NOTATION

m, porosity; s, water saturation; ρ_i, density; v_i, filtration velocity; k, absolute permeability; f_i, relative permeability; μ_i, viscosity; e_i, specific energy; h_i, specific heat; α_1, coefficient of compressibility of water; β_1, coefficient of thermal expansion of water; α_s, elastic modulus of skeleton; λ_i, thermal conductivity of the i-th phase; Λ, effective thermal conductivity of the mixture; $P = P_r(T)$, saturation vapor pressure at the given temperature; c_p^i, isobaric heat capacity of the i-th phase; c_s, heat capacity of the skeleton; ρ_i^*, density at a discontinuity. Indices: 1) water; 2) vapor.

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CHANGE IN BOILING REGIMES ON THICK HEATING SURFACES

V. U. Sidyganov and E. V. Ametistov

UDC 536.423

An analysis is made of the dependence of the structure and velocity of the boiling-regime transition front on the level of heat release and the properties of a heating surface.

Changes in boiling regimes on heating surfaces are an important engineering problem. Solving this problem will make it possible to improve the efficiency of processes involving quenching and thermal stabilization and increase the reliability of steam generators, heat exchangers, and other heat-engineering apparatus. The dynamics of the regime transition determines the design response time for the protection of superconducting devices and the structure and properties of materials that are quenched.

There are presently two approaches to the study of boiling-regime changes. The first approach focuses on hydrodynamic and heat-transfer conditions in the vapor-liquid layer. The characteristic scales and times of these processes are determined by growing bubbles and jets of vapor which displace the liquid and wet the heating surface with drops of the liquid. The dynamics of other small hydrodynamic structures [1] also play a role in determining the characteristic scales and times [1]. The thermal perturbations generated by these structures penetrate the heating surface to a certain depth, so that the inertial thermal properties of the material of the surface affect the rate of heat transfer and the critical thermal loads [2].

In the second approach, the evolution of the temperature fields inside the heat-emitting surface is regarded as a very slow process which determines the dynamics of the boiling-regime shift [3]. Here, it is assumed that the Nukiyami boiling curve is externally assigned, either on the basis of an experiment or in accordance with some semi-empirical theory developed by the first approach. The evolution of the temperature fields should occur at scales greater than the size of the small nonsteady hydrodynamic structures mentioned above.

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The rate of evolution of the field should be small enough so that the boiling curve obtained for steady-state conditions can be used to describe heat transfer.

Within the framework of the second approach, until now the problem of the change in boiling regimes during evolution of the temperature field $T(x, \tau)$ has been solved only for a unidimensional, infinitesimally thin heat-emitting surface [4-7]. The authors of these studies sought the self-similar solution $T(x - u\tau)$ of the nonlinear equation

$$c\rho T'_{\tau} = \lambda T''_{xx} + [q_{\text{wa}}(T) - q_{W}(T)]\frac{1}{\delta} \tag{1}$$

with the boundary conditions $\lim\limits_{x \to +\infty} T = T_1$, $\lim\limits_{x \to -\infty} T = T_2$, $\lim\limits_{x \to \pm\infty} \frac{\partial T}{\partial x} = 0$.

If there are two boiling regimes on an infinitely long surface (for example, if film boiling is realized to the left at $x < 0$ and nucleate boiling is realized to the right at $x > 0$), then, depending on the amount of heat released, the regime transition front moves either to the right ($u > 0$, the film-boiling regime propagates over a wider area as the area occupied by the nucleate-boiling regime decreases) or to the left ($u < 0$, the reverse process occurs and film boiling is replaced by nucleate boiling). In this case, the temperature distribution along the surface has the form of a developed step $T(x - u\tau)$ which moves right or left without changing its shape. The form of the temperature profile stabilizes over time, becomes constant, and becomes independent of the details of the initial temperature distribution. The above-noted similarity solution has been referred to as a travelling regime-change wave. This solution describes the empirically observed transition from one boiling regime to another.

Unidimensional model (1) is unconditionally valid only in the region $\text{Bi} \ll 1$. The heat-emitting surfaces encountered in actual production processes have a finite thickness. In addition, various types of heat-insulating coatings can be applied to them. Thus, in the general case it is necessary to solve the problem of the evolution of the temperature field $T(x, y, \tau)$ in a two-dimensional surface whose properties change through the thickness. Let us analyze features of the qualitative behavior of the boiling-regime transition processes caused by the presence of the second measurement (y) inside the heating surface.

