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HEAT TRANSFER EXPERIMENTS OF MONO-DISPERSED VERTICALLY IMPACTING SPRAYS

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Abstract—The heat transfer of vertically impacting water sprays has been investigated experimensally using a one-dimensional mono-size spray. The liquid mass flux, droplet size and droplet velocity of the spray are independently variable in ranges. At low liquid flux, the film boiling heat transfer of an impacting spray is affected by the droplet size and velocity; however, at high liquid flux these effects become much less observable. The contribution of air convection to the overall heat transfer is low. The dominant parameter affecting the impacting spray heat transfer is the liquid mass flux. The film boiling heat transfer of impacting sprays has a power-law dependency on the liquid mass flux with the power varying from unity to a fraction as the liquid mass flux is increased.

1. INTRODUCTION

Sprays have been used effectively to cool hot subjects in many industrial processes. Typical applications are found in the continuous casting processes of metallurgical industries and the emergency core cooling of nuclear reactors. In order to achieve the desired rate of cooling, great attention must be paid to the selection of nozzles and their operation conditions. However, these selections have been made mainly based upon experience instead of analysis.

The heat transfer process of spray cooling is complicated because various heat transfer mechanisms are involved. Even for the simple case of a droplet impacting on hot surfaces the heat transfer process involves transient boiling heat transfer together with the complex droplet dynamics. When a spray is considered, interaction between droplets may occur when impacting on a hot plate so that the heat transfer mechanisms are further complicated.

Heat transfer studies of individual impacting droplets have been conducted. Wachters & Westerling (1966) studied heat transfer of a single water droplet impinging vertically on a hot plate. They presented film boiling heat transfer results in a broad range of Weber numbers. Later, McGinnis & Holman (1969) conducted similar experiments to examine the effects of droplet impinging velocity, the frequency of droplet impaction and the angle of impaction on the overall heat transfer. Pedersen (1970) studied the dynamic and heat transfer behavior of individual water droplets impinging upon a heated surface. He used various sizes and velocities of the impinging droplets and observed significant effects of the droplet size and the velocity. Kendall & Rohsenow (1978) conducted experiments similar to that of Pederson but at low Weber number (We < 25). Recently, Shoji *et al.* (1985) and Takeuchi *et al.* (1983) investigated the heat transfer and breakup behavior of impinging liquid droplets. Through these investigations, preliminary understanding of the heat transfer of an individual impacting droplet has been achieved. However, this understanding is still not sufficient to allow for the generalization of the published results to various spray applications.

Impacting heat transfer of sprays which have significant droplet number densities has been investigated less frequently. Mizikar (1970) conducted experiments with impacting water sprays and obtained heat flux profiles at various liquid mass fluxes. Bolle & Moureau (1982a) studied film boiling heat transfer of water sprays impacting downward or upward on a horizontal hot plate. Heat transfer correlations at various liquid fluxes are obtained. Also, they discussed the spray cooling heat transfer both analytically and experimentally in their review paper (Bolle & Moureau 1982b). Hoogendoorn & den Hond (1974) and Hall (1975) also studied impacting water spray heat transfer in the film boiling region. They reported that the droplet size and impacting velocity did

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not exhibit any significant effect on the overall heat transfer. Although these studies provided information on impacting spray heat transfer, the results could not be generalized and even, sometimes, indicated contradictory trends. This is because each study was performed with selected nozzles so that the generated sprays had specific combinations of droplet size spectrum, velocity and liquid flux. These parameters cannot be varied independently in ranges. Therefore, the experimental results were very restricted in general applicability.

On the other hand, impacting spray heat transfer has been analyzed by Liu & Yao (1982), considering droplet impaction, air convection and thermal radiation mechanisms. The overall heat transfer results compared favorably with some existing data of Mizikar (1970); however, the heat transfer mechanisms could not be fully justified because the available data did not reveal the effects of each parameter clearly.

