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HEAT TRANSFER IN BOILING OF WATER IN A FILL OF SPHERICAL ELEMENTS

V. V. Lozovetskii

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An experimental study has been made of heat exchange in bubble and transient regimes of boiling in spherical-element fills as applied to the cores of nuclear reactors with spherical fuel microelements based on uranium dioxide with multilayer ceramic coatings. Critical dependences describing experimental data and making it possible to calculate the heat-transfer coefficient in such regimes of boiling have been obtained.

Heat exchange in different regimes of boiling in fills of spherical elements, particularly fuel micro- and macroelements 2 to 60 mm in diameter, has attracted scientists' recent attention in connection with the possibility of using them in WWERs [1–3].

In the present work, we have investigated heat transfer in bubble (nucleate) and transient regimes of boiling in a fill of spherical lead elements 3 mm in diameter. A diagram of the experimental setup is presented in Fig. 1. It consisted of the working portion 5 manufactured from ebonite, which made it possible to bring the spherical-element temperature up to 300°C in the experiments. The inside diameter of the working portion was 30 mm and the length was 75 mm. A supporting grid with seven holes of diameter 5 mm was installed in its lower part; the holes were covered with a high-porosity net above which a fill of spherical lead elements 3 mm in diameter was arranged. For its fixation the spherical elements were held down from above by a grid analogous in structure.

Water entered the working portion from an overflow pressure tank 1, traversing heat exchanger 8 in which it was heated to a temperature 2 to 4°C lower than the saturation temperature T_s. In the working portion, water was heated to T_s by heat exchange with the spherical-fill elements heated by high- or ultrasonic-frequency currents; the currents were generated by inductor 7 powered by a high-frequency-current system or a UZG-4-type ultrasonic generator 11. The evaporated water was condensed in a cooling coil 9 and was collected in condenser 10. The constancy of the water flow rate was ensured by maintaining the level of liquid in the pressure tank; the flow rate was changed by varying this level in the sinking or lifting of the overflow pipe. After the corresponding measurements, the water was discharged from the condenser to the sewer system.

During the experiments conducted at atmospheric pressure, we measured the water temperature using chromel-coppel thermocouples of diameter 0.1 mm. Three analogous thermocouples were installed in three cross sections along the height of the working portion of radially arranged spherical elements; from the readings of the thermocouples, we determined the average surface temperature of the spherical elements T_w. The emf of the thermocouples was measured using KSP-4 (cl. 0.25) *2* or PP-63 3 devices. The experimental bench had additional equipment used periodically: a thermostat, an inclined micromanometer, stop and control valves, etc. The heat flux was calculated from the amount of the evaporated water according to the formula

$$Q = rm_{\text{wat}} .$$

The value of m_{wat} was determined from the amount of water in the condenser over the corresponding period of time. It is noteworthy that such a method of determination of the heat flux Q is quite accurate, since the quantity of heat utilized in heating of water to the saturation temperature T_s did not exceed 20% of the quantity of heat going to evaporate it. A detailed evaluation of the error of determination of the heat flux with such a technique showed that it did no exceed 17% and amounted to 1.5 to 10% in most experiments.

Moscow State University of Forest, 1ya Institutskaya Str., Mytishchi, Moscow Region, 141005, Russia; email: lozovetsky@mail.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 80, No. 4, pp. 35–39, July–August, 2007. Original article submitted December 19, 2005; revision submitted April 6, 2006.

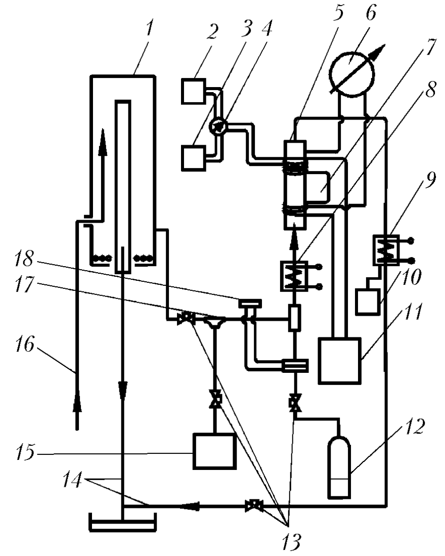

Fig. 1. Diagram of the experimental bench: 1) overflow pressure tank; 2) KSP-4; 3) PP-63; 4) thermocouple switch; 5) working portion; 6) piezometers; 7) inductor; 8) heat exchanger; 9) cooling coil; 10) condenser; 11) UZG-4 generator; 12) vessel; 13) RC valves; 14) discharge to the sewer system; 15) thermostat; 16) supply from the water pipe; 17) T-joint; 18) inclined micromanometer.

