SELF-EXCITATION OF OSCILLATORY PROCESSES WHEN A LIQUID IS INJECTED INTO A PLASMA JET

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The process of cooling of a wall by a liquid injected into a plasma jet through a circular opening is studied experimentally. Different flow regimes in a vapor-liquid system, including self-excited oscillatory regimes associated with the transfer of the region of boiling from the exterior side of the wall into the interior cavity of the casing, were obtained. Self-excited oscillations of the wall temperature are described with the help of approximation formulas.

The structural elements of thermal-power plants can be cooled with liquid more economically and efficiently than with gas. Liquids have better thermophysical properties than gases, and in liquids heating can bring about phase transformation. In systems with phase transformations, however, unstable processes associated with oscillations of the flow rate of the liquid [1, 2], which transform the thermo-gas dynamic parameters of the gas flow near the wall, thereby significantly distorting the heat-transfer process, can occur on a surface or within a permeable wall. For this reason, two-phase cooling systems require carful experimental and theoretical investigation in order to determine the most efficient and safest operating parameters.

In this work we study the process of heat transfer for a blunt body placed in a high-temperature flow with liquid injected in a direction toward the incident flow. Figure 1 shows a diagram of the models tested 1. The models consisted of a frustum of a cone 2 with a small hemispherical base. The models, which were made of X18H9T stainless steel, were placed in the working sections of an air plasma jet 3, generated with a ÉDP-104A/50 electric-arc plasmatron 4. The output opening of the plasmatron anode has a diameter of $14 \cdot 10^{-3}$ m. The distance from the cutoff of the output opening of the plasmatron anode for the front critical point of the model ranged from $2.5 \cdot 10^{-2}$ up to $7.5 \cdot 10^{-2}$ m. The coolant (water) 6 was injected from the interior volume of the model through a circular opening 5 in the wall on the symmetry axis 5. The diameter of the opening was equal to $d = 1 \cdot 10^{-3}$ m, the diameter of the model was equal to $20 \cdot 10^{-3}$ m, and the thickness of the wall was equal to $h = 1 \cdot 10^{-3}$ m.

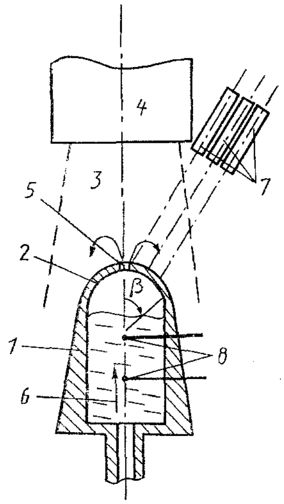

Fig. 1. Layouts of the models tested.

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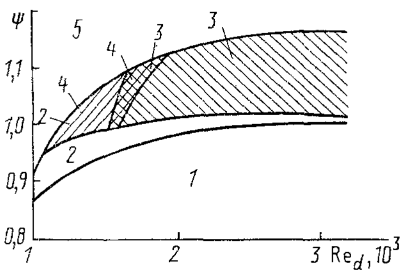

Fig. 2. Regions of flow in the vapor-liquid system.

TABLE 2. Experimental Conditions

T_∞, K	G_∞, 10^{-3} kg/sec	T_e, K	v_e, m/sec	G_w, 10^{-3} kg/sec	q_w, 10^6 W/m^2
3600	0,9	4100—2800	62—24,3	0,1—1,0	5,3—3,1
δT_∞, %	δG_∞, %	δT_e, %	δv_e, %	δG_w, %	δq_w, %
10,1	4,6	8,9	8,0	4,6	9,9

In the course of the experiments the flow rate of the liquid G_w was checked with the help of rotameters of the type PC, PM, and GF. The wall temperature T_w was checked at the points $\beta = 5$, 30, and 60 by determining the brightness temperature with the help of a fast-response photoelectric pyrometer 7. The temperatures T on the symmetry axis inside the volume of the model at distances $10 \cdot 10^{-3}$ m and $20 \cdot 10^{-3}$ m from the hemispherical blunt end were determined with the help of chromel-alumel thermocouples 8 using the well-known methods employed in [3, 4].

