Int. J. Heat Mass Transfer. Vol. 12, pp. 95–108. Pergamon Press 1969. Printed in Great Britain

INDIVIDUAL DROPLET HEAT-TRANSFER RATES FOR SPLATTERING ON HOT SURFACES

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(*Received* 18 *March* 1968 *and in revised form* 5 *August* 1968)

Abstract—An experimental study of the splattering and bouncing of water, acetone, and alcohol droplets from a heated plate reveals that the heat transfer per drop exhibits a maximum at a temperature excess of approximately 300°F and that a satisfactory correlation for this maximum

$$\frac{Q_{\max}}{\rho_L\, d^3 \lambda} = 8{\cdot}44(10^{-4})\left(\frac{\rho_L^2 V^2\, d}{\rho_{V_F} \sigma g_c}\right)^{0{\cdot}341}$$

The effect of impact angle is also investigated and the general result is that the normal component of velocity is the important factor. A normalized heat flux-temperature excess curve is presented for the three fluids tested. The maximum point in heat transfer is postulated to result from opposing effects of increasing thermal gradient and decreasing droplet contact time in the splattering process.

NOMENCLATURE

A,	area [ft^2];
C_p,	specific heat at constant pressure [Btu/lb °F];
C,	constant in equation (6);
d,	drop diameter [ft];
g_c,	constant of proportionality in Newton's second law;
h,	heat-transfer coefficient [Btu/ft^2 h °F];
h_{fg},	enthalpy of vaporization [Btu/lb];
J,	conversion factor from Btu to ft lbf;
k,	thermal conductivity [Btu/ft h °F];
N,	drop rates [drops/s];
P,	heater power consumption [W];
q,	
q_{net},	net rate of heat transfer to drops [Btu/s or W];
Q,	heat transfer per drop [Btu/drop];
t,	time [s];
T,	temperature [°F];
ΔT_x,	$T_p - T_s$, saturation temperature excess [degF];
V,	velocity [ft/s];
W_e,	$\sigma g_c/\rho_L V^2 d$, Weber number [dimensionless].

Greek symbols

δ,	effective conduction distance [ft];
θ,	plate angle and impact angle [degrees];
λ,	modified heat of vaporization defined by equation (3) [Btu/lb];
ρ,	density [lb/ft^3];
σ,	surface tension [lbf/ft];
τ,	droplet contact time [s].

Subscripts

F,	film, evaluated at film temperature;
G,	gross;
L,	liquid.

INTRODUCTION

COLLISIONS involving liquid droplets and hot surfaces are of interest in a number of areas of applied technology. The cooling of turbine blades by means of impinging liquid droplets and the cooling of aluminum ingots with water sprays are representative of this process. The

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problem of determining heat transfer rates as a re-entry vehicle passes through a rainstorm is one which requires detailed understanding of the droplet-hot surface collision.

When a liquid droplet and a solid surface are brought together at some finite relative velocity, a number of interesting, sometimes useful and often destructive, processes have been observed. The erosion of surfaces due to raindrop impingement has been a subject of considerable interest since the advent of high-subsonic and supersonic aircraft. An extensive survey of the literature of rain erosion has been made by Beltran [1]. The great majority of the research in the area has been experimental, as typified by the work of Engel [2] and Jenkins and Booker [3]. Notable exceptions are the analytical studies of Engel [4] and Savic and Boult [5] in which theoretical expressions for the impact pressure distribution are obtained. In addition, Savic and Boult obtained an expression for the shape of the spreading liquid mass.

When the surface involved in the collision is a heated one, other interesting effects have been observed. Elperin [6] observed order of magnitude increases in heat-transfer rates when water was injected into an air flow upstream of a tube bank. These results were verified by Acrivos [7] and the process was successfully analyzed by Goldstein [8]. However, the experimental conditions were such that little evaporation of the liquid phase was observed. Parker and Grosh [9] studied the mist flow of steam in a cylindrical test section and noted sharp variations in wall temperature and heat-transfer rate, particularly at points where the annular liquid film disappeared and where the wall temperature exceeded the value required for stable film boiling. The investigators recommended that studies be made to determine the behaviour of droplets striking a hot channel wall at various angles and velocities. It is this phenomenon, known as splattering, which is the subject of this work.

A liquid droplet is said to have splattered from a hot surface if it strikes the surface and disintegrates without significantly wetting the surface. This phenomenon is observed when the surface temperature exceeds the value required for film boiling. The heat-transfer aspect of this process has been investigated by Savic [10]. In that work water droplets were made to impinge upon a hot silver surface while high-speed motion pictures were taken. Because of the small size of the heated surface, rapid heater temperature transients were observed upon droplet impingement. Thus, no attempt was made to obtain quantitative heat-transfer data. Photographic observations indicated that the spreading of a droplet over a hot surface is at least superficially similar to the cold surface impact process and that the ultimate disintigration of the droplet results from vapor bubbles penetrating the upper free surface of the droplet.

Wachters and Westerling [17] also investigated the heat transfer from very hot surfaces to impinging water droplets. However, the impact velocitics investigated were less than the value required for splattering. The critical impact velocity, above which the droplet disintegrates during impact, was found to be about 5 ft/s for 0·07 in dia. water droplets. Heat-transfer measurements were made by means of a transient technique and agreed well with the theory only for temperature excesses approaching 600 deg F. In a subsequent paper, Wachters *et al.* [18] investigated heat transfer from a hot well to a mist of very small droplets, 60 μ in diameter. Again, impact velocities were below the value required for splattering.