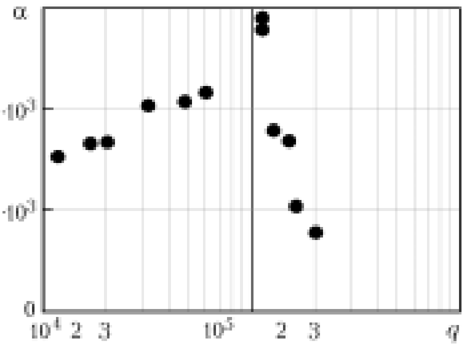

Fig. 2. Heat-transfer coefficient vs. heat-flux density. α, W/(m·K); q, W/m.

During the experiments, the basic parameters characterizing heat transfer in the spherical-element fill varied within the following range: T_{wat} varied from 96 to 100°C; pressure p was $\cong 10^5$ Pa; the surface temperature of the spherical elements T_{w} varied from 101.5 to 150.9°C, heat-flux density q — from $1.159 \cdot 10^4$ to $2 \cdot 10^5$ W/m^2, and water flow rate m_{wat} — from $0.3 \cdot 10^{-3}$ to $10.6 \cdot 10^{-3}$ kg/sec; the steam quality β calculated as the ratio of the mass of the steam formed in the channel m_{st} to the mass of water in the channel $m_{\text{wat.ch}}$ amounted to 1.74 to 58.5%.

Processing of experimental data showed that, when the differences of the surface temperature of spherical elements and the saturation temperature $\Delta T_{\text{s}} = T_{\text{w}} - T_{\text{s}}$ were small, the heat-transfer coefficient α increased with heat-flux density (Fig. 2). It is noteworthy that the surface temperature was determined from the readings of the thermocouples installed, as has been indicated above, in the spherical elements in three cross sections along the working-portion height as their average value according to the formula

$$T_{\text{w}} = \sum_{i=1}^{n} T_{\text{w}i}/n , \quad n = 9 .$$

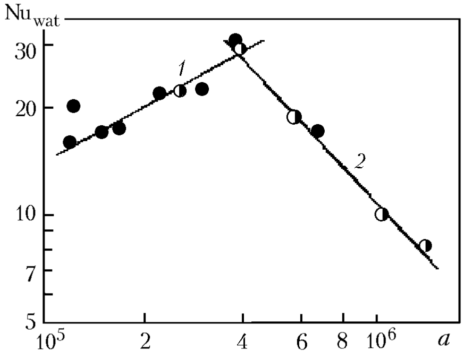

Fig. 3. Nu_{wat} number vs. number a: 1 and 2) bubble and transient regimes of boiling respectively:

$$a = \left[\frac{d_{sph}}{\sqrt{\dfrac{\sigma}{g\,(\rho_{wat} - \rho_{st})}}}\right]^{0.9} \left[\frac{r}{C_{eq}\Delta T_s}\right]^{n} \mathrm{Pr}_{wat}^{\;2.73} \left(\frac{\lambda_{eq}}{\lambda_{wat}}\right)^{m} .$$

An increase in the heat-transfer coefficient with heat-flux density was noted to $q \sim (1.09–1.1)\cdot 10^5$ W/m^2 (Fig. 2). It is assumed that, up to this instant, the regime of boiling in the spherical fill was of the bubble type, in which the heat-transfer coefficient increases with heat-flux density, as in the case of pool boiling. This is due to the growth in the number of nucleation sites on the surface of spherical elements and to the increase in the velocity of motion of the steam medium because of the increase in the steam quality. In the case of boiling of a liquid under the conditions of forced motion in the spherical fill, heat is transferred from the heating surface to the core by steam bubbles formed on it and by convection of the liquid. The quantity of heat transferred by the steam is mainly dependent on the heat-flux density on the sphere surface. In the case of low steam qualities the quantity of heat transferred by convection of the liquid is determined by the circulation velocity.