If we consider the complexity of the dynamic process we are discussing, then it would obviously be most useful to attempt to describe it by using one of the well-known base models of active media. We will show that the process of boiling-regime shift on a laminated heat-emitting surface is naturally described by a system of diffusion equations that are connected with each other through the absolute terms.

Let two metallic layers 1 and 3 be separated by a layer of thermal insulation 2 (Fig. 1). The thermal conductivity and heat capacity of the insulation are much less than the analogous properties of the metal. Joule heat $q_{\text{wa}}(T_3)$ is released in the layer 3, while boiling occurs on the surface of layer 1 with the heat-transfer rate $q_W(T_1)$.

The self-similar processes which take place in such a structure will be described by a system of two nonlinear equations which represent the energy balances in layers 1 and 2:

$$\begin{aligned} c_1\rho_1 T'_{1\tau} - \lambda_1 T''_{1xx} &= \frac{1}{\delta_1}\left[\frac{T_3 - T_1}{\delta_2}\lambda_2 - q_W(T_1)\right]; \\ c_3\rho_3 T'_{3\tau} - \lambda_3 T''_{3xx} &= \frac{1}{\delta_3}\left[q_{\text{wa}}(T_3) - \frac{T_3 - T_1}{\delta_2}\lambda_2\right]. \end{aligned} \tag{2}$$

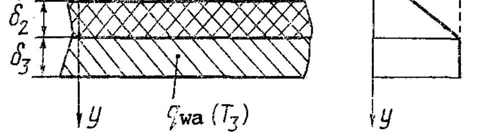

Fig. 1. Diagram of the structure of the laminated surface and the temperature distribution through its cross section.

A system of two coupled nonlinear differential equations of the diffusion type which is similar to (2) is the base model for a great many physical and biological problems. It presumes the existence of a qualitatively wider range of self-similar processes than does Eq. (1) and reduces to (1) only when $\delta_1/\delta_3 \to 0$ or $\delta_1/\delta_3 \to \infty$.

It can be shown that a system of type (2) describes the process of the transition from one heat-transfer regime to another not only on special laminated surfaces, but also on ordinary monolithic plates of finite thickness and thermal insulation.

Let the evolution of the temperature field T(x, y) inside a plate of thickness δ be described by the heat-conduction equation

$$c\rho \frac{\partial T}{\partial \tau} = \lambda_x \frac{\partial^2 T}{\partial x^2} + \lambda_y \frac{\partial^2 T}{\partial y^2}. \tag{3}$$

The heat transfer which occurs on one surface of the plate (y = 0) depends on the temperature at this point of the surface

$$\lambda_y \frac{\partial T}{\partial y}\Big|_{y=0} = q_W (T|_{y=0}). \tag{4}$$

On the other surface (y = δ), let a constant heat flux be given inside the plate

$$\lambda_y \frac{\partial T}{\partial y}\Big|_{y=\delta} = q_{\mathrm{wa}}. \tag{5}$$

In the first stage of the analysis, it is easy to reduce two-dimensional equation (3), with boundary conditions (4-5), to a unidimensional model analogous to (2). Then, in subsequent stages, it would be possible to use methods of constructing solutions that have already been developed for such systems.

Long-Wave Approximation of the Solution. We insert temperature T(x, y, τ) into Eq. (3) in the form

$$T(x,\ y,\ \tau) = \sum_{i=0}^{\infty} T_i (x,\ \tau)\, y^i. \tag{6}$$

We obtain an identity in y which requires satisfaction of the following condition for any i (i = 0, 1, 2,...)

$$\left(c\rho \frac{\partial}{\partial \tau} - \lambda_x \frac{\partial^2}{\partial x^2}\right) T - \lambda_y (i+1)(i+2)\, T_{i+2} = 0. \tag{7}$$