In order to conduct fundamental experiments on spray heat transfer which are free from the restrictions of particular nozzles, it would be ideal to generate large quantities of droplets of uniform diameter with independently variable liquid mass flux and droplet velocity. Although a vibrating capillary techique has been used in previous experiments (Pedersen 1970; Kendall & Rohsenow 1978; Shoji *et al.* 1985; Takeuchi *et al.*, 1983), only one string of uniform droplets can be generated. Recently, Ashgrizzadeh & Yao (1980) used an impulse-jet technique to produce uniform size liquid droplets in large quantities to form a one-dimensional spray with independent variable liquid mass flux, droplet size and droplet velocity for their combustion research. The same principle has been applied in the present experiment with substantial improvements to produce such an ideal spray, that the fundamental behavior of impacting spray heat transfer can be investigated.

The objectives of the present paper, therefore, are to:

(i) describe the impulse-jet technique which may have broad applications beyond those of the present expeirments;

(ii) examine the parametric effects of liquid mass flux, droplet size and droplet impinging velocity on the heat transfer in the film, transition and nucleate boiling regimes;

and

(iii) develop a general correlation for heat transfer in the film boiling region at various liquid mass fluxes in the range of liquid mass fluxes and droplet diameters attainable using experimetnal apparatus.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the experimental setup is shown in figure 1. Each component is described below.

2.1. Mono-dispersed spray generator

The principle of the impulse-jet technique is to utilize the pressure pulses from a piezoelectric transducer to control the breakup of Rayleigh jets. As shown in figure 1, the generator is composed of a liquid chamber with a multi-orifice plate mounted on the bottom side and a 4.13 cm dia circular piezoelectric transducer on the top side.

The piezoelectric transducer is excited by a pulse generator. When a specific pulse frequency is applied to the piezoelectric transducer, streams of liquid Rayleigh jets break up into uniform size droplets. Details of droplet formation by applied disturbances are presented in Ashgrizzadeh & Yao (1980). The generated droplets were not dispersed naturally, instead, they traveled in a line and impacted on certain areas of the heating target because the inertia of the droplets was relatively high. Therefore, an air supply system was employed to disperse the droplets evenly in the spray. As shown in figure 1, the air supply consists of two parts: one supplies small amounts of air normally to the droplet streams so that the liquid droplets are properly dispersed; the other part supplies air to the spray to vary its bulk air velocity. By controlling the total amount of air supplied, the impinging velocity of the spray has been varied from 2.72 to 5.84 m/s in this research.

The size of the droplets and the droplet velocity in the spray can be controlled independently. When the liquid pressure in the chamber is fixed, the liquid jet velocity through an orifice is kept constant. The droplet size is then controlled by the applied frequency of the piezoelectric

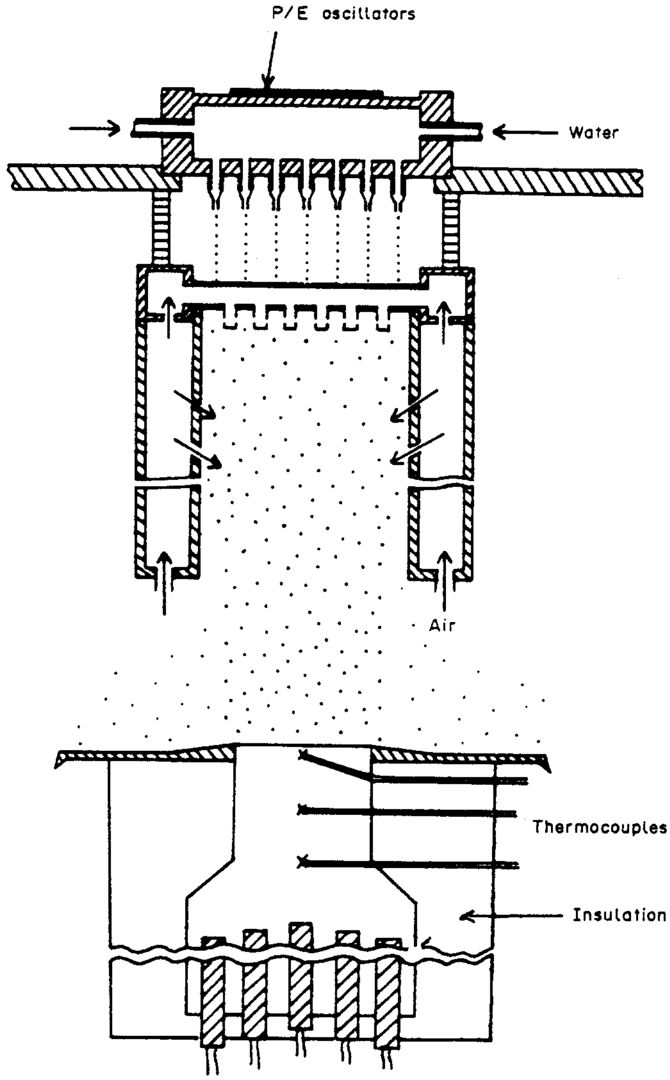

Figure 1. Schematic of the spray generator and the heat transfer target.

