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AN EXPERIMENTAL STUDY OF THE DYNAMIC BEHAVIOR AND HEAT TRANSFER CHARACTERISTICS OF WATER DROPLETS IMPINGING UPON A HEATED SURFACE

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Abstract—Heat transfer data for individual water droplets impinging upon a heat surface are presented. The droplet diameters ranged from 200 to 400 μm, and the approach velocities from 8 to 33 ft/s. The effect of surface temperature variation from the saturation temperature to 1800°F was studied. Photographs of the impingement process are presented which show that even the small droplets studied break up upon impingement at moderate approach velocities. The heat transfer data show that approach velocity is the dominant variable affecting droplet heat transfer and that surface temperature has little effect on heat transfer in the non-wetting regime.

NOMENCLATURE

c, specific heat [Btu/lb_m°F];
D, jet diameter [ft];
f, frequency [Hz];
h_{fg}, latent heat of vaporization [Btu/lb_m];
l, slab thickness;
M, droplet mass [lb_m];
Q, heat transfer per drop [Btu];
r, droplet radius [ft or μm];
T_W, inlet water temperature [°F];
T_{sat}, saturation temperature [°F];
t, time;
V, jet velocity [ft/s];
α, thermal diffusivity;
ε, effectiveness (equation 5).

1. INTRODUCTION

THE PROCESS of cooling a high temperature surface with a water spray is widely used in the steel industry. In spite of the widespread use there exists a conspicuous lack of knowledge of the factors which affect the rate of heat transfer. As generally applied, spray cooling is a very inefficient process in terms of water utilization. In many applications this fact alone could be tolerated provided the heat transfer rate was high enough, or for that matter, if it could be predicted. Generally this is not the case; thus, the intelligent design of spray cooling equipment is a difficult task.

The physics of the heat transfer process involved in spray cooling is not well understood It is apparent that it involves boiling heat transfer coupled with the dynamics of the droplets. Boiling heat transfer under simpler conditions is not completely understood, and when the additional complication of droplet dynamics is added the problem becomes quite complex. This study, which considers individual droplets, was made in an attempt to obtain fundamental information concerning the heat transfer processes in spray cooling.

Only in recent years have pertinent articles appeared in the literature. The experimental work of Gaulger [1] and Corman [2] determined the overall heat transfer under sprays. They obtained average coefficients near the centerline of sprays from conventional nozzles. The heat transfer coefficients were determined by a transient technique utilizing the solution of the inverse conduction problem.

The impingement of individual droplets was studied by Harvey [11]. A recent series of papers by Wachters *et al.* [3–5] reported experimental studies of the heat transfer from relatively large single droplets [3] and from sprays of smaller droplets [5].

The present work presents an experimental study of individual droplet heat transfer for droplets an order of magnitude smaller than those of [3], and having approach velocities several times higher than those studied in [11]. The diameters and velocities used in the present study were chosen because they represent more closely those found in actual spray applications.

It is felt that an understanding of spray cooling will be developed in steps, starting with an understanding of individual droplets. Assuming that this understanding can be obtained, the next step will be to study the interaction of droplets in sprays. The third step will be an attempt to combine the information obtained in the first two steps and predict the behavior of sprays of droplets.

This paper presents the experimental part of a study made to gain understanding about the behavior of impinging individual droplets.

Since a film boiling model has been successful in correlating the evaporation times for stationary droplets evaporating on hot plates [4,13], it was postulated that the same type of model might be applicable to the dynamic situation. In that case, it would be necessary for the pressure forces generated in the vapor layer beneath the droplet to become sufficiently high to rebound the droplet away from the plate.

An initial analytical study along these lines using a rigid droplet model confirmed that the pressure forces could reach a magnitude sufficient to rebound the droplet away from the surface. However, when the accompanying heat transfer part of the problem was modeled, by assuming conduction across the vapor layer, it was found that the heat transfer predicted analytically was several orders of magnitude less than that actually experienced in spray cooling devices. It was then apparent that the dynamics involved in droplet impingement were more complex than those considered by the model, and that other factors would have to be included.

Before a more complex model could be developed, it was felt that additional qualitative and quantitative information on the behavior of impinging individual droplets was needed. The study described in this paper was made in order to provide this information.

The details of the simple film boiling model can be found in [10]. More complex models utilizing the information obtained in this experimental study are under development at the present time [12].

2. THE EXPERIMENTAL APPARATUS

The amount of heat necessary to completely vaporize a droplet of the size used in most spray cooling applications is best expressed in μBtu. Since the droplet is not completely vaporized when it strikes the plate, it is obvious that the determination of the heat transfer per droplet is difficult. With this in mind, the general scheme chosen for the experiment was the measurement of the heat flux from a steady stream of droplets of uniform size and having a uniform approach velocity.

The uniform stream of droplets was produced by making use of the fact that a cylindrical jet of water is unstable under the action of surface tension. As a result it will break into droplets. If the break-up is allowed to proceed naturally, the resulting droplets are of random size. However, if the stream can be perturbed uniformly, droplets of a uniform size can be produced. In this experiment, a stream of water was subjected to uniform transverse sinusoidal vibrations.

The disturbance in the jet produced by the vibrations has a wavelength equal to the jet velocity divided by the frequency of the vibrations. Rayleigh [6] has shown that the wavelength of such a disturbance must be greater than the circumference of the jet in order to produce break-up. The experiments performed by Rayleigh utilized longitudinal vibrations; however, experiments at the Charged Particle Research Laboratory at the University of Illinois [7–9] demonstrated that transverse vibrations are similarly satisfactory. Furthermore, the same wavelength criterion holds and there is an optimal droplet production wavelength which is approximately 4·5 times the jet diameter.

