earized theory. Deviation from linearization led to a significant improvement in the agreement between the calculated and experimental values of $\bar{u}_{1m}$ and $\bar{u}_{2m}$.

NOTATION

t, width of slit; $\bar{x} = x/t$, $\bar{y} = y/t$, dimensionless longitudinal and transverse coordinates; u_∞, velocity of incoming flow; u_0, velocity of discharge of jet from slit; $m = u_\infty/u_0$; $\bar{u} = u/u_\infty$, relative value of the longitudinal component of mean velocity; $\bar{u}_{1m} = u_{1m}/u_\infty$, $\bar{u}_{2m} = u_{2m}/u_\infty$, dimensionless defects of mean velocity; u', v', w', pulsations of the velocity along the flow, across the flow, and along the span of the slit; $\overline{u'v'}$, Reynolds shear stresses; e, kinetic turbulence energy; δ_1, δ_2, characteristic transverse dimensions; ρ, density; τ, shear stress; ν_t, eddy viscosity coefficient; $\varkappa$, constant.

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EXPERIMENTAL STUDY OF HEAT TRANSFER BETWEEN A HOT WALL AND IMPINGING DROPS

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UDC 536.24

We have studied heat transfer between the wall and impinging drops by using quick-response temperature sensors. We have obtained transient surface-temperature profiles and the heat-removal characteristics.

In spite of the wide use of high-efficiency cooling by spray jets, data on heat transfer between a wall and impinging drops are meager and contradictory [1-3]. It was noted in [4] that under similar conditions the results of various experimenters on heat removal of a drop differ by an order of magnitude and more, which is accounted for by the imperfection of the experimental methods, mainly the large and uncontrollable inertia of the surface-temperature sensors (STS). Transient profiles $T_t(\tau)$ were first obtained in [5, 6], but there are no data on the dynamic characteristics of the temperature sensors.

We present the results of experiments performed in the development of [7, 8].

Measuring System. We have employed thermocouple STS similar to those used earlier for the thermometry of barrels of rapid-firing guns [9, 10]. A Chromel thermoelectrode 0.3 mm in diameter was placed in a hole in a nickel calorimeter (a cylinder 30 mm in diameter and 20 mm high) and electrically insulated from it by an oxide film formed by preliminary annealing in an oven. When the heat-transfer surface (the end of the calorimeter) was polished together

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Northwestern Correspondence Polytechnic Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 47, No. 6, pp. 911-919, December, 1984. Original article submitted September 19, 1983.

0022-0841/84/4706-1400$08.50

with the thermoelectrode the interpenetration of material formed the hot junction of a semiartificial nickel—Chromel thermocouple. The reliability of the sensor was increased by depositing a galvanic or gas-plasma coating on the heat-transfer surface, which was then polished. Since the thermophysical properties of the calorimeter, the thermoelectrode, and the coating are negligibly different, the temperature sensor introduced only small perturbations in the temperature distribution of the wall. The hydrodynamic and boiling conditions of the spreading drops are generally not perturbed by the sensor.

The inertia of the STS was determined by using the solution of the problem of the pulsed heating of a semiinfinite body [11]. Radiation from a motion picture lamp was concentrated by a parabolic mirror on a spot ∿10 mm in diameter, and interrupted by a disk shutter. The amplitude and frequency characteristics of the measuring system plotted in $(\Delta T/\sqrt{\tau_\iota}, f)$ coordinates show that the time resolution of the STS is 1 msec [12].

The calorimeter also contained Chromel—Alumel thermocouple junctions in holes bored near the axis of the cylinder, at the ends and lateral surface, which permitted the determination of the change in the average temperature during the experiment.

The drop generator included an elastic element vibrating in an alternating magnetic field whose frequency was tuned to the natural frequency of the vibrator. A drop accumulating on the end of a cut-off hypodermic needle was shaken off by inertia forces. The frequency of the vibrations and the rate of incidence of the drops were determined by using an ST-1 strobotac, and the dimensions were determined by weighing. The water drops studied were 0.5–3 mm in diameter.

