THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Chemical and Metallurgical Engineering

Progress Report

FLASHING AND CAVITATION STUDIES

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I. INTRODUCTION

Earlier reports from the current research program have shown considerable promise in vaporization techniques as a means of improving spray formation. The result was a decision to proceed somewhat more thoroughly along these lines, and this report presents the status of this work.

The phrase "vaporization techniques" is applied only to generalize several actions being studied, but vaporization in the usual sense of boiling caused by heat transfer from the surroundings to the liquid is <u>not</u> being considered here. Such a process is generally far too slow to affect spray formation significantly, although excessive environmental temperatures would constitute an exception. The term "vaporization" is applied here to processes occurring adiabatically as a result of sudden decreases in pressure of a liquid, either locally or in bulk. A sudden decrease in pressure of a liquid at uniform temperature may change its condition from equilibrium to superheat. Equilibrium can be restored only by vaporization of part of the liquid, which can be achieved only by increasing the enthalpy of the portion vaporizing, which in turn can be achieved only by decreasing the enthalpy of the remaining portion. This action quickly establishes an equilibrium condition at a lower temperature and with the original liquid now present as a mixture of liquid and vapor. This broad definition is common to all the high-speed phenomena with which we are concerned here, but various special cases may be distinguished.

If the pressure throughout a body of a liquid is lowered below the vapor pressure corresponding to the bulk temperature of the liquid, vapor will evolve throughout the volume and particularly at the surface of the issuing jet. This phenomenon is commonly referred to as "flashing." Evolution of a dissolved gas may be obtained by reducing the bulk pressure of the liquid mixture below that of the equilibrium value, and is a phenomenon quite similar to the flashing. Its inception, its performance, and its driving force are quite similar to flashing of an ordinary liquid. The effect on the spray characteristics should be similar.

The pressure also may be lowered locally below the vapor pressure corresponding to the bulk temperature, even if the bulk of the liquid has no tendency to vaporize. This usually causes some very tiny vapor bubbles to nucleate and grow. Subsequently these bubbles collapse within the liquid as they encounter a region of higher pressure. This phenomenon is called cavitation. Its inception, control, and effect on the general performance of hydraulic equipment has been studied intensively in recent years. The violent collapse of the bubbles (which is the origin of the name "cavitation") represents an extremely concentrated release of energy and as such has a pronounced mechanical effect on the condition of the flowing liquid.

The abruptness of cavitation in liquid flow may be compared with the abruptness of a shock wave in gas flow.

The evolution of a vapor phase in a liquid ejecting from a spray nozzle was first considered as a promising way of generating some very small particles. The earlier progress reports indicated that this phenomenon, whether originating as distributed throughout the liquid volume (boiling, flashing) or confined to the surface of the jet (accelerated local vaporization due to some low-pressure area in the receiving medium), or even taking place at individual points somewhere in the flow system (cavitation), had pronounced effects on all the major spray characteristics. Not only were the observed spray particles finer but the spatial distribution of these particles, the cone angles, the penetration of the spray, and the metering characteristics were entirely different. A quantitative study of these effects on both special and standard spray nozzles performing under controlled sets of conditions was begun and is discussed in this progress report.

The effect of flashing on spray formation and flow metering, and the effect of controlled cavitation on spray formation and flow metering are discussed in the light of available theory, experimental work, applications, and long-range objectives.

The effects of flashing and cavitation have also been tested on new types of nozzles to explore the suitability of some different design ideas to performance under flashing and cavitating conditions. These exploratory tests are covered under separate headings in the report.

II. EFFECT OF FLASHING ON SPRAY FORMATION AND FLOW-METERING

OBJECTIVES

When any liquid undergoes a pressure reduction, and the temperature of the liquid at the higher pressure is greater than its saturation temperature at the lower pressure, some of the liquid will vaporize. This process is called flashing. In the case of an adiabatic throttling process, the latent heat for this vaporization is provided by the sensible heat of the liquid as it cools to the saturation temperature.

In a previous report,[1] some preliminary results were presented of the study of sprays formed when water above 212°F was injected into air. The results qualitatively indicated that a finer spray resulted when only a small percentage of water was vaporized. Some data were obtained on the reduction in flow rate with rising liquid temperature at constant injection pressure. The study was continued for two reasons: (1) to obtain a quantitative measure of the effect of flashing on spray formation by measuring drop sizes, and (2) to examine the influence of nozzle design on the flow-rate—temperature relationship.

EXPERIMENTAL APPARATUS AND PROCEDURE

The same injection system was employed as in the previous investigation.[1] Liquid is injected by steam or air pressure as shown in Fig. 1. A Fischer-Porter variable-area Florator (No. C-1425-SS-L) was added to the injection system for these experiments. The flowmeter was calibrated volumetrically. Photographs of the sprays were taken using Kodak Super-Pan Press Type B film at f-4.5 and an exposure time of 1/100 sec. The camera was held approximately 3 ft from the spray and faced perpendicular to the direction of flow. Two Ken-Rab photoflood lamps were used for lighting.