Having inserted (6) into boundary conditions (4) and (5), we obtain:

$$\lambda_y T_1 = q_W (T_0), \tag{8}$$

$$\lambda_y \sum_{i=1}^{\infty} i T_i \delta^{i-1} = q_{\mathrm{wa}}. \tag{9}$$

Having made use of the fact that a long-wave approximation is being constructed, in Eqs. (7-9) we limit ourselves to the determination of a finite number of terms. Here, the number of unknowns and equations will always be the same and the mathematical description will be closed. If we leave T_0, T_1, and T_2, then system (7-9) will be equivalent to Eq. (1) – the unidimensional model. If we keep the first five terms of series (6) (T_0–T_4), then we find the sought approximation:

$$\begin{gathered} c\rho T'_{0\tau} = \lambda_x T''_{0xx} + 2\lambda_y T_2, \\ c\rho T'_{1\tau} = \lambda_x T''_{1xx} + 6\lambda_y T_3, \\ c\rho T'_{2\tau} = \lambda_x T''_{2xx} + 12\lambda_y T_4, \\ \lambda_y T_1 = q_W (T_0), \\ \lambda_y [T_1 + 2T_2\delta + 3T_3\delta^2 + 4T_4\delta^3] = q_{\mathrm{wa}}. \end{gathered} \tag{10}$$

Having excluded T_1, T_3, and T_4 from system (10), we obtain:

$$c\rho T'_{0\tau} = \lambda_x T''_{0xx} + 2\lambda_y T_2,$$

$$c\rho T'_{2\tau} = \lambda_x T''_{2xx} + \frac{3}{\delta^3}\left[q_{\mathrm{wa}} - q_W(T_0) - 2\lambda_y T_2\delta - \frac{\partial q_W}{\partial T_0} T_2\delta^2\right]. \tag{11}$$

System (11) will describe self-similar processes under the condition that the length of the wave is greater than the characteristic thickness of the heat-emitting surface L = 1/k > δ.

When there is a large difference between the thermal resistance of the material of the surface δ/λ and the thermal resistance associated with heat transfer during boiling 1/α (i.e. when Bi > 1), the cooling (or heating) of the upper and lower layers of the heating surface may take place on very different time and space scales.

To simplify the analysis of the consequences of this effect, we make the substitution $T \to \frac{T_\delta - T_0}{2\delta^2} - \frac{q_W(T_0)}{2\lambda_y\delta}$ in (11). We change the equations we have obtained to dimensionless form $\frac{T_\delta}{T_{c2}} \to \tilde{T}_\delta$, $\frac{T_0}{T_{c1}} \to \tilde{T}_0$, $\frac{\tau}{\tau_*} \to \tilde{\tau}$, $\frac{x}{l_*} \to \tilde{x}$. The resulting system of equations

$$\tilde{T}'_{0\tilde{\tau}} - \frac{\lambda_x\tau_*}{l_*^2 c\rho}\tilde{T}''_{0\tilde{x}\tilde{x}} = F_0(\tilde{T}_0, \tilde{T}_\delta), \tag{12}$$

$$\tilde{T}'_{\delta\tilde{\tau}} - \frac{\lambda_x\tau_*}{l_*^2 c\rho}\tilde{T}''_{\delta\tilde{x}\tilde{x}} = \frac{T_{c1}}{T_{c2}} F_\delta(\tilde{T}_0\ \tilde{T}_\delta),$$

where

$$F_0(\tilde{T}_0, \tilde{T}_\delta) = \frac{\lambda_y\tau_*}{\delta^2 c\rho}\left[\left(\frac{T_{c2}}{T_{c1}}\tilde{T}_\delta - \tilde{T}_0\right) - \frac{\delta}{\lambda_y T_{c1}} q_W(\tilde{T}_0)\right];$$

$$F_\delta(\tilde{T}_0, \tilde{T}_\delta) = -\frac{\lambda_y\tau_*}{\delta^2 c\rho}\left\{6\left[\left(\frac{T_{c2}}{T_{c1}}\tilde{T}_\delta - \tilde{T}_0\right) - \frac{\delta}{\lambda_y T_{c1}} q_{\mathrm{wa}}\right] + \left(\frac{2\delta}{\lambda_y T_{\ 1}}\frac{\partial q_W}{\partial T_0} - 1\right)\left[\left(\frac{T_{c2}}{T_{c1}}\tilde{T}_\delta - \tilde{T}_0\right) - \frac{\delta}{\lambda_y T_{c1}} q_W(\tilde{T}_0)\right]\right.$$

is analogous to system (2), while $\tilde{T}_\delta$ corresponds to the temperature of a point located somewhere in the middle of the heat-emitting surface.

There is currently considerable interest in systems of type (12), with the small parameter $\varepsilon = T_{c1}/T_{c2}$. It is known [8] that for sufficiently small values of ε there are two different classes of propagating chemical wave fronts. The same is evidently also true for fronts of boiling-regime changes.

