FEATURES OF HEAT TRANSFER IN THE IMPACT OF A DROP AGAINST A HOT SURFACE

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A physical model is proposed for heat- and mass-transfer processes occurring in the impact of a drop against a hot surface, and results are presented from an experimental check.

Determining the laws governing the interaction of a single drop with a hot surface is important as a step in organizing the jet cooling of bodies by flows of drops. This problem is also of independent interest, such as for finding the conditions of drop rebound in certain processing units.

The subject of the behavior of a drop lying still on a heated surface has been investigated quite fully. It has been established that the transient regime separating the regime of wetting of the surface by the drop and the regime in which the drop is in a purely spheroidal state is determined by two temperatures. These temperatures respectively characterize the maximum and minimum drop evaporation rates [1]. There is no unanimous agreement regarding features of the development of the process for the case of a falling drop [2, 3]. It is assumed in some studies that there is always a vapor interlayer between the drop and the surface [3]. Other studies emphasize that the rebound effect is due to sudden boiling up of heated layers of liquid [2] at the contact boundary.

In essence, a given representation of the physical pattern of the process is determined by how the investigator answers the question of the presence of contact between the drop and the surface at the moment of interaction. Correct solution of this problem is necessary not only to determine the mechanism of interaction of the drop with the surface, but it is also of practical importance – such as in connection with the possibility of corrosion in the case of interaction of brines with a hot surface.

Studies we conducted in the surface-temperature range 373-1073°K and the data obtained by other authors [2, 4] show that a falling drop comes into direct contact with the surface. We will therefore proceed on the basis of a model corresponding to representation of the existence of direct contact. Within the framework of this model, the behavior of the drop after interaction is determined by the temperature on the contact boundary. If this temperature is below the equilibrium temperature corresponding to the pressure in the contact zone, contact is kept. In the opposite case, a vapor interlayer is formed and the drop rebounds. The phenomenological theory of heat conduction [5] makes it possible to find this temperature. If the interaction surface in the scale of the drop itself is not too small, then the problem is solved fairly easily: the temperature on the contact boundary is determined from the equation for the temperature of the interface between two contacting plates

$$\frac{T - T_2}{T_1 - T_2} = \frac{K}{1 + K}, \tag{1}$$

where $K = \sqrt{\lambda_1 c_1 \rho_1 / \lambda_2 c_2 \rho_2}$.

We performed appropriate experiments to check the above solution. A low-density flow of monodisperse drops (a method of obtaining low-density flows of monodisperse drops was examined in [6]) fell onto a heated plate. The plate was heated by a strong alternating current. To reduce the errors in the measurement of the temperature of the surface directly below the drop, as transducers we used two microthermometers (50 μm in diameter). The recording device was an electronic digital voltmeter. The variables in the test were: the temperature of the heating surface, the incident velocity of the drops, and the radius of the drops.

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TABLE 1. Comparison of Theoretical and Experimental Values of the Temperature of a Heated Surface Corresponding to "Pure" Rebound of a Drop

Material of surface	Working liquid	T_2, °C	Temp. of "pure" rebound, °C		
			from Eq. (1)	from Eq. (2)	expt.
Copper	Water	16	104	196	160
	Alcohol	5	80	120	115
	Acetone	−2	57	85	95
Aluminum	Water	16	106	234	175
	Alcohol	5	80	137	120
	Acetone	−2	58	96	96
Aluminum oxide	Water	16	113	190	175
	Alcohol	5	82	119	120
	Acetone	−2	59	84	96
Iron	Water	16	108	192	190
	Alcohol	5	81	118	126
	Acetone	−2	58	83	98
Lead	Water	16	119	321	310
	Alcohol	5	85	174	180
	Acetone	−2	61	121	131
Mercury	Water	16	129	302	290
	Alcohol	5	88	165	170
	Acetone	−2	63	115	126
Ceramic	Water	16	191	262	260
	Alcohol	5	108	148	150
	Acetone	−2	78	103	105

The drop velocity range of 0.7-2.5 m/sec was established on the basis of the condition $\mathrm{We} < 80$, in which the drops do not break up during the interaction with the surface [7]. The drop radii in the tests were 0.24, 0.37, 0.78, and 1.05 mm. The tests were conducted with different liquids. The heated plates were made of different materials to study the effect of the condition of the hot surface. Here, the roughness of the surface might have ranged within 0.1-20 μm. The temperatures of the dispersed liquid and the environment were kept constant.