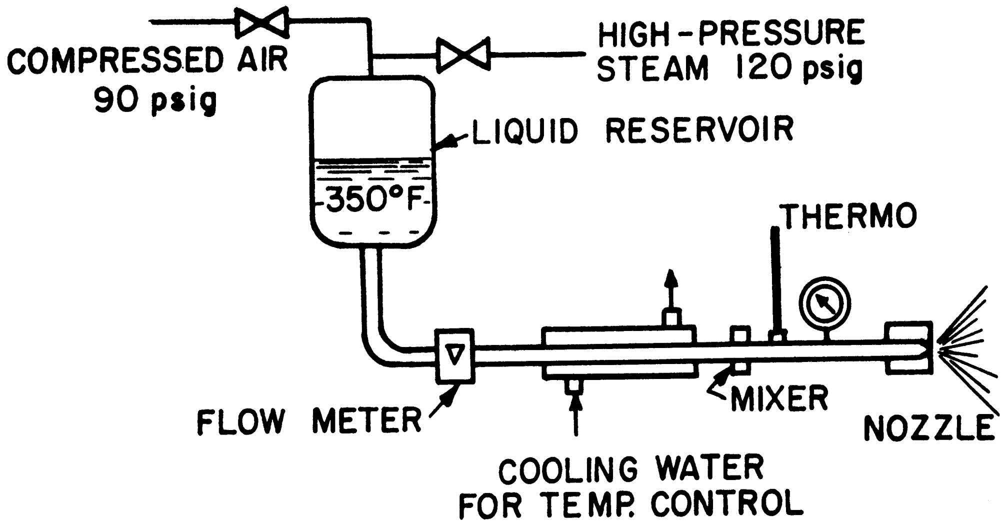

Fig. 1. The experimental layout.

Drop sizes were measured using a photographic calibration. The camera arrangement is shown in Fig. 2. The lens was an Argus with a focal length of 50 mm and a between-the-lens aperture setting of f-4. Lighting was from the rear with a General Electric Photolight Cat. No. 9364688G1, which provides a high-intensity flash for approximately 1 μsec. This was sufficient to "stop" the spray droplets on Kodak Contrast Process Ortho film at a magnification of 10X.

These experiments did not require a precise measurement of drop sizes therefore, only two photographs were taken at one location in the spray zone. The photographs were usually made at the center of the spray, as shown by Fig. 2, unless otherwise noted. Figure 3 is a typical photograph of the spray.

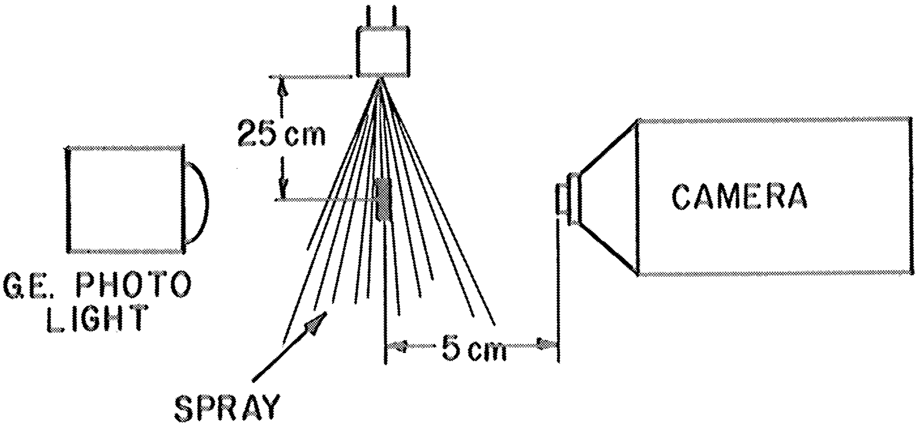

Fig. 2. Camera arrangement for drop-size analysis.

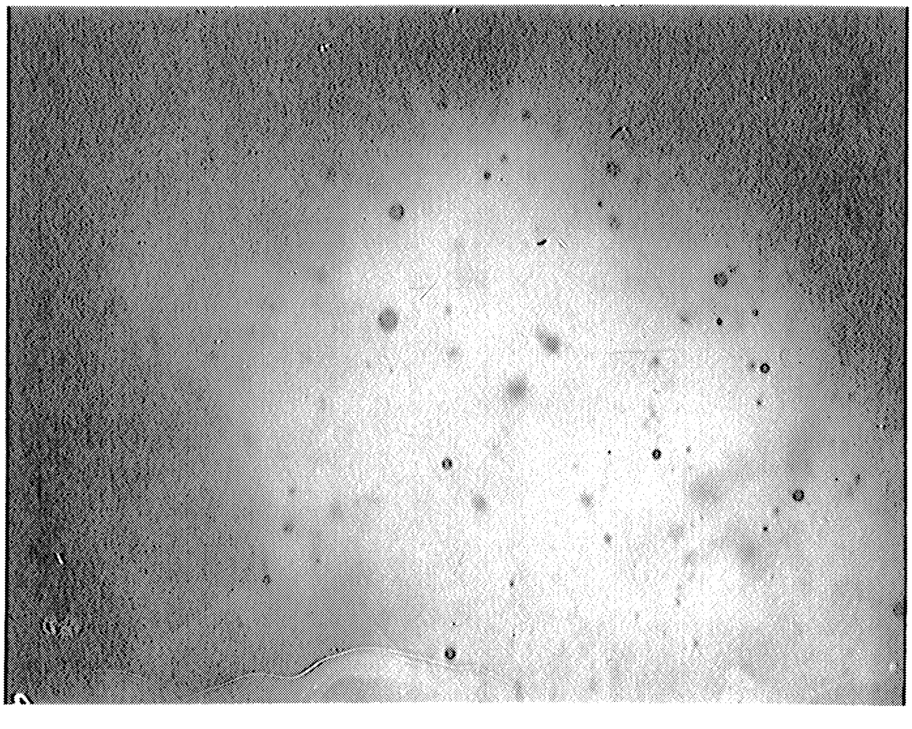

Fig. 3. Drops from spray.
(magnified 10 times)

Twenty drops that were in focus were chosen arbitrarily and measured. The arithmetic average diameter of the drops is reported in each case. It must be emphasized that, although the photographic method accurately gives the SRE of a given drop in focus, bias may be introduced by the fact that only a small section of the spray zone was analyzed. To have provided accurate average drop sizes and drop size distributions, samples should have been taken throughout the spray zone. Visual examination of the sprays gave no obvious reason to suspect that these sampling locations were not adequately representative, although a complete analysis would be needed to verify this further.