Depending on the relation of the heat-flux density and the circulation velocity the contributions of boiling (transfer of heat by steam bubbles) and convective transfer in the process of heat transfer will be different. For small circulation velocities the heat-transfer coefficient is virtually independent of velocity, is determined mainly by the process of boiling, and grows with heat-flux density (Fig. 2). As the circulation velocity increases, the influence of the heat-flux density on the heat-transfer coefficient gradually becomes insignificant and its dependence on the circulation velocity begins to manifest itself.

In sufficiently developed boiling, when the content of steam near the spherical-element surface becomes considerable, the high intensity of heat transfer in bubble boiling is determined by the low thermal resistance of a thin liquid film which is left on the heat-transfer surface itself. The effective thickness of this layer of liquid decreases with increase in the heat load, which causes the heat-transfer intensity to increase.

An analysis of the quantities influencing the boiling in this region in the transient regime of boiling, too, has shown that the heat-transfer coefficient can be expressed by the functional relationship between the Nusselt number and a number of dimensionless numbers as follows:

$$\mathrm{Nu}_{wat} = f\left[\frac{d_{sph}}{\sqrt{\dfrac{\sigma}{g\,(\rho_{wat} - \rho_{st})}}}\,;\ \frac{r}{C_{eq}\Delta T_s}\,;\ \mathrm{Pr}_{wat}\,;\ \frac{\lambda_{eq}}{\lambda_{wat}}\right] = \frac{\alpha d_{sph}}{\lambda_{wat}} .$$

The equivalent specific heat and the equivalent thermal conductivity were determined from the formulas

$$C_{eq} = \varepsilon C_{wat} + (1 - \varepsilon)\, C_{sph}\,; \quad \lambda_{eq} = \varepsilon \lambda_{wat} + (1 - \varepsilon)\, \lambda_{sph} .$$

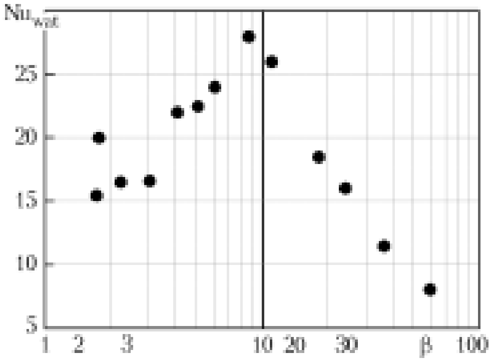

Fig. 4. $\mathrm{Nu_{wat}}$ number vs. steam quality β. β, %.

The values of the physical properties of water were determined at the saturation temperature, whereas the values of the density of steam were determined at $T = (T_w + T_s)/2$. Data on heat transfer in the bubble regime of boiling are presented in Fig. 3. They are well described by the relation

$$\mathrm{Nu_{wat}} = 0.03 \left[\frac{d_{\mathrm{sph}}}{\sqrt{\dfrac{\sigma}{g\,(\rho_{\mathrm{wat}} - \rho_{\mathrm{st}})}}} \right]^{0.48} \left[\frac{r}{C_{\mathrm{eq}} \Delta T_s} \right]^{n} \mathrm{Pr}_{\mathrm{wat}}^{1.79} \left(\frac{\lambda_{\mathrm{eq}}}{\lambda_{\mathrm{wat}}} \right)^{m} , \tag{1}$$

where

$$m = 0.69 \left[\frac{d_{\mathrm{sph}}}{\sqrt{\dfrac{\sigma}{g\,(\rho_{\mathrm{wat}} - \rho_{\mathrm{st}})}}} \right]^{0.6} ; \quad n = -\,0.313 \mathrm{Pr}_{\mathrm{wat}}^{0.3} .$$