transducer. As shown in figure 2, for an orifice of 0.24 mm dia and a liquid flow rate of 0.075 ml/s, the droplet diameter varies from 0.407 to 0.530 mm with the change in frequency, the water is at room temperature which is about 24°C. As the liquid flow rate per orifice varies, an applied frequency can be selected to generate droplets of the same size again. The liquid flux of the spray changes when the jet velocity varies. However, different orifice plates may be used to provide various sets of operation ranges for these parameters.

The diameter of droplets at a certain operational condition can be easily calculated with the known jet velocity of an orifice and an applied frequency using a mass conservation equation; i.e.

$$D_d = \left(\frac{3}{2} D_n^2 \frac{V_j}{f}\right)^{\frac{1}{3}} \qquad [1]$$

or

$$D_d = \left(\frac{6m_n}{\pi \rho f}\right)^{\frac{1}{3}},$$

where D_n, V_j, f, ρ and m_n are the orifice diameter, the liquid velocity through the orifice, the impulse frequency, the liquid density and the liquid mass flow rate through the orifice, respectively. Throughout all the experiments, the water operating temperature was 24°C. In figure 2, the dashed

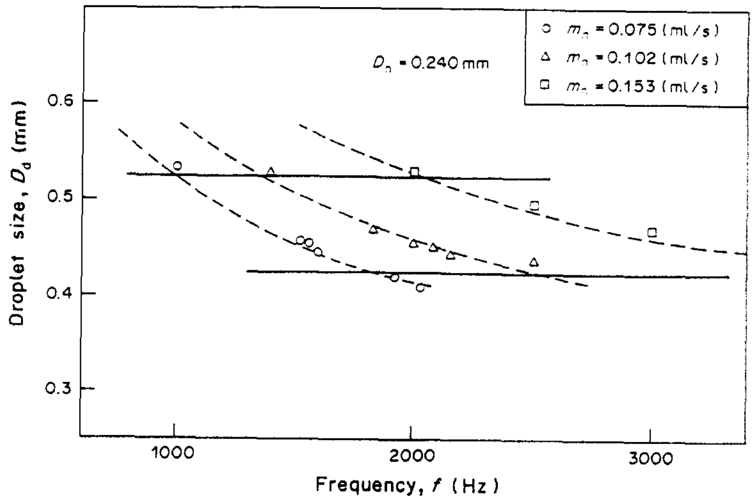

Figure 2. Operational ranges of a mono-size droplet generator.

lines were calculated from [1] for three different flow rates; they compare favorably with the droplet sizes measured from photographs.

Although mono-size droplets are produced near the orifices, during the dispersion process of the streams, some of the droplets may collide with one another and coalesce. Figure 3 is a typical droplet spectrum of a spray prior to impacting on the heat transfer target for the case of $m_n = 0.153$ g/s, $f = 2100$ Hz. The result shows that the majority of droplets are still of the original size (about 0.52 mm), but a small fraction have changed size.

The present spray generator produced a limited range of droplet sizes. Therefore, a different kind of mono-droplet generator needs to be employed when very large droplets of 1.03 mm dia are needed. Talley & Yao (1984) developed such a droplet generator in their combustion research. However, since this type of ejector has a single orifice, the liquid mass flux of the spray was limited to 0.0091 g/cm^2 s.

2.2. *Heat transfer target*

The heat transfer target was made of copper because of its high thermal diffusivity. As shown in figure 1, the heat transfer target was 14.4 cm long. The top of the target was 4.32 cm dia and the bottom was 7.62 cm dia. The top surface was plated with 2 μm chrome and polished to a mirror finish. The total hemispherical emittance of the surface was estimated to be <0.15. A stainless-steel disc (4.45 cm i.d.) was attached to the top surface of the copper block by silver brazing to maintain smooth air flow along the top surface.