The calorimeter was heated in an oven to an initial temperature of $T_0 \approx 650°C$, and sprayed with a succession of drops. The thermoelectromotive force of the STS was fed through an F1510 amplifier to an N-117 oscillograph, and the thermocouple responses were recorded on a KSP-4 potentiometer. Strobograms of the break-up of the drops were obtained also (the shape of a drop, changing during impact, and tracks of the dispersing drop fragments) with a 2.5-msec interval between successive exposures.

Transient Profiles of the Surface Temperature. Figure 1 shows $T_{t.\mathrm{meas}}(\tau)$ for a water drop (D_d = 3.0 mm, T' = 21°C; w = 2 m/sec, We = 180). The curves are similar to those in [5] which were obtained by using a 1.6 × 0.9 mm nickel resistance thermometer attached to a stainless steel wall. In the experiments reported in [5], boiling conditions on a temperature sensor covered with a protective layer of SiO could be distinguished from conditions on the wall; the perturbations introduced in the hydrodynamics and temperature distribution by the thermal resistor are difficult to estimate.

For $T_t \gtrsim 350°C$ (film boiling) the thermal contact of a drop with the wall at the point of incidence lasts for a time $\tau_c \approx 2.5$ msec, and lowers T_t. The time of contact of the liquid phase with the wall before a vapor layer appears was $\sim 10^{-9}$ sec, and then, as a result of the growth of homogeneous vaporization centers, a vapor layer of thermodynamic origin is formed. The time resolution of the STS used was inadequate to permit an investigation of the details of this process. Heat removal in this range is determined by the underheating of the liquid and the hydrodynamics of the break-up of the drop. In a characteristic time of the order of a microsecond, shock waves and rarefaction waves are intermingled, cavitational voids are formed and collapse [13], and cumulative jets are formed.

Lowering the wall temperature in a high-speed collision process at $T_0 < 350°C$ leads to wetting of the wall, and the character of the transient processes is changed. Motion pictures and strobograms show that at this stage of the experiment wet spots appear under a drop, but they dry up before the next drop impinges. With further lowering of T_t the diameter of the wet spot and the time for it to dry up increase, the dimensions of the secondary drop fragments increase, their rate of dispersion decreases, and the curvature of the trajectory increases. At the stage of the experiment when wet spots are drying up, isothermal areas appear on the $T_t(\tau)$ curves, and the duration of the wetting phase for the same T_t is unstable, sometimes differing by a factor of three or four for neighboring drops. This appears to be related to random processes (the phase of the Rayleigh oscillations of a drop with respect to the equatorial plane, the variation of the point of incidence). Inertia, frictional, and surface tension forces in a film ∿10 μm thick are of the same order of magnitude.

Local characteristics of dynamic processes under an impinging drop were investigated by scanning the spot of thermal contact. The calorimeter was moved with a constant velocity of ∿1 cm/sec, so that the STS was at different distances from the point of impact for suc-

