THE FIRST CRITICAL HEAT-FLUX DENSITY OF KEROSENE IN STEPWISE AND STEADY-STATE RELEASES OF HEAT

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Experimental results on determination of stationary and nonstationary first critical densities of heat fluxes for the TS-1 hydrocarbon fuel are presented. As a consequence of the investigations carried out in a wide range of subcoolings and pressures, it has been established that for kerosene, just as for water, hydrogen, and helium, the first nonstationary critical heat-flux density $q_{cr.1n}$ coincides with the stationary one q_{cr1}.

Jet fuels for high-speed airplanes serve as the sole coolant that ensures standard temperature conditions of the power unit and elements of flying vehicles [1]. However, fuels for cooling are used only in a liquid phase, which limits the cooling resource realized. Its significant increment can be attained at the expense of the heat of fuel vaporization. In order to use boiling fuels for cooling, one has to solve a number of problems, one of which is the determination of the laws governing heat transfer in boiling of fuels [2].

The problem of safety and reliability of high-performance heat exchangers is first of all associated with their operation under transient and emergency conditions. In practice, there may occur rapid changes in operating conditions that may many times exceed the rate of development of the process of boiling and lead to a thermal shock. The necessity of reliably determining justified indicators of the thermal state of structures (storage reservoirs of oil products, fuel tanks of airplanes, systems of cooling of liquid-propellant rocket-engines, etc.) under the action of a thermal shock (unsteady-state conditions) arises. In the long run, investigations along these lines are reduced to obtaining experimental data under the conditions of unsteady-state heat transfer and construction of a model of heat transfer at the enclosure–liquid interface.

Of substantial practical interest is the question whether a premature transition to film boiling in the case of stepwise heat release on the heat-transfer surface is possible for hydrocarbon fuels, i.e., when $q_{\mathrm{w}} < q_{\mathrm{cr.1}}$. Thus, in the early 1960s, the authorities of the I. V. Kurchatov Institute of Atomic Energy initiated works [3] devoted to a similar question — is there a possibility of a boiling crisis for water on increase in a supplied heat flux below the stationary critical one? Water is the most natural heat carrier in the nuclear reactors of atomic power plants. The investigations carried out have shown that for water the nonstationary value of $q_{\mathrm{cr.1n}}$ coincides with the stationary $q_{\mathrm{cr.1}}$, but for organic heat carriers, under certain conditions, there is the possibility of transition to film boiling on increase in supplied heat flux that is several times smaller than $q_{\mathrm{cr.1}}$. Thus, a great national-economic and scientific problem has been solved.

However, for hydrocarbon fuels the solution of this problem has been greatly complicated, since these fuels in a state of boiling have a number of specific features [2]. First, the differences in the properties of the oil produced are the reasons for the different fractional compositions of fuels of the same brand in the oil-chemical processes of oil refining. Second, when a fuel is heated, pyrolysis of oil products occurs, i.e., there is a decrease in their thermal-oxidative stability as well as gumming of the channel walls, which deteriorate heat transfer and the boiling crisis occurs not on the surface itself but rather on the layer of carbon deposit. The gumming is caused by oxidation of the fuel components by dissolved oxygen. Third, it is known that in the course of boiling of fuels, the processes of heat transfer are accompanied by those of mass transfer. The vapor bubbles formed on the surface are enriched with light fractions and the surface layer — with heavy ones.