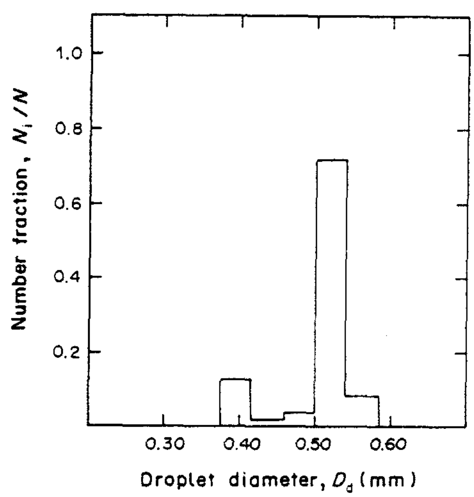

Figure 3. Droplet size spectrum of the spray before impacting on the target.

A total of 13 cartridge heaters, each with a maximum power of 350 W, were embodied in the lower portion of the copper block and controlled by a variac. Six stainless-steel sheathed unground Chromel–Alumel thermocouples (type K) with 0.102 cm o.d. were used for temperature measurements. The six thermocouples were press-fitted into holes at 0.159, 1.429 and 2.699 cm from the top surface at the geometric center of the copper block and at one-half radius from the centerline. Three of the six thermocouples were recorded on an IBM PC/XT through a digital data acquisition system at 0.5 s time intervals.

2.3. Procedure and data analysis

The water spray will be considered presently. In the experiments, measurements of the local liquid mass flux impinging on the heat transfer target, liquid temperature air velocity (without liquid droplets) and droplet approach velocity were taken. The liquid mass flux G_L was measured by direct collection of the local impacting spray. The air velocity without droplets was measured with a hot-wire anemometer. The droplet impinging velocity was determined by a double-exposure photograph of droplets taken with a stroboscopic light source at 2000 Hz frequency and a Nikon camera at a shutter speed of 1/1000 s. When the loop circulation pump was switched on, the heat transfer target was protected from the impinging spray. After the surface temperature reached approx. 450°C, the spray was allowed to impact on the target. Thus, an experiment was conducted either in a slow quenching by turning off the heater or at a steady state in film boiling through fine adjustments of the heater power. Since most of the transient process is very slow (order of several minutes), no difference was observed between steady-state and transient results.

Temperatures were recorded at three locations. Two thermocouples located at 0.159 and 1.429 cm from the top surface at the centerline of the copper block were used to measure the surface temperature and flux. The third thermocouple was at a half-radius location near the top surface to monitor the radial temperature distribution. Using the measurements, the transient temperature profile between the two centerline thermocouples is calculated numerically by heat conduction. With the known instantaneous temperature and flux at the location of the top thermocouple the surface temperature and flux are calculated as inverse heat conduction. Numerical calculations following the hyperbolic equation proposed by Weber (1981) have been used. Finally, the surface heat flux is evaluated from the temperature profile near the top surface via a three-point polynomial fit. Throughout this paper the surface heat flux q''_w refers to the overall surface heat flux minus the radiative heat flux from the wall.

3. RESULTS AND DISCUSSION

3.1. Effect of liquid mass flux

The typical relationships between the surface heat flux q''_w and the surface temperature T_w are shown in figure 4 for various liquid mass fluxes. It is observed that three regions can be recognized on each curve: namely, the film boiling region, the transition boiling region, and the nucleate boiling region. The higher the liquid mass flux, the higher the heat transfer at each region of the curve. Further examination of figure 4 leads to the following observations:

(1) At low liquid mass flux ($G_L \leqslant 0.0376$ g/cm²), the critical heat flux occurred at about $T_w = 135$°C. The heat flux decreased smoothly with a minimum at about 260°C. Beyond this temperature, the heat flux was almost constant and independent of the surface temperature in the present experimental range.

