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EXPERIMENTS ON INDIVIDUAL DROPLET HEAT TRANSFER RATES

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Abstract—Experimental results for droplet heat transfer during splattering have been extended to smaller drop sizes than previously available through the use of an electrostatic drop generation device. Droplet diameters vary from 0·02 to 0·15 in. The range of physical properties is also extended with the use of Freon 11 and 113 and an excellent correlation of all previous and present data is obtained as

$$\frac{Q_{max}}{\rho_L d^3 \lambda} = 18{\cdot}50 \times 10^{-4} \left(\frac{\rho_L V^2 d}{\rho_{V_f} \sigma g_c}\right)^{0{\cdot}341}.$$

NOMENCLATURE

C_p, specific heat at constant pressure;
d, drop diameter;
d_n, needle diameter;
E, voltage [kV];
g_c, constant of proportionality in Newton's second law;
h_{fg}, enthalpy of vaporization;
N, drop rate (drops/s);
P, heater power consumption;
Q, heat transfer per drop;
T, temperature;
T_f, film temperature, $(T_p + T_s)/2$;
T_p, plate surface temperature;
T_s, saturation temperature;
ΔT_x, $T_p - T_s$, saturation temperature excess;
V, drop impact velocity normal to plate.

Greek
λ, modified heat of vaporization, $= h_{fg} + C_{pv}(T_p - T_s)/2$;
ρ, density;
σ, surface tension.

Subscripts
F, evaluated at film temperature;
L, liquid;
V, vapor.

INTRODUCTION

A PREVIOUS paper by one of the authors [1] has presented individual droplet heat-transfer rates for acetone, alcohol, and water splattering on a hot surface. While the results of the previous study were quite satisfactory, it was desirable to extend the range of applicability of the empirical correlation to include (1) fluids with wider diversity in thermophysical properties, and (2) a wider range of droplet sizes, particularly small droplet sizes applicable to mist flows. With information available on heat transfer to individual droplets the calculation of heat transfer resulting from a mist flow impingement on a hot surface is much easier, though still open to many questions. Reference [1] has shown that the droplet heat-transfer rates depend on the impingement velocity component normal to the heat transfer surface and the physical properties which influence the phenomena enter through the Weber number and liquid to vapor density ratio. Various photographic studies of droplet impingement with heat transfer have been conducted, notably those of [2, 3] and more recently that of [4].

The physical and analytical discussion of [1] indicated that the droplet heat transfer is dependent on the vapor film thickness generated

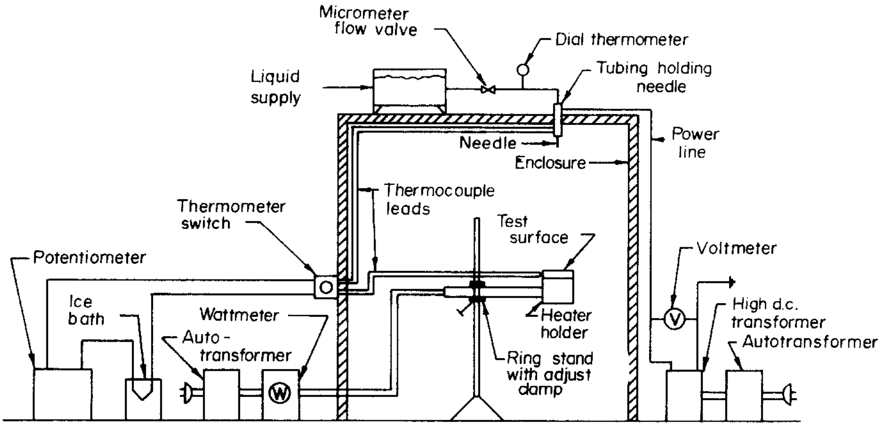

FIG. 1. Schematic diagram of experimental apparatus.

during the impingement process and that the characteristic maximum heat flux is the result of the opposing effects of increasing thermal gradient in the film and decreasing droplet contact time. The previous experimental results were limited in that the smallest drop diameter studied was about 0·10 in. For the droplet heat transfer correlation to be applicable to mist flows additional data are required at smaller drop diameters. The present study furnishes such information.