From Fig. 4, it follows that for the steam quality β = 8.58% and $q = 1.098 \cdot 10^5$ W/m^2 the heat transfer is maximum. With further growth in the steam quality, which is caused by the increase in the heat-flux density, the heat-transfer coefficient decreases and reaches its minimum corresponding to $\mathrm{Nu_{wat}} = 8.06$ at β = 58.6% for this series of experiments. The reason for the decrease in the heat-transfer coefficient is that both on the spherical-element surface itself and near it, steam bubbles continuously coalesce, forming steam pools; these pools make the access of water to the heat-transfer surface increasingly more difficult. Dry spots appear in its individual regions; their number and density continuously increase with T_w and accordingly with ΔT_s and β. These portions are eliminated from the heat exchange with the liquid medium; they are in contact with steam, the heat transfer to which is much less intense than that to water.

A decrease in the heat transfer with growth in the heat-flux density corresponds to the transient regime of boiling to describe which we have obtained the following criterial dependence:

$$\mathrm{Nu_{wat}} = 8.93 \cdot 10^{6} \left[\frac{d_{\mathrm{sph}}}{\sqrt{\dfrac{\sigma}{g\,(\rho_{\mathrm{wat}} - \rho_{\mathrm{st}})}}} \right]^{-0.884} \left[\frac{r}{C_{\mathrm{eq}} \Delta T_s} \right]^{n_1} \mathrm{Pr}_{\mathrm{wat}}^{-2.69} \left(\frac{\lambda_{\mathrm{eq}}}{\lambda_{\mathrm{wat}}} \right)^{m_1} , \tag{2}$$

where

$$m_1 = -1.28 \left[\frac{d_{\mathrm{sph}}}{\sqrt{\dfrac{\sigma}{g\,(\rho_{\mathrm{wat}} - \rho_{\mathrm{st}})}}} \right]^{0.6} ; \quad n_1 = -\,0.579 \mathrm{Pr}_{\mathrm{wat}}^{0.3} .$$

CONCLUSIONS

1. Throughout the investigated range of variation in the heat-flux density, we observe its monotonic growth with T_s, which is somewhat retarded in the region of high values of this parameter.

2. We have obtained the criterial equations (1) and (2) satisfactorily describing data on heat transfer respectively for the regions of bubble and transient regimes of boiling in a spherical fill.

3. Transition from the film regime of boiling to a transient one occurs for certain values of the heat-flux density and accordingly superheatings of the surface of spherical elements and is accompanied by a decrease in the heat-transfer coefficient.

NOTATION

C_{wat}, specific heat of water, kJ/(kg·K); C_{sph}, specific heat of the material of a spherical element, kJ/(kg·K); C_{eq}, specific equivalent heat of water, kJ/(kg·K); d_{sph}, diameter of a spherical element, m; g, free-fall acceleration, m/sec^2; m_{wat}, mass of the evaporated water, kg/sec; $m_{\mathrm{wat.ch}}$, mass of water in the channel, kg; m_{st}, mass of the generated steam, kg; $\mathrm{Nu}_{\mathrm{wat}}$, Nusselt number for water; n, number of spherical elements in the channel; p, pressure in the channel, Pa; $\mathrm{Pr}_{\mathrm{wat}}$, Prandtl number for water; Q, heat flux, W; q, heat-flux density, W/m^2; r, specific heat of vaporization, J/kg; T_{wat}, water temperature, $^{\circ}$C; T_s, saturation temperature, $^{\circ}$C; ΔT_s, difference of the surface temperature of spherical element and the saturation temperature of water, $^{\circ}$C; T_w, average surface temperature of a spherical elements, $^{\circ}$C; α, heat-transfer coefficient, W/(m^2·K); β, steam quality, %; ε, porosity of a spherical fill; λ_{wat}, thermal conductivity of water, W/(m·K); λ_{sph}, thermal conductivity of the material of spherical element, W/(m·K); λ_{eq}, equivalent thermal conductivity, W/(m·K); ρ_{wat}, water density, kg/m^3; ρ_{st}, steam density, kg/m^3; σ, surface tension, N/m. Subscripts: wat, water; ch, channel; st, steam; sph, spherical element; eq, equivalent; s, saturation; w, wall.

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