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INFLUENCE OF A LONG STAY OF THE HEAT-RELEASE SURFACE IN KEROSENE ON THE CRITICAL HEAT FLUX IN BOILING IN IT UNDER STEADY-STATE AND STEP CONDITIONS OF HEAT RELEASE

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Results of experimental investigations of the influence of a long stay of the heat-release surface in kerosene on the first critical density of the heat flux in boiling under the steady-state and step conditions of heat release are given.

The use of boiling kerosene for cooling of aircraft engines instead of removal of heat by a single-phase fluid will make it possible to substantially boost its power system and significantly increase its service life. Unfortunately, the number of works published on boiling heat transfer of fuels is very small [1, 2].

Hydrocarbon fuels as boiling fluids have a number of distinctive features. First, in heating of fuels, pyrolysis occurs, i.e., the thermooxidation stability of the fuels decreases and coke is formed on channel walls, which deteriorates heat transfer; burnout occurs not on the surface itself but on the layer of carbon deposit. Coke formation occurs because of the oxidation of the fuel component by dissolved oxygen. Second, mass transfer influences the evaporation rate, i.e., the intensity of heat transfer, since vapor bubbles formed on the surface are enriched with low-boiling components while the wall layer of the fluid is enriched with high-boiling components. The saturation temperature of the fluid in the wall layer increases, while the actual temperature head and hence the heat-transfer coefficient decreases (as compared to the boiling of a single-component fluid with the properties of a mixture). Third, there is a difference in the fractional composition of fuels of the same grade; this difference is related to the petroleum-chemical processes of processing of the fuel grade and influences the temperatures of the beginning and the end of boiling of the fuels.

Despite a number of distinctive features inherent in kerosene, Golovin et al. [1, 3–5] note that the dependence $\alpha \sim f(q)$ is in satisfactory agreement with data on the boiling of single-component fluids in character and level of quantities.

In their investigations and projects, some development engineers, scientists, post-graduate students, and students do not take into account the influence of the running time of the surface on the critical heat flux q_{cr1}. In some cases, this can lead to the underestimation of the high internal cooling powers of liquid hydrocarbon fuels and hence their insufficient use; in others, this can result in a rapid failure of the power system with the possibility of occurrence of a fire and damage to the entire aircraft [6]. In order to take correct account of the distinctive features of occurrence of a burnout on surfaces with different degrees of preparation under conditions of forced convection of the fuels, one must investigate them primarily under natural convection.

The characteristics of boiling become stable with time after a certain period of operation, i.e., on surfaces "run-in" by preboiling. Most of the investigations of boiling heat transfer have been performed on

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run-in surfaces (the works of S. S. Kutateladze, M. A. Styrikovich, A. I. Leont'ev, V. I. Tolubinskii, D. A. Labuntsov, V. M. Borishanskii, V. V. Yagov, and many others).

In the opinion of the authors, the running time of the surface in boiling can be subdivided into three stages whose boundaries are established based on the real objective signs, i.e., the characteristics of boiling:

1) the "running-in" stage during which the characteristics of boiling change most substantially (by a factor of 2 to 3), accidental additional nucleation sites are removed, the "initial roughness" of the "fresh" surface is "counterbalanced," etc;

2) the stage of the "run-in" surface begins after running-in when the integral characteristics of boiling are stabilized and correspond to those traditional for these conditions and is completed when the "deposits" formed (scale, oxides, coke, etc.) act on the process of boiling, i.e., their influence exceeds the existing technological spread in boiling parameters; this stage is the longest and the most important; after its completion, the working surface is replaced as a rule; it is precisely for this period that most of the investigations have been performed and correlations for the characteristics of boiling have been obtained;

3) the "operating" stage during which a considerable amount of deposits is formed whose thermal activity substantially influences the coefficient of thermal activity ($\lambda\rho c$) of the material of the wall (the heat-transfer surface); to calculate the characteristics of boiling on such surfaces in this period one must introduce a correction in the form of the effective coefficient of thermal activity into the relations obtained for run-in surfaces (this coefficient is constructed using the coefficients of thermal activity of the wall and the deposits). The form of the coefficient of thermal activity depends on the relation between the thickness of the deposits and the depth of penetration of temperature disturbances.

The running-in period has been studied least extensively; the characteristics of boiling in this period virtually defy all attempts at reliable quantitative description for a wide range of fluid–wall combinations. One has to reconcile oneself to this, and there is nothing surprising in this situation since no universally accepted theory has appeared for a run-in surface over the period of more than 70 years of investigations of boiling heat transfer. This is explained by the complexity of the process of boiling and by the influence of a large number of factors. For an unrun surface the number of these factors (including uncontrolled ones) increases. Unfortunately, there are no works in which the described physical processes occurring in the period of running-in of the surface would finally be taken into account in design recommendations on the integral characteristics of boiling confirmed by a rather wide range of experimental data.