At this wavelength each disturbance produces one droplet. As a result, the optimal droplet production frequency is related to jet diameter and velocity by the relationship

$$f \simeq \frac{V}{4{\cdot}5D}. \tag{1}$$

Since each droplet produced starts as a cylinder of length 4·5D, its radius can be determined from

$$\frac{4\pi r^3}{3} = \frac{\pi D^2}{4}(4{\cdot}5D) \tag{2}$$

or

$$r \simeq 0{\cdot}85D. \tag{3}$$

With the droplet center-to-center spacing of 4·5D, the resulting droplet separation is slightly greater than 1·5 droplet diameters.

The study was undertaken with a view toward using droplet diameters and approach velocities which were representative of those actually obtained in spray cooling (100–500 μm dia. and 10–30 ft/s). These values require a droplet production frequency from 6500 Hz and up.

If all the droplets from such a stream were allowed to impinge directly on a surface, they would certainly collide with each other in the process. In addition, the close spacing of the droplets would undoubtedly cause adjacent droplets to collide in the stream long before they reached the target. In order to eliminate these two difficulties, the apparatus was designed so that most of the droplets could be removed from the stream. Those remaining were allowed to impinge upon a heat transfer target.

This was accomplished by selectively charging some of the droplets in the stream and deflecting them into a collector. The equipment was designed to allow every second, fifth or tenth droplet (and decade multiples of these numbers) to impinge upon the target. Since the heat flux is directly proportional to the droplet impingement rate, this flexibility permitted a wide variation in heat flux, which was used to check droplet heat transfer data for consistency.

The experimental apparatus is shown in block diagram form in Figs. 1 and 2. The sinusoidal output from a signal generator was

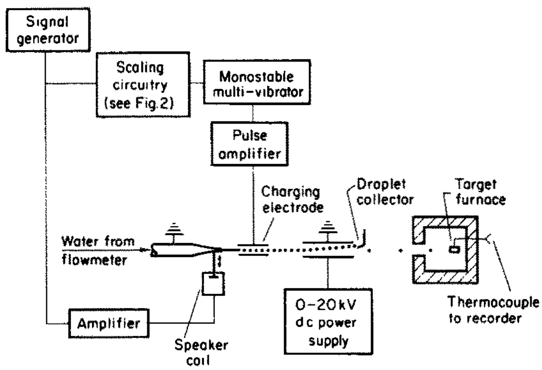

FIG. 1. Block diagram of experimental apparatus.

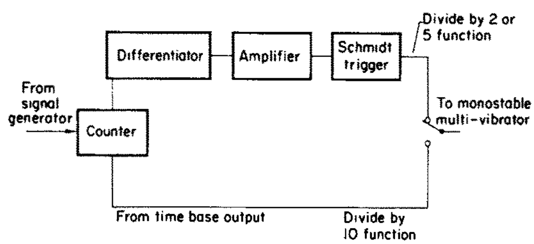

FIG. 2. Block diagram of scaling circuitry.

amplified to provide power for an ordinary radio speaker. The cone was removed from the speaker and replaced by a support element to which a small glass nozzle could be glued. Distilled water entering the nozzle from the flow meter emerged as a thin jet. The imposed vibrations created a wave disturbance on this jet. The distance from the nozzle at which the water jet finally broke into droplets was found to be dependent upon the jet velocity, the amplitude of the imposed vibrations, and the smoothness of the nozzle. These factors also affected the vibrations which were present in the individual droplets after they separated. These effects are in opposition, so the amplitude of the imposed vibration was maintained as low as possible consistent with a reasonable break-off length, and the glass nozzles were fire-polished to make them smooth.

The droplets which were to be removed from the stream were charged by placing a cylindrical electrode around the jet at the position downstream from the nozzle where the droplets finally broke away from the upstream jet. Another electrode was placed in the water stream itself. The existence of an electrical potential between these two electrodes at the time a droplet broke away from the jet would cause the droplet to be charged. By pulsing the potential at the appropriate time, a stream of droplets in which only selected droplets were charged could be produced. The details of the electronics required to synchronize the charging potential with the disturbance can be found in [10].

In operation a constant d.c. bias was placed across the electrodes so that the charging pulse dropped the potential to zero, producing, with each pulse, an uncharged droplet. The uncharged droplets were allowed to impinge upon the heat transfer target. Figure 3 shows a stream of droplets which had every twentieth droplet pulsed out of the main stream. The direction of droplet motion is from right to left and it can be seen that the increased drag on the droplets pulsed out of the main stream has caused their velocity to decrease relative to the main stream. Their original locations were the discontinuities which appear in the main stream. In actual operation the main stream would be caught in a collector.

The heat transfer surface upon which the droplets impinged was the end of a small stainless steel cylinder 0·25 in. long by 0·25 in. dia. It was suspended in a small furnace by two chromel–alumel thermocouple leads 0·010 in. dia., individually spot welded to the cylinder to form an intrinsic thermocouple junction. The target was heated by radiation from the surrounding furnace which was electrically heated. The heat flux caused by the droplets was determined from the temperature transient experience by the target when the droplets were allowed to impinge upon it suddenly.