OBSERVED FLASHING MECHANISMS

When hot water is injected through a simple orifice nozzle, the liquid jet is disintegrated partly by the evolution of water vapor from the liquid. This disintegration of the liquid jet has been observed to take place in one of two distinct manners, depending on surface roughness of the orifice.

Figures 4a and 4b are two photographs of water being injected at 120 psig and 300°F through orifice nozzles having diameters of about 0.02 in. Figure 4a shows a nozzle made by drilling a hole in a 1/2-in. pipe cap. The orifice has a length-to-diameter ratio of about 6. Figure 4b shows a Delavan 6:00-80° oil burner nozzle without the distributor. The Delavan nozzle had a short, smoothly machined orifice.

At this injection temperature, 9% of the liquid will vaporize if all the sensible heat of the water provides latent heat for the vaporization of a portion of it. With the rough orifice nozzle, one can observe that a well-mixed zone of liquid drops and steam issues from the orifice. Apparently, vaporization of part of the liquid has started within the orifice and the mixing of water and steam initiates there. Observation of the smooth orifice nozzle reveals a quite different phenomenon. The liquid jet remains intact about 1/2 in. from the exit of the orifice. It then splits into thin filaments of liquid and steam. These filaments are unstable and oscillate in an irregular manner. Associated with this phenomenon is a loud screeching sound. The sound will stop when an obstruction, moved toward the orifice, reaches the intact portion of the liquid jet. This indicates that the noise originates where the liquid jet starts to disintegrate. The noise associated with this breakup indicates that some cavitation may be occurring. This phenomenon is elaborated upon in the section of the report concerned with cavitation.

DROP-SIZE STUDIES

An analysis was made of the drops from the disintegration of a cold-water jet made by injection of water at 120 psig through a 0.02-in.-diameter rough orifice. Since the jet did not break up close to the orifice, the analysis was made 4.4 ft from the orifice. The arithmetic average drop diameter was 460μ. Drop sizes for flashing water ejected through this nozzle at 230°F (2% flashing) and 284°F (7.5% flashing) were about 1/10 the average diameter of the drops from the cold-liquid jet.

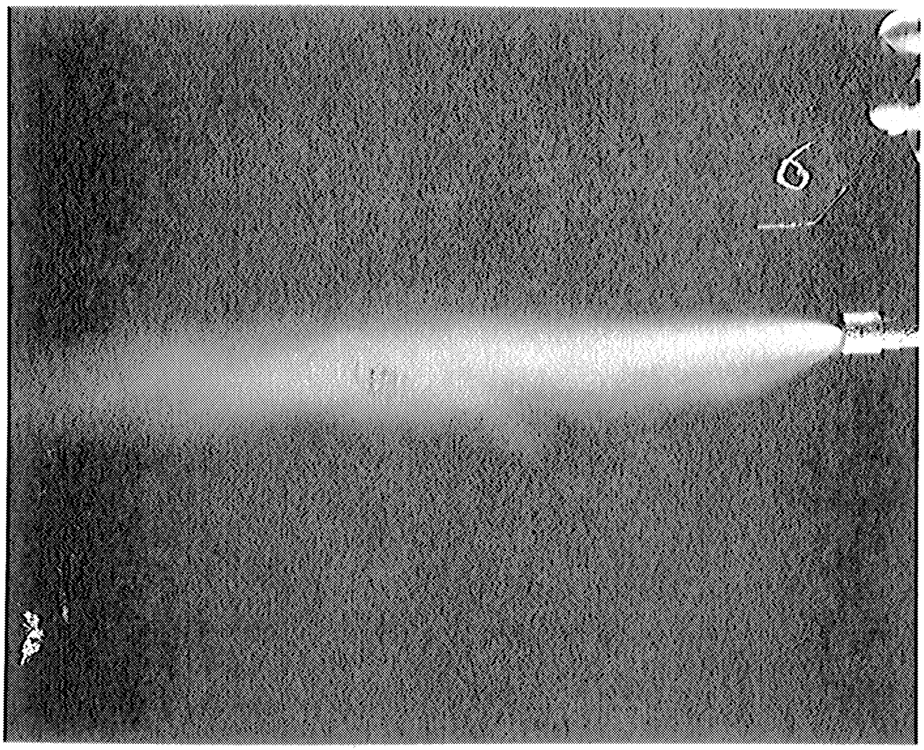

Fig. 4a. Rough orifice nozzle.