It should be noted that the splattering process may be thought of as an extension of the classic Leidenfrost problem to the case of finite impact velocity. This phenomenon has been widely observed and investigated. Recent work in this area includes the investigation of Baumeister [11], Schoessow [12], and Gottfreid [13]. It is apparent that splattering is a least in part a film boiling process, and thus a number of the physical quantities governing heat transfer in the Leidenfrost phenomenon are of similar importance to the splattering process.

The transient, random nature of the process of disintegration of a droplet striking a high temperature surface, coupled with a lack of information as to what physical phenomena comprise the process, makes a direct analytical attack extremely difficult. Thus, the present paper is confined to an experimental investigation of the characteristics of splattering heat transfer. Because of the lack of previous work, the decision was made to investigate the behaviour of a stream of freely falling droplets of uniform size splattering from a heated surface, rather than a dispersion or spray of droplets. Subsequent investigations would logically include work with multi-droplet sprays and with two phase flows, e.g. water droplets entrained in an air stream. The specific objectives of the work were as follows:

1. To obtain data for the quantity of heat transferred in a single droplet-surface collision as a function of surface temperature for a range of drop sizes, drop impact velocities, and drop substances.
2. To develop a correlation for maximum heat transfer per drop. Preliminary results indicated that a maximum exists in the curve of heat transfer per drop vs. surface temperature.
3. To determine the effect of variation of impact angle, defined as the angle between the normal to the heated surface and the drop velocity vector, on the heat transfer per drop.
4. To develop a physical description of the process using the experimental data and observations of the process.

Experimental apparatus and method

The experimental apparatus is shown schematically in Fig. 1. The test surface was a 5 × 5 × 0·25 in copper plate, nickel plated and polished to mirror finish, resting on a resistance heating element. Total hemispherical emittance of the surface was estimated to be less than 0·10. Copper was chosen as the plate material in order to closely approximate an isothermal surface. The resistance heating element was a 750 W unit, and was controlled by a Variac. The plate-heater assembly was mounted on a levelable platform and hinged at one end to provide for variation in drop impingement angle. This angle could be varied in discrete increments of approximately 15° by adjusting the supporting bar provided. The entire assembly could be illuminated for observation purposes.

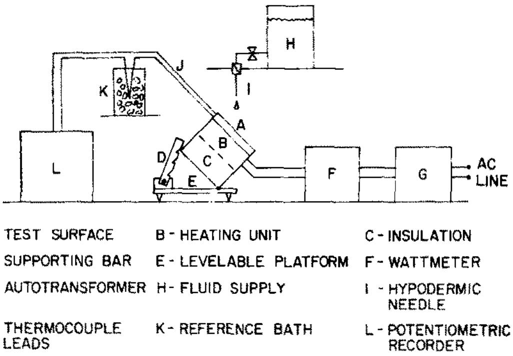

FIG. 1. Schematic diagram of experimental apparatus.

The heated plate was instrumented with two 30 gauge iron–constantan thermocouples. One thermocouple was located at the geometric center of the plate, directly beneath the point of droplet impact, while the other was located one-half the plate width from the center. Thermocouple outputs were recorded on a recording potentiometer accurate to ±0·2 per cent of full scale. A Strobotac, accurate to ±5 per cent, was used in the determination of drop rates and impact velocities. The fluid reservoir temperature was measured with a mercury-in-glass thermometer.

The test liquids were:

1. Water: distilled, b.p. 100·0°C
2. Ethanol: reagent, b.p. 78·5°C
3. Acetone: reagent, b.p. 56·5°C.

The drop generator consisted of a fluid reservoir supplying a hypodermic needle through a valved connecting line. The reservoir was operated at fixed head by the simple expedient of allowing the fluid to overflow at the desired level. The surplus fluid was recirculated by a low pressure scavenge pump which picked up the overflow and returned it to the reservoir. Gross drop rate variations were obtained by adjusting the connecting line valve. Calibration runs made with the aid of a Strobotac indicated that for a fixed valve opening drop rates could be maintained within 5 per cent of a typical value of 10 drops per second with the constant head system. The actual drop formation occurred at the tip of a hypodermic needle. Five stainless steel needles of 13, 15, 18, 20 and 24 gauge were filed to a flat tip and calibrated at room temperature by collecting at various drop rates known numbers of droplets in a container of known mass, then measuring the gross mass. All masses were measured with a precision beam balance, and the repeatability of this method was excellent. From this information the mean mass per drop and the corresponding mean drop diameter could be computed, and thus the variation of drop size with drop rate was obtained. An uncertainty analysis indicated that drop diameters determined in this fashion were accurate within 2 per cent for the worst case investigated. The results indicated that the size of water droplets decreased significantly with increased drop rate. A correction for this effect was made if the drop rate varied more than 10 per cent during an experimental run. Because of the relatively low surface tensions of acetone and ethanol, the sizes of droplets with these substances did not vary significantly with drop rate over the range investigated.

The impact velocity of impinging droplets was varied by adjusting the height of the hypodermic support above the test surface. The apparatus allowed a maximum drop velocity of approximately 25 ft/s. Impact velocities were estimated assuming free fall without drag and were experimentally determined for each run by means of a Strobotac and a calibrated height scale. The latter method involved determination of the time required for the droplet to traverse some small, observed final distance before striking the plate. An uncertainty analysis indicated this method to be slightly less accurate than the length measurement, estimated at approximately 5 per cent.