EXPERIMENTAL METHOD

The experimental apparatus is shown schematically in Fig. 1. The test surface was a 2 in. dia. copper plate, nickel plated and polished to a mirror finish. This plate was attached to a resistance heater composed of 5 ft of 26 gauge nichrome wire and controlled by a variac. Figure 2 illustrates the crossectional dimensions of the heater. The heater was mounted on the end of a 16 in. long piece of galvanised tubing through which the power lines were run to the heater. The galvanized tubing holding the heater was mounted in a movable 2-way clamp which allowed the heater surface to be set at almost any angle relative to the drop impingement. During the study, the surface was set at an angle of 27° from the horizontal for the duration of the tests because large portion of the data of [1] were collected for the 27° angle. It was established in those studies that the heat transfer was dependent on the velocity component normal to the plate; thus, angular variations were not deemed necessary in the present experimental work and

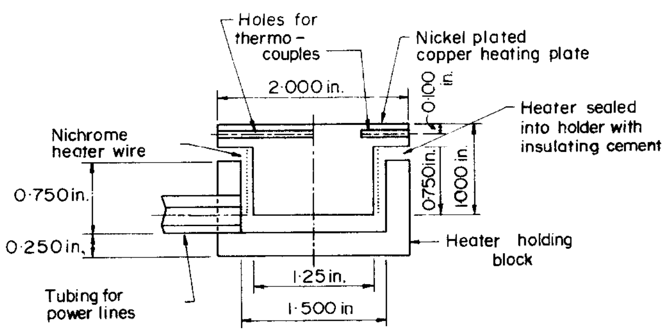

FIG. 2 Section through heater.

attention was concentrated on droplet size variations. The adjustable clamp was mounted on a vertical ring stand and different drop velocities were obtained by varying the height at which droplets were allowed to fall on the heater.

The temperature of the heated plate was recorded by two 30 gauge iron–constantan thermocouples. One thermocouple was located at the center of the plate, directly beneath the point of drop impingement, while the other was mounted one-half the plate radius from the center. A strobotac was used to determine drop rates and impact velocities in the same manner as reported in [1]. The fluid reservoir temperature was measured with a mercury-in-glass thermometer and the fluid temperature was also measured in two places as it proceeded to the needle; after the needle valve and in the hypodermic needle. This was done primarily to note the temperature of the Freons because they were used in a cooled state.

The drop generation system consisted of a constant head, thermally insulated reservoir, a scavenging pump, hypodermic needles, a 20 kV d.c. power transformer, a variac and associated wires, a micrometer valve, and the various tubing needed to transport the liquid. The fluid was pumped from a fluid supply to a thermally insulated reservoir which was maintained at a constant head by utilizing an overflow valve. This overflow was returned to the liquid supply where it was recirculated by a scavenge pump. The drop generation was accomplished by connecting a hypodermic needle to a piece of copper tubing which was attached to a piece of Tygon tubing. This tubing then was attached to a micrometer valve which allowed accurate control over the flow rate from the reservoir. McGinnis [1] reported that for a constant head and a fixed valve opening, drop rates could be maintained within 5 per cent of a typical value of ten drops per s. By using the micrometer valve in this experiment, calibration runs were well within this range.

Because the size of the drop falling from a needle is limited by the liquid properties (density, surface tension, and needle tip conditions, etc.), a special method was devised to obtain the small drop diameters required for this study. By attaching the positive lead from a high voltage power supply to the copper tubing holding the needle, a high positive charge was imparted to the liquid. The power was monitored on the voltmeter and controlled by a variac which regulated the a.c. voltage into the high voltage transformer. This in turn varied the high positive voltage applied to the hypodermic needle. This positive charge opposed the surface tension on the bottom of the drop of water falling from the needle. With the decrease in surface tension, less mass of liquid is required to overcome the surface tension, and as a result a smaller drop falls from the needle tip. Thus, by increasing the voltage to the needle, smaller drops can be emitted at a higher drop rate as shown in the data for water droplets in Fig. 3. It was possible

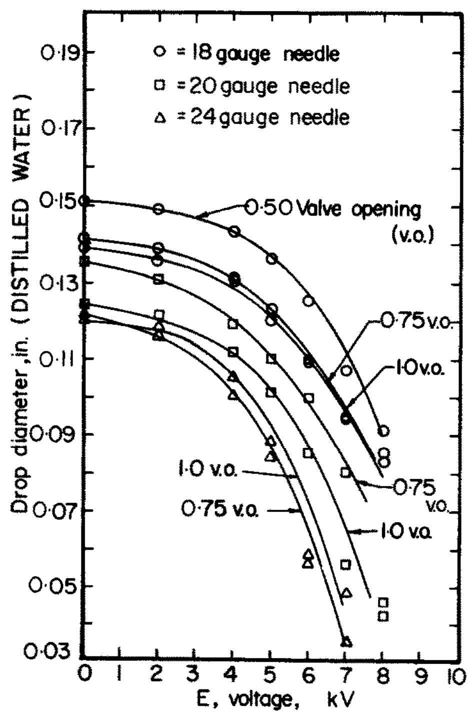

FIG. 3. Drop diameter as function of needle voltage.