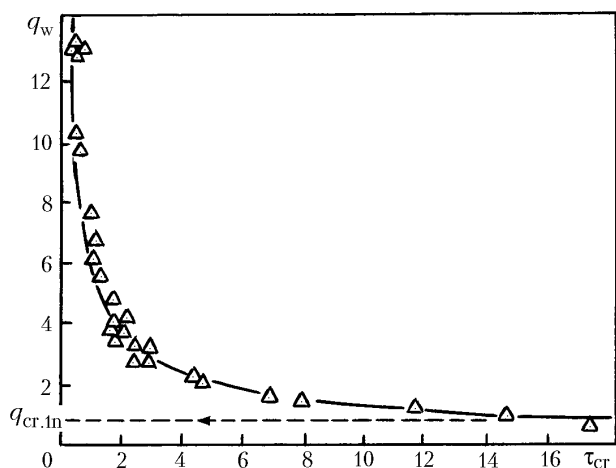
Fig. 1. Toward determination of the first nonstationary critical heat-flux density $q_{cr.1n}$: points — TS-1, $T_f = 20^oC$, $p = 0.1$ MPa, 12Kh18N9T plate — $\delta = 0.5$ mm (heat transfer is directed upward, the lower side of the plate is thermally insulated). q_w, MW/m^2; τ_{cr}, sec.
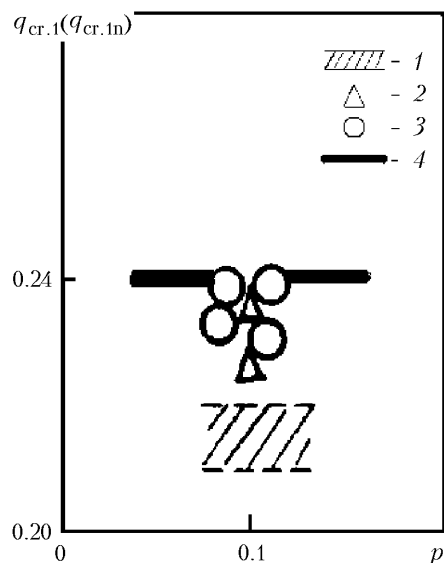
Fig. 2. Comparison of the stationary and nonstationary first critical heat-flux densities: 1–3) TS-1, $T_f = 100^oC$, $p = 0.1$ MPa; 1) data (ranges) of [4]; 2, 3) data of the present work, tubes with $d_{out} = 10$ mm, $\delta = 0.2$ mm; [1, 3) steady-state heat release; 2) stepwise heat release]; 4) calculation by a formula from [5]. $q_{cr.1}$ ($q_{cr.1n}$), MW/m^2; p, MPa.

For boiling hydrocarbons only two values of the critical heat-flux density under steady-state conditions are known; they were determined in works carried out at the Kazan State Technological Institute [4]: "... for the TS-1 fuel the crisis occurred at heat loads $q = 210$–220 kW/m^2, for other fuels at $q = 230$–250 kW/m^2." Under unsteady-state conditions of heat release, there are no data on $q_{cr.1n}$ at all. Therefore, experiments were run to study the problem posed above. The tests were carried out in a rectangular vessel 64 liters in capacity made from duralumin with viewing ports in the side walls. The transparent walls made it possible to use ordinary and high-speed motion-picture photography and fix the occurrence of the crisis. Experimental samples consisted of 12Kh18N9T stainless steel tubes of diameter $d_{out} = 10$ mm, wall thickness $\delta = 0.2$ mm, and working length $l = 150$–170 mm as well as rectangular plates of size 56×188 mm from 12Kh18N9T stainless steel of thickness 0.5 mm or from D16AT duralumin of thickness 0.58 mm. They were brought into an electric circuit with the aid of copper current-leading busbars. The plates were located horizontally or set vertically up-edge, with heat release occurring from both sides. On increase in the supplied heat flux, a sample was heated by an alternating current from a TK-404 welding transformer of power 100 kW; under steady-state conditions it was heated from an AOMN-10-220-75 variable-ratio autotransformer. Kerosene occupied a large volume under the conditions of natural convection. The pressure varied in the range $p = 0.1$–0.6 MPa and the subcooling temperature changed in the range $T_{sub} = 100$–180 K. The heat flux density on the surface can be calculated from $q_w = Q/F$. The estimations made have shown that the maximum relative error in determination of the heat-flux density does not exceed 7%.