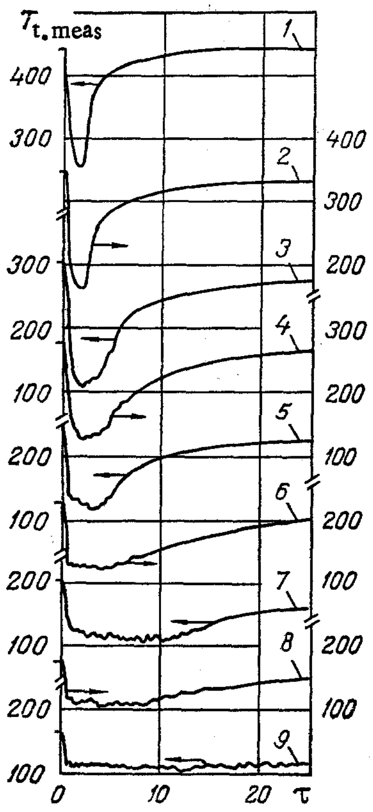

Fig. 1

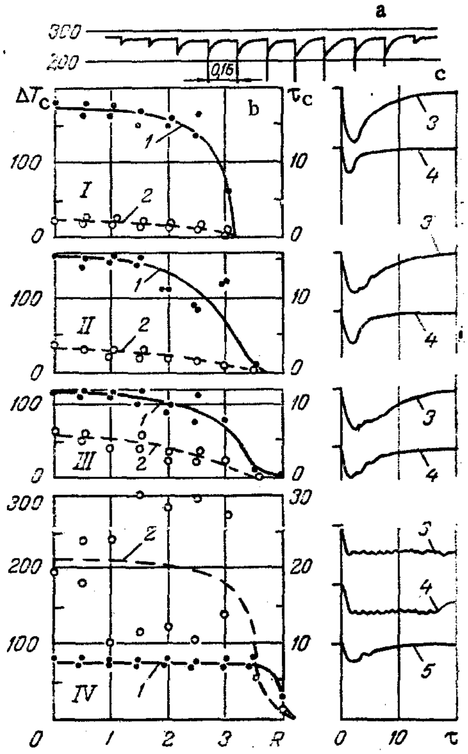

Fig. 2

Fig. 1. Transient surface-temperature profiles $T_{t.meas}$ (°K) vs time τ (msec) during incidence of a water drop on a nickel calorimeter: 1) T_0 = 444; 2) 343; 3) 302; 4) 282; 5) 250; 6) 222; 7) 202; 8) 176; 9) 162°C.

Fig. 2. Results of scanning the thermal contact spot of a water drop (D_d = 3.0, w = 2 m/sec, T' = 21°C, We = 180) impinging on a nickel wall: a) sample of oscillogram (ordinate is T_0 in °C; abscissa is τ in sec); b) variation of 1) ΔT_c (°K) and 2) τ_c (msec) with the distance R (mm) along the radius of the contact spot; c) typical temperature profiles τ (msec): I) T_0 = 336; II) 286; III) 222; IV) 190°C; 3) R = 0; 4) 3; 5) 4 mm.

cessive impinging drops. Figure 2 shows the results of one of the experiments. In the range of film boiling for We = 180, the diameter of the thermal contact spot is of the order $1.5D_d$. The value of τ_c varies negligibly with the radius. In the range of drying up wet spots, lowering T_t increases the fluctuations of τ_c; its average value decreases appreciably on the periphery of the wet spot.

Heat Loads. For film boiling the values of q, averaged over the time of thermal contact, were determined by using the solution [11] of the problem of heat conduction in a semiinfinite body heated by square pulses within a circle of radius R_0 (the rest of the surface is assumed adiabatic). For T_0 = 442°C, using the values ΔT_c = 234°K and τ_c = 2.5 msec from the oscillogram in Fig. 1, we obtain from the solution [11], averaged over the time τ_c, $q_0 = 7 \cdot 10^7$ W/m² for the heat load. For widely spaced pulses ($\tau_c/\tau_* = 0.015 \ll 1$) the relation $q = 0.5\Delta T_c \cdot (\pi\lambda\rho c/\tau_1)^{0.5}$ gives practically the same result.

In the initial phase of the impact process (a sharp drop of the recorded $T_t(\tau)$ curve), the heat load calculated from the temperature gradient $dT_t/d\tau$ is substantially larger than the value given, but the transient profiles were recorded at the limit of the resolving power of the STS, and therefore we give only its average value. Heat removal by a single drop is determined from the relation

$$Q_d = 2\pi \int_0^{\tau_c} \int_0^{R_d} qR\,d\tau\,dR = q_0 F_{eff}\tau_c. \qquad (1)$$

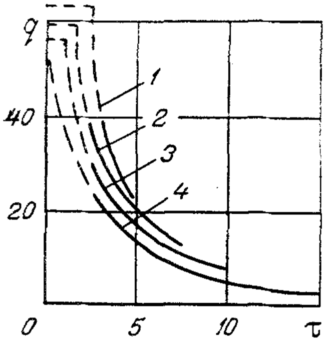

Fig. 3. Transient heat loads under a drop during impact; 1) $T_w = 151$; 2) 124; 3) 111; 4) 106°C. Experimental conditions are the same as in Fig. 1; q is in MW/m² and τ is in msec.