The initial step in the experimental procedure was that of obtaining a calibration of heater power consumption vs. steady-state plate temperature with no drops falling on the test surface. Such a curve represents total losses from heater system due to radiation and free convection and was obtained by fixing the power input to the heater and noting the corresponding steady-state temperature. The curves in Fig. 2 were so obtained for the system under consideration. Variations in room temperature, power leads, and location did not change the calibration measurably. However, variations in the plate angle changed the heat transfer characteristics of the system significantly, as shown by the curves for plate angles of 0° and 45°. Because of the very high thermal-conductivity of copper, steady-state temperature gradients in the plane of the plate were found to be negligible. Thus a single curve of power requirement versus steady-state temperature is representative of all locations on the plate.

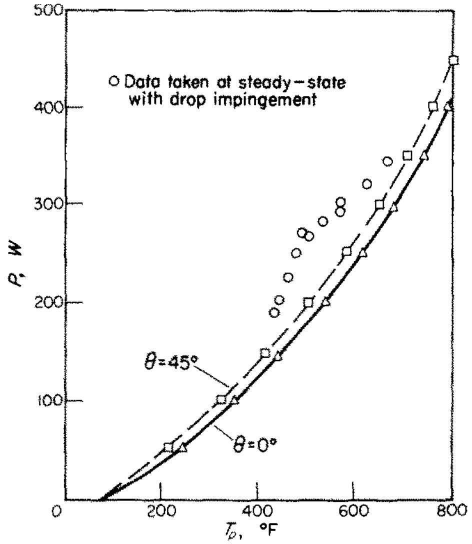

FIG. 2. Heater power consumption without droplet impingement vs. steady-state test surface temperature for test surface inclinations of 0° and 45°; typical data taken with droplet impingement shown.

With the drop generation apparatus set up to give a known drop size and impact velocity, and with the test surface inclined at some known angle, the flow of droplets was begun and a drop rate measurement made. The heater power input was then set, and when steady-state conditions were reached, corresponding thermocouple outputs were recorded and the drop rate again determined and recorded. The power input was then changed and the process repeated, thus generating another curve of power requirement vs. steady-state temperature. A typical set of data points is represented by the circular symbols in Fig. 2. The net heat-transfer rate is defined as the difference between the power consumption with droplet impingement and the power consumption without droplet impingement, both powers being evaluated at the steady-state surface temperature in question. It was assumed that the total rate of heat transfer to the droplets, for a particular surface temperature, is given by the net heat-transfer rate.

The determination of heat-transfer rates is predicted upon the assumption that the steady-state temperature distribution in the heater system is not significantly affected by removal of heat from a small area at the center of the test surface. Thus losses from the system by the radiation and free convection modes are assumed to be the same at a given steady-state surface temperature, with and without droplet impingement, so that the difference in power requirement reflects only heat transfer to the impinging droplets. This assumption was verified by means of experimental temperature measurements and is valid because of the ability of the copper to rapidly conduct heat toward the point of drop impingement. In addition, the magnitude of the local temperature transient induced by the impinging droplet was estimated and found to be extremely small.

The data obtained by the method described in the preceding sections were reduced to average heat transfer per drop by dividing the net heat-transfer rate by the rate of drop impingement:

$$Q(\text{heat transfer per drop}) = \frac{P(\text{with droplet impingement}) - P(\text{without droplet impingement})}{N(\text{drops per second})} \tag{1}$$

The uncertainty in the value of heat transfer per drop computed by this method is a result of uncertainties in power measurements and drop rate measurements. For a typical set of data the uncertainty was found to vary from 5 per cent at the maximum value of heat transfer per drop to 10 per cent at the minimum value measured. An examination of Fig. 2 reveals that the difference between the power consumption with and without drop impingement is small compared to the power consumption itself, so that this uncertainty increases rapidly as the heat transfer per drop decreases.

RESULTS AND DISCUSSION

The ranges of experimental conditions are given in Table 1. A data point consists of a value of heat transfer per drop and the corresponding surface temperature. A minimum of nine such data points constituted a run. The heat transfer per drop was found to have a maximum value in the temperature range investigated. If necessary more data points were taken in order to satisfactorily define the magnitude and location of this peak value. The runs involving variation of drop rate, drop size, and drop impact velocity were made with the test surface at 27° angle with respect to the horizontal. This was done so that any splattered fragments striking the surface would rapidly roll off, thus minimizing secondary heat-transfer effects and assuring that the heat transfer measured was that of

Table 1. Ranges of experimental conditions for the individual substances investigated

Substance	d (in)	V (ft/s)	θ (degrees)
Water	0·112 → 0·151	3·44 → 16·75	6–74
Acetone	0·100 → 0·143	5·55 → 19·50	13–59
Ethanol	0·106 → 0·132	5·88 – 14·85	27–74

initial impact and disintegration. Throughout the experiment, care was taken to eliminate any spurious effects not directly associated with splattering.