Fast Front. Let us examine the character of the null isoclinic lines $F_0(\tilde{T}_0, \tilde{T}_\delta) = 0$ and $F_0(T_0, T_\delta) = 0$ of system (12) (see Fig. 2). At ε → 0, the curve $F_0(T_0, T_\delta) = 0$ is a quasisteady surface. Since $\tilde{T}_f$ changes very slowly, the quantity u_f – the rate of rapid change in T_0 – is calculated as the eigenvalue of the equation

$$u_{b}\tilde{T}'_{0\xi} - \frac{\lambda_x\tau_*}{l_*^2 c\rho}\tilde{T}''_{0\xi\xi} = F_0(\tilde{T}_0, \tilde{T}_{\delta 1}) \tag{13}$$

with the boundary conditions $\lim\limits_{\xi\to-\infty}\tilde{T}_0 = \tilde{T}_{01}$, $\lim\limits_{\xi\to+\infty}\tilde{T}_0 = \tilde{T}_{c3}$ and $\tilde{T}_\delta = \tilde{T}_{\delta 1}$ (for the transition from nucleate to film boiling).

With the passage of the fast front, there is a transition from the point $(\tilde{T}_{01}, \tilde{T}_{\delta 1})$ to the point $(\tilde{T}_{03}, \tilde{T}_{\delta 1})$ (see Fig. 2a). The fast regime-change front is followed by slow heating along the quasisteady surface $F_0(\tilde{T}_0, \tilde{T}_\delta) = 0$ from the point $(\tilde{T}_{03}, \tilde{T}_{\delta 1})$ to the point $(\tilde{T}_{02}, \tilde{T}_{\delta 2})$ in the film-boiling regime described by the system of equations

$$\frac{\partial}{\partial\tilde{\tau}}\tilde{T}_\delta = \frac{T_{c1}}{T_{b2}} F_\delta(\tilde{T}_0, \tilde{T}_\delta),$$

$$F_0(\tilde{T}_0, \tilde{T}_\delta) = 0.$$

For the fast-front model we are examining, there is also a value of $\tilde{T}_f$ at which the velocity determined from model (13) is equal to zero: $\tilde{T}_\delta = T_{\delta *} \to u_\delta = 0$; $T_{\delta *}$ is the eigenvalue of the equation

$$\int\limits_{\tilde{T}_{04}}^{\tilde{T}_{03}} F_0(\tilde{T}_0, \tilde{T}_{\delta *})\, d\tilde{T} = 0. \tag{14}$$

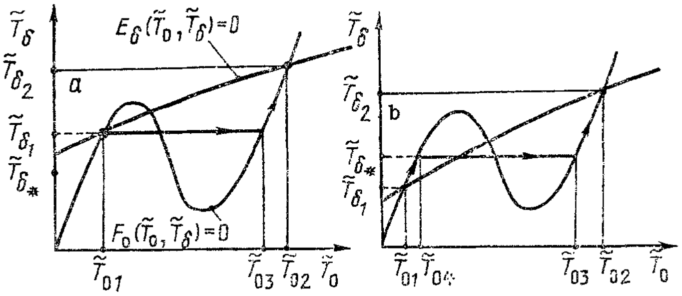

Fig. 2. Fast (a) and slow (b) fronts in the transition from nucleate to film boiling.

The above-described sequence of heating processes will occur at $\tilde{T}_{\delta 1} > \tilde{T}_{\delta *}$. However, the transition from nucleate to film boiling can also take place at $\tilde{T}_{\delta 1} > \tilde{T}_{\delta *}$ if, in accordance with the theorem of "equal areas" [3, 4], $\Phi > 0$. Here,

$$\Phi = \int_{\tilde{T}_{01}}^{\tilde{T}_{02}} [q_{wa} - q_W(\tilde{T}_0)]\, d\tilde{T}_0.$$

In this case, the regime change will be realized by means of a slow front.

Slow Front. The boiling regime transition occurs in a slow but steep (with respect to the coordinate x) front when $\tilde{T}_\delta = \tilde{T}_{\delta *}$ (see Fig. 2b). The profile of this front is described by the equation

$$\frac{\lambda_x \tau_*}{l_*^2 c\rho} \tilde{T}''_{0\xi\xi} = F_0(\tilde{T}_0, \tilde{T}_{\delta *}) \tag{15}$$

with the boundary conditions $\lim\limits_{\xi\to-\infty} \tilde{T}_0 = \tilde{T}_{04}$, $\lim\limits_{\xi\to+\infty} \tilde{T}_0 = \tilde{T}_{03}$. Here $\tilde{T}_\delta = \tilde{T}_{\delta *}$.