Assuming, in accordance with Fig. 2, that for a drop with $D_d = 3$ mm the effective diameter of the thermal contact spot is 4.5 mm, we obtain from (1) $Q_c = 2.8$ J. Later we present data on heat removal of drops at similar temperatures which agree with the value given.

With the appearance of a dried-up spot, the heat load in the initial phase of the impact (up to the emergence of the $T_t(\tau)$ curve into the isothermal area) is estimated in the same way as in the range of pure film boiling. Then boundary conditions of the first kind are established under the liquid film. The motion pictures show that there is no nucleate boiling in the liquid film, the heat removed from the wall is conducted through the film, and liquid is evaporated from the free surface. The heat load removed by the drying layer is determined by the relation

$$q = \lambda (dT/dz)_{z=0} = \lambda (T_0 - T_t)/(\pi a \tau)^{0.5}. \qquad (2)$$

Figure 3 shows the values of $q(\tau)$ at the point of impact of the drop; the computational parameters were determined from the oscillograms in Fig. 1. The parts in the film boiling range and in the initial phase of wetting are shown by dashed lines.

The energy balance at the film surface (at z = h; the z coordinate is measured from the wall surface) is determined by the equation

$$\lambda' (dT/dz)_{z=h} = \rho r dh/d\tau. \qquad (3)$$

For a boundary condition of the first kind $T_{z=0} \doteq T_t = \text{const}$ and a linear temperature profile over the thickness of the film $T_z = (T_t - T_{sat})(1 - z/h)$, we find the duration of the wetting phase τ_w (the time of evaporation of a film of initial thickness h_0) by integrating (3):

$$\tau_w = \rho' r h_0^2 / 2\lambda' (T_0 - T_t). \qquad (4)$$

According to Eq. (4), the average value of h_0 in the experiment for which the temperature profiles are shown in Fig. 1 is 9 μm, and does not depend on T_0. As a result of the variations of τ_c for the same T_0, the thickness of the film under individual drops differs from the average value by up to 50%.

The maximum diameter D_w of the wet spot in the experiment for which the measured values of $T_t(\tau)$ are shown in Fig. 1 is ∿15 mm. The corresponding heat removed by the drop $Q_d = q_0 F_{eff} \tau_1 + \pi D_w^2 \rho' h_0 (r + c_p' \Delta T_{und})/4$ is ∿5 J. The sum of the work done by the forces of internal fiction and the increase of surface energy becomes equal to the initial kinetic energy of the impinging drop. At this stage of the process drop fragments which are formed on the periphery of the wet spot have a low velocity, and some of them remain on the surface of the calorimeter and boil in a transient and nucleate regime during which heat removal reaches a maximum. As a result the heat-transfer surface is cooled to $T < T_{sat}$, the incidence of the next drops leads to its flooding, and the heat-removal intensity in the stage of single-phase convection is sharply lowered. The result of a more complete analysis, taking account of the heating of the initially unheated liquid, deviates from Eq. (4) by less than 10%. We note that in [14], where evaporation in wet spots is also considered, it is assumed that the initial volume of a spot is equal to the total volume of the impinging drop. In our experiments most of the drops are atomized on impact, even in a developed wet spot.

Heat Removal of Drops. In the range We > 80 investigated, a drop is atomized on impact; the heat removed is approximately proportional to its mass. We find the heat removed by a single drop Q_d and then the heat Δi removed by a unit mass of the cooling liquid from the gradient of the average temperature of the calorimeter $d\bar{T}/d\tau$ from the relation

$$Q_d = [\Delta I' (\bar{T}) - \Delta I'' (\bar{T})]/(n \Delta \tau), \quad \Delta i = Q_d/m, \qquad (5)$$