(2) At high liquid mass flux ($G_L > 0.0376$ g/cm² s), the behavior of the boiling curve was somewhat different from that at low liquid mass flux. The critical heat flux occurred at temperatures of 145–155°C, slightly higher than before. The heat flux in the transition boiling region showed two-step changes but with the minimum temperature at, again, about 260°C. The cause of the two-step change in the heat flux is not known at this moment. The heat flux in the well-developed film boiling region is, again, almost constant.

It is interesting to compare the temperatures at which the critical heat flux occurred in the present study and in previous investigations. The surface temperatures where critical heat fluxes occur have

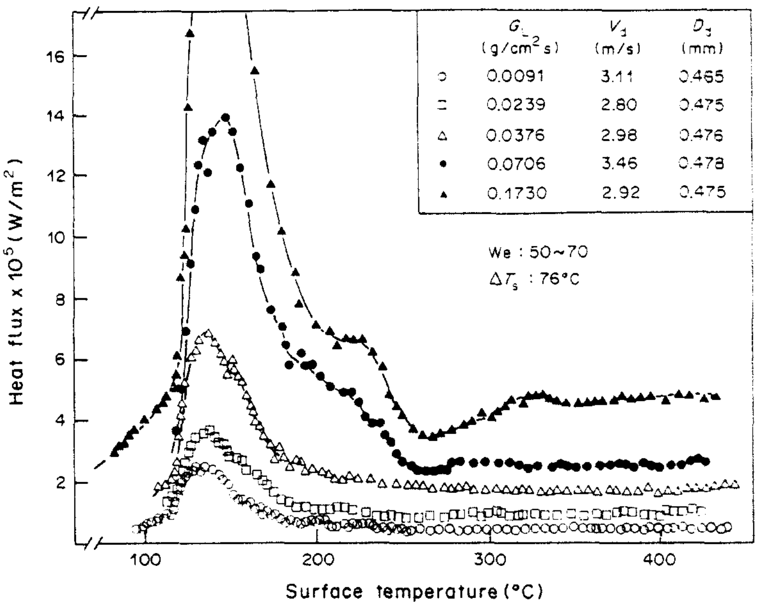

Figure 4. Heat flux vs surface temperature of the impacting spray at various liquid mass fluxes.

been reported to be 270, 180–200 and 130°C by McGinnis & Holman (1969), Pedersen (1970) and Kendall & Rohsenow (1978), respectively, for individual droplet impactions. At high liquid mass fluxes ranging from 0.222 to 1.492 g/cm^2 s, Mizikar (1970) used a commercial full-cone nozzle to impact horizontally on a large heating target. His results indicated that the critical heat flux occurred at between $T_w = 156$ and 182°C, depending on the liquid mass flux. Although the results (McGinnis & Holman 1969; Pedersen 1970; Kendall & Rohsenow 1978) for droplets show some discrepancy, and it is therefore hard to justify the present result at low mass flux, we can see reasonable agreement between the present result and Mizikar's (1970) result at high mass flux.

It is also interesting to examine the critical heat flux at various liquid mass fluxes. When the liquid mass flux is $\leqslant 0.07$ g/cm^2 s, the value of the critical heat flux is very close to the calculated heat flux required to evaporate the liquid flux completely. At higher liquid flux values, the critical heat flux is substantially lower than the calculated maximum flux. This implies the almost comlete evaporation of liquid at the critical heat flux when the spray mass flux is low. When the spray has a high mass flux, excess liquid will exist even at the critical heat flux.

3.2. Effect of droplet velocity

To achieve high droplet velocity at a constant liquid mass flux, a modified air supply system has been used. Some of the air was supplied axially in the spray near the orifices so that the droplets were accelerated in addition to being dispersed. The effect of the droplet impinging velocity V_d on the heat transfer at a high liquid mass flux ($G_L = 0.205$ g/cm^2 s) is shown in figure 5. The velocity range was varied from 4.02 to 5.84 m/s, but the droplet size was kept constant at 0.475 mm; therefore, the droplet Weber number was in the range 106–224. It is interesting that heat transfer in the film boiling region is not significantly affected by the droplet impinging velocity, whilst heat transfer in both the transition and nucleate boiling regions is clearly influenced by the droplet velocity. This is possible because the droplet–wall interaction is comparatively weak at film boiling as compared with transition and nucleate boiling.