If the test surface were isothermal and if there were no droplet interference effects, then it would be expected that the heat transfer per drop would be independent of the number of drops striking the surface per unit time, other conditions being equal. However, if the drop impact results in a local temperature transient of sufficient magnitude and if the duration of the transient is long compared to the frequency of drop impact, then the effective surface temperature, and thus the heat transfer per drop, will be a function of drop rate. Obviously, such an effect is a function of the thermal response characteristics of the test surface. Thus a large, thick copper surface was chosen for use in the present work. The temperature depression for such a surface subjected to local heat removal of the order of magnitude of that encountered in this work was estimated and found to be negligible. A second possible effect of drop rate is that of droplet interference. As the drop rate is increased, subsequent droplets could collide with splattered fragments of preceding droplets, thus altering the heat-transfer process. Such an effect is inherent in the process and as such cannot be designed out of the experiment. Thirdly, at high drop rates the droplets produced could deviate significantly from a spherical shape, thus introducing another effect·

For a typical condition of water droplet size and impact velocity, values of heat transfer per drop were obtained as a function of saturation temperature excess for nominal drop rates of 5, 10 and 15 drops per second. The drop rate range investigated was limited by inaccuracies in heat-transfer measurements at low drop rates and by non-uniformity of droplets generated at high drop rates. The results are shown in Fig. 3. A slight decrease in heat transfer per drop is noted as the drop rate increases. However, this decrease is attributed to the decrease in size of water droplets generated with increasing drop rate as previously described. Observations of the falling droplets made with the aid of the Strobotac revealed no perceptible change in sphericity at high drop rates and high impact velocities. Thus the effects of drop rate variation discussed in the preceding paragraph are not believed to be significant in this experiment.

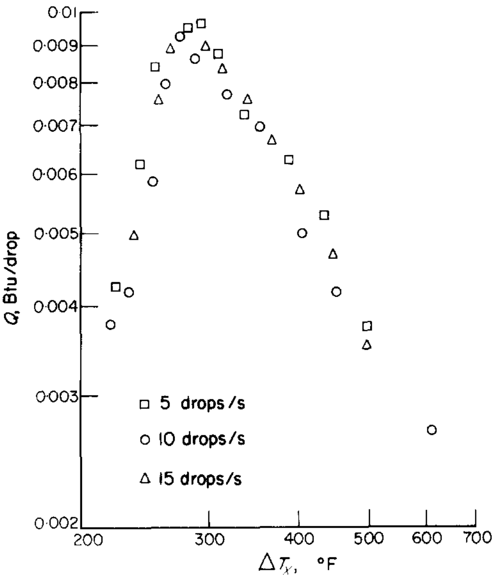

Fig. 3. Effect of drop rate on the curve of heat transfer per drop vs. saturation temperature excess. Water droplets, $d = 0{\cdot}112$ in, $V = 7{\cdot}75$ ft/s, and $\theta = 27°$

Under conditions of constant impact velocity and constant impact angle, data were taken for a total of twelve combinations of drop size and drop substance. In each case the peak values of heat transfer per drop occurred at a saturation temperature excess of approximately 300 deg F. The drop diameter range investigated is equivalent to a fourfold change in drop volume. The results indicate that the peak heat transfer per drop is proportional to the drop diameter to a power slightly greater than three. This result is verified by assuming total evaporation and noting that in that case the heat transfer per drop increases in direct proportion to the mass available for evaporation and thus in direct proportion to the cube of drop diameter. The qualitative effect of changes in drop substance would seem to be that of enthalpy of vaporization. The higher the enthalpy of evaporation, the higher the heat transfer per unit mass evaporated, and this trend is present in the data.

With drop size and impact angle held constant, data were taken for ten values of water droplet impact velocity, four values of ethanol droplet impact velocity, and four values of acetone droplet impact velocity. The trend of the data indicates that the heat transfer per drop increases in direct proportion to impact velocity until some critical velocity is reached, after which it begins to decrease. This result is explained as follows. Using the results of [5], one may show that the area over which an impacting droplet has spread at a given time after impact is a monotonically increasing function of the normal component of impact velocity. This result was verified by observations made with the aid of a Strobotac during the course of the present work. The Strobotac was used to "stop" the falling droplets just after impact, and the radius of the spreading liquid film was seen to increase with increasing velocity. However, the time increment over which the heat-transfer process occurs decreases with increasing velocity as a result of the tendency of the droplet to shatter. Thus at some critical velocity the effect of decreased contact time exceeds the effect of increased area, and the total heat transfer then decreases for further increases in velocity. If the results obtained are directly extrapolated to zero impact velocity, a zero value of heat transfer per drop is indicated. This result is consistent with the experimental condition of 27° plate angle. As the impact velocity approaches zero, the droplet deforms less and less and finally simply slides off the test surface, supported by a vapor film, with negligible heat transfer. If the impact surface were absolutely horizontal and if the impact velocity were zero, then the non-disintegrating droplet would remain on the hot surface until it completely evaporated, thus yielding the maximum heat transfer per drop corresponding to the Leidenfrost problem. This special case has been widely investigated and was therefore not considered in the present work.

A general expression for values of peak heat transfer per drop in terms of impact velocity, drop size, and pertinent thermophysical properties would be of use in the application of the spattering process to practical problems. The appearance of the data discussed in the preceding paragraphs indicate that such an expression exists. A similitude analysis of the pertinent physical quantities yields the following expression:

$$\frac{Q_{\max}}{\rho_L \mathrm{d}^3 \lambda} = \left(\frac{\sigma g_c}{\rho_L V^2 \mathrm{d}}\right)^A \left(\frac{\rho_{VF}}{\rho_L}\right)^B \left(\frac{\rho_L \mathrm{d} \lambda J}{\sigma}\right)^C \tag{2}$$

where the modified heat of vaporization λ is defined as follows:

$$\lambda = h_{fg} + c_{pv} \frac{T_p - T_s}{2} \tag{3}$$

and thus represents the energy required to vaporize a unit mass of saturated liquid and superheat the resulting vapor by one-half the saturation temperature excess. Since the process under consideration is a form of film boiling, the parameter λ represents the energy content per unit mass of the generated vapor and is (therefore) the appropriate quantity for use in the normalization of the heat transfer data. The left-hand grouping in equation (2) represents the dimensionless heat transfer per drop and is a measure of the fraction of the droplet evaporated. The first grouping on the right-hand side of the equation is recognized as the Weber number and as such it characterizes the deformtion of the droplet on impact.