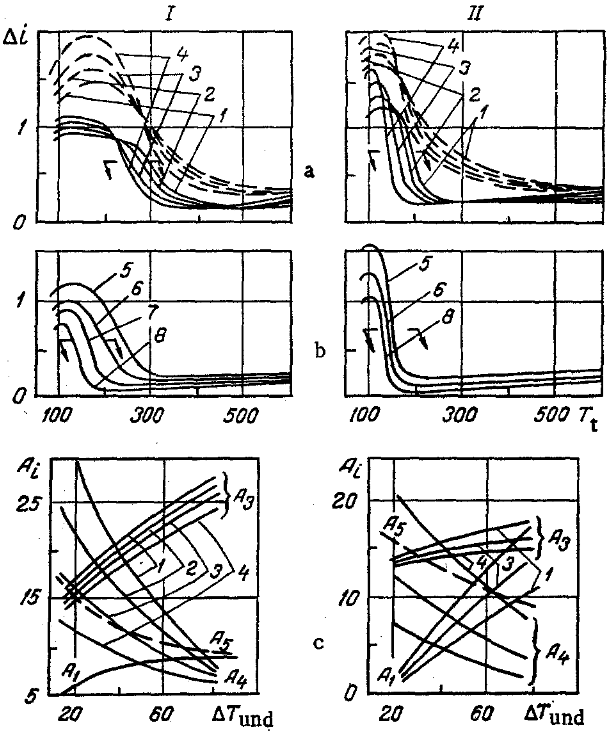

Fig. 4. Heat removal by water drops (MJ/kg) as a fucntion of wall temperature T_t (°C): I) St12Kh18N10T; II) M1; a) effect of Weber number, T' = 21°C (dashed lines are for a surface with a capillary-porous coating); b) effect of underheating, We = 180; c) parameters of Eq. (6) as functions of underheating: 1) We = 1800; 2) 900; 3) 450; 4) 180; 5) ΔT_{und} = 80; 6) 60; 7) 40; 8) 20°K; $A_1 \cdot 10^2$ MJ/kg; $A_3 \cdot 10^{-1}$ °K; A_4; $A_5 \cdot 10$.

where $\Delta I' = cm\Delta\bar{T}$ is the change in enthalpy of the calorimeter during spraying by drops; $\Delta I''$ is the same in an experiment without drops (in air). The efficiency of drop cooling is determined by the relation $E = \Delta i/\Delta i_{max}$, where $\Delta i_{max} = r + c_p'\Delta T_{und}$ is the maximum amount of heat which can be removed by a kilogram of liquid (for water at room temperature Δi_{max} = 2.58 MJ/kg).

Figure 4 shows Δi as a function of T_t obtained in experiments on water cooling of steel and copper calorimeters. Calorimeters with a heat-transfer surface coated with a 0.25-mm-thick nickel capillary-porous layer of ~50% porosity were tested also; particles of nickel 50 μm in diameter were deposited by a gas-thermal method.

The efficiency of cooling a smooth surface in the film boiling range (T_t > 450 and 300°C for steel and copper, respectively) is 4-8% (0.3% according to data in [1], and ~10% according to data in [3]). Here the underheating of the liquid has a decisive effect on heat removal. In the range of maximum heat removal (before flooding of the wall) E = 45% on steel (~80% according to data in [3]) and 55% on copper. A coating of a capillary-porous material, oxide, or impurity increases Δi_{max} and initiates a transition to wetting for a higher T_t (the latter cannot of course be reliably determined for a coating by extrapolation of the readings of buried temperature sensors).

The effect of the velocity of impact, or the Weber number, is manifested in two ways. On the one hand, an increase in w intensifies heat exchange with the surrounding air and forced convection to the liquid; as a consequence of the increase in pressure in the initial phase of the impact, the vapor layer is thinned out, and wetting is facilitated. On the other hand, an increase in w decreases the time of contact of the drop with the wall. In the range of film boiling an increase in velocity leads to a decrease in heat removal. This result contradicts Pedersen's data [3]. In our opinion these differences are related to the fact that in the experiments in [3] the calorimeter-traget was placed inside a small oven-heater. Secondary drop fragments cooled the radiating surface of the oven, which, in the method Pedersen used to calculate heat removal, led to its overestimate in comparison with data in [2] and our values. In addition, for a high velocity of a primary drop, the fragments reflected from the heated walls again strike the calorimeter, producing the illusion of an increase in heat removal with an increase in the velocity of impact.