to correlate all of these data with the relation

$$1 - d/d_0 = f(d_n)E^{2 \cdot 67} \qquad (1)$$

where

$$f(d_n) = 2{\cdot}113\, d_n^2 - 0{\cdot}204\, d_n + 0{\cdot}00608. \qquad (2)$$

This correlation is plotted in Fig. 4 indicating the clear exponential dependence of drop size on impressed voltage, for all the needle sizes employed. The electrostatic system permitted generation of substantially smaller individual droplets for the heat transfer study than had heretofore been obtained.

Six stainless steel needles of 13, 15, 18, 20, 24, and 27 gauge were filed to a flat tip to aid in obtaining spherical drops. The needles were calibrated at room temperature by collecting known numbers of droplets in a container of known mass. All masses were measured with a precision beam balance. From this information, the mean mass per drop was obtained and an effective drop diameter was determined.

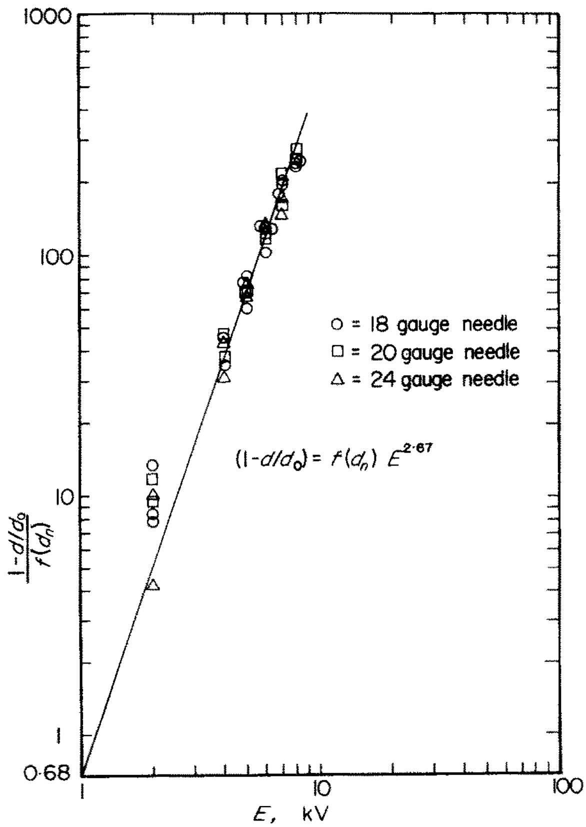

FIG. 4. Correlation of drop diameters.

McGinnis [1] reported that an uncertainty analysis indicated that drop diameters determined in this manner were accurate within 2 per cent.

The impact velocity of the falling drops was varied by positioning the clamp on the vertical ring stand (Fig. 1) at three different positions below the hypodermic needle. Impact velocities were experimentally determined for each run by means of a strobotac and a calibrated scale. The method consisted of determining the time required for the drop to fall an observed. final distance before striking the plate. An uncertainty analysis in [1] indicated this procedure would yield results with approximately 5 per cent accuracy.

The experimental procedure consisted of determining the steady state conditions without a drop impingement. and then monitoring the change of power consumption resulting from drop impact on the heated surface. The steady state heater power consumption with no drop impingement represents the total heat loss in the system due to conduction, radiation, and free convection. Because copper has such a high thermal conductivity the heated surface essentially represents an isothermal surface. To obtain the heat transfer per drop, the flow of known size drops at a known velocity was started. The heater power input was then set and the drop rate measured. When steady state conditions again were reached, the thermocouple outputs were recorded. The power input was then changed and the process repeated, thus generating a series of curves representing the power required vs. steady-state temperature.

The net heat transfer was found as the difference between the power consumption with droplet impingement and the power consumption without droplet impingement. Using the results of the above procedures, the average heat transfer per drop was determined by dividing the net heat transfer rate by the rate of drop impingement:

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

where both power terms were evaluated at the same steady state surface temperature.