The absence of viscosity from the correlation is a result of the dominance of inertial and surface tension forces in the deformation process. For a typical set of experimental conditions, inertial forces were estimated to be greater than viscous forces by some three orders of magnitude, and surface tension forces were estimated to be greater than viscous forces by two orders of magnitude.

Making use of thermophysical properties from [14–16] values of the four dimensionless groups in equation (2) were computed for each of the twenty-seven maximum heat-transfer data points described in the two preceding sections. Vapor properties were evaluated at atmospheric pressure and at the arithmetic mean of surface and saturation temperatures, defined as the film temperature and denoted by the subscript F:

$$T_F = \frac{T_p + T_s}{2}. \tag{4}$$

The results are shown in Fig. 4. The five data points representing the highest impact velocities investigated exhibit the decrease in dimensionless heat transfer per drop noted previously. These data points were set aside and a straight line fitted to the remaining data by the method of least squares. The resulting fit is shown in Fig. 4, and the data points fall within 10 per cent of that line. Thus the expression

$$\frac{Q_{\max}}{\rho_L\,\mathrm{d}^3\lambda} = 8{\cdot}44\,(10^{-4})\left(\frac{\rho_L^2 V^2\,\mathrm{d}}{\rho_{VF}\sigma gc}\right)^{0{\cdot}341} \tag{5}$$

is an excellent representation of the data obtained for maximum splattering heat transfer with values of the independent variable in the range of 10^5–10^7. This expression will over-predict at higher values of the independent variable but extrapolation to lower values seems reasonable.

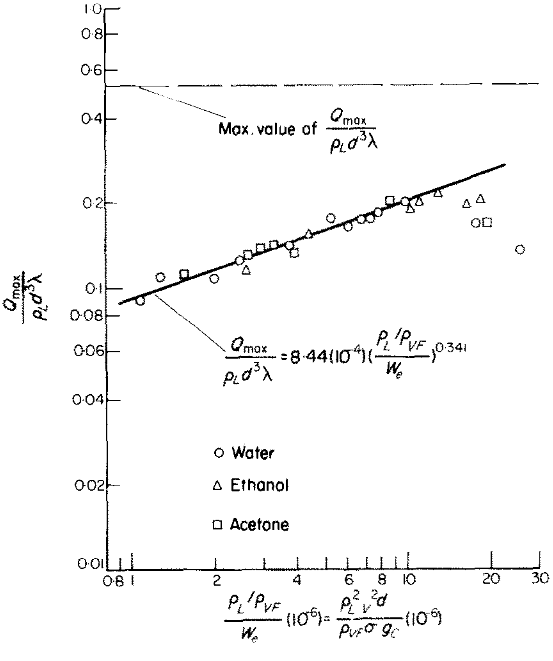

FIG. 4. Correlation of peak heat transfer per drop, $\theta = 27°$.

Obviously, a maximum value of the dimensionless heat transfer per drop exists. The quantity $\pi\rho_L d^3\lambda/6$ is the energy required to evaporate the entire droplet and superheat the vapor to the mean of surface and saturation temperature, by definition of λ. Thus, the maximum possible value of the dimensionless heat transfer per drop is $\pi/6$ and is shown as such in Fig. 4.

The efficiency of the splattering process is defined as the ratio of observed dimensionless heat transfer per drop to this maximum possible dimensionless heat transfer per drop:

$$\text{efficiency} = \frac{Q}{(\pi/6)\,\rho_L d^3\lambda}. \tag{6}$$

A simple calculation based on the data of Fig. 4 inidicates that the maximum efficiency of the process is approximately 50 per cent for the case of the 27° impact angle. The efficiency based on peak value drops off to about 20 per cent at the lower velocities investigated. In addition, the efficiency of the process decreases rapidly as the surface temperature rises above or falls below the peak value. However, the above mentioned values of efficiency correspond to a single, initial impact. In a practical application subsequent impacts of splattered fragments would increase the overall efficiency.

The above correlation for peak heat transfer per drop also provides a means for normalizing the data for heat transfer per drop as a function of saturation temperature excess. As mentioned above, these curves peaked at a saturation temperature excess of approximately 300 degF, the reasons for which will be discussed in the next section. Thus a plot of

$$\frac{\dfrac{Q_{\max}}{\rho_L d^3\lambda}}{8{\cdot}44(10^{-4})\left(\dfrac{\rho_L^2 V^2 d}{\rho_{VF}\sigma g_c}\right)^{0{\cdot}341}}$$

vs. saturation temperature excess is a satisfactory technique for normalizing all the heat transfer data. Such a plot is presented in Fig. 5. The data points for the twenty-two runs used in obtaining the peak value correlation are shown, and the degree of normalization is satisfactory. No explanation is available for the trend of the acetone data toward higher values in the lower portion of the temperature range; however, the agreement at higher temperatures is very good.