It is relevant to point out that the reported film boiling heat transfer of impacting individual droplets by Pedersen (1970) indicated a 20% effect due to the variation of droplet velocity in the same range of Weber number as in figure 5. The present result of insignificant droplet velocity effects at film boiling is probably due to the high droplet number density or the higher liquid mass flux in the spray. In the spray, droplets deform after impaction; however, the deformed droplets are usually interrupted by other incoming droplets. As a result, the effects of the detailed impacting dynamics may become less significant.

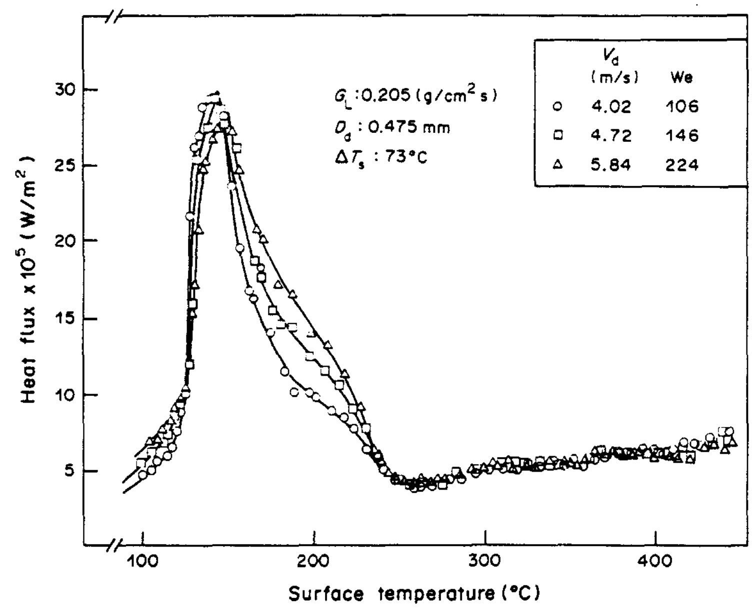

Figure 5. Effect of droplet velocity on the impacting spray heat transfer.

3.3. *Effect of droplet size*

The effect of droplet size on the impacting spray heat transfer at low liquid mass flux ($G_L = 0.0091$ g/cm^2 s) is presented in figure 6. In the film boiling region, the spray heat transfer of large droplets ($D_d = 1.03$ mm) is 1.43 times higher that of small-droplet sprays ($D_d = 0.478$ mm) at the same liquid mass flux.

In order to analyze this situation more extensively, it is appropriate to introduce a non-dimensional parameter, the heat transfer effectiveness, which has been used frequently by many previous investigators in studies of droplet impinging heat transfer. The heat transfer effectiveness ϵ is defined as the ratio of the actual heat transfer due to the effect of impinging droplets to the total heat transfer which is required for complete evaporation of the liquid droplets (Pederson 1970). Thus,

$$\epsilon = \frac{q''_w}{G_L(h_{fg} + C_{pl}\Delta T_S)}, \qquad [2]$$

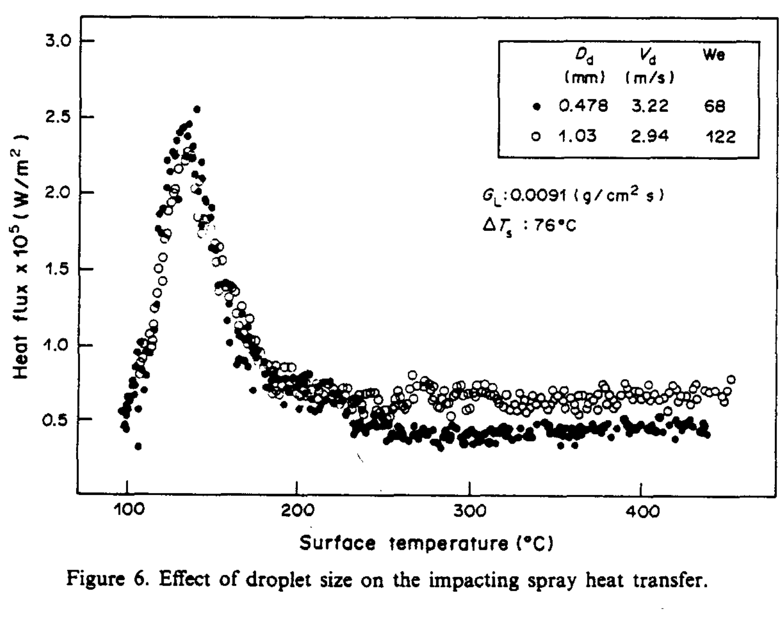

Figure 6. Effect of droplet size on the impacting spray heat transfer.