3. EXPERIMENTAL PROCEDURE

To make a run, the furnace and target were allowed to reach temperature equilibrium while situated well out of the droplet trajectory. To facilitate the procedure, the furnace was mounted on rollers which moved on a horizontal track perpendicular to the trajectory. When equilibrium had been reached, the droplets were started and the pulse control was adjusted to produce the desired droplet impingement rate. The resulting stream of droplets (hereafter called the sparse stream) was allowed to impinge upon a dummy target attached to the furnace and located a predetermined horizontal distance from and at the same elevation as the real target. When the trajectory was satisfactory, a small sheet metal barrier was placed in the path of the sparse droplet stream, thus preventing droplets from impinging upon the dummy target. The furnace was then moved along the tracks the required distance to place the active heat transfer target in position. After a short wait to assure that equilibrium conditions still existed, a strip chart recorder was activated and the sheet metal barrier was removed. This allowed the droplets to impinge upon the target and the resulting temperature transient was recorded.

After a short time the sheet metal barrier was again placed in the droplet stream and the target was allowed to return to the original temperature.

FIG. 3. Photograph showing every twentieth pulsed from main stream.

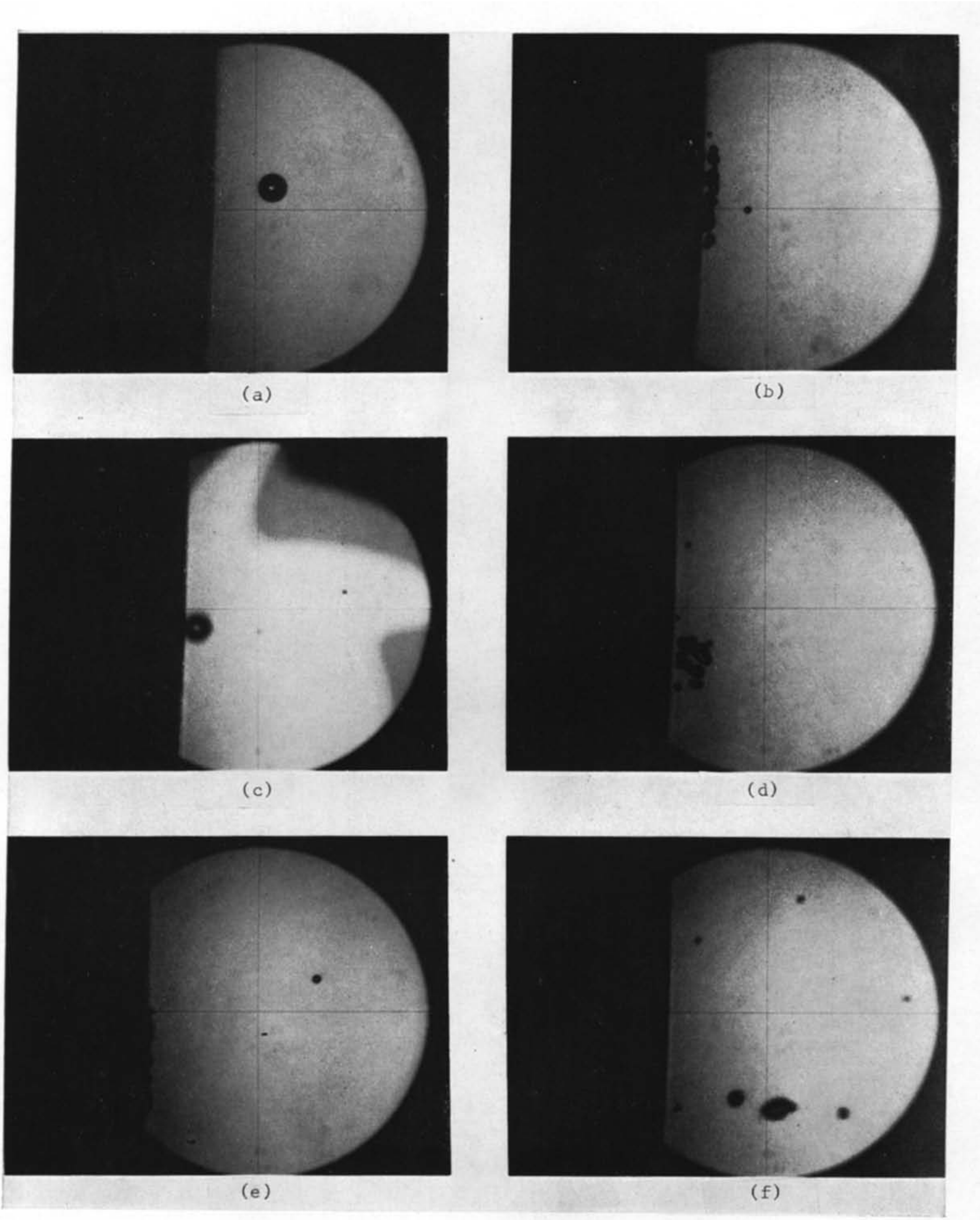

FIG. 8. Non-wetting impingement of 400 μm droplet, 15 ft/s approach velocity.

