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EXPERIMENTAL INVESTIGATION OF DROPLET-EVAPORATIVE COOLING OF HEATED METAL SURFACES

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To study heat transfer between a flow of droplets and heated metallic surfaces, a special rig has been fabricated and experiments have been carried out with varied wetting density, size and velocity of the droplets. For the temperature of maximum heat removal and the corresponding heat transfer rate empirical relations have been obtained which agree well with an approximate theoretical description of the process. Physical justification is given for the thermal hysteresis observed in the heating-cooling cycle.

Introduction. For a variety of complex technical facilities droplet-evaporative cooling is virtually the sole possible means of controlling their thermal regime because of complexity of the configuration, limited overall dimensions, and inaccessibility of the most heated portions of the surface. However, complex thermohydraulic processes which take place when a cooling liquid agent wets surfaces heated above its boiling temperature have not as yet been described theoretically with an accuracy sufficient for practical purposes. Therefore, in addition to its principal purpose of establishing the basic laws governing thermal interaction, the proposed experimental approach will allow one to refine the formulation of boundary conditions and afterwards to develop adequate mathematical models of heat transfer for a given mode of cooling. Generalization of experimental data by certain empirical or semiempirical correlations will undoubtedly be useful at the present stage for selecting rational design and operation parameters of systems of liquid droplet-evaporative cooling.

To study heat exchange of a flow of droplets with a heated surface, a special test rig was designed and fabricated allowing, on the one hand, variation of the hydrodynamic parameters and flow rate characteristics of the flow of droplets from experiment to experiment and, on the other hand, provision of the identity of the indicated parameters within one experiment at different extents of heating of the cooled surface.

1. Design, Characteristics and Operation of the Rig (Fig. 1). Functionally, the design of the rig is divided into two parts: the generator of droplets and the block for measuring heat fluxes.

The droplet generator consists of rotating hollow flywheel 1 with capillary 2 installed in its side wall and of bearing plate 3 in combination with a cowling and a cover. A dosed flow of droplets is formed by side hole 4 in the cowling and by shutter mechanism 5. The cooling liquid is held in containers 6 communicating through pipelines, a valve and capillary 2 of the flywheel.

The heat flux measuring block involves: specimen 8 attached to frame 7 and thermally insulated on the side of the frame; plane heater 9 connected with specimen 8, and Chromel-Copel thermocouple 10 imbedded in the specimen surface; the electric circuit of heater 9, involving power supply unit 13, ammeter and voltmeter; the block for recording temperature, consisting of thermocouple 10, potentiometer 11, power supply unit 13 and relay 12 of the heater circuit; the lamp of strobotac 14, installed directly under specimen 8, the flash of which is synchronized with the instant of escape of droplets through shutter 5.

When the valve is open, the cooling liquid from upper container 6 enters under the action of a hydrostatic head into the cavity of flowheel 1, rotating with angular speed ω, and then, passing capillary 2, precipitates in the form of droplets on the inner surface of the cowling. Falling down from the cowling surface, the cooling liquid accumulates in lower container 6 and then returns to upper container 6.

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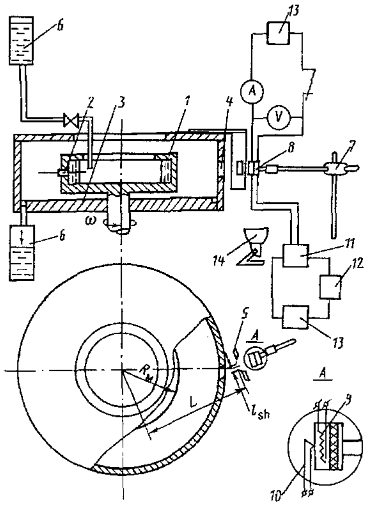


Fig. 1. Schematic of the experimental rig.

A portion of the liquid, having passed through hole 4 and shutter 5, arrives at specimen 8 in the form of a group of droplets; the number of groups of droplets per unit time is equal to the number of revolutions of the flywheel $n = \frac{\omega}{2\pi}$ 1/sec.