RANGE OF EXPERIMENTAL VARIABLES

As mentioned previously, the objective of the experiments was to extend the work of [1]. This was accomplished by generating water droplets with substantially smaller diameters and by using Freon-11 and Freon-113 to obtain greater variations in fluid properties. Table 1 gives the range of drop diameters and impact velocities in the present study, while Table 2 gives the combined ranges of this study and [1]. Table 3 summarizes the thermophysical properties of the five fluids studied. The key property is the enthalpy of vaporization, h_{fg}, which varies by a factor of 15 for these fluids.

All data were taken with the heater angle at a constant 27° from the horizontal. Figure 5 illustrates a typical plot of the heat transfer rate vs. saturation temperature excess for a specified set of conditions. A peak heat transfer rate was found to exist at a temperature excess of approximately 400°F.

Data for the peak heat transfer for the present study were compared with the correlation presented in [1]. A numerical error in the constant term of the correlation was discovered, but when corrected, indicated excellent agreement between the previous work and the present

Table 1. Ranges of experimental conditions for present study

Substance	*d* (in.)	*V* (ft/s)	*θ* (degrees)
Water	0·021 → 0·124	1.00 → 2·70	27
Freon-113	0·068 → 0·089	2·86 → 8·00	27
Freon-11	0·089 → 0·110	2·15 → 7·00	27

Table 2. Ranges of all experimental conditions for present study and [1]

Substance	*d* (in.)	*r* (ft/s)	*θ* (degrees)
Water	0·021 → 0·151	1·00 → 16·75	6-74
Freon-113	0·068 → 0·089	2·86 → 8·00	27
Freon-11	0·089 → 0·110	2·15 → 7·00	27
Acetone	0·100 → 0·143	5·55 → 19·50	13-59
Ethanol	0·106 → 0·132	5·88 → 14·85	27-74

Table 3. Pertinent thermophysical properties for fluids studied at 1 atm, 77°F

Substance	ρL (lbm/ft^3)	h_{fg} (Btu/lbm)	σ_L (lbf/ft)	c_p (liquid)
Water	62·247	970·3	0·00493	0·998
Freon-11	92·14	77·58	0·001254	0·208
Freon-113	97·69	63·12	0·001302	0·218
Acetone	48·98	223	0·001583	0·514
Ethanol	49·01	364	0·001530	0·584

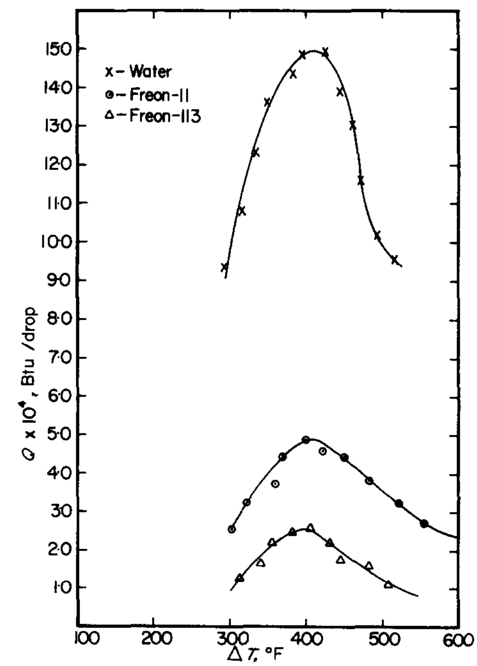

FIG. 5. Typical heat-transfer data.

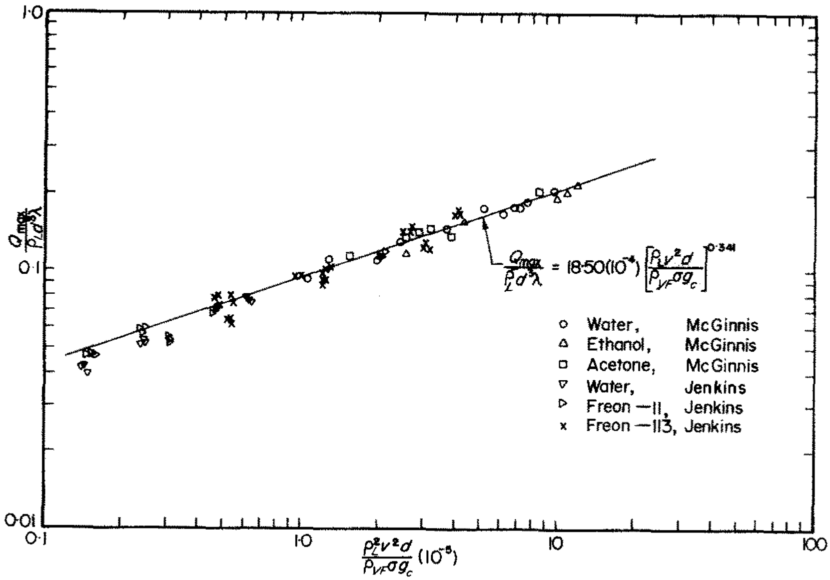

FIG. 6. Correlation of all heat-transfer data.