During the motion of a drop in air at a temperature equal to the initial temperature of the drop, the drop is cooled as a result of evaporation of part of the liquid. The cooling effect was determined theoretically and experimentally by means of an aspirated psychrometer with a variable aspiration rate [8].

Visual observation of the interaction of the drop with the hot surface yielded the following picture. With a gradual decrease in the surface temperature from values corresponding to stable rebound of drops, first there is some change in the rebound angle beginning with a certain temperature. Vapor generation then intensifies and is accompanied by "crackling," and the drops begin to break up. The temperature at which these phenomena appear is the lower boundary of the interval of stable drop rebound, and we will tentatively refer to it as the temperature of "pure" rebound. With a further decrease in temperature, drops cease to rebound, and the liquid, adhering to the surface, flows over it. Beginning with this moment, a sharp reduction in surface temperature is recorded.

The tests showed that, in the investigated range of drop velocities, drop radii, and roughnesses of the hot surface, the temperature of "pure" rebound remains practically constant.

However, as can be seen from Table 1, the experiment gives a higher value of pure rebound temperature than does Eq. (1). This difference can be attributed to the fact that the actual temperature of the surface at the initial moment of contact turns out to be different from the temperature calculated on the basis of the results of the classical theory of heat conduction. This theory, which leads to infinitely large values of the temperature gradient at the initial moment of time, is evidently inapplicable under the given conditions.

It is reasonable to assume as an approximation that at the initial moment only finite, limitingly thin surface layers of bodies of different volumes interact. Accordingly, the entire process could be calculated on the basis of the mixing principle. Here, the approach to the surface temperature is determined on the basis of the balance equation

$$\frac{T_1 - T_s}{T_s - T_2} = \frac{c_2\rho_2}{c_1\rho_1}. \qquad (2)$$

If this temperature is greater than the pure rebound temperature, then a vapor phase will be instantaneously formed in the interaction volume and the drop will rebound, while the temperature of the surface will remain nearly constant. If the temperature is below the pure rebound temperature, then intermolecular forces associated with the surface layers of the contacting bodies come into play. Here, the temperature takes a value determined from Eq. (1). A very complicated situation is created under these conditions.

Visual observations permit the following interpretation of the process. Under the influence of intermolecular forces associated with the interaction of the drop with the surface, the drop is spread out and changed into a plane liquid layer. At surface temperatures just below the pure rebound temperature, a vapor layer is formed under the drop as a result of the development of sheet boiling. Under these conditions, it is possible for the drop to receive additional momentum, which is manifest in an increase in its velocity. At lower temperatures (insufficient for the development of sheet boiling), the process is complex in character. The liquid phase is superheated and becomes viable small nuclei. Vaporization centers are seen on different elements of the surface as well and are introduced by the liquid itself [9].

It can be seen from the table that the calculated temperatures obtained in accordance with the above theory are in satisfactory qualitative agreement with the test data. At first glance, an exception to this is the temperature obtained for aluminum. However, if we take into account the certain presence of a thin oxide film on the aluminum surface and introduce a corresponding correction, we obtain satisfactory agreement between theory and experiment in this case as well. This further confirms the validity of the proposed theory.

NOTATION

T_1, initial temperature of heated plate; T, temperature of heated plate at moment of interaction; T_2, temperature of drop surface before interaction; T_S, saturation temperature; λ_1, thermal conductivity of the plate material; c_1, ρ_1, specific heat and density of the plate material; λ_2, thermal conductivity of the liquid; c_2, ρ_2, specific heat and density of the liquid.

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