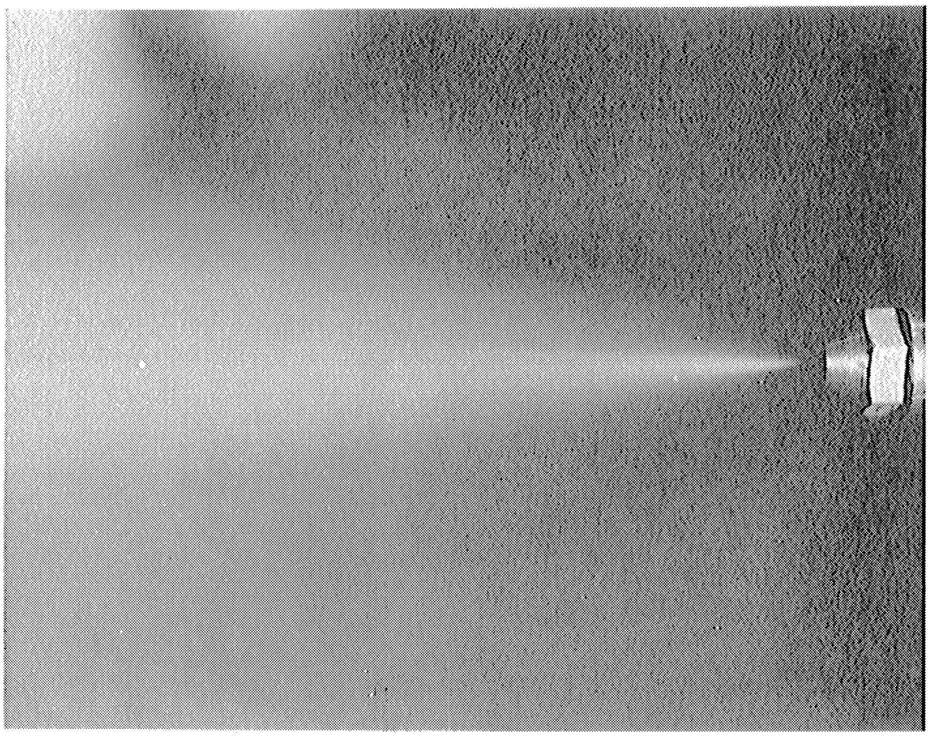

Fig. 4b. Smooth orifice nozzle.

Drop-size analyses were also made when hot water was injected through a Delavan 6:00 nozzle without the distributor, a Delavan 12:00 nozzle with the distributor, and two cone nozzles. A summary of the drop-size data is presented in Fig. 5.

In view of the approximate nature of the drop-size analyses and some of the inconsistencies of the results from the various nozzles, we hesitate to draw any definite conclusions concerning the effects of the nozzle design on the drop size with flashing water. The data do seem to indicate, however, that a difference of 2% flashing and 7.5% flashing has a small effect on drop sizes. The drop sizes of the spray from the swirl nozzles with flashing are about one-half the drop sizes when cold water is used.

FLOW-RATE STUDIES

When flashing liquid passes through an orifice, the predicted flow rate is about one-fifth the predicted cold-liquid flow rate. A detailed discussion of the thermodynamic basis for this prediction was given in a previous report.[1] Briefly, the specific volume of a mixture of a liquid and a small fraction of its vapor is considerably greater than the specific volume of the pure liquid. The large increase in the specific volume of a liquid when flashing occurs as it passes through an orifice is the reason for the predicted reduction of mass flow rate. In practice, the reduction in flow rate of a flashing liquid below the cold-water flow rate is only a small fraction of that thermodynamically predicted. The thermodynamic calculation is based upon the assumption that, at any point in the orifice, the liquid temperature has dropped to the saturation temperature for the corresponding pressure at that point. This condition of thermodynamic equilibrium is never reached and the liquid is slightly superheated when passing through the orifice. Therefore, the equilibrium fraction of vapor is not produced within the orifice and the actual mass flow rate remains higher than it would be if all the vaporization took place within the orifice. Nozzle design should have an effect on the flow rate of flashing liquids since the design probably influences the rate of approach to thermodynamic equilibrium within the nozzle.

Flow-rate measurements were made on four nozzles to test the influence of nozzle design on the flow rate of flashing. The tests were made at constant injection pressure (120 psig) and various injection temperatures. At injection pressures above 212°F, the fraction of liquid flashing is directly proportional to the injection temperatures. The data are plotted in Fig. 6.

Comparing the rough orifice nozzle and the smooth orifice nozzle (Delavan 6:00-80°A without distributor), one sees that at 300°F (9% flashing), the flow rate in the rough orifice nozzle has decreased 25%, and the smooth orifice, only 5%. Figure 4a shows that some vaporization occurs inside the rough orifice, since a mixture of water and steam issues from it. This reduction in flow rate is therefore to be expected. In the smooth orifice, however, there should be