A complete two-factor experiment was performed: the flow rate of the cooling liquid and the heat flux q_w into the wall of the models (without injection of coolant) were varied. The heat flux q_w was changed by changing the distance from the front critical point of the model up to the output opening of the plasmatron anode, i.e., by varying the values of T_e. The heat flux was determined by the well-known exponential method with the help of heat-flux sensors [3, 4].

The experimental conditions and the maximum errors in the parameters determined are given in Table 1. Here T_∞ and v_∞ were determined from the condition that the energy expended by the plasmatron be balanced by the energy expanded in PC rotameter; T_e and v_e were determined with the help of water-cooled enthalpy meter and total-pressure gauge using well-known methods [5].

Figure 2 shows the range of the dimensionless factors that were varied and the corresponding regions of flow in the vapor-liquid system. Here $Re_d = 4G_w/\pi\mu d$, $\Psi = q_w/q_0$, $q_0 = 4.6 \cdot 10^6$ W/m^2 is the critical value of the heat flux to the wall, i.e., the minimum value of the heat flux for which self-excited oscillatory processes arise in the system. The confidence limits for Ψ and R_e, calculated from the results of three to six measurements, with a probability of 0.95 and Student's coefficient 1.96 did not exceed $I_\Psi = (\Psi \pm 0.03)$; $I_{Re_d} = (Re_d \pm 58)$.

The flow region 1 (Fig. 2) corresponds to the regime in which the wall is cooled as a result of forced convection of the liquid. Figure 3 shows a typical oscillogram of the wall temperature at the points $\beta = 5$ (curve 1), $\beta = 30$ (curve 2), and $\beta = 60$ (curve 3) as a function of the time t; $\Psi = 0.95$ and $Re_d = 3140$. The wall temperature assumes stationary values. In this regime of cooling of the wall the volume enclosed by the casing is completely filled with the liquid phase, and the water jet flows out through the circular opening and evaporates in the plasma jet at a distance of $0.5 \cdot 10^{-3}$ m to $1.0 \cdot 10^{-3}$ m from the wall.

The flow region 2 (see Fig. 2) corresponds to the inverted dispersion-circular regime of cooling of the wall. The terminology is taken from [6, 7]. Unstable pulsations of the parameters are observed in the oscillograms of the wall temperature and the temperature on the axis of symmetry inside the volume of the model at a distance $10 \cdot 10^{-3}$ m from the hemispherical blunt end (see Fig. 4a); $\Psi = 1.02$ and $Re_d = 1352$. This flow regime is caused by

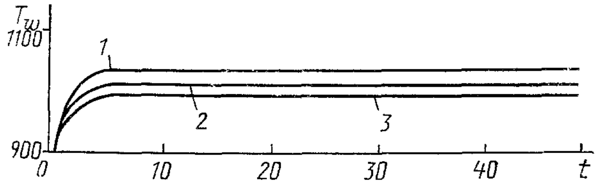

Fig. 3. Wall temperature of the model as a function of time for the single-phase convection regime. T_w, K; t, sec.

developed bubble boiling of the liquid. A vapor-liquid jet is injected through the circular opening into the plasma. The flow rate of the jet is unstable in time and varies chaotically as a result of the efflux of the two-phase flow through the quite small circular opening. The diameter of the vapor bubbles becomes comparable to that of the output opening.

The flow region 3 (see Fig. 2) corresponds to self-excited oscillatory regime of cooling of the wall. Figures 4b and c show the self-excited oscillations of the wall temperature at the point $\beta = 5$ (Fig. 4b, $\Psi = 1$, $Re_d = 1794$) and at the points $\beta = 5$, 30, and 60 (Fig. 4c, curves 1-3, $\Psi = 1.109$, $Re_d = 3140$) and the temperature on the axis of symmetry inside the volume of the model at a distance $10 \cdot 10^{-3}$ m. Bubble boiling commences on the interior side of the wall with relatively low flow rates of the liquid, and in the process the wall temperature increases rapidly, which intensifies the evaporation process, and film boiling arises. Propagation of the film separating the liquid and vapor into the volume of the model can be traced via the appearance of surges of the wall temperature at different times at the points $\beta = 5$, 30, and 60 (Fig. 4c) as well as from measurements of T at points on the symmetry axis of the model at distances $10 \cdot 10^{-3}$ m and $20 \cdot 10^{-3}$ m from the hemispherical blunt end (see Fig. 4b).