The effect of impact angle, defined as the acute angle between the drop velocity vector and the normal to the test surface, was the subject of a separate investigation. For conditions of constant drop size and impact velocity, data were obtained for twelve combinations of impact angle and drop substance. The minimum angle investigated was 6°, while the maximum angle obtainable with the apparatus was 74°. It was desired to normalize the resulting values of peak transfer per drop with respect to the value at zero impact angle so that the angular dependence could be more readily observed. This was accomplished by first extrapolating the data in the form of dimensionless heat transfer per drop to zero impact angle, then normalizing the data with respect to the value so obtained. The results are shown in Fig. 6. The normalized angular dependence illustrated in Fig. 6 is not a simple one. However, observations made during the course of the experiments provide some insight into the physical nature of that dependence. At very small impact angles, corresponding to glancing impact, the droplet tends to smear out over the surface thus increasing the area for heat transfer. At intermediate impact angles neither of these effects appears to be significant, so it is logical to conclude that the variation in this region is a function of the normal velocity component. But the dimensionless heat transfer per drop is known from the preceding section to be a function of $V^{0{\cdot}682}$, and thus the normal velocity effect is that of $(\cos\theta)^{0{\cdot}682}$. A curve of this function dependence was fitted through data points for intermediate angles

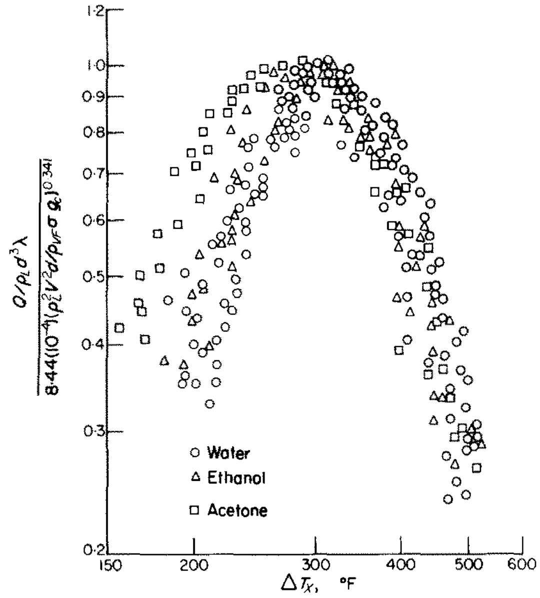

FIG. 5. Normalized data, heat transfer per drop vs. saturation temperature excess, $\theta = 27°$.

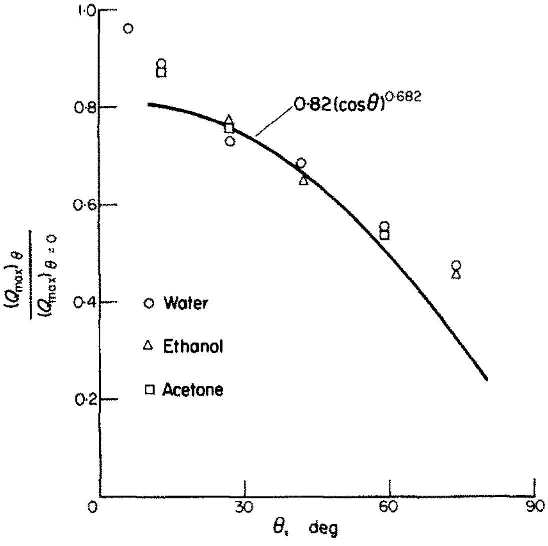

FIG. 6. Effect of impact angle on peak heat transfer per drop.

and is shown in Fig. 6. The deviation from this curve is due to increased residence time at small impact angles and increased contact area at large impact angles.

Analysis of the splattering heat transfer process

Observations made during the course of the present work indicate that the heat transfer mechanism is that of conduction across a vapor film, so that the instantaneous heat-transfer rate may be approximated by:

$$q = \frac{k_{VF} A \Delta T_x}{\delta}. \tag{7}$$

The vapor thermal conductivity is a function of temperature alone if it is assumed that the process takes place at atmospheric pressure. The area for heat conduction is a function of time as a result of the spreading of the droplet, while the temperature difference across the vapor film is a constant for a given hot surface temperature since the liquid is vaporizing at saturation conditions. The tactic assumption is made that the liquid adjacent to the hot surface rises to the saturation temperature immediately upon contacting the hot surface. The effective conduction distance δ is a function of time and is also coupled to the heat-transfer rate through the rate of vapor generation. This distance is, in reality, a function of radial location from the point of impact, but for this analysis it will be taken as some average value. Obviously, this description applies to some particular set of experimental conditions: drop size, impact velocity, and impact angle. The total heat transfer during the process is thus given by:

$$Q = \int_0^\tau q \,\mathrm{d}t = \int_0^\tau \frac{k_{VF} A(t) \Delta T_x}{\delta(t)} \,\mathrm{d}t \tag{8}$$

where the quantity τ is the contact time. This time is defined as the time increment beginning with first contact and ending with the termination of heat transfer. As mentioned previously, the heat-transfer process is terminated by the penetration of vapour bubbles, large and small, through the upper surface of the liquid layer. Thus τ is strongly dependent upon the rate of vapor generation and consequently dependent upon virtually all the variables of the problem.

Some quantitative aspects of the behavior of the parameters upon which the total heat transfer per drop depends will now be discussed. The area covered by the spreading liquid can be approximated by the results of [5] which were derived for a droplet striking a cold surface. These results were reduced during the course of the present work to the form:

$$A = CtdV^{1.5} \tag{9}$$

where C is a constant depending on the liquid properties, t is the time elapsed since initial contact, V is the normal impact velocity, and d is the diameter of the undeformed droplet. An expression for the effective conduction distance δ can be obtained by assuming that at any instant all the vapor generated since the initial impact is contained in the region beneath the spreading droplet. The assumption is made that all the heat transferred across the vapor gap is used in vapor production. This is an approximation since some of the heat transferred increases the sensible heat content of the remaining liquid. However, inclusion of this effect complicates the analysis and does not alter the general nature of the information obtained since the sensible heat increase amounts to only approximately 20 per cent of the total heat transferred. Thus conduction into the liquid is not considered, and the following integral equation results:

$$\rho_{VF} A \delta = \int_0^t \frac{q}{\lambda} \,\mathrm{d}t = \frac{k_{VF} \Delta T_x}{\lambda} \int_0^t \frac{A}{\delta} \,\mathrm{d}t. \tag{10}$$