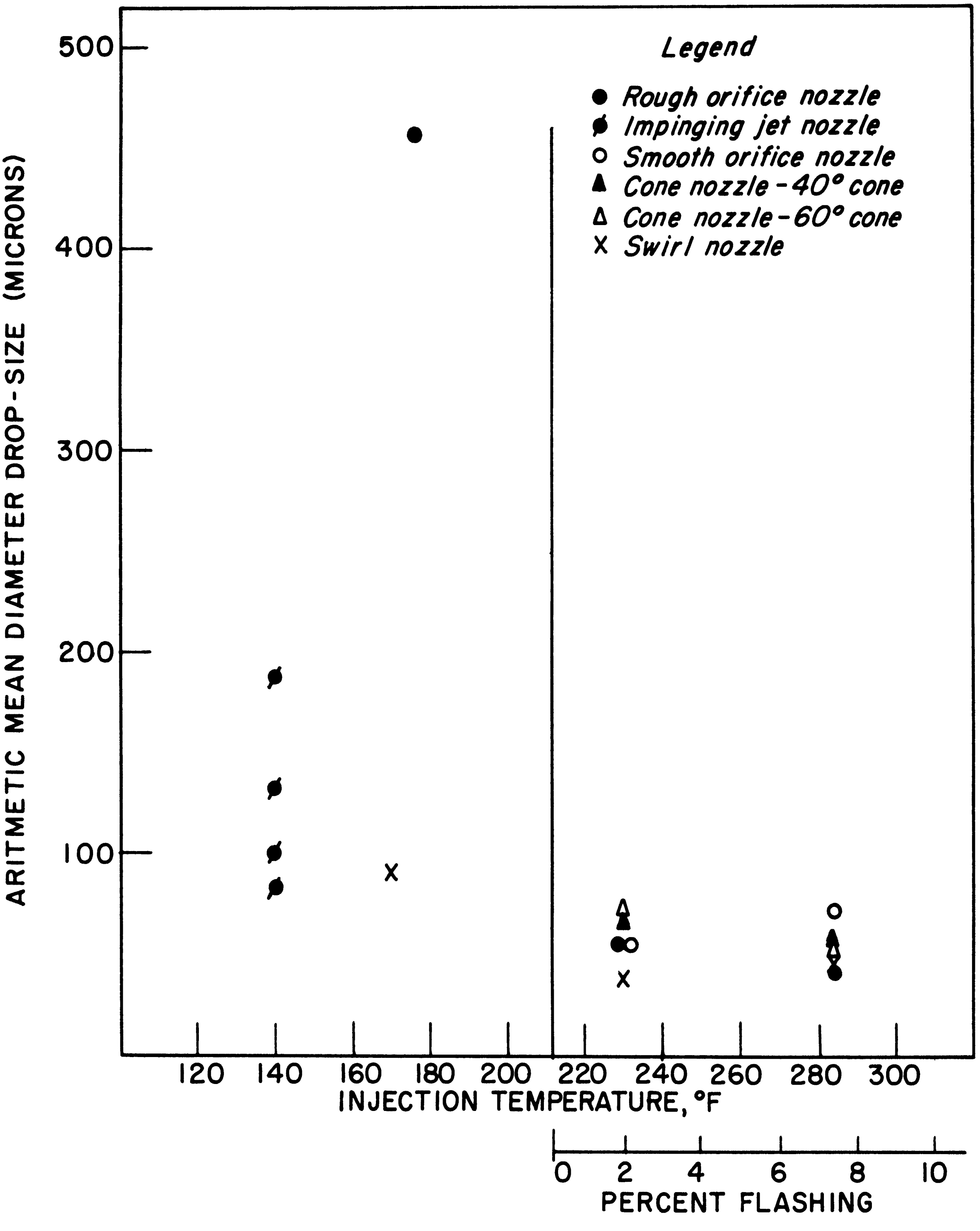

Fig. 5. Summary of drop-size data.

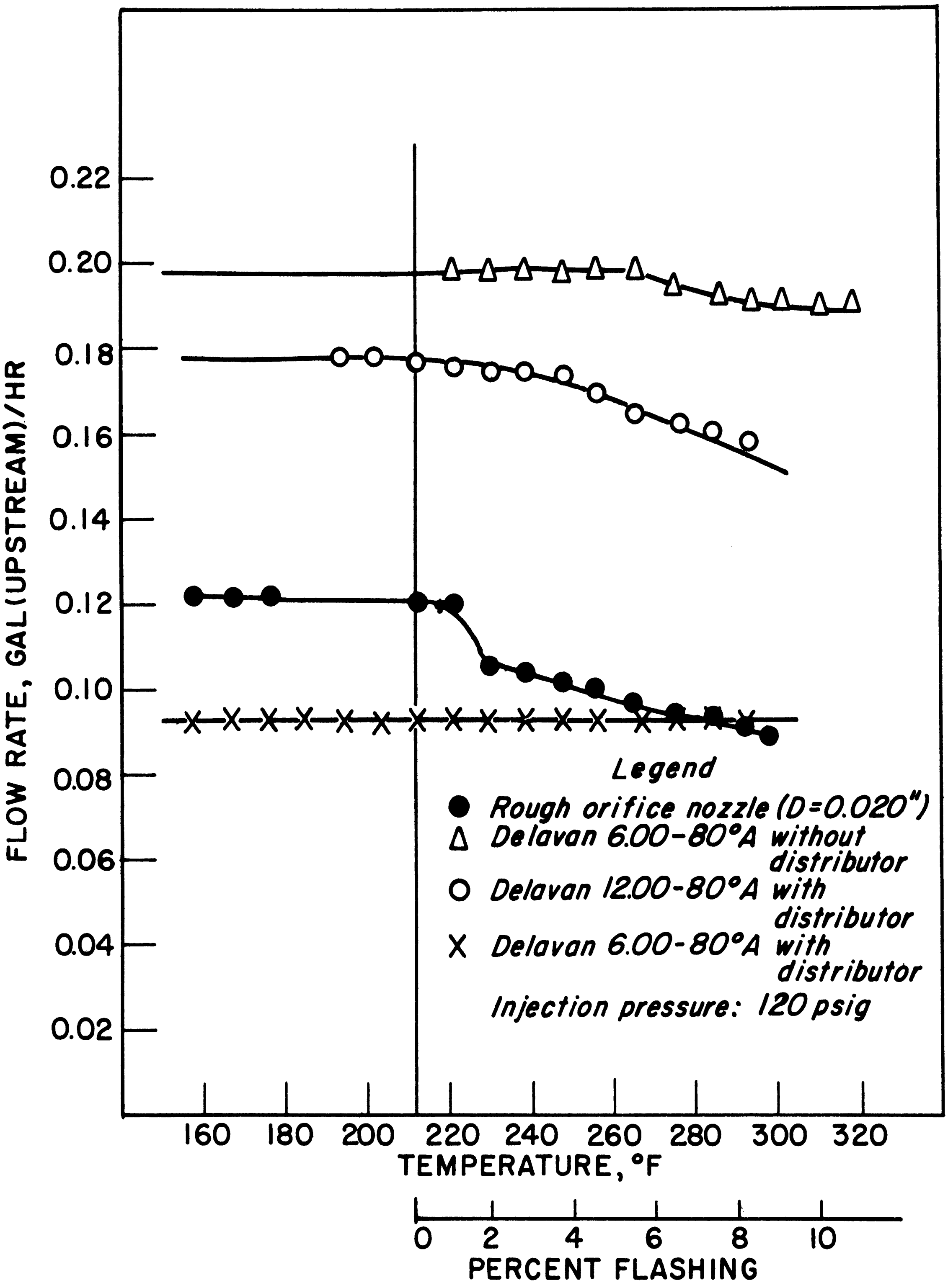

Fig. 6. Flow rate—injection temperature relation for various nozzles.

no reduction in flow rate, as Fig. 4b shows that all the flashing occurs outside the orifice. The observed 5% reduction in flow rate corresponds to the 5% reduction in water density as its temperature is raised from 212°F to 300°F.