An increase of the underheating of the liquid, like an increase in the velocity of the drops, leads during the gradual cooling of the sample to an increase in heat removal because wetting begins at a higher T_t.

The combined effect of underheating and the Weber number for the ranges of the film boiling and the drying of wet spots is generalized by a correlation obtained by the superposition of a linear law for the increase of Δi with an increase in T_t in the film boiling range and a hyperbolic law in the range of drying up of wet spots:

$$\Delta i = A_1 + A_2 (T_t - A_3) + A_4 (T_t - A_3)^{-A_5}. \tag{6}$$

The values of A_i for water drops impinging on steel and copper walls are shown in Fig. 4c; $A_2 = 2.5 \cdot 10^{-4}$. The experimental data do not differ from the values calculated with Eq. (6) by more than 30% in the film boiling range, and than 50% in the range of drying up of wet spots. The limits of applicability of Eq. (6) are indicated by arrows in Fig. 4.

In addition to water, we performed experiments with methyl, ethyl, and butyl alcohol drops. The transient profiles of the surface temperature and the heat-removal data show that at room temperature heat removal by drops of low-boiling methanol in the film boiling range is very low, $E < 1\%$. In the range of maximum heat removal the efficiency of cooling by alcohol exceeds that of water by 10% on the average, reaching 55% on the steel calorimeter and 73% on the copper calorimeter. This may be a result of better wetting.

Experiments on thick walls showed that when the time between drops is long enough for the wall temperature to recover before the next drop strikes, the statistical fluctuations of the transient profiles $T_t(\tau)$ are smooth and minor.

Therefore, in the cooling of a wall by dispersed jets (sprayer, water—air jets, etc.) with a low density of spraying when the Weber numbers of individual drops correspond to the test range, it is natural to determine the flux of heat removed by the relation

$$Q_\Sigma = G'\Delta i + Q'', \tag{7}$$

where the heat removal Δi by drops of liquid is found from (6) or Fig. 4, and the heat removal by a gas jet (the second term on the right-hand side) by known relations (e.g., [15]). In the film boiling range for $T_t > 600°C$, Eq. (7) gives results close to the data in [16]. In our opinion the results for $T_t < 600°C$ differ because of the different inertia of the temperature sensors (in [16] T_t was measured with a thermocouple at a depth of 2 mm in a stainless steel calorimeter).

NOTATION

A_i, parameters in Eq. (7); a, thermal diffusivity of wall, m²/sec; c, specific heat, J/kg·°K; D, diameter, m; D_d, D_w, diameters of drop and wet spot; E, cooling efficiency; F, heat-transfer area, m²; G', mass flow rate of liquid, kg/sec; h, thickness of liquid film, m; I, enthalpy of calorimeter, J; Δi, increment of specific enthalpy of liquid, J/kg; M, mass of calorimeter, kg; m, mass of drop, kg; n, number of drops; Q, heat flux, W; Q_d, heat removal of a drop, J; q, heat load, W/m²; R, radius, m; r, latent heat of vaporization, J/kg; T, temperature, °K, °C; ΔT_c, decrease of surface temperature during time of contact with drop, °K; w, velocity, m/sec; $We = \rho' w_2 D_d/\sigma$, Weber number; z, coordinate normal to heat-transfer surface; λ, thermal conductivity, W/m·°K; ρ, density, kg/m³; σ, surface tension, N/m; τ, time, sec; τ_c, duration of thermal contact during impact, sec; τ_1, duration of film boiling phase, sec; τ_*, period of incidence of drops, sec. Indices: 0, initial state; ', liquid phase; ", air; ‾, average; sat, saturation; w, wetting; eff, effective; und, underheating; t, surface.

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