TEMPERATURE OF A THINNED FLOW OF DROPS REFLECTED FROM A HEATED SURFACE

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Some results are presented from a theoretical and experimental study of heat exchange during the impact of drops against a hot surface.

Explaining the basic laws governing the interaction of a flow of drops with a heated surface is important for calculating and designing heat-and-power engineering equipment which employs drop cooling [1, 2]. At the same time, study of heat exchange between drops and a hot surface is interesting for developing methods of controlling drop flows and changing their parameters. The extensive literature devoted to drop cooling has mainly examined aspects of heat exchange of drops with a surface, while in many cases it is important to know the degree of heating of drops reflected from the surface.

The present article studies the mechanism of interaction of drops with a heated surface and determinines the temperature of the liquid after its reflection.

We proceeded on the basis of the following considerations in our theoretical study. A drop striking the surface flows over it. In conformity with heat-conduction theory, the temperature at the contact boundary is established almost instantaneously and depends on the thermal activities of the material of the hot surface and the incident liquid, as well as on their initial temperature [3]. When the temperature of the surface exceeds the Leidenfrost point, an intervening film of vapor is formed on the surface as the drop impinges on it. Heat is transferred to the drop through this film. The pressure established in the interaction zone corresponds to the sum of the ambient pressure and the pressure created by the deceleration of the drop. However, the latter, the stagnation pressure, is negligible compared to the atmospheric pressure because the velocity of the drop is limited by the requirement We < 80 [4], which is a sufficient condition for preventing breakup of the drop. Thus, we will henceforth ignore this effect. As a result, the temperature of the liquid–vapor boundary should be considered known and equal to the saturation temperature. Then the question of the heating of the drop reduces to determination of the law governing its flow over time.

Three models of interaction were examined to obtain theoretical relations.

In accordance with the first, tenetatively titled "segment" model, drops retain the form of spherical segment (Fig. 1a) during the entire interaction. Its volume in this case is considered to be constant (the slight change due to evaporation will be ignored), and the area of the interaction zone is completely determined by the height of the segment:

$$S' = \frac{\pi}{3}\left(8\frac{R_0^3}{h} - h^2\right), \tag{1}$$

where h is related to the position of the center of mass by the equation

$$H_{\text{cm}} = \frac{h}{3} + \frac{h^4}{48R_0^3}. \tag{2}$$

In turn, the law of change in the position of the center of mass is determined by the expression

$$\sigma\frac{dS}{dH_{\text{cm}}} = m\frac{d^2H_{\text{cm}}}{d\tau^2}, \tag{3}$$

here

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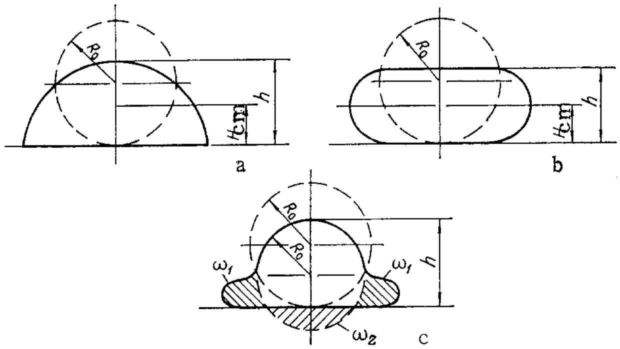

Fig. 1. Change in configuration of drop with different models of interaction: a) "segment" model; b) "oval" model; c) "immersion" model.

$$S = \frac{16\pi R_0^3}{3h} + \frac{\pi h^2}{3}. \quad (4)$$

The solution of system (2)-(4), with a known initial drop velocity, makes it possible to determine the complete time of interaction of the drop and the law of change in its height over time, which then makes it possible to use Eq. (1) to determine $S' = f(\tau)$.