As was noted in [7], it is practically impossible to evaluate the running-in time as a function of the influence of the indicated factors using the quantitative recommendations. Here one must rely on the available experimental data. In the opinion of the author, it is more significant to establish the relations between the characteristics of boiling on the run-in surface (i.e., steady parameters that are stable with time and known well to investigators) and on the unrun surface. To identify the run-in and unrun surfaces for kerosene TS-1 we carried out experimental investigations on the influence of the running-in time on q_{cr1} at a fixed load of preboiling. The conducted experiments showed (Fig. 1) that in preboiling with $q_{\mathrm{preb}} = 0.06$ MW/m^2, the values of q_{cr1} are stabilized after 60–70 min and correspond to the values traditional for these conditions.

In so doing, we determined the conditions of preparation of the surface for correspondence to the state and term "run-in surface." In conducting experiments on the influence of the subcooling and the pressure on the characteristics of boiling, we revealed that these parameters do not change the relation between the critical heat loads on the run-in and new surfaces. Based on this detected fact we proposed a correlation (widely known equations of S. S. Kutateladze for a saturated and subcooled fluid with the use of the criterion of hydrodynamic stability determined experimentally for the case of boiling on an unrun surface; the thermophysical properties of the fuel were found from the handbook [8]) for determination of q_{cr1} on the new surface of heat transfer ($q^{\mathrm{n}}_{\mathrm{cr1}}$). The critical heat flux on the run-in surface is approximately twice as large as the heat flux on the new surface.

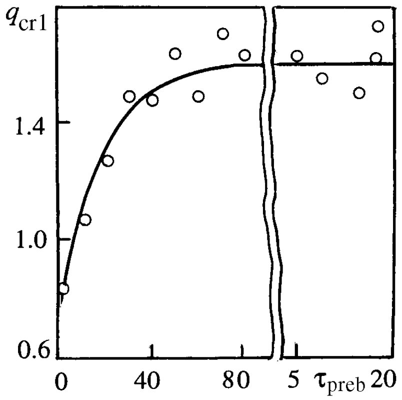

Fig. 1. Critical heat flux vs. preboiling time of fuel TS1, $T_f = 20^oC$ for $q_{preb} = 0.06\ MW/m^2$. q_{cr1}, MW/m^2; τ_{preb}, min and h.

Running-in of the surface and the basic experiment on determination of the critical density of the heat flux were carried out in different vessels. For the "purity" of the experiments the kerosene was replaced by a fresh one after each run. Visualization of the experiment (high-speed filming, photographing) showed that the boiling of kerosene on the new surface and on the run-in surface is characterized by the distinctive features typical of the boiling of water [9]. After the running-in, the samples became turbid, lost their gloss, and became coated with a layer of hydrocarbon deposits (soot). It should be noted that the boiling of kerosene TS-1 on the new surface is characterized by a good reproducibility of the results on q_{cr1} (small spread) and on the heat-transfer coefficient. Boiling on the run-in surface, conversely, is extremely unstable and is characterized by a large spread in parameters.

The formed and moving-away bubbles of the absorbed air, the gas, and the oxygen dissolved in the fuel and the formation of the layer of carbon deposit create a situation in which hydrodynamic instability sets in under substantially smaller heat loads. With such a wide range of the affecting factors it is practically impossible to evaluate the running-in time of the surface by quantitative recommendations. Here it is expedient to rely only on the available experimental results.

Thus, it has been proved experimentally that, despite the complexity of the processes that accompany the boiling (running-in) of hydrocarbon fuels, for kerosene, just as for water, the subcooling and the pressure do not change the quantitative relation of the critical heat fluxes for the "fresh" and run-in surfaces. For a quantitative evaluation of the total influence of the factors, one must use the traditional method of generalization of experimental data [9] by introduction of the coefficients K_s into the design relations for q^n_{cr1} or the dimensionless numbers Pe^n_{cr}:

$$q^n_{cr1} = K_s\, q^r_{cr1} \quad \text{or} \quad Pe^n_{cr} = K_s\, Pe^r_{cr}\,,$$

where q^r_{cr1} and Pe^r_{cr} refer to the run-in surface with fixed characteristics.