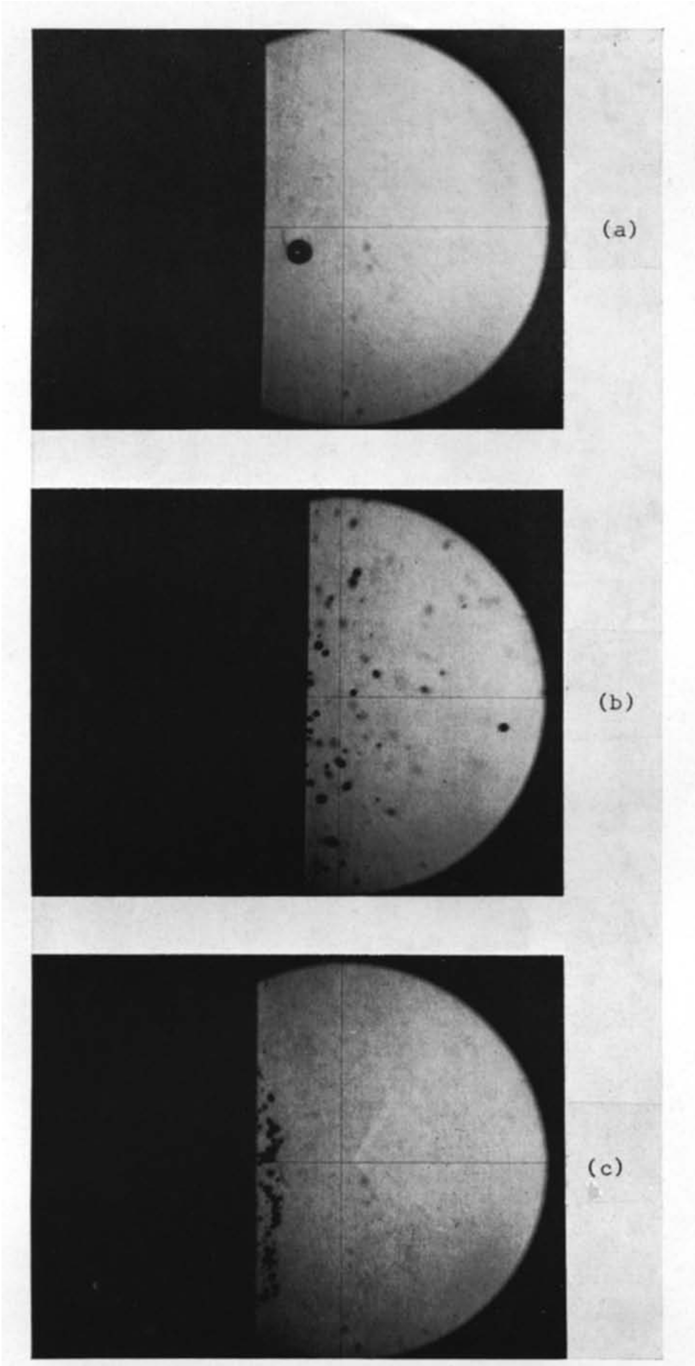

FIG. 9. Impingement in transition to wetting, 300 μm droplet, 30 ft/s approach velocity.

Then the process was repeated several times with different impingement frequencies.

The droplet approach velocity was determined by illuminating the sparse stream with a stroboscopic light source synchronized to the charging voltage pulses. The separations of the "stopped" droplets then could be measured easily with a conventional scale. Large droplets moving at high velocities exhibited very little jitter and the measurements were made with considerable ease. However, in the case of small droplets travelling at low velocities the normal air currents in the room produced considerable jitter in the position as illuminated by the stroboscopic source. Under these circumstances the measurements were somewhat more difficult to make and were subject to greater experimental error.

The experimental procedure used for the wetting regime studies differed somewhat from that described previously. Rather than using a droplet impingement frequency which would cause a modest heat flux and target temperature depression, one which caused the target to quench to the boiling temperature was used. When this occurred, the scaling factor was quickly changed to provide a lower droplet impingement frequency. and the droplet stream was interrupted momentarily to allow the target to dry. As soon as the target dried, as evidenced by a rapid increase in target temperature, the stream was allowed to impinge upon the target again. Under this new impingement rate, the droplet heat flux was less than the heat flux by radiation from the furnace to the target so that it heated slowly. This heating transient was recorded on the strip chart recorder. Following this, the target was again quenched and then allowed to reheat with no droplets impinging upon it. This transient was also recorded. The heat flux due to the droplets was determined from the difference between the two transients.

4. REDUCTION OF EXPERIMENTAL HEAT TRANSFER DATA

Heat transfer data obtained in the experiment consisted of time–temperature (e.m.f.) curves obtained on a Mosley 7100B strip chart recorder. The recorder had both adjustable range and adjustable zero so that the transients could be expanded to fill the entire 10 in. chart if necessary. Thus, the graphical interpretation of the recordings could be made with great accuracy.

Since the target was in temperature equilibrium with its surroundings before the droplet stream was allowed to impinge on it, the initial slope of the time–temperature curve obtained as the target departed from equilibrium could be related directly to the droplet heat flux, assuming the target behaved as a lumped element. This implies that the temperature gradients which existed within the target were negligible. The following paragraphs discuss the gradients in detail.

Because of the normal droplet scatter due to air currents, they impinge somewhat randomly over nearly the entire front surface of the target. This causes a periodic heat flux in the front surface, but the effect of the time dependency of this heat flux is quite small. Droplet impingement frequencies were never less than 40/s and were usually about 100/s. At these frequencies the amplitude of a characteristic steady periodic temperature fluctuation is about 1°F. In addition, the recorder would damp out a signal of this frequency. Therefore, it is reasonable to treat the droplet heat transfer as a sudden, steady heat flux over the entire front surface of the target.

A characteristic Biot number for the target may be defined using a heat transfer coefficient which is droplet heat flux divided by the frontal area of the target and the difference between target and water temperatures. The characteristic length can be taken as the length of the target, $\frac{1}{4}$ in. For the representative droplet heat transfer rates, this produces a Biot number of 0·01–0·05, which is small enough to permit neglecting internal gradients in the target at all times after the occurrence of a short initial transient. However, this initial transient which sets up the quasi-steady internal gradients is of primary importance. If it is not short compared to the time period which is utilized to determine the initial slope of the target temperature curve, it could affect the results.