experiments. All of the data are shown in Fig. 6 and with the new experimental data the range of the correlation has been extended by an order of magnitude. The final correlation obtained was

$$\frac{Q_{max}}{\rho_L d^3 \lambda} = 18{\cdot}50 \times 10^{-4} \left(\frac{\rho_L V^2 d}{\rho_{Vf} \sigma g_c}\right)^{0{\cdot}341}. \quad (3)$$

As before, vapor properties were evaluated at atmospheric pressure and the film temperature defined by

$$T_f = \frac{T_p + T_s}{2}. \quad (4)$$

Observations of the splattering process with the small droplets indicates the same behavior as with the larger droplets so that the physical concepts used to explain equation (3) still seem valid. The fact that the experimental data now extend over a wide range of droplet sizes and more than an order of magnitude variation in fluid properties further establishes the validity of the correlation and suggests that it may be used with confidence for a variety of fluids.

CONCLUSIONS

It has been demonstrated through the use of an electrostatic drop generation process that the peak heat transfer for splattering of a wide variety of fluids can be predicted within ten per cent with equation (3). The present experiments have extended the applicability of this relation by an order of magnitude so that it is now valid for

$$10^4 < \frac{\rho_L{}^2 V^2 d}{\rho_{vf} \sigma g_c} < 2 \times 10^6. \quad (5)$$

ACKNOWLEDGEMENT

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EXPÉRIENCES SUR LES FLUX THERMIQUES PAR GOUTTE INDIVIDUELLE

Résumé—Des résultats expérimentaux relatifs au transfert thermique à chaque goutte pendant l'éclaboussement ont été étendus à des tailles de gouttes plus petites que celles antérieurement réalisées en utilisant un générateur électrostatique de gouttes. Les diamètres des gouttes varient de 0,51 à 3,81 mm. On étend le domaine des propriétés physiques en considérant les Fréon 11 et 113 et on obtient une excellente représentation de tous les résultats antérieurs ou présents par:

$$\frac{Q_{max}}{\rho_L d^3 \lambda} = 18{,}50 \times 10^{-4} \left(\frac{\rho_L V^2 d}{\rho_{v_f} \sigma g_c}\right)^{0{,}341}$$

VERSUCHE ZUM WÄRMEÜBERGANG AN EINZELTROPFEN

Zusammenfassung—Für den Wärmeübergang an Tropfen beim Zerstäuben wurden experimentelle Ergebnisse durch Ausdehnung der Versuche auf kleinere Tropfen erzielt, im Gegensatz zu den früher willkürlich mit einem Elektrostatik-Tropfen-Erzeugungsgerät gewonnenen. Der Tropfendurchmesser variierte von 0,5–3,8 mm.

Der Bereich der physikalischen Zustandsgrössen wurde durch Verwendung von Freon 11 und Freon 113 ebenfalls erweitert. Alle früheren und neu hinzugekommenen Daten werden durch die angegebene Korrelationsgleichung

$$\frac{Q_{max}}{\rho_L d^3 \lambda} = 18{,}50 \times 10^{-4} \left(\frac{\rho_L V^2 d}{\rho_{V_f} \sigma g_c}\right)^{0{,}341}$$

in guter Übereinstimmung beschrieben.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ИНТЕНСИВНОСТИ ТЕПЛООБМЕНА ОТДЕЛЬНЫХ КАПЕЛЬ

Аннотация—Полученные ранее экспериментальные результаты по теплообмену капель при распылении, образованных с помощью электростатического генератора, использованы для исследования теплообмена капель меньших размеров. Диаметры капель менялись от 0,02 до 0,15 дюйма. Был также расширен диапазон физических свойств благодаря применению фреона-11 и фреона-113. Получена хорошая связь между експериментальными результатами предыдущих исследований и результатами данной работы. Эта связь представлена в форме:

$$\frac{Q_{max}}{\rho_L d^3 \lambda} = 18{,}50 \times 10^{-4} \left(\frac{\rho_L V^2 d}{\rho_{V_f} \sigma g_c}\right)^{0{,}341}$$