The reduction in flow rate of the larger swirl nozzle at 300°F is 12%. The flow rate of the swirl nozzle is not reduced as much as that in the rough orifice nozzle because of the separation of phases in the nozzle. Complete mixing of the phases in the swirl chamber is prevented by the flow of liquid along the walls of the swirl chamber.

The flow rate in the smaller swirl nozzle remains constant throughout the temperature range. Complete separation of phases is apparently maintained in the smaller nozzle to a higher temperature. The importance of nozzle size is a result of the fact that initiation of phase mixing in a swirl chamber depends upon the degree of turbulence in the liquid. There is less turbulence in smaller nozzles at a given pressure as a result of the lower flow rates. This explanation is supported by the data of Silver and Mitchell,[7] who show that, when water is injected at a given temperature and pressure through a number of orifice nozzles a greater reduction in flow rate below cold-water flow rate is found in larger diameter nozzles.

Comparing the two nozzles that suffer no reduction in flow rate because of flashing, the smooth orifice nozzle and the small swirl nozzle, we see that the flow rate through the smooth orifice nozzle is affected by liquid density while the flow rate through the swirl nozzle is not. This observation is compatible with our explanation of the mechanics of flashing flow through a swirl nozzle. In a swirl nozzle, flashing occurs in the swirl chamber. The vapor separates from the liquid and leaves the nozzle through the open vortex of the swirling liquid. Since flashing occurs before the orifice of the nozzle, the liquid temperature has decreased to 212°F before reaching the orifice. In the smooth orifice nozzle, however, the liquid is superheated when passing through the orifice. The density of liquid at the orifice controls the volumetric flow rate. Since the liquid temperature at the orifice of a swirl nozzle remains at 212°F, there is no reduction in flow rate as a result of liquid density changes.

The flow-rate—temperature curve for the rough orifice nozzle makes a sudden dip at 220°F. This is probably the point where flashing begins to occur within the orifice. After this initial dip, the flow rate falls linearly with injection temperature as the fraction flashing increases.

The Delavan 12.00-80°A with a distributor and the 6.00-80°A without a distributor were flow-tested with oil at the factory and found to give almost the same flow rate, but a 10% difference is noted in Fig. 6. The difference is only in the nozzle with the swirl as the smaller nozzle checks with the factory test. The factory test was made with ps-111 fuel oil and these experiments with water so that the difference in the swirl nozzle flow rate is explained by the different liquid viscosities resulting in different Reynolds numbers, and therefore different discharge coefficients.

In all the nozzles tested, there is essentially no reduction in flowmetering up to an injection temperature of 222°F, which corresponds to 1% flashing. Flashing can therefore be used to help reduce drop sizes in these nozzles without reducing flow metering up to 1% flashing.

III. EFFECT OF CONTROLLED CAVITATION ON SPRAY FORMATION AND FLOW METERING

When the minimum pressure in a liquid flow field falls below the vapor pressure at the bulk temperature of the liquid, the formation of bubbles is usually nucleated within the body of the liquid phase. The inception growth and subsequent collapse of these bubbles are commonly referred to as the phenomenon of cavitation. In hydraulic equipment performance, the cavitation is often accompanied by severe maintenance problems such as vibration, noise, erosion, and pitting of the metal surface.

It was known for some time that in some aerosol dispensers for insect sprays or cosmetic products, a fine spray mist is produced by two mechanisms (Cf. Univ. of Mich. Res. Inst. Report 2815-2-P). The lower boiling constituents vaporize rapidly as soon as the pressure drops to their vapor pressure and this results in cavitation boiling which seems to shatter the liquid phase or the larger particles into fine liquid droplets. While this phenomenon is usually considered as flash vaporization, the latent heat required for the evaporation cools the surroundings and causes some of the vapors to recondense into tiny drops. It was suggested that this effect would offer interesting possibilities for application to spray nozzles where the disintegration of issuing liquid may be at least partially set off by cavitation phenomena. A basically unstable free surface must depend on some sort of mechanical disturbance to set off the disintegration phenomena. The superposition of the small-amplitude, high-frequency disturbances caused by cavitation phenomena was considered a likely source from which tiny liquid drops could be obtained. One of the major problems in the design of hydraulic systems is often the prediction and suppression of cavitation. Only recently was the idea of promotion of cavitation in a controlled geometry conceived and successfully tried. This idea is based upon the premise that the phase of the cavitation phenomenon which will damage the solid surfaces is the collapse of bubbles. If the hydraulic equipment is designed so that controlled cavitation takes place, the incipient bubbles might be carried safely down stream before they collapse violently.