The duration of this initial transient may be estimated by considering the target as being an infinite slab, initially in temperature equilibrium, insulated on one surface, and suddenly subjected to a heat flux on the other surface. Under these conditions the slab experiences an initial transient during which the temperature change is a function of both position and time, followed by a transient condition during which the temperature at all points in the slab is a function of time only. An analytical solution of this problem is readily obtained and shows that the initial transient dies out at the center of the slab when $\alpha t/l^2 \geqslant 0{\cdot}04$. Substituting the appropriate target parameters into this criterion gives $t = 0{\cdot}3$ s. The center of the slab is the point of interest, since the thermocouple was attached at the center of the target axially.

The chart speed used in most of the experimental runs in the program was 1·0 in./min. Accordingly, the initial slope used in the data analysis was determined from a time interval of about 10 s. Since this was more than an order of magnitude longer than the initial transient of $\frac{1}{3}$ s, it was concluded that the initial transient did not substantially affect the slopes determined from the strip chart.

The validity of this conclusion was also substantiated experimentally by the following procedure. Heat flux for a given droplet size and approach velocity was determined at two widely varying impingement rates: in one case differing by a factor of ten. It was necessary to use a higher chart speed at the higher impingement rate so the slope determination was made over a considerably shorter time interval, and any effect of the initial gradient would be amplified. No effect could be detected. For the case where the impingement rate and the resulting heat flux varied tenfold, the individual droplet heat transfer varied by less than 10 per cent.

The actual procedure for data analysis was:

1. The intial slope of the e.m.f.–time curve was determined from the strip chart.
2. Using the Type K, chromel–alumel thermocouple characteristics from NBS circular 508, these slopes were converted to temperature–time slopes.
3. Using the specific heat data for 304 SS from [14], the average droplet heat fluxes, q_D, were determined from

$$q_D = mc\frac{\mathrm{d}T}{\mathrm{d}t}\bigg|_{\text{at departure from equilibrium}} \tag{4}$$

4. These heat fluxes were divided by the droplet impingement rate to obtain the heat transfer per droplet.
5. The heat transfer per droplet was converted to effectiveness with the relationship

$$\varepsilon = \frac{Q}{M[h_{fg} + c(T_{\text{sat}} - T_W)]}. \tag{5}$$

The water temperature was 72 ± 2°F for all runs.

5. HEAT TRANSFER RESULTS

Experimental data were obtained with droplets having diameters of approximately 200, 300 and 400 μm. The experimental apparatus limited the arrival velocities of the larger droplets to approximately 30 ft/s. At higher velocities the droplet charging apparatus could not produce sufficient charge difference between a charged and an uncharged droplet to permit them to be separated from one another. The low electrical conductivity of distilled water contributed to this problem. As the jet velocity was increased, the distance from the nozzle at which jet break-up occurred increased. This necessitated moving the charging electrode farther away from the jet, thus increasing the conduction path length.

The air drag experienced by the small droplets caused them to slow down considerably before they reached the target, especially if the stream was very sparse. For this reason, high jet velocities were necessary to produce moderate arrival velocities for droplets. The high jet velocities, in turn, dictated a high disturbance frequency. The electronic equipment used had relatively poor high frequency characteristics resulting in a 10 ft/s arrival velocity limit for 200 μm droplets.

The effect of droplet approach velocity on heat transfer in the non-wetting regime is shown in Fig. 4. The data are for droplets ranging

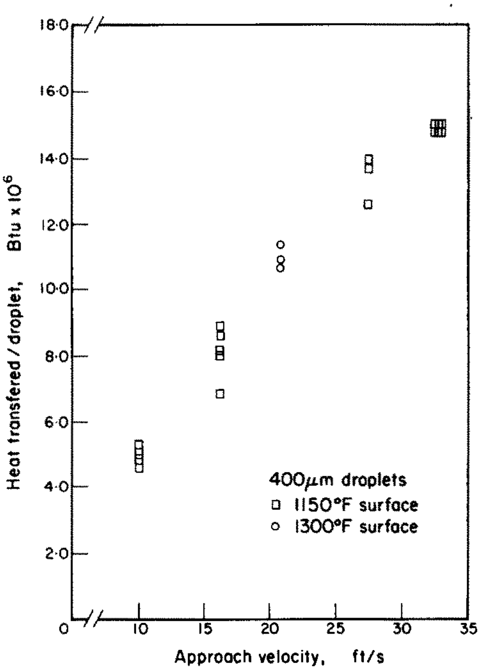

FIG. 4. Effect of approach velocity on droplet heat transfer.

in diameter from 400 to 410 μm. The plot shows that the heat transfer per droplet increases significantly as the approach velocity increases. There is no definite change in slope to an approach velocity of 33 ft/s. Most of the data on Fig. 4 were obtained with a surface temperature of approximately 1150°F; however, one set obtained with a 1300°F surface also is shown on the plot. Its position indicates that the surface temperature has little effect on the heat transfer in the non-wetting regime.

This effect was also checked for a greater temperature variation. Several experimental runs were made with a target temperature of 1780°F and compared with a similar runs having a target temperature of 1150°F. The results showed a mean effectiveness of 22 per cent at 1780°F compared with 16 per cent at 1150°F. This relatively slight increase with increasing surface temperature was also borne out by the results of Corman [2].

It is natural to expect that the droplet size would have a significant effect on the heat transfer per droplet. Because of the difference in surface area and mass, the total heat transfer for a large droplet could be significantly greater even if the heat flux under it was identical to that under a smaller droplet. On an effectiveness basis a comparison is more meaningful since the effect of droplet size is practically eliminated. Droplet velocity then becomes the dominant variable. Figure 5 is a plot of effectiveness as a function of approach velocity for all droplet sizes studied. The data of Fig. 5 are for the non-wetting regime with a surface temperature of about 1150°F. It can be seen that the variation of effectiveness with velocity follows a similar pattern for all droplet sizes. The relatively high values for effectiveness obtained are somewhat surprising in light of the usual spray cooling experiences. However, it must be emphasized that the high actual approach velocities shown in Fig. 5 are probably greater than those attainable for droplets in sprays. This will be discussed further later in the paper.

