heat transfer modes (see figure 4): nucleate boiling during the time \( \tau_{cr} \) and film boiling with a duration \( (T_v - \tau_{cr}) \). However, an attempt to explain the rapid decrease of the heating element surface temperature within the framework of this approach leads to a contradiction: the obtained values of \( \tau_{cr} \) are much longer than the time required for the fusion of vapor nucleates into the vapor film when the liquid touches a highly superheated surface.

It should be recognized that to date there is no correct theory of unstable film boiling, therefore, in this case empirical correlations should be used.

In this paper, to calculate the heat transfer under unstable film boiling after of internal heating release it is used correlation:

\[
Nu_a = 0.545 \ Re_j^{0.25} \ Ar_{s}^{-0.042} - 0.07
\]

where \( Re_j = j l_v / \nu \), \( Ar_{s} = (l_a / l_v)^3 \) – Archimedean number [7].

![Figure 3. Wave surface for film boiling [7]](image)

![Figure 4. Periodic change in the heat transfer coefficient for unstable film boiling](image)

4. Results of experiments and calculation

The Figures 5-6 show a comparison of the experimental data obtained on the facility “Impulse” with the results of the calculation. The calculations were performed both with allowance for the film boiling instability effect (curve 1) and without one (curve 2). From the figures it follows that in the calculations it is necessary to take into account the instability of film boiling after internal heating release.
5. Conclusion
The results of calculations based on the calculate procedure developed in this paper satisfactorily agree with the experimental data on the pulse heating of the heating element in subcooled water. The proposed calculate procedure takes into account the experimentally confirmed fact that post-CHF film boiling along the heating element is unstable with the disappearance of internal heating.

The procedure of calculating can be used to analyze the thermal state of the reactor fuel element in case of accidents with unauthorized introduction of excessive reactivity in process of core loading and accidents in pool-type reactors.

6. References
[1] Maklafin T, Monakhan Sh, Pruvost N, Frolov V, Ryazanov B, Sviridov V 2003 *Overview of nuclear criticality accidents* (New Mexico: Los Alamos National Laboratory) p 210
[2] Kudinovich I V 2009 *The temperature state of a heating rod simulator with pulsed heating* Proc. of the Krylov State Scientific Center vol 45 pp 135-144
[3] Kudinovich I V 1998 *The temperature state of a heating element simulator in standing cold water with its pulse heating* Proc. of the Second International Conference on Shipbuilding ISC’98 section D (St. Petersburg) pp 210-216
[4] Kirillov P, Yuryev Yu S, Bobkov V P 1984 *Handbook of thermohydraulic calculations (nuclear reactors, heat exchangers, steam generators)* (Moscow: Energoatomizdat) p 296
[5] Galin N M, Kirillov P L 1987 *Heat and mass transfer (in nuclear power engineering)* (Moscow: Energoatomizdat) p 376
[6] Budov V M, Samoilov O B, Sokolov V A 1988 *Heat transfer at film boiling at a vertical surface with a constant heat flux* (Moscow: Atomic energy) vol 65 issue 3 pp 173-176
[7] Gogonin I I, Shemagin I A, Budov V M 1993 *Heat transfer at film condensation and film boiling in the elements of the equipment of the atomic power station* (Moscow: Energoatomizdat) p 208
[8] Koshkin V K, Kalinin E K, Dreitser G A et al. 1973 *Non-stationary heat transfer* (Moscow: Mechanical engineering) p 328
[9] Leskin M A 2009 *Investigation of the film mode of heat exchange and the effect of burn up during the boiling of an underheated liquid* PhD thesis (Moscow) p 176

[10] Thei Lwin W 2007 *Unsteady heat exchange and the boiling the effect of burn up of water under the conditions of a rapid change in energy release* PhD thesis (Moscow) p 140

[11] Zar Nee Aung 2013 *The patterns of heat transfer and the boiling the effect of burn up in water, underheated to saturation temperature* PhD thesis (Moscow) p 141

[12] Deev V I, Kruglov V B, Kutsenko K V, Lavrukhin A A, Thehey Lwin U, Kharitonov V S 2005 *Experimental and theoretical study of the heat transfer the effect of burn up under the conditions of a rapid change in the heat dissipation capacity* Proc. of the 4th International Scientific and Technical Conference "Ensuring the Safety of Nuclear Power Plants with WWER” (Russia: Podolsk)

[13] Grigoryev V S, Zhilin V G, Zeigarnik Yu A., Ivochkin Yu P., Glazkov V V, Sinkevich O A 2005 *Behavior of a vapor film on a highly overheated surface submerged in underheated water* vol 43 issue 1 pp 100-114