The second, "oval" model assumes, in contrast to the first model, that the drop takes an oval shape (Fig. 1b). In this case the dependence of the interaction area on the position of the center of mass is found from the equation

$$S' = \left(\sqrt{\left(\frac{\pi^2}{16} - \frac{3}{2}\right) H_{\text{cm}}^2 + \frac{3}{2}\frac{R_0^3}{H_{\text{cm}}}} - \frac{\pi H_{\text{cm}}}{4}\right)^2 \pi, \quad (5)$$

while the total surface area of the drop

$$S = \left(\frac{8\pi}{3} - \frac{\pi^3}{2}\right) H_{\text{cm}}^2 + \frac{4\pi R_0^3}{3H_{\text{cm}}} + \sqrt{\left(\frac{\pi^2}{16} - \frac{2\pi^4}{3}\right) H_{\text{cm}}^4 + \frac{2\pi^4 R_0^3 H_{\text{cm}}}{3}}. \quad (6)$$

We assume that the rate of advance of the phase boundary is very low compared to the velocity of the temperature front inside the drop and that the effect of convective heat transfer in the liquid phase can be completely ignored. In actuality, there is still heat transferred by radiation. However, under normal conditions such heat transfer is fairly small and can be allowed for when necessary.

A specific feature of the problem is that the temperature on the surface of interaction of the drop, despite the complexity of the mechanism of the process in equation, depends only on the phase transformation pressure and in our case remains constant. Also, in view of the short time the drop is on the surface, it can be assumed that the temperature front does not reach the outer boundary of the drop. The latter, therefore, can be regarded as a semiinfinite region. Thus, we arrive at a familiar problem of heat conduction with boundary conditions of the first kind.

For the two above-examined models, due to the complexity of the law of change in the interaction surface over time (Eqs. (1), (5), and (3)), the solution can be obtained only in numerical form.

We write the following for the amount of heat transferred to the drop and the increment in temperature:

$$Q = \frac{2\sqrt{2}}{\sqrt{\pi}} \Delta t' \sqrt{\lambda c \rho} \int_0^{S'} \sqrt{(\tau_{\text{f}} - \tau)}\, dS, \quad (7)$$

$$\Delta t = \frac{3Q}{4\pi R_0^3 c\rho}. \quad (8)$$

Figure 1c shows the configuration of the third model, tentatively called the "immersion" model. The character of the deformation that occurs is determined by the equality of the

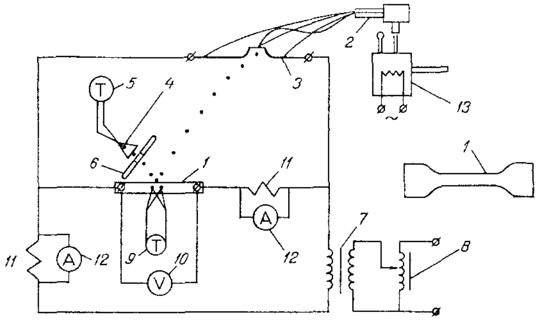

Fig. 2. Diagram of experimental stand.

volumes of an imaginary spherical segment with a diametrical cross section ω_2 and an annular figure with a cross section ω_1.

Simple geometric considerations show that the surface area of the zone of interaction of the drop with the heated surface is determined as

$$S' = \frac{\pi\left[4R_0^2 - h^2 + (4R_0^3 + h^3 - 3R_0h^2)\frac{\rho v_f^2}{6\sigma}\right]}{2}. \tag{9}$$

Here we assume that during the final shaping of the drop its kinetic energy is transformed into interfacial energy, so that there is an increment in the surface:

$$\Delta S = \frac{\pi}{3}(4R_0^3 + h^3 - 3R_0h^2)\frac{\rho v_f^2}{2\sigma}. \tag{10}$$

If we assume that the velocity of the uppermost point of the drop remains constant during the entire interaction and changes sign only during reflection, i.e., the time of interaction of the drop on the surface is determined as

$$\tau_f = 2R_0/v_f, \tag{11}$$

then the equation of motion (3) can be excluded from our examination and the problem of drop heating can be completely solved analytically.

The expression for the increase in the temperature of the reflected drop is

$$\Delta t = \frac{3\Delta t'\sqrt{v_f}}{\sqrt{2\pi}\,R_0^3}\sqrt{\frac{\lambda}{c\rho}}\int\limits_0^{\frac{2R_0}{v_f}}\sqrt{(2R_0 - v_f\tau)^3}\left(1 + \frac{\rho v_f^3\tau}{4\sigma}\right)d\tau. \tag{12}$$