Although the primary purpose of this study was to investigate the heat transfer to impinging droplets in the non-wetting state, a limited amount of data were obtained in the wetting and transition regimes. The data shown on Fig. 6 were obtained with 330 μm dia. droplets having an approach velocity of 31 ft/s. These data were obtained with the alternate wetting regime experimental procedure described previously. It can be seen that the peak effectiveness is approximately 90 per cent at a target temperature of 350°F. In the temperature range from 450 to 550°F the effectiveness drops to below 20 per cent. Also shown in the figure

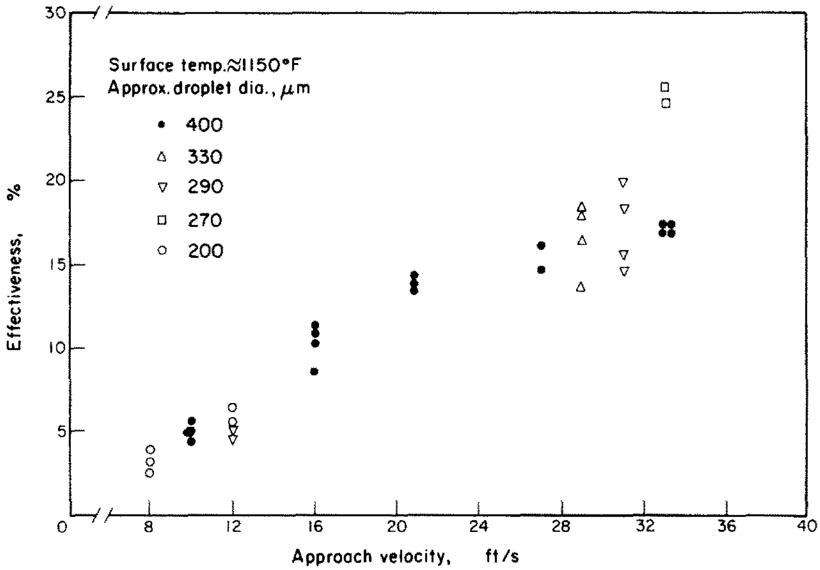

FIG. 5. Non-wetting droplet heat transfer effectiveness.

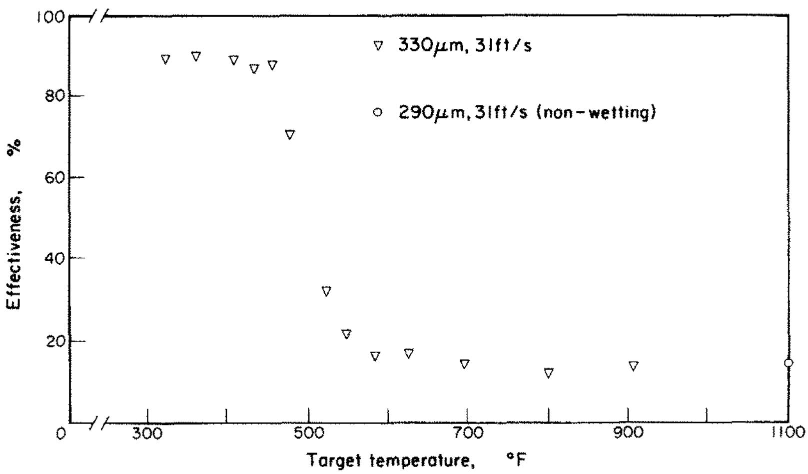

FIG. 6. Droplet heat transfer effectiveness in wetting regime.

is one data point obtained at 1100°F by the non-wetting experimental procedure. The close agreement is obvious.

6. DISCUSSION OF RESULTS AND COMPARISON WITH OTHER DATA

The heat transfer measured in this experiment can be considered as being made up of two parts: A convection heat transfer which occurs because the impinging droplets disturb the air near the surface, and a heat transfer directly to the droplet through the vapor layer separating droplet and surface. The convective effect is enhanced by the fact that the exploded droplet presents a large surface area to the air for heat and mass transfer. These processes cool the air near the surface. It is this cooled air which is violently stirred by the exploding droplet.

No attempt to separate these effects was made in this experiment. It would be reasonable to expect that droplet interaction in a spray would decrease the effectiveness of the convective part of the heat transfer. A steam environment such as that used in [5] would also decrease the mass transfer aspects discussed above.

Other studies pertinent to this work have considered both sprays and individual droplets. A study of heat transfer to individual droplets has been performed by Wachters and Westerling [3] and Harvey [11]. The study of [11] is the nearest to the present study in terms of droplet diameter; however, the approach velocity range studied was below that studied in the present work. The experimental technique used in [11] was to catch the droplets after impingement and determine their decrease in volume. Since the volume of the droplet was determined by a diameter measurement, any experimental error was effectively cubed in the translation to volume decrease. As a result, the data show considerable scatter, and it is difficult to make a comparison with the present data.

Since all approach velocities used in [11] were below the range used in the present study, Fig. 5 would indicate that the decrease in volume would be below 4 per cent in the non-wetting regime. The data of [11] at a surface temperature of 900°F show a mean volume decrease, in per cent, of -2 (volume increase), with a root mean square deviation of 5. Thus, the deviation is greater than the quantity being measured.