Synchronization of the instant of the flash of the lamp of tachometer 14 with the time of escape of a group of droplets allows visual observation of the process of interaction of droplets with the cooling surface of specimen 8.

By setting a number of fixed angular speeds for the flywheel (for this purpose an adjustable belt drive is provided), a stepwise change in the velocity of the droplets is achieved. The dispersity of the flow of droplets is varied by applying capillaries with different flow areas.

2. Experimental Procedure. The following flow rate characteristics were recorded in the course of the experiment:

—the total mass flowrate of liquid per second G_0 as the difference of the volumes in containers 6, related to the time of the experiment;

—liquid flowrate per second through the shutters $G = l_{sh}G_0/2\pi R$, where l_{sh} is the width of the opening of the shutters; $R = \sqrt{R_M^2 + L^2}$ is the reduced radius of jet rotation; repeated experimental checking of the given relation showed that its error does not exceed 5%.

The mean area of the spot of contact of a group of droplets S_{sp} is determined after a series of experiments with a constant flowrate by the imprint left on the cooling surface. The wetting density J is defined as the ratio of the flowrate per second to the contact spot area: $J = G/S_{sp}$.

The heat flux removed by droplets in the process of cooling is calculated from the difference of electric powers supplied to the cooled, W_h', and noncooled, W_h, heater at the same (for both cases) surface temperature T_S, fixed by the calibrated scale of the potentiometer. Since in droplet cooling the heater temperature T_h' and, consequently, losses to the surrounding medium are higher than those without cooling, the heat flux Q_k removed by the droplets is determined with the introduction of the correction factor $k<1$:

$$Q_h = k(W_h' - W_h).$$

The coefficient k is calculated with allowance for the mean coefficient of heat transfer to air and for the heater geometry.

Prior to the start of the work, the cooling surface of specimen 8 is positioned so that droplets could settle down at its center. The power was measured for different temperatures T_S in the range 100-400°C; for each temperature T_S the corresponding electric power is selected, which is supplied to the heater.

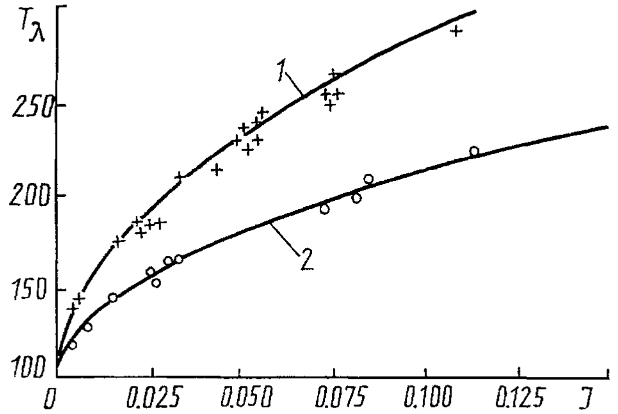


Fig. 2. Temperature of maximum heat removal vs wetting density: 1) steel; 2) duralumin. T_λ, °C; J, kg/(m^2·sec).

In a series of experiments at different surface temperatures T_S, a constant wetting density J and dispersity of the flow of droplets were ensured. Distilled water was used as a cooling fluid.

To obtain different dispersities of the flow of droplets and different wetting areas, capillaries with diameters of 0.23, 0.46, and 0.93 mm were used as well as fixed speeds of flywheel rotation: 52, 94, 157, and 258 rad/sec.

3. The results of visual observations and heat removal measurements at J = const allow one to separate three characteristic temperature ranges in which the interaction of the flow of droplets with the heated surface has significant special features.

The first range extends from the saturation temperature T_{sat} to a certain characteristic temperature T_λ. In this range, as the temperature of the cooled surface rises, heat removal increases and attains a maximum at $T = T_\lambda$. Thus, T_λ is the temperature of maximum heat removal. At a surface temperature exceeding T_λ, the process of static deposition of droplets on the cooled surface ceases, i.e., they do not "adhere" to the surface. In this temperature range the heat transfer is predominantly governed by the size of the droplets and by the thickness of the film formed on the cooled surface. The film is stable, although it has mobile boundaries; the film is uneven and has separate burrs; secondary sprays and small fountains of sprays appear on the approach of the droplets and small bangs are heard.