A series of experiments was conducted on a special stand (Fig. 2) to determine the degree of heating of a drop reflected from a surface. A flow of monodisperse drops is directed perpendicular or at an acute angle to a flat heated surface 1. The drop size is kept constant by superimposing lengthwise mechanical oscillations on the stream of liquid (Rayleigh separation) [5]. Since the relaxation time of the surface temperature should be shorter than the interval between two successive impacts of drops at a given point of the surface, it is necessary to create a thinned flow of drops. We did this by supplementing the lengthwise high-frequency oscillations with transverse low-frequency oscillations, the latter also being superimposed on the stream coming from the capillary tube 2 [6]. Individual monodisperse drops were sampled by means of collimator slits on a thermohydrophobic surface 3. The method just described is simpler and more reliable than the method presently used [7] and makes it possible to obtain a wide range of flow densities. The increase in the temperature of the liquid was measured by collecting drops reflected from the surface in a nearby mirrored vessel 4 with a built-in thermocouple leading to potentiometer 5. The cold junction of the thermocouple was placed in the vessel containing the initial liquid. The effect of radiant heat exchange between the vessel and the heated plate was eliminated by installing a double shield 6 with a hole to permit passage of the drops. The stainless steel plate serving as the heated surface was heated by an alternating current of several hundred amperes supplied from a transformer 7 by a method similar to that described in [8]. The plate temperature was set by changing the voltage in the primary winding of the transformer with voltage regulator 8. Plate temperature was measured by inserting two thermocouples 9 into the back side of the

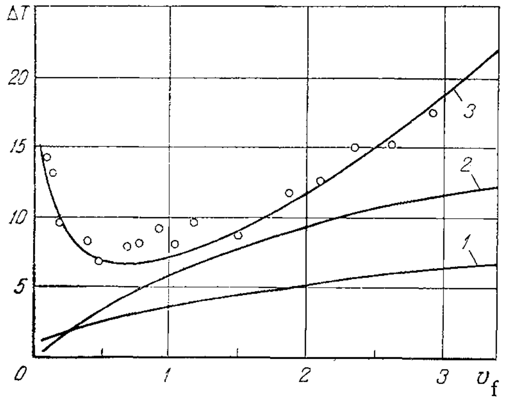

Fig. 3

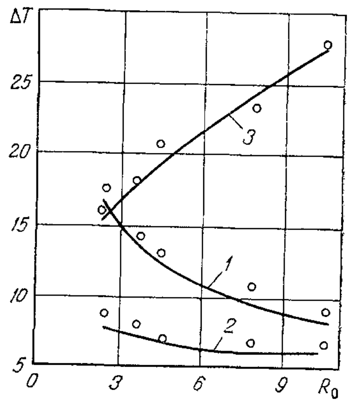

Fig. 4

Fig. 3. Dependence of the increase in the temperature of the drops reflected from the heated surface on their normal impact velocity at with $R_0 = 3.7 \cdot 10^{-4}$ m. Interaction models: 1) "segment"; 2) "oval"; 3) "immersion"; points — experiment. v_f, m/sec; Δt, °C.

Fig. 4. Dependence of the increase in the temperature of drops reflected from the heated surface on drop radius for the "immersion" model. Normal impact velocities of the drops at the surface: 1) 0.1 m/sec; 2) 0.7; 3) 2.9; points denote experiment; curves denote calculation. $R_0 \cdot 10^{-4}$; Δt, °C.

plate 1 mm from the surface being sprayed. One thermocouple was connected to a portable PP-63 potentiometer, while the other was connected to an automatic KSP-4 potentiometer. The voltage on the working section of the plate was measured by a voltmeter 10, while current was measured with calibrated shunts 11 and ammeters 12. The water was supplied by a peristaltic metering pump. Drop velocity was determined by calculation, by measurement using high-speed filming, and by a photoelectric method based on measurement of the time of passage of the drops over the section between two photodiodes located along the flow. The latter were installed so that the flow of drops passed above their working surface, which was positioned coaxially with regard to the light source. The readings of the photodiodes were recorded by a frequency meter. A thermostat 13 was used to keep the temperature of the outflowing liquid constant.

In the experiment we varied the plate temperature, the velocity of the thinned flow of monodisperse drops, the angle of inclination of the flow to the plate, and the drop radius.

Figures 3 and 4 compare the test data with calculated results for the models examined.

It is evident from Fig. 3 that only the "immersion" model gives a satisfactory agreement between the theoretical and empirical results. The presence of the minimum is due to the fact that the time of interaction of the drops with the surface changes in inverse proportion to v_f, while the surface area of the interaction zone changes roughly in proportion to v_f^2.

It is interesting to note the weak dependence of the temperature change on radius (Fig. 4).