The experimental data of [5] show that the heat transfer by 60 μm dia droplets to an oxidized copper surface gives an effectiveness of approximately 3 per cent. The approach velocity of the droplets in this case was about 16 ft/s. This result is low when compared with the effectiveness shown on Fig. 5. However, it must be remembered that the data from [5] were obtained with droplets in a mist spray, and it might realistically be expected that the effectiveness would be reduced because of droplet interaction.

Wachters and Westerling [3] also studied heat transfer from individual droplets. They obtained data for droplets 2·3 mm dia., approach velocities varying from 1·08 to 1·47 m/s, and surface temperatures varying from 210°C to 350°C. Their data indicated a very low effectiveness, ranging from a maximum of 1·5 per cent at 410°F to a minimum of 0·15 per cent at 660°F. The 1·47 m/s data are indicated by the solid line on Fig. 7.

Heat transfer data obtained from sprays are presented in [1, 2]. Some representative data

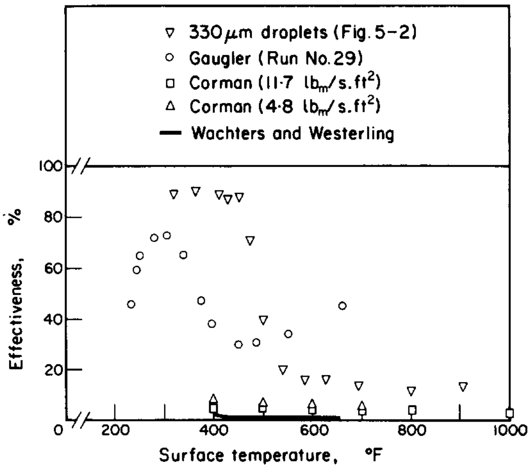

FIG. 7. Comparison with published heat transfer effectiveness in wetting regime.

points from these studies are also shown on Fig. 7. The wetting and transition data from [1] were obtained with a mean droplet diameter of 195 μm and a calculated approach velocity of 54 ft/s; however, the actual approach velocities were undoubtedly not that great.

The experimental apparatus and data analysis procedures were the same for the studies in [1] and [2]. The difference between the heat transfer effectiveness arises because much greater mass flux rates were used in [2]. Although the total heat flux due to the spray was greater, a smaller fraction of the total spray was evaporating. This would indicate that droplet interaction has a very large detrimental effect on effectiveness.

7. PHOTOGRAPHIC STUDIES OF DROPLET IMPINGEMENT

In order to obtain a better understanding of the impingement dynamics, part of the effort of this study was directed toward photographing the collision of droplets on a heated target.

For photographic purposes the droplets were allowed to impinge upon a small resistance heated stainless steel target. The same droplet production and scaling apparatus was used to provide the impinging stream of droplets as was used in the heat transfer studies.

The magnification required to photograph the small droplets used in this study was accomplished by means of a telemicroscope. The image from the telemicroscope was recorded with a 4×5 in. format camera. The linear magnification obtained with this system was $15{\cdot}5\times$ with a Polaroid roll film back.

Back lighting was employed to provide sufficient illumination for a satisfactory exposure with one flash from a stroboscopic light source. The light from the stroboscope was collimated by placing a small aperture between it and the target. The frequency of the back lighting stroboscope was controlled remotely by slaving it to a second identical unit located near the camera. In order to take a picture, the stroboscope frequency was adjusted so that it was nearly equal to the frequency of droplet impingement. Usually a frequency slightly lower than the droplet impingement frequency was used so that the droplets appeared to be moving very slowly toward the target. In this way it was possible to observe the collision process quite clearly.

Exposures were made by manually tripping the shutter when the collision process was in the desired stage. The shutter speed was adjusted to ensure that the shutter would be open long enough to receive at least one flash.

Using the foregoing procedure, a sequence of photographs could be obtained of the collision process. Such a sequence is shown in Fig. 8. It should be emphasized that the photographs so obtained are not of the same droplet, but are photographs of different droplets at the same site, approaching the plate under similar conditions, and in different stages of the collision process.

Figure 8 shows the collision between a 400 μm dia. droplet moving at approximately 15 ft/s and a flat plate heated to 1100°F. The sequence is as follows: Photograph (a) shows that the droplet is nearly a perfect sphere as it approaches the plate moving from the right. Then, as it strikes the plate, it spreads until its outer diameter is four or five times the droplet diameter as evidenced by photograph (c). In photograph (d) the droplet has broken into many smaller droplets that begin to rebound away from the surface in photograph (e). As they rebound, some of them coalesce and form larger droplets. In the last photograph a droplet has coalesced into two main parts and a series of smaller particles which are rebounding away from the plate.

After break-up occurred, the small droplets which were formed appeared to drift away from the plate quite slowly. As a result the small droplets shown on the right side of photograph (c) are most likely a remainder from a previous collision. Similarly, some of the small droplets in photograph (d) could possibly have come from a previous collision. Photograph (b) is an example of the results obtained when two stroboscopic flashes occurred during the time the shutter was open. It was extremely difficult to obtain photographs of droplets in that particular stage of the process. Apparently the currents induced in the air near the target by the exploding droplets were sufficiently strong to make the flight of the droplet quite erratic over the last fraction of an inch near the target. No difficulty was experienced in photographing the droplets spread out over the surface shown in photographs (c) and (d).

The total duration for the sequence shown in Fig. 8 was estimated by measuring the apparent change in position of an incoming droplet from the beginning to the end of the sequence. The stream was illuminated with a stroboscope for this determination. This change of position when translated into elapsed time indicated that the process shown occurred in approximately 1 ms. The collision process with this approach velocity and size was observed with the stroboscope at various target temperatures up to 1800°F. In all cases the collision process was essentially the same as that shown in Fig. 8.