It is clear that the surface, being under the fluid level for a long time, undergoes running-in [10]. However, up to the present the influence of this factor on the characteristics of boiling (q_{cr1}) has been studied only under steady-state conditions of heat release (such investigations have not been carried out for fuels). In actual power-generating units cooled by a single-phase heat-transfer agent, we can have thermal disturbances, including shock-type ones. Then in evaluating the effectiveness of heat-release surfaces, prediction of the regimes of heat transfer is required; this prediction is impossible without knowledge of the critical heat load on an unrun surface which stays for a long time under the layer of a fluid under conditions of step heat release.

Results of experimental investigations of the influence of a long stay of the heat-release surface in water on the first critical density of the heat flux in boiling under steady-state and step conditions of heat release are given in [7]. It has been proved experimentally that running-in of the surface occurs after its stay

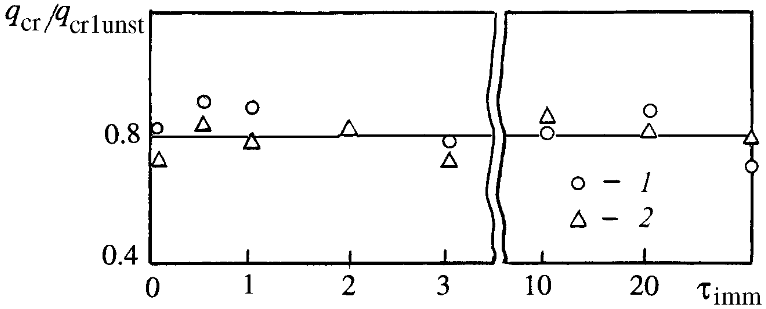

Fig. 2. Critical heat flux (minimum unsteady critical density of the heat flux) vs. time of stay of the heat-release surface in jet fuel TS-1 (p = 1 bar, T_f = 20°C) in surface boiling under steady-state conditions and in the case of step heat release: 1) steady-state conditions and 2) step heat release $q_{cr1}/q_{cr1unst}$, MW/n^2; τ_{imm}, days.

in water for longer than 2–3 days and the q_{cr1} determined in the experiments correspond to the value of the critical density of the heat flux which is well known for these conditions. In step heat release, no running-in occurs on the surface that is in water for a long time. The unsteady critical density of the heat flux $q_{cr1unst}$ is equal to the steady-state critical density of the heat flux q_{cr1}^{n} on the new surface which is unrun by preboiling.

In this work, we carried out investigations on the influence of the time of stay of the surface in kerosene q_{cr1} under steady-state and step conditions of heat release. The experimental setup and procedure are given in [7] in detail.

In the experiments with jet fuel TS-1 (Fig. 2), it was revealed that when the heat-release surface stays for a long time under the fluid level, running-in occurs neither for the steady-state conditions of heat release nor for the step conditions and both q_{cr1} and $q_{cr1unst}$ are equal to the first critical density of the heat flux on the new surface q_{cr1}^{n} (see Figs. 1 and 2).

Running-in occurs for kerosene TS-1 neither under steady-state conditions nor in the case of a surge, and the characteristics should be calculated from the dependences recommended earlier for new heating surfaces. In the opinion of the author, one must be very attentive with generalized experimental data on investigation of boiling heat transfer. On the one hand, one can only welcome generalizations of the great amount of experimental data; on the other, such dependences should be used with extreme care in the region under study. Thus, many Western scientists believe that there cannot be any universal theory for boiling heat transfer and it is preferred to present experimental data in the form of tables (similarly to the skeleton tables of P. L. Kirillov), special nomograms, simple functional dependences, etc.

Conclusions. In the experiments with jet fuel TS-1, it has been revealed that when the heat-release surface stays for a long time under the level of the fluid, running-in of the surface occurs neither for the steady-state conditions of heat release nor for the step conditions and q_{cr1} and $q_{cr1unst}$ are equal to the steady-state critical density of the heat flux on the new surface.

NOTATION

q, heat-flux density, W/m^2 (MW/m^2); q_{cr1}^{n}, first critical density of the heat flux on the new unrun surface, W/m^2 (MW/m^2); $q_{cr1unst}$, first unsteady critical density of the heat flux, W/m^2 (MW/m^2); τ, time, sec (min, h, days); α, heat-transfer coefficient, W/(m^2·K); c, specific heat, J/(kg·K); λ, thermal-conductivity coefficient, W/(m·K); ρ, density, kg/m^3; Pe, Péclet number; p, pressure, bar. Subscripts: cr, critical; cr1, first (premature) burnout; preb, preboiling; imm, immersion; f, ambient medium; unst, unsteady; s, surface. Superscripts: n, new unrun surface; r, run-in surface.

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