Whether it is desired to suppress or promote cavitation, the essential problem which must usually be solved first is the prediction and understanding of incipient cavitation characteristics. Experience has shown that, if a body is sufficiently smooth, the onset of cavitation can be determined adequately from the theoretical value of the minimum pressure. But if a surface irregularity protrudes a significant distance into the main stream, the pressure will be lower at some point than that of the smooth surface. Under this condition, the flow system may cavitate at lower main flow velocities than those which would be required to bring about cavitation with smooth surfaces. The effect of surface roughness to the cavitation characteristics has been investigated and reported in the literature by J. W. Hall,[3] Shalnev[5,6] Calehuff and Wishicenus,[2] and Walker.[8]

The recent work on the effects of height of the surface roughness relative to the boundary-layer thickness, the geometry of the flow boundaries, and the degree of turbulence on the cavitation characteristics indicate that there is a distinct possibility for designing special spray nozzles with orifices capable of producing cavitating flow. It is important to realize, on the other hand, that while a cavitating nozzle may be very effective in producing finer and better sprays, its metering characteristics must meet some minimum requirements. The research carried on so far on the effect of flashing on metering characteristics indicates that the evolution of the gas phase from within the liquid phase may rather severely block the cross-sectional area of the orifice available for the flow of liquid jet. This results in low mass flow rates for the sprayed material for a given pressure drop. This was precisely why we concluded earlier that only about 1% flashing, and no more, will produce the maximum benefit in reducing the particle size without seriously affecting the mass flow deliverability of the nozzle. Recently F. Numachi, M. Yamabe, and R. Oba, at Tohoku University, presented interesting data[10] on cavitating flow of hot water through sharp-edged orifice plates. According to the data presented in this paper, even under the most violently cavitating condition the discharge coefficient does not change by more than 1/2 of 1%. There appear to be two basic reasons for this observation: first, the amount of volume represented by the nucleating tiny vapor bubbles is so small that its effect on the reduction of cross-sectional area available to liquid flow is almost imperceptible; secondly, before a vapor bubble grows to any substantial size, it is carried downstream and recollapses before having any adverse effect on the relationship between flow rate and pressure difference.

In summary, it appears that:

1. It is possible to design special cavitating orifice nozzles.

2. The probable effect of cavitation on liquid disintegration and jet break-up phenomena should be very pronounced and should result in much finer sprays.

3. While improving the particle size, the cavitating nozzles are not expected to have inferior metering characteristics.

Based on the conclusions listed above, a series of critical experiments to evaluate the practicality of cavitating nozzles has been planned. The first of these nozzles was designed as a solid impingement nozzle to promote cavitation outside of the orifice exit. This nozzle and its test data are discussed next. Other cavitating nozzles now being planned for construction and evaluation will include triangular and round surface irregularities designed within their orifice passages.

SOLID IMPINGEMENT NOZZLE

The impingement of a liquid jet against a solid is a common means of making a spray. In this experiment, an attempt is made to use solid impingement as a means of promoting cavitation in a liquid jet issuing from an orifice (Fig. 7). A cylindrical water jet is directed upon a flat surface perpendicular to the direction of flow and having the same diameter as the jet. The nozzle used in this experiment is shown in Figs. 8 and 9.

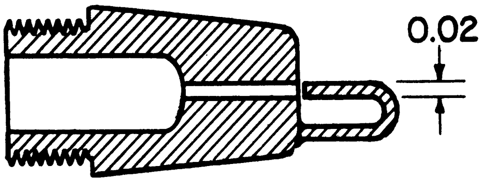

Fig. 7. Solid impingement nozzle.

The nozzle was tested at an injection pressure of 120 psig. Both cold and hot (300°F) water was used. The cold- and hot-water tests are shown in Figs. 8 and 9. In both cases the axisymmetrical spray pattern was disrupted by the support of the blunt object. The spray pattern was also extremely sensitive to the position of the obstruction. It was impossible to center the obstruction exactly in the path of the jet since the diameters of the jet and solid were small—0.02 in. The spray flux appeared to vary considerably around the axis of the water jet. A drop-size measurement was made for a cold-water jet injected at 87 psig which corresponds to a jet velocity of 115 fps. The arithmetic average drop diameter was 42μ. The drop size with hot water was 25μ. These measurements may be subject to a strong bias as a result of the nonuniformity of the spray. The photographs were taken at the same location in the spray so the relative drop sizes are significant.

It is not possible to determine whether this reduction in drop size was purely a result of flashing of the liquid or whether cavitation had some effect. The loud noise and vibration commonly associated with cavitation were not observed during the tests. Proper design of the geometry of the solid obstruction of this nozzle would alter the flow so that the onset of cavitation would be more likely. Future experiments will be conducted with the application of controlled geometries for cavitation promotion.

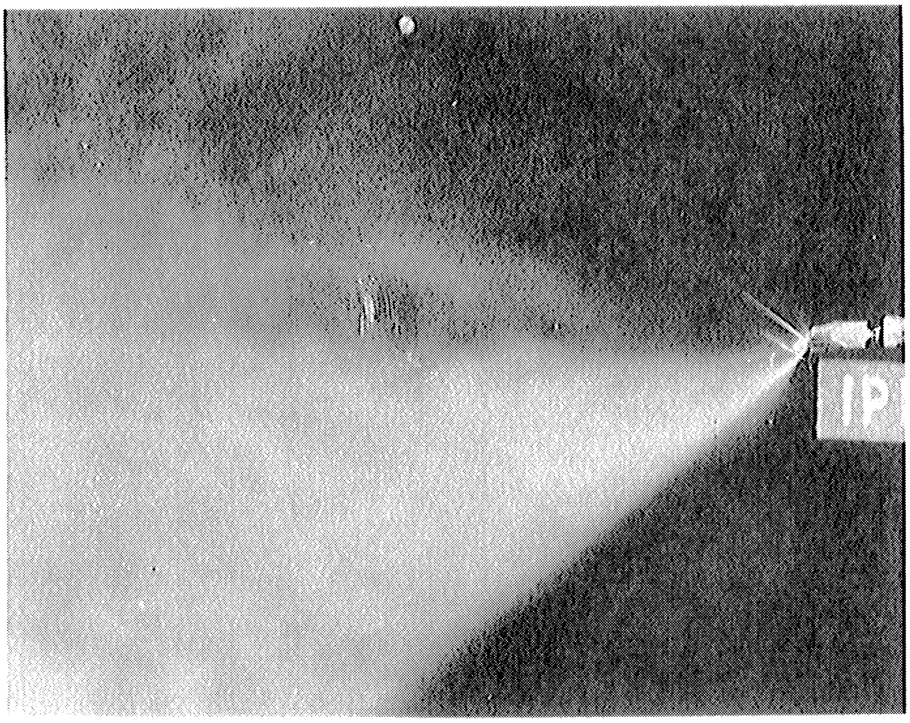

Fig. 8. Solid impingement nozzle.