The second range spans from the temperature T_λ to a certain temperature T_m which is the temperature of minimum heat removal. Heat transfer in this range is governed by both the characteristics of the flow of droplets (velocity, density of wetting) and the thermal activity of the cooled-surface material. Moving droplets in the form of "patches" are seen on the cooled surface as well as vapor expulsions, and intense bangs are heard. At the temperature T_m the liquid does not remain on the surface, and full dispersion of droplets is observed. In this range, as the cooled-surface temperature increases, heat removal falls and attains a minimum at $T = T_m$.

The third range is $T_S > T_m$; it is characterized by water dust pulsation in a plane parallel to the cooled surface beyond its contour; the sonic effects are weakened.

4. The efficiency of heat removal as a function of the wetting density and cooled-surface temperature was investigated for steel and duralumin specimens with the velocity of the droplets varying within the limits 7.8-39 m/sec and the diameter of the droplets from 0.1 to 1.5 mm; this allowed one to have a rather wide range of wetting densities (from 0.005 to 0.15 kg/(m^2·sec)).

The experimental dependence of the temperature of maximum heat removal on the wetting density is represented in Fig. 2 by a discrete distribution of points. The substantial dependence of the temperature T_λ on the material and the distribution of the experimental points allow it to be approximated by a relation of the form

$$T_\lambda = T_{sat} + AJ^{1/2}, \qquad (1)$$

where the coefficient A depends on the thermal activity of the surface material $\beta = \sqrt{\lambda \rho c}$ and on the thermophysical characteristics of the cooling liquid.

The mean efficiency of heat removal in a series of n tests at $T_S = T_\lambda$ was determined from the relation

$$\bar{e} = \frac{1}{\Delta i n} \sum_{i=1}^{n} (Q_k^i / G), \tag{2}$$

where Q_k^i is the heat flux removed by the droplets; Δi is the difference of vapor enthalpies at saturation.

For the distillate the mean efficiency of heat removal amounted to $\bar{e} = 0.92$ testifying to its rather high heat-removing ability.

It is found that when large droplets do not form on the cooling surface, the efficiency of heat removal for the first range (T_{sat}—T_λ) obeys the relation

$$e_1 = e_0 \left(1 - \sqrt{1 - \frac{T_S}{T_\lambda}}\right). \tag{3}$$

The experimental relationship between the maximum heat flux q_{max} removed by the droplets and the cooled-surface temperature $T_S = T_\lambda$ is represented by a discrete distribution of points in Fig. 3, and for practical applications it can be approximated by the quadratic relation

$$q_{max} = \frac{\bar{e} \Delta i}{A^2} (T_S - T_{sat})^2. \tag{4}$$

where A and Δi have the same values as in relations (1) and (2).

5. **An approximate computational estimate of the regime of maximum heat removal** can be obtained on the basis of a one-dimensional "film" analogy and well-known relations for thermal shock [1].

We replace the flow having an isotropic distribution of droplets by a flow of thin films of thickness Δx_0 that approach the cooled surface with the same velocity u_0 but with the step x_0. For the wetting density J we can write

$$J = \rho' \frac{\Delta x_0}{x_0} u_0,$$

where ρ' is the liquid density in the film.

We avail ourselves of the well-known expression [1] for the heat transfer rate in the case of thermal shock

$$q = \frac{\beta \Delta T}{\sqrt{\pi}} \tau^{1/2}, \tag{5}$$

where τ is time reckoned from the start of the thermal shock; $\Delta T = T_S - T_k$ is the difference between the initial temperature of the surface and the temperature of liquid contact with the surface at time $\tau = 0$.

We assume that during the time of contact τ_k the temperature T_k does not change substantially; this assumption is valid for the regime of maximum heat removal, since the time of interaction τ_k is small.