where h_{fg}, C_{pl} and ΔT_S are the latent heat of liquid vaporization, the heat capacitance of the liquid and the liquid subcooling temperature, respectively. The heat transfer effectiveness at the critical heat flux and low liquid mass flux is about 100%, which means almost all of the droplets are vaporized right after impacting on the hot surface. As shown in figure 6, when the film boiling heat transfer results are expressed in terms of heat transfer effectiveness, the effectiveness of the large-droplet spray is 18% and the effectiveness of the small-droplet spray is about 12%. The heat transfer effectiveness of our present results of spray in the film boiling region can be compared with previous results of individual impinging droplets (Wachters & Westerling 1966; Pedersen 1970; Kendall & Rohsenow 1978). The parameters of droplet size and droplet impinging velocity in previous studies can be converted to the droplet Weber number. The Weber number is defined as $We = \rho D_d V_d^2/\sigma$, where ρ and σ are the liquid density and surface tension, respectively. The heat transfer effectiveness was found to increase with the Weber number. Kendall & Rohsenow (1978) and Pedersen (1970) reported effectiveness values of about 7% at We = 14 and 11% at We = 120, respectively, for horizontally impacting single droplets. The trends are consistent with the present spray results. It is also pertinent that the present research was conducted in the orientation of vertical sprays impacting on a horizontal surface such that a second contact of the droplets and the surface may occur after the first impaction, resulting in a higher heat transfer effectiveness.

The effect of droplet size has been tested at a medium liquid mass flux of 0.041 g/cm^2 s. With the droplet diameter varied from 0.41 to 0.49 mm, no observable effects on the spray heat transfer appear. Although the range of variation tested is not substantial, the general trend is consistent with what Hoogendoorn & den Hond (1974) reported for a dense spray: that when the liquid flux is high the droplet size and velocity have insignificant effects on heat transfer.

3.4. *Effect of air convection*

In most of the industrial sprays the air is entrained and flows with the spray. It is extremely difficult to measure the air convective heat transfer in the impacting spray; however, an order-of-magnitude examination of the air convection contribution can be performed with the present setup by supplying the air without droplets to the system. This is because the air in the present spray is not entrained but supplied to match the droplets velocity.

Figure 7 shows the heat transfer results of bulk air convection at 3.45 m/s on the hot plate with the air supplied without liquid droplets. Comparing with figure 4, it is found that the heat transfer by air convection at the surface tempeature of 350°C is only 6–7.5% of the overall heat transfer of a spray with the corresponding air flow. The air convection contribution observed here is comparatively small with regard to what Kendall & Rohsenow (1978) and Hall (1975) reported in their papers. In fact, the convection discussed here is not the same convection as discussed in their papers. In their studies air convection refers to the air flow induced by a single droplet which moves in a stagnant environment. In the present study the air convection comes from the bulk air flow in the spray. In fact, the relatively small contribution of air convection to the impacting spray heat transfer is reasonable because the volume of air flow per droplet in a spray is much less than that of a single droplet moving in stagnant air. It is also expected that the denser the spray, the smaller the bulk air convection contribution to the overall heat transfer.

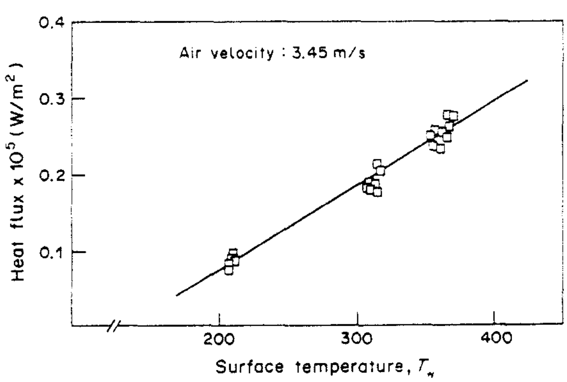

Figure 7. Heat transfer of air convection.