Since A is a known function of time through equation (9), this equation is at least in principle soluble. If the thermal properties are assumed to be functions of temperature alone, the following solution is obtained:

$$\delta = \left(\frac{2 k_{VF} \Delta T_x t}{3 \rho_{VF} \lambda} \right)^{0.5}. \tag{11}$$

Thus the effective thickness of the vapor layer increases with the square root of time. With this information, an expression for the total heat transfer per drop can be obtained:

$$Q = \int_0^\tau q\,\mathrm{d}t = (\tfrac{2}{3}C^2 k_{VF}\rho_{VF}\lambda\Delta T_x d^2 V^3 \tau^3)^{0\cdot 5}. \quad (12)$$

However, this expression contains one final unknown, the contact time τ. As mentioned previously, this quantity is itself a complex function of the heat-transfer rate, the impact velocity, and the droplet size. A number of possible criteria for the determination of the contact time were investigated, including the following: contact time dependent upon a critical thickness of the vapor layer, contact time dependent upon a critical rate of growth of the vapor layer, and contact time dependent upon a critical ratio of liquid layer thickness to vapor layer thickness. None of these simplified approaches yield results for the variation of total heat transfer per drop with temperature approximating the experimental results. Thus, it appears that the termination of the heating process is a subject requiring additional, detailed study. Nevertheless, the equation for total heat transfer per drop shown above provides useful information as to the dependence of that quantity on the variables of the process.

With the aid of the preceding results, the important features of the heat transfer per drop vs. saturation temperature excess curves can be discussed. The effect of temperature is present in the thermal properties, in the temperature excess explicitly, and in the contact time in some unknown form. Referring to Fig. 5 the characteristically pronounced peak in the curve of heat transfer per drop vs. saturation temperature excess is seen. The results of the preceding paragraph indicate that the heat transfer is dependent upon the product of vapor density, vapor thermal conductivity, and the parameter λ which is defined by equation (3). This product was evaluated and found to be a fairly weak function of temperature. Thus the peak in the heat-transfer curve is primarily a result of the opposing effects of increasing thermal driving force and decreasing contact time.

It is apparent that the quantity of heat transferred to a droplet will again increase as the surface temperature falls below the minimum value investigated. Below some critical temperature the droplet will begin to wet the surface and will ultimately undergo complete evaporation. However, in that situation the rate of heat transfer will be small, the relatively long contact time being determined primarily by droplet mass rather than by droplet size and impact velocity. Finally, since the contact time does not vary greatly over the range of conditions investigated in the present study, the variation of splattering heat flux with surface temperature is qualitatively similar to that of heat transfer per drop.

The fact that the peak value of heat transfer per drop occurs at a saturation temperature excess of approximately 300 degF for all three fluids investigated is also of interest. It was suggested above that the contact time is determined in some complex way by the rate of growth of the vapor layer and thus by the time rate of change of the parameter δ. Thus the critical value of contact time, after which the total heat transfer begins to fall off, should have a thermal property dependence similar to that of δ. This dependence was found above to be of the form $k_{VF}/\rho_{VF}\lambda$. Referring to Fig. 7, it is seen that this parameter has similar values and similar thermal variation for all three substances investigated. As a matter of interest, values of this product for Freon 12 are also plotted in Fig. 7 and are seen to be of the same magnitude as those of the fluids investigated. Thus, the peaking at a common value of saturation temperature excess for different fluids is reasonable well explained, and subsequent investigations may well show the same effect for other fluids.

The question arises as to whether or not this peaking effect can be compared to the

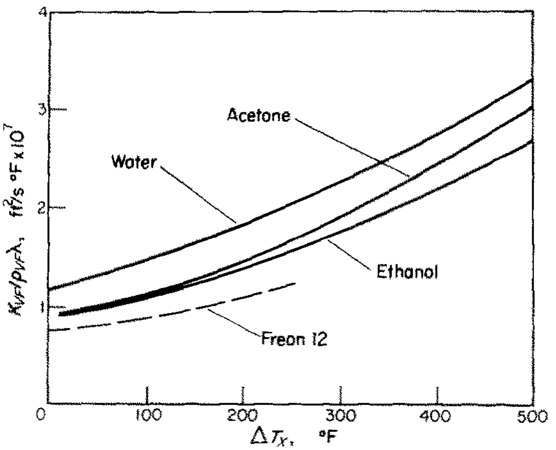

FIG. 7. The parameter $k_{VF/VF}$ vs. saturation temperature excess, $P = 1$ atm.

phenomenon of burnout in a conventional pool boiling process. The two effects are similar in that they involve the isolation of the liquid phase from the hot surface by the presence of a vapor layer. However, the peaking temperature for the splattering process is some 200 degF higher than that of burnout.