Since the heat flux removed from the surface in cooling is spent for heating the liquid and its evaporation, it can be expressed in terms of the difference of the vapor and liquid enthalpies Δi:

$$q = -\rho' \frac{d(\Delta x)}{d\tau} \Delta i. \tag{6}$$

Taking into account Eq. (5), we have

$$\frac{\beta \Delta T}{\sqrt{\pi}} \tau^{1/2} = -\rho' \frac{d(\Delta x)}{d\tau} \Delta i.$$

Integration of this expression with the initial condition $\Delta x(0) = \Delta x_0$ at $\tau = 0$ yields

$$\Delta x(\tau) = \Delta x_0 - \frac{2\beta}{\sqrt{\pi}}\frac{\Delta T}{\rho'\Delta i}\tau^{1/2}. \tag{7}$$

Since $\Delta x(\tau_k) = 0$, the time of contact is determined by

$$\tau_k = \frac{\pi}{4\beta^2}\frac{\Delta i^2}{\Delta T^2}\rho'^2\Delta x_0^2.$$

On the other hand, the time of contact can be determined with the aid of the coordinating coefficient K by

$$\tau_k = K\frac{\Delta x_0}{u_0}.$$

Equating the latter two expressions, we obtain

$$\Delta T = \sqrt{\frac{\pi}{4\beta^2}\Delta i^2\rho'^2\Delta x_0\frac{u_0}{K}},$$

or with allowance for the resulting expression for J

$$\Delta T = \varepsilon\frac{\Delta i}{\beta}J^{1/2},$$

where $\varepsilon = \left(\frac{\pi}{4}\rho'\cdot\frac{x_0}{K}\right)^{1/2}$.

When $J \to 0$, $T_k \to T_{sat}$, and consequently

$$T_S = T_\lambda = T_{sat} + \varepsilon\frac{\Delta i}{\beta}J^{1/2}. \tag{8}$$

Taking into account the fact that the wetting density $J = q_{max}/\Delta i$, we obtain the following expression for the maximum heat transfer rate:

$$q_{max} = \frac{\beta^2}{\varepsilon^2\Delta i}(T_\lambda - T_{sat}). \tag{9}$$

Comparison of Eqs. (8) and (9) with empirical formulas (1) and (4) obtained ealier shows the dependence of the involved empirical coefficient A on the thermal activity of the material β and on the thermophysical properties of the liquid:

$$A = \frac{\varepsilon\Delta i}{\beta}. \tag{10}$$

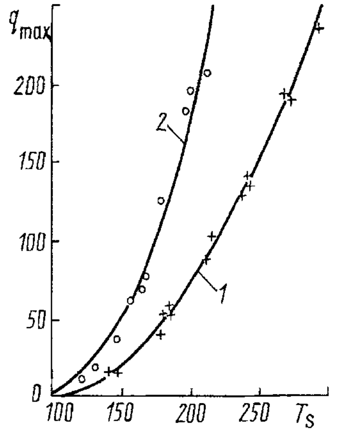
Additional investigation demonstrated that the value of ε is practically independent of the flow parameters and of the cooled-material characteristics; in all of the tests with the distillate $\varepsilon \simeq 3$ kg$^{1/2}$/m.

The actual assumption about free spreading in the form of a thin film at the time of droplet impact with the cooled-surface, which was adopted to derive relations (8) and (9), is valid at a Weber number We not exceeding a certain value determined by the surface tension force σR and the inertia force $\rho' u^2 R^2$ corresponding to the moment of droplet impact [2, 3]:

$$\mathrm{We} = \frac{2\rho_{fl}u^2R}{\sigma}. \tag{11}$$

Since the Weber number was larger than 0.9 in all of the experiments carried out, this value can be regarded in the first approximation as the lower boundary of the application of relations (8) and (9).