Intense evaporation of liquid results in an increase of the vapor pressure inside the volume of the model and strong injection through the circular opening. This forces the plasma jet back and the wall temperature drops. In Fig. 4b T_w and T oscillate in antiphase. The sections on the curve of T, which refer to the liquid ($T < 373$ K), correspond to an increase of the wall temperature and injection of vapor at temperatures $T > 373$ K results in a decrease of T_w.

The decrease of the wall temperature slows the rate of evaporation and results in displacement of vapor out of the interior volume of the model by the incoming liquid. This process repeats periodically.

Visual observations also confirm the proposed mechanism of the self-excited oscillatory cooling regime. When the jet of liquid appeared the brightness of the wall increased with time, indicating that the temperature of the wall increased, and when vapor was injected the plasma jet was forced back and the brightness of the wall decreased. The jet of liquid penetrated through the boundary layer with virtually no distortion of the hydrodynamic pattern of the gas flow, and the jet of vapor forced back the incident flow and reduced the thermal load on the shielded wall.

The frequency f and the amplitude A of the self-excited oscillations of the wall temperature and the heating time of the system up to the time t_b at which film boiling appears (time up to the appearance of a surge in the oscillogram of T_w) as a function of the flow rate of the liquid and the heat flux to the wall were approximated with the help of the following formulas:

$$\mathrm{Sh} = (2 \cdot 10^{-6}\,\mathrm{Re}_d^2 - 1.16 \cdot 10^{-2}\,\mathrm{Re}_d + 17.35)\,\Psi - 2.2 \cdot 10^{-6}\,\mathrm{Re}_d^2 + 1.24 \cdot 10^{-2}\,\mathrm{Re}_d - 17.89, \quad (1)$$

$$b = (-1.4 \cdot 10^{-3}\,\mathrm{Re}_d - 0.33)\,\Psi + 1.63 \cdot 10^{-3}\,\mathrm{Re}_d + 0.53, \quad (2)$$

$$\Theta = 1.89\,\Psi + 7.4 \cdot 10^{-5}\,\mathrm{Re}_d - 1.32, \quad (3)$$

$$\tau = 0.393\,\mathrm{Re}_d - 347.96 - (7.35 \cdot 10^{-5}\,\mathrm{Re}_d^2 - 0.685\,\mathrm{Re}_d + 731.81)\,\Psi, \quad (4)$$

where $Sh = fD/v$ is the oscillatory Strouhal number; D is the inner diameter of the model; $v = 4G_w/\pi\rho D_2$ is the average flow velocity of the liquid; $b = A/A_m$ is the dimensionless amplitude of the self-excited oscillations; $A_m = 495$ K is the maximum amplitude of the self-excited oscillations; $\Theta = T_w/T_m$ is the dimensionless temperature of the wall (the average

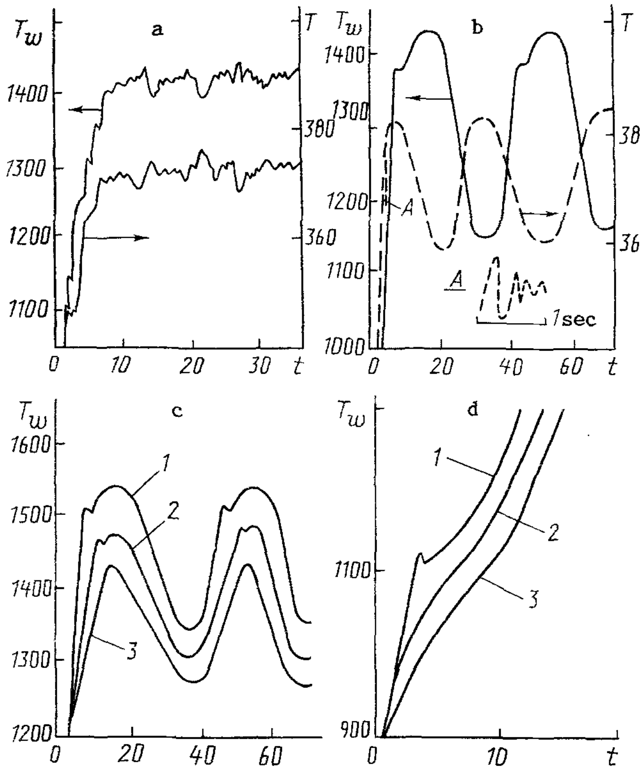

Fig. 4. Wall temperatures of the model and temperatures inside the volume enclosed by the casing as a function of time for the inverted dispersion-circular flow regime (a), for the plug flow regime (b), for the self-oscillatory flow regime (c), and for the vapor flow regime (d).