Heating of the surface from the point $(\tilde{T}_{01}, \tilde{T}_{\delta 1})$ to $(\tilde{T}_{04}, \tilde{T}_{\delta *})$ occurs in the nucleate boiling regime, while heating from the point $(\tilde{T}_{03}, \tilde{T}_{\delta *})$ to the point $(\tilde{T}_{02}, \tilde{T}_{\delta 2})$ takes place in the film boiling regime in accordance with the equations:

$$u_{\text{м}} \tilde{T}'_{\delta\xi} - \frac{\lambda_x \tau_*}{l_*^2 c\rho} \tilde{T}''_{\delta\xi\xi} = \frac{T_{c1}}{T_{c2}} F_\delta(\tilde{T}_0, \tilde{T}_\delta), \tag{16}$$
$$F_0(\tilde{T}_0, \tilde{T}_\delta) = 0,$$

where the corresponding branches of the boiling curve $q_W(T_0)$ are taken for each regime. The velocity of the slow front can be found from the condition of continuity of the heat flux along x inside the heat-transfer surface:

$$\lambda_x \left.\frac{d\tilde{T}_\delta}{d\xi}\right|_{\xi=+0} = \lambda_x \left.\frac{d\tilde{T}_\delta}{d\xi}\right|_{\xi=-0}.$$

A shift in boiling regimes is realized at the point $\xi = 0$ (in the scales of problem (16): film boiling ($\tilde{T}_0 = \tilde{T}_{03}$, $\tilde{T}_\delta = \tilde{T}_{\delta *}$) to the right of zero $\xi = +0$; nucleate boiling ($\tilde{T}_0 = \tilde{T}_{04}$, $\tilde{T}_\delta = \tilde{T}_{\delta *}$) to the left of zero $\xi = -0$.

All of the considerations discussed above in regard to the transition from nucleate to film boiling apply with only slight modification to the opposite transition from film to nucleate boiling.

The question of the shift in boiling regimes is resolved very clearly by resorting to the above-mentioned theorem of "equal areas" [3, 4]. Here, a comparison is made between the areas of the curve which describes heat release and the curve which describes heat transfer (see Fig. 3a). If $S_2 > S_1$, then film boiling propagates and the area of nucleate boiling decreases. The case $S_2 < S_1$ corresponds to the opposite situation. If $S_2 = S_1$, then the thermal load is equal to the equilibrium thermal load q_e and the boundary between the nucleate and film boiling regimes is stationary.

Let us find the loads which characterize the presence of the fast and slow classes of fronts at large Bi. In Fig. 3b, we constructed the curve

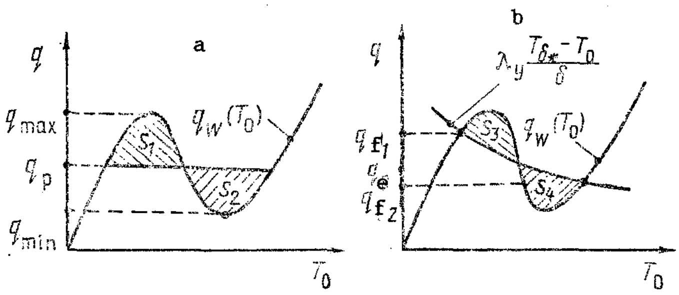

Fig. 3. Illustration of the theorem of "equal areas" [3, 4] and theorem of "equal areas for a fast front."

$$q = \lambda_y \frac{T_{\delta *} - T_0}{\delta}, \tag{17}$$

representing heat release on the surface when $\tilde{T}_f = \tilde{T}_{f*}$ (see Fig. 2b). Here, the condition $S_3 = S_4$ (see Eq. (14)) will be referred to as the "theorem of equal areas for the fast front." Such a dependence of heat release on T_0 remains constant with respect to τ for fast fronts and with respect to x for slow (in the scales of problem (15)) fronts.

Thus, we showed that with a constant heat flux on sufficiently thick, low-heat-conducting surfaces, there are two types of boiling-regime transition fronts:

1) a front which is steep with respect to the coordinate x and is fast-moving; such a front affects only the upper layers of the heat-conducting surface, with the surface subsequently heating (or cooling) in a steady-state boiling regime after passage of the fast front;

2) a front which is steep with respect to the coordinate x in the upper layers but slow and stretched out in the interior layers; its velocity is determined by the time of heating of the internal layers of the heat-transferring surface.