6. Thermal Hysteresis. The experimental dependence of the heat flux removed by a flow of droplets on the temperature of the cooled surface is presented in Fig. 4 for two values of the cooling density J. For a fixed value of J a change in temperature to the side of its increase shows the heat flux maximum at $T_S = T_\lambda$ and minimum at $T_S =$



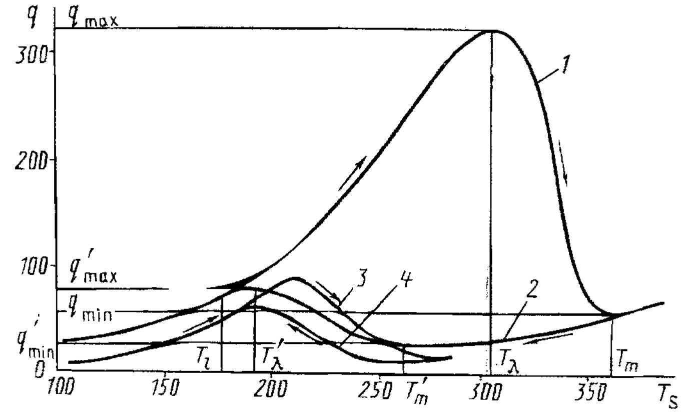


Fig. 3. Dependence of the maximum heat transfer rate on the cooled-surface temperature: 1) steel; 2) duralumin. q_{max}, kW/m^2; T_S, °C.

Fig. 4. Heat flux removed by a flow of droplets vs cooled-surface temperature: 1, 2) J = 0.125 kg/(m^2·sec); 3, 4) 0.035.

T_m (curve 1). However, when the temperature changes after this to the side of its decrease (curve 2), heat removal does not increase, but even decreases somewhat, attaining a second minimum at the temperature $T_S = T'_m$, which is much smaller than T_m. Afterwards, an increase is observed in heat removal with a decrease in T_S down to a second maximum at a certain temperature T'_λ. In the zone of low temperatures with $T_S < T_l$, when the cooling-liquid film is preserved on the cooled surface, curves 1 and 2 coincide. The same behavior but at other temperatures and heat fluxes was also observed at J = 0.035 kg/(m^2·sec) (curves 3 and 4).

Thus, the heat flux removed from the cooled surface is determined not only by its temperature at the given time but also by the temperature state in the preceding period, i.e., the phenomenon of thermal hysteresis is observed, which is a delayed change in heat flux with change in temperature.

This phenomenon can be explained by analyzing the appearance of the so-called "spots of chilling" of the cooled surface. The presence of such spots could be observed on the cooling surface in stroboscopic illumination in the temperature range from T_λ to T_m. When the stroboscope lamp flash was synchronized with the time of droplet interaction with the surface, a zone of contact existing for a short time was observed on the latter in the form of a group of spots.

Spots of chilling on the descending branch of curve 1 appear because of the boiling of droplets and the formation of local zones on the surface with a temperature lower than the mean one. The presence of these zones ensures direct contact of liquid with metal at the temperature at which complete evaporation of the liquid takes place without the formation of a vapor interlayer. As the surface temperature subsequently increases, the overall area of these zones, i.e., of chilling spots, decreases and at $T_S = T_m$ they disappear. At the temperature T_m the droplets-fragments, formed as a result of breaking of the main droplet, make contact with the surface only for a very short interval of time, and then they hover on a vapor cushion and disperse, not giving effective heat dissipation.

Starting from this instant, absence of chilling spots determines the low efficiency of heat removal when the surface temperature falls to T'_m (curve 2). When the temperature T'_m is attained and a further decrease in temperature occurs, chilling spots appear again but for a very short interval of time, so that they disappear by the time of arrival of the next portion of droplets. This is explained by the fact that the thermal state of the specimen was preceded by complete "dispersion" of the droplets and that in the given case the overall area of the droplets and the temperature drop between the surface and a spot are much smaller than those on curve 1.

Conclusion. Droplet-evaporative cooling ensures a high efficiency of cooling in certain rather narrow ranges of the cooled-surface temperature; specific values of these ranges depend substantially on the thermophysical characteristics of the surface material and on the wetting density produced in the cooling facility. Experiments conducted on a special rig have allowed us to obtain empirical relations for the temperature of maximum heat removal and the corresponding heat transfer rate; the relations obtained agree well with an approximate theoretical description of the process with the aid of a "film" analogy and relations for the thermal shock. Surface temperature fluctuations at constant wetting density change the efficiency of heat removal (the heat flux removed) several times. This produces the need in specific cooling systems for automatic control of the efficiency of atomizers.

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