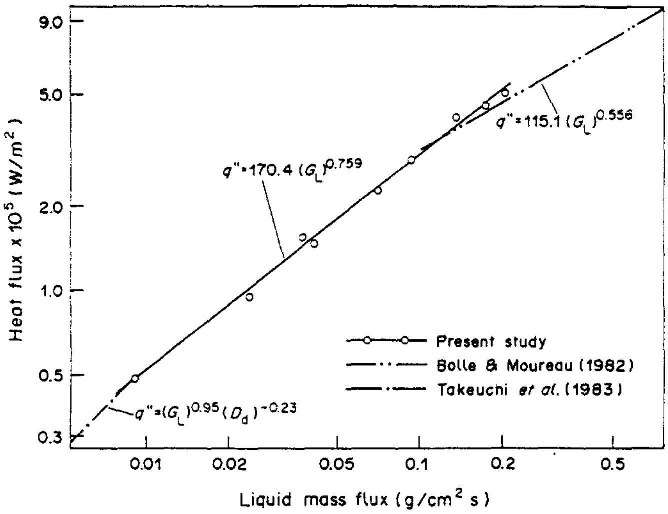

Figure 8. Variations of film boiling heat transfer as a function of liquid mass fluxes.

3.5. Correlation

From the previous discussion, it is reasonable to say that the film boiling heat transfer of an impacting spray will depend strongly on the amount of liquid mass flux but weakly upon the impinging velocity or the droplet size. This is in agreement with the study of industrial sprays conducted by Hoogendoorn & den Hond (1974), who mentioned that in dense sprays the droplet size, ranging from 0.2 to 1.0 mm and the impinging velocity, ranging from 10 to 30 m/s, had little effect on heat transfer in the film boiling region.

Before a large data base is fully established, correlation of impacting spray film boiling heat transfer as a function of the liquid mass flux needs to be established to reveal their functional relationship. The present spray data, with droplet dia = 0.46 mm, velocity = 2.8–3.4 m/s (We = 50–70) at surface temperature <450°C, are plotted in figure 8 on a logarithmic scale. All these water spray data can be correlated by liquid mass flux in the form

$$q''_w = 170(G_L)^{0.76}. \quad [3]$$

The range of G_L is between 0.0091 and 0.21 g/cm^{2}s. This equation indicates that the heat flux increases with increasing liquid mass flux but at a rate less than that of a linear relationship.

At liquid mass flux values below the range of the present study, the reported data for a single stream of droplets of Shoji *et al.* (1985) and Takeuchi *et al.* (1983) are noteworthy: after some reduction, their results show that the heat flux varies with the liquid mass flux in a linear and a 0.95 power relationship, respectively. It is also important to know that at low mass flux the heat transfer correlation depends clearly upon droplet size and velocity in addition to the liquid flux.

At high liquid mass flux, the power of G_L decreases such that the dependence of the heat flux on the liquid mass flux becomes less significant. At liquid mass flux values above the range of the present study, Bolle & Moureau (1982) conducted dense spray experiments, where the spray was vertically ejected on to a hot horizontal plate. As shown in figure 8, their heat flux results were proportional to $G_L^{0.556}$. Therefore, it is clear that the power of $G_L^{0.556}$ depends on the liquid mass flux.

4. CONCLUSIONS

(1) A special type of spray generator was invented and used to study impacting spray heat transfer. In the spray, most of the droplets are of the same size. The droplet velocity, number density and air velocity can also be varied independently in ranges.

(2) Parametric study of the vertically impacting spray reveals that at very low liquid flux the droplet size and velocity have observable effects on the film boiling heat transfer; however, at high mass flux the effects become insignificant. The contribution of air convection in the spray to the overall heat transfer is relatively low. The major parameter affecting the impacting spray heat

transfer is the liquid mass flux. It affects all the boiling regions significantly, as shown in figure 4.

(3) The impacting spray heat flux has a power-law dependency (cf. [3]) on the liquid mass flux. At low mass flux the relationship is close to linear; at higher mass flux the power reduces.

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