temperature of the wall at the point $\beta = 5$, for which self-excited oscillations are observed); $T_m = 1600$ K is the maximum temperature; $\tau = t_b/t_h$ is the dimensionless heating time of the system (time up to the appearance of a surge of the wall temperature in the oscillogram); $t_h = h^2/a$ is the characteristic heating time of the wall; and, a is the thermal diffusivity. The formulas (1)-(4) are valid for

$$1 \leqslant \Psi \leqslant 1.11;\ 1790 \leqslant \mathrm{Re}_d \leqslant 3140.$$

The approximation errors did not exceed $\delta\,\mathrm{Sh} \lesssim 4.1\%$, $\delta b \lesssim 3.8\%$, $\delta\Theta \lesssim 2.4\%$, $\delta\tau \lesssim 4.9\%$.

Analysis of the results of our investigation of the self-excited oscillatory regime of cooling of the system shows the following. Increasing the flow rate of the liquid decreases the frequency and increases the amplitude of the self-excited oscillations of the wall temperature and decreases the average wall temperature and increases the heating time of the system.

Increasing the heat flux to the wall increases the frequency and decreases the amplitude of the self-excited oscillations of the wall temperature, increases the average wall temperature, and decreases the heating time of the system.

Elementary estimates of the heating time of the system are consistent with the measurements shown in the oscillograms $t_b \approx 4$-9 sec:

$$t_b \simeq \frac{m_c c_c (T_w - T_{w0})}{q_w s - [r + c(T - T_0)]\, G_w}.$$

Increasing q_w decreases the heating time of the system and therefore increases the frequency of the self-excited oscillations. Increasing the flow rate of the liquid decreases the heating time of the system, and the frequency of the self-excited oscillations then decreases.

The flow region 4 (see Fig. 2) corresponds to the plug flow regime of cooling of the system. The terminology is that of [6]. A wave packet (see Fig. 4b), indicating passage of a vapor bubble in the volume of the model, appears in the oscillograms of the temperature on the axis of symmetry inside the volume of the models at distances of $10 \cdot 10^{-3}$ and $20 \cdot 10^{-3}$ m. In contrast to the plug flow regime of the vapor-liquid flow in the pipe, described in [6], the vapor bubble moves not with the flow of liquid but rather upstream; in all probability, this is caused by the intense heat loads on the cooled wall. The plug flow regime could give rise to inverted dispersion-circular and self-excited oscillatory regimes of cooling of the system (see Fig. 2).

The flow region 5 (Fig. 2) corresponds to vapor cooling of the system. The vapor cooling regime arises with low flow rates of the liquid and high heat fluxes to the wall. Vapor is injected through the circular opening toward the plasma jet, but the flow rate of the gas is too low to force away the plasma flow, so that the temperature of the wall continuously increases (see Fig. 4d). The liquid boils in virtually the entire monitored volume of the model (curves 1-3 in Fig. 4d, obtained for the points $\beta = 5$, 30, and 60; $\Psi = 1.12$; $Re_d = 1425$).

NOTATION

β, half angle with a small base of the cone; T, temperature on the symmetry axis in the volume of the model; q_w, heat flux density; T_∞, average mass temperature; G_∞, flow rate of the plasma-forming gas; v_∞, average flow velocity; T_e, local temperature; v_e, local velocity; Re_d, Reynolds number; μ, coefficient of dynamic viscosity; Ψ, relative heat flux; f, frequency; A, amplitude; t_b, heating time; Sh, Strouhal number; ρ, density; a, thermal diffusivity; m_w, mass of the wall; c_w, specific heat capacity of the wall; S, surface area; r, latent heat of vaporization; c, specific heat capacity of the liquid; and T_0, initial temperature of the liquid.

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