Also important is the practical independence of drop heating (and, thus, the heat-transfer rate) on the temperature of the heated surface in the temperature region above the Leidenfrost point. This agrees with the findings of other authors [8].

NOTATION

H_{cm}, height of center of mass of drop at given moment of time; h, height of drop at given moment of time; R_0, initial radius of drop; S, total surface area; S', area of interface between drop and heated surface during interaction; ω_1, ω_2, diametrical cross sections of deformed parts of a drop; τ_f, time of impingement of a drop on heated surface; τ, running time of impingement of drop on heated surface; m, mass; σ, surface tension of drop; ρ, c, λ, density, heat content, and thermal conductivity of water; v_f, normal velocity of impact of drop on heated surface; Q, quantity of heat; Δt, increase in the temperature of the reflected drop; Δt', difference between phase transformation temperature and initial temperature of drop.

LITERATURE CITED

1. A. Diner, "Survey of literature on heat transfer in jet cooling," Chernye Met., No. 4, 26-29 (1976).
2. M. A. Styrikovich, V. S. Polonskii, and G. V. Tsiklauri, Heat and Mass Transfer and Hydrodynamics of Two-Phase Flows in Nuclear Power Plants [in Russian], Nauka, Moscow (1982).
3. A. V. Lykov, Theory of Heat Conduction [in Russian], Vysshaya Shkola, Moscow (1967).
4. L. H. J. Wachterst and N. A. J. Westerling, "The heat transfer from a hot wall to impinging water drops in the spherical state," Chem. Eng. Sci., 21, 1047-1056 (1966).
5. B. G. Hollin, Centrifugal and Vibrating Melt Granulators and Liquid Sprayers [Russian translation], Mashinostroenie, Moscow (1977).
6. A. Z. Voltynets, A. V. Rozhdestvenskii, and S. N. Rodionov, "Obtaining low-density flows of monodisperse granules," in: Summary of Documents of the Second All-Union Conference "Modern Technology for Granulating and Encapsulating Fertilizers," NIUIF, Moscow (1983), pp. 65-66.
7. C. O. Pedersen, "An experimental study of the dynamic behavior and heat transfer characteristics of water droplets impinging upon a heated surface," Int. J. Heat Mass Transfer, 13, No. 2, 369-381 (1970).
8. L. I. Urbanovich et al., "Study of heat transfer in the forced water cooling of hot metal surfaces," Inzh.-Fiz. Zh., 39, No. 2, 315-322 (1980).

RELATIONS FOR GASDYNAMIC DISCONTINUITIES FOR TWO-PHASE FLOWS OF A NONEQUILIBRIUM CONDENSING VAPOR

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Equations of characteristics and relations along characteristics are presented along with relations for normal and oblique shock waves for a two-phase flow of a nonequilibrium condensing vapor.

1. We will examine a two-dimensional steady-state flow of a nonequilibrium condensing vapor in the initial condensation zone in a one-velocity approximation. We assume the vapor phase to be a perfect gas.

The system of conservation equations in this case has the form [1]

$$\operatorname{div}(\rho\vec{w}) = 0,\ \rho(\vec{w}\cdot\nabla)\vec{w} + \nabla p = 0,\ \operatorname{div}(\rho I\vec{w}) = 0, \tag{1}$$

where

$$\rho = \rho' s + \rho''(1-s);\ I = i + \frac{w^2}{2};\ i = \frac{\rho' s i' + \rho''(1-s) i''}{\rho}; \tag{2}$$

$$p = \rho'' R T'';\ i'' = \frac{k}{k-1}\frac{p}{\rho''}. \tag{3}$$

Excluding the derivatives of density from system (1) with the use of equation of state (3), we obtain

$$(u^2 - a_{\text{tp}}^2)\frac{\partial u}{\partial x} + uv\frac{\partial u}{\partial y} + uv\frac{\partial v}{\partial x} + (v^2 - a_{\text{tp}}^2)\frac{\partial v}{\partial y} = m a_{\text{tp}}^2, \tag{4}$$

where a_{tp} is the analog of the speed of sound in the two-phase medium,

$$a_{\text{tp}} = \sqrt{\frac{k-1}{1-ks}},\ i = \sqrt{\frac{k-1}{1-ks}\ \frac{\rho' s i' + \rho''(1-s) i''}{\rho}}; \tag{5}$$

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