Having used q_{f1} and q_{f2} to denote the heat releases corresponding to the points of intersection of above-constructed curve (17) with the heat-transfer curve (see Fig. 3b), we formulate conditions for the shift in regimes on thick heating surfaces.

If $q_e < q_{wa} < q_{max}$, a transition from nucleate to film boiling is possible. This transition is realized in the form of a fast-moving front under the condition $q_{f1} < q_{wa} < q_{max}$ and in the form of a slow-moving front under the condition $q_e < q_{wa} < q_{f1}$.

If $q_{min} < q_{wa} < q_e$, a transition from film boiling to nucleate boiling is possible. This transition is realized in the form of a fast front under the condition $q_{min} < q_{wa} < q_{f2}$ and in the form of a slow front under the condition $q_{f2} < q_{wa} < q_e$.

Thus, a qualitative analysis of the evolution of the temperature field in a thick heat-emitting surface makes it possible to establish the existence of two different types of boiling-regime transition fronts and to find quantitative relations that can serve as criteria for realizing a given type of front. The result obtained here is of practical interest, since a knowledge of the dynamics of boiling-regime changes is important for the development of many types of power plants and engineering processes.

NOTATION

q, heat flux, W/m^2; $q_W = q_W(T_0)$, boiling curve, W/m^2; $q_{wa}(T)$, heat releases on the surface, calculated per unit area, as a function either of temperature or of the heat flux inside the plate, W/m^2; T, temperature, K; T_0, T, temperature of the external and internal layers of the heat-transferring surface, respectively, K; $\tilde{T}_0$, $\tilde{T}_\delta$, same in dimensionless form; T_{c1}, T_{c2}, characteristic values of T_0 and T, respectively, K; δ, thickness of the heat-emitting surface or one of its layers, m; c, heat capacity, J/(kg·K); ρ, density, kg/m^3; λ, thermal conductivity, W/(m·K); λ_x and λ_y, thermal conductivity of an anisotropic body, W/(m·K); Bi, Biot number; τ, time, sec; x, longitudinal coordinate, m; $\tilde{\tau}$, $\tilde{x}$, same in dimensionless form; τ_*, characteristic time, sec; ℓ_*, characteristic length, m; $\xi = \tilde{x} - u\tilde{\tau}$ dimensionless similarity variable; u, dimensionless velocity of fast (u_f) or slow (u_s) boiling-regime transition front.

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SOME UNIQUE FEATURES OF HEAT LIBERATION IN BOILING OF HYDROCARBON FUELS IN LARGE VOLUME

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UDC 536.248.2.001.5

Heat liberation coefficients are measured for boiling of hydrocarbon fuels in large volume at pressures up to 0.31 MPa. It is established that oxygen dissolved in the fuels encourages formation of precipitates and affects heat exchange during boiling. The dependence of the heat liberation coefficient upon thermal flux and pressure is presented for bubble boiling of deoxygenated fuels.

At the present time the literature has accumulated a wide amount of material on heat liberation upon boiling of various individual substances, including hydrocarbons, from a large volume. There is significantly less data available on heat exchange during boiling of multicomponent hydrocarbon mixtures, and in particular, data on wide fraction petroleum products is quite limited [1].

The present study will offer results of an investigation of heat liberation during boiling in a large volume of the fuels RT (GOST 10227-86) and T-6 (GOST 12308-80), two substances with markedly differing physicochemical properties. The experiments were performed in an apparatus (Fig. 1) consisting of a cylindrical bath 1, 0.15 m in diameter and 0.22 m high, with three view windows 2 equally spaced around the lateral surface and one window in the bath lid. Liquid boiling occurred on a horizontally oriented tube 3, made of 12Kh18N10T stainless steel, with outer diameter 0.00705 m, inner diameter 0.00605 m, and length 0.143 m, which was heated by an electrical current. The tube surface finish corresponded to that of seamless tubing.

The vapors of the boiling fuel were condensed in a glass condenser 4, installed on the bath lid, or on a water-cooled metal condenser. The glass condenser was used in experiments performed at atmospheric pressure and the metal one, above atmospheric pressure.

To maintain saturation temperature in the boiling volume the condensate was collected by baffle 5 and subfloor 6 and returned to the boiling volume by heated tube 7. Moreover, compensation heaters and a layer of asbestos insulation on the bath side wall were used for the same purpose. In the experiments at elevated pressure the latter was created by vapor

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