Photographs of the impingement dynamics in the wetting regime were also obtained in this study. These photographs were especially interesting because they aided in explaining the very high measured effectiveness in the wetting regime. It was apparent from the photographs that the droplet did not vaporize suddenly upon hitting the plate in the wetting regime, but it actually wetted a considerable area of the surface. After the surface was wetted, it appeared that conventional nucleate boiling took place.

The photographs in Fig. 9 show the collision process during the transition from the wetting to the non-wetting regime. The droplet diameter in these photographs is about 300 μm and the approach velocity is about 30 ft/s. The violent break-up in photograph (b) occurred at the surface temperature where the droplet first ceased to wet the surface. This particular break-up was more violent than those which occurred at higher plate temperatures. Photograph (c) is characteristic of break-up with higher plate temperatures. The temperature in this case was about 1450°F. Droplets having approach velocities as high as those shown in these photographs showed very little tendency to coalesce upon rebounding from the surface.

8. CONCLUSIONS

In considering both the heat transfer data and the visual observations obtained in this study, it is possible to make the following conclusions:

1. There is a definite transition from wetting to non-wetting impact for individual droplets. Within the velocity range studied, there was no evidence of any penetration of the so-called Leidenfrost barrier once the non-wetting state was reached. It appears that the temperature of transition can be affected by the impact velocity of the droplets and surface conditions (roughness, oxide, etc.).

2. In the non-wetting state the effectiveness of the heat transfer can be increased by increasing the approach velocity. No upper limit for this behavior was found in the study; however, the rate of increase was declining at a velocity of 33 ft/s in the case of 400 μm dia. droplets.

3. At a given surface temperature in the non-wetting state, the heat transfer effectiveness of all sizes of droplets studied cluster around a single velocity-dependent line (see Fig. 5–3).

4. The effect of increasing surface temperature in the non-wetting state is to increase heat transfer effectiveness supporting a conventional film boiling viewpoint for that regime; however, the temperature effect is not large.

5. Droplets do not vaporize instantaneously as they near the plate at the peak flux in the wetting state. The high heat transfer occurs as the droplet is spread out in a thin film over the surface.

6. For any fixed set of parameters there appears to be a minimum velocity below which the droplets deform considerably without break-up upon impingement. This behavior occurs only in the non-wetting state.

7. The droplet deformation and break-up behavior for droplets as small as 200 μm dia. does not appear significantly different from that for large droplets. (For example, those of [3].)

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ETUDE EXPERIMENTALE DU COMPORTEMENT DYNAMIQUE ET DES CARACTERISTIQUES DE TRANSPORT DE CHALEUR DE GOUTTELETTES D'EAU FRAPPANT UNE SURFACE CHAUFFEE

Résumé—On présente les résultats de transport de chaleur pour des gouttelettes d'eau isolées frappant une surface chauffée. Les diamètres des gouttelettes allaient de 200 à 400 μm et les vitesses d'approche de 2,44 à 10, 1 m/s. L'effet de la variation de la température de la surface a été étudié à partir de la température de saturation jusqu'à 1800°C. On présente des photographies du processus d'impact qui montre que même les petites gouttelettes étudiées se brisent au moment de l'impact à des vitesses d'approche modérées. Les résultats de transport de chaleur montrent que la vitesse d'approche est la variable dominante affectant le transport de chaleur vers les gouttelettes et que la température superficielle a peu d'effet sur le transport de chaleur dans le régime non mouillant.

EXPERIMENTELLE UNTERSUCHUNG DES DYNAMISCHEN VERHALTENS UND DER WÄRMEÜBERGANGSCHARAKTERISTIK VON WASSERTROPFEN DIE AUF EINE BEHEIZTE FLÄCHE PRALLEN.

Zusammenfassung—Es werden Wärmeübergangsdaten angegeben für Wassertröpfchen, die auf eine beheizte Fläche prallen. Die Tröpfchendurchmesser lagen zwischen 200 und 400 μm und die Aufprallgeschwindigkeiten zwischen 2,5 und 10 m/s. Der Einfluss der Oberflächentemperatur zwischen Sättigungstemperatur und 1800°C wurde untersucht. Photographische Aufnahmen von Aufprall zeigen, dass sogar die kleineren Tröpfchen bei geringen.

Aufprallgeschwindigkeiten platzen. Die Wärmeübergangsdaten zeigen, dass die Aufprallgeschwindigkeit die wesentliche Einflussgrösse ist, die den Wärmeübergang an den Tröpfchen beeinflusst und dass die Oberflächentemperatur im nicht benetzenden Bereich auf den Wärmeübergang nur geringen Einfluss hat.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ДИНАМИЧЕСКИХ И ТЕПЛООБМЕННЫХ ХАРАКТЕРИСТИК ВОДЯНЫХ КАПЕЛЬ, ПАДАЮЩИХ НА НАГРЕТУЮ ПОВЕРХНОСТЬ

Аннотация—Представлены данные по теплопереносу для отдельных водяных капель, падающих на нагретую поверхность. Диаметры капель — от 200 до 400 μm, скорость падения — от 8 до 33 фут/сек. Исследован эффект колебаний температуры поверхности от температуры насыщения до 1800°. Даны фотографии процесса падения, которые показывают, что даже мелкие капли разбиваются при умеренных скоростях падения. Данные по теплопереносу показывают, что скорость падения является определяющим фактором, влияющим на теплоперенос каплей, и что температура поверхности незначительно влияет на теплоперенос при несмачиваемом режиме.