An estimate of the order of magnitude of the peak heat flux in splattering can be made with the aid of certain simplifying assumptions. If the characteristic area is assumed to be the cross-sectional area of the impinging droplet, and if the heat transfer rate is taken as the total heat transfer distributed over a typical contact time of 1 ms, then the peak heat flux is given by

$$\left(\frac{q}{A}\right) \approx \frac{Q_{\max}}{(\pi/4)\,d^2\tau} \approx 10^9 \text{ Btu/h ft}^2 \qquad (13)$$

where the numerical estimate is based on the data of a typical water droplet run. One millisecond is the approximate time necessary for a typical droplet to traverse a distance equal to its diameter. This value of splattering heat flux is some two orders of magnitude greater than typical values of pool boiling burnout heat flux. It is believed that the unconfined nature of the splattering process accounts for these differences. Since a portion of the vapor generated escapes from beneath the spreading liquid and since a portion of the energy transferred manifests itself as kinetic energy of the splattered particles, the heat transfer rate, and thus the temperature excess, necessary to achieve the critical rate of vapor generation is greater than for pool boiling.

CONCLUSIONS

1. The quantity of heat transferred during the splattering process exhibits a very definite maximum with respect to surface temperature. This maximum occurs at a saturation temperature excess of approximately 300 degF for the substances tested.

2. Experimental observations and the results of a simplified analysis indicate that this maximum is a result of the opposing effects of increasing thermal gradient and decreasing droplet contact time. In addition, the analysis shows that the temperature excess at which the maximum occurs is a function of the thermal property grouping $k_{VF}/\rho_{VF}\lambda$. This grouping has numerically similar values for the substances tested, thus explaining the peaking of heat-transfer curves at a common temperature excess.

3. The magnitude of the maximum heat transfer per drop is given within 10 per cent of the experimental results by

$$\frac{Q_{\max}}{\rho_L d^3 \lambda} = 8{\cdot}44(10^{-4})\left(\frac{\rho_L^2 V^2 d}{\rho_{VF}\sigma g_c}\right)^{0{\cdot}341}$$

for values of the independent variable in the range of 10^5–10^7 and for an impact angle of 27°. The above equation is also used to satisfactorily normalize curves of heat transfer per drop versus saturation temperature excess.

4. The efficiency of the process, defined as the ratio of actual heat transfer per drop to maximum possible heat transfer per drop is on the order of 50 per cent for a single collison. Subsequent collisions of splattered particles with the hot surface tend to increase the overall efficiency.

5. The effect of impact angle can be satisfactorily accounted for by use of the normal component of impact velocity. At the extremes

of impact angle, corresponding to head-on and glancing collisions, secondary effects tend to increase the heat transfer per drop.

It must be emphasized that there are many aspects of the splattering process itself which are not yet fully understood, particularly the complex mechanism of droplet disintegration. Subsequent work will logically include investigations of multiple collisions, such as would be experienced by a droplet injected into an enclosure. In addition, experiments with numbers of droplets, perhaps in channel flow, will provide information about interference effects.

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Résumé—Une étude expérimentale du clapotis et du rebondissement de gouttelettes d'eau, d'acétone et d'alcool à partir d'une plaque chauffée révèle que le transport de chaleur par goutte présente un maximum pour un excès de température d'environ 165°C et qu'il existe und corrélation satisfaisante pour ce maximum:

$$\frac{Q_{\max}}{\rho_L d^3 \lambda} = 8{,}44\,.\,10^{-4}\left(\frac{\rho_L^2 V_d^2}{\rho_{VF}\sigma g_c}\right)^{0{,}341}$$

L'effet de l'angle d'impact est également étudié et le résultat général est que la composante normale de la vitesse est le facteur important. Une courbe de flux de chaleur normalisé en fonction de l'excès de température est présentée pour les fluides essayés. On suppose que le maximum de transport de chaleur résulte des effets contraires de l'augmentation du gradient thermique et de la décroissance du temps de contact de la gouttelette dans le processus de clapotis.

Zusammenfassung—Eine experimentelle Untersuchung beim Auseinanderspritzen und Springen von Tröpfchen aus Wasser, Aceton und Alkohol auf einer geheizten Platte zeigt, dass der Wärmeübergang pro Tropfen ein Maximum bei einer Übertemperatur von ungefähr 300°F (149°C) aufweist. Folgende Beziehung gibt dieses Maximum hinreichend wieder:

$$\frac{Q_{\max}}{\rho_L d^3 \lambda} = 8{,}44\,.\,(10^{-4})\left(\frac{\rho_L^2 V^2 d}{\rho_{VF}\sigma g_c}\right)^{0{,}341}$$

Eine Untersuchung des Aufprallwinkels ergab, dass nur die normale Komponente der Geschwindigkeit bedeutsam ist. Eine geglättete Kurve des Wärmestroms über der Übertemperatur für diese Flüssigkeiten wird geprüft. Das Maximum des Wärmeübergangs wird als abhängig von den gegenläufigen Effekten des steigenden Temperaturgradienten und der abnehmenden Kontaktzeit beim Prozess des Auseinanderspritzens angenommen.

Аннотация—Экспериментальное изучение теплообмена единичных капель воды, ацетона и спирта, отскакивающих от нагретой пластины показало, что максимальная интенсивность процесса наблюдается примерно при 300° и хорошо аппроксимируется предлагаемым уравнением

$$\frac{Q_{\max}}{\rho_L d^3 \lambda} = 8{,}44\,.\,(10^{-4})\left(\frac{\rho_L^2 V^2 d}{\rho_{VF}\sigma g_c}\right)^{0{,}341}$$

Кроме того, изучалось влияние угла столкновения, и сделан важный вывод о том, что нормальная компонента скорости оказывает существенное влияние. Для изученных жидкостей приводится кривая изменения теплового потока в зависимости от температур. Максимум теплообмена объясняется воздействием противоположных эффектов — увеличения температурного градиента и уменьшения времени контакта капель при соударении.