In carrying out experiments on determining $q_{cr.1}$, the crisis was attained by gradually increasing the electric power supplied, with the power increasing more smoothly closer to the crisis. The boiling crisis was fixed visually by reddening of the heating surface and the temperature jump (practically in all of the tests these techniques gave the same result). At that instant the electric current, electric voltage, and temperature were indicated by universal voltmeters; simultaneously, two N-117 oscillographs duplicated the signals of critical values.
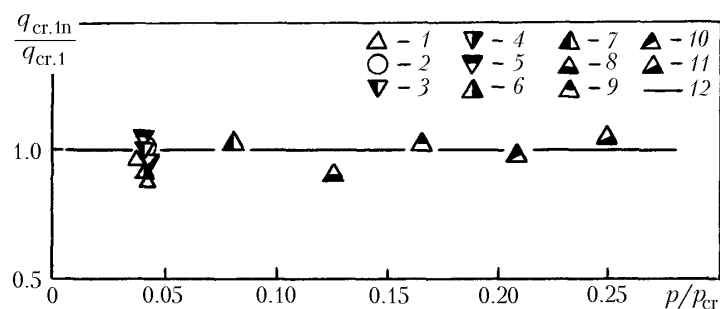
Fig. 3. Dimensionless first nonstationary heat-flux density on stepwise heat release vs. the reduced pressure for the TS-1 jet fuel: 1–6) $p = 0.1$ MPa; 7) 0.2; 8) 0.3; 9) 0.4; 10) 0.5; 11) 0.6 [1) $\Delta T_{sub} = 0$; 2) 140; 3) 100; 4) 160; 5) 170; 6) 140; 7) 148; 8) 156; 9) 164; 10) 172; 11) 180 K]; 12) calculation of $q_{cr.1}$ according to [5]; 1, 2) 12Kh18N9T steel tubes; 3–5) 12Kh18N9T steel plates; 6–11) D16AT plates.

To find the nonstationary first critical heat-flux density $q_{cr.1n}$ a series of experiments were run. In the sample immersed into the liquid, heat of a certain magnitude was released stepwise. If the sample was broken, the power supplied was decreased, and the experiment was repeated; if the boiling crisis had not set in, the experiment was repeated at a higher power of the transformer. The process parameters were determined by analyzing the oscillogram. As the value of the first nonstationary critical heat-flux density $q_{cr.1n}$, we took the minimum power released in the element and related to the heat-transfer surface at which burnout heat transfer occurred after switching-in of the source from which the test element was heated (Fig. 1).

As a result of the investigations carried out, it has been established that for the TS-1 fuel the nonstationary critical heat-flux density $q_{cr.1n}$ coincides with the stationary one, $q_{cr.1}$ (Figs. 2 and 3). As is seen from the figures, the experimental data obtained are satisfactorily correlated by the formula of S. S. Kutateladze [5].

The use of the dependence from [6], which satisfactorily correlates experimental data on $q_{cr.1n}$ for cryogenic fluids, is hardly possible for fuels. The estimations made for the TS-1 kerosene have shown that the condition of heat balance is satisfied and, consequently, transition to film boiling on stepwise release of a heat flux smaller than $q_{cr.1}$ is possible. (For water, hydrogen, and helium the heat balance equation is not satisfied, i.e., transition to film boiling on increase in a heat load smaller than $q_{cr.1}$ is impossible, which was proved experimentally.) Theoretical calculations contradict the results of our experiments. This phenomenon is explained by the multi-fractional composition of oil products: on increase in a heat load smaller than the stationary critical one, effervescence of low-boiling fractions occurs and the quantity of the vapor bubbles formed is insufficient for them to coalesce into a continuous vapor film.

CONCLUSIONS

1. As a result of the investigations carried out in a wide range of subcoolings and pressures, it has been revealed that for the TS-1 fuel, just as for water, hydrogen, and helium, the first nonstationary critical heat flux density $q_{cr.1n}$ coincides with the stationary one, $q_{cr.1}$.

2. Experimental results on $q_{cr.1n}$ and $q_{cr.1}$ for kerosene are satisfactorily correlated by the dependence obtained within the framework of the hydrodynamic theory of burnout heat transfer in boiling that was developed by S. S. Kutateladze and A. I. Leontiev.

NOTATION

d_{out}, outer diameter of a tube, mm; F, heat-transfer surface area, m^2; l, working length, mm; p, pressure, MPa; p_{cr}, critical pressure, MPa; q, heat-flux density, W/m^2; $q_{cr.1}$, the first stationary critical heat-flux density, W/m^2; $q_{cr.1n}$, the first nonstationary critical heat-flux density, W/m^2; q_w, density of heat flux from the wall, W/m^2; Q, power, W; T, temperature, K (^{o}C); ΔT_{sub}, liquid subcooling below saturation temperature, K (^{o}C); T_f, heat-carrier temperature,

K (^{o}C); δ, wall thickness, mm; τ_{cr}, time of onset of the boiling crisis, sec. Subscripts: cr, critical; cr.1, the first stationary boiling crisis; cr.1n, the first nonstationary boiling crisis; out, outer surface; sub, subcooling; f, heat carrier; w, parameter on the wall.

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