Fig. 9. Solid impingement nozzle.

IV. EXPLORATORY TESTS ON NEW TYPES OF NOZZLES

Through study of the fluid mechanics of spray formation, we have developed some concepts of novel methods of producing sprays. Some of these are related to principles and mechanisms radically different from the ones generally applied to current principles of liquid atomization, for example, the use of controlled cavitation to support spray formation. Other methods are simply variations on systems of spray formation that have already been suggested or are in current use, for example, the impinging jet nozzle using three liquid jets. These experiments explore the possibilities of these new methods to future engineering applications which may also incorporate flashing, boiling, or cavitating service conditions.

CONE NOZZLES

Some nozzles were made up of a simple orifice nozzle with a conical section at the exit (Fig. 10). In such a nozzle the liquid jet from the orifice will drag vapor along with it. The vapor replacing it will flow from the surroundings along the inside of the wall of the cone toward the liquid jet at the orifice. An energy balance indicates that there will be a region of lower pressure at the junction of the orifice and conical section as a result of the high vapor velocity. This local pressure reduction may be severe enough to accelerate vaporization of the liquid. The vaporized liquid might then recondense downstream as a fine mist.

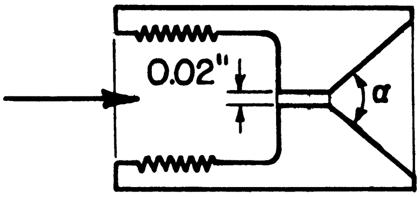

Fig. 10. Cone nozzle.

Nozzles with 0.02-in. orifices and cone angles of 20°, 40°, and 60° were tested. The Cone height was 0.5 in. Injection pressures with water were varied from 0 to 120 psig. By an energy balance, an injection pressure of 120 psig corresponds to a jet velocity of 133 fps for water. In all cases the observed effect of the cone in aiding disintegration of the liquid jet was negligible when comparing the jet with that issuing from a plain orifice. The undisturbed straight jet shown in Fig. 11 is issuing from the 60° cone nozzle at 133 fps.

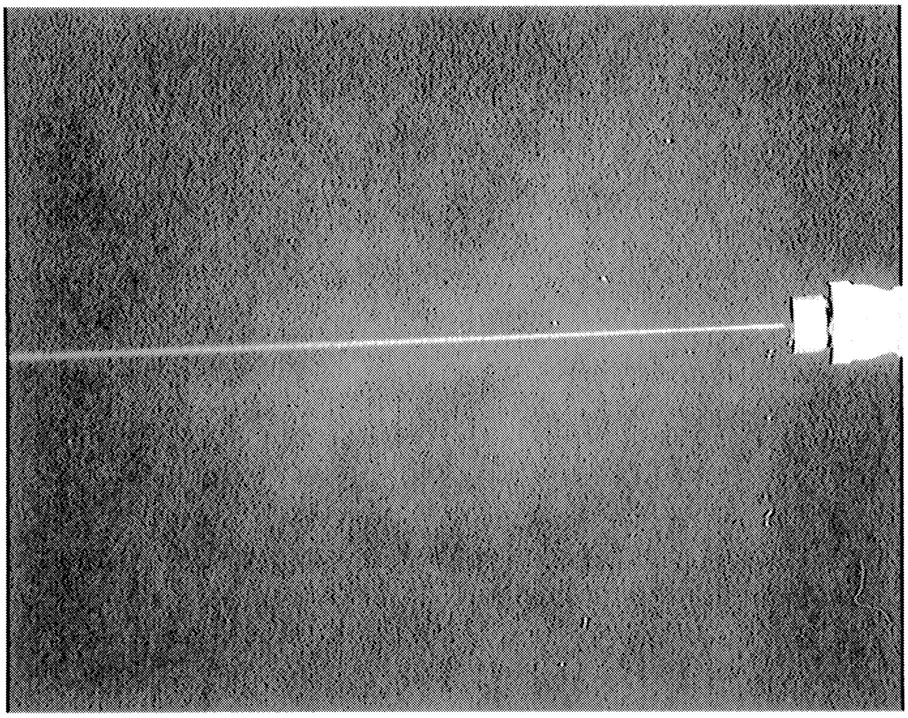

Fig. 11. 60° cone nozzle.

For the range of jet velocities in these experiments, the cone nozzle is not an effective way of producing a spray. This may not necessarily be the case at much higher jet velocities.

The cone nozzle responds to flashing in the same way as a straight orifice of the same diameter. The data in Fig. 5 seem to show a larger drop size for the cone nozzle than for the straight nozzle, although this difference may be within the limits of the drop-size analysis error. The mixing of steam and liquid droplets in the conical section produces a uniform spray zone. Figure 11 is a photograph of 244°F water being injected through a 60° cone nozzle. Figure 12 illustrates flashing with a cone nozzle.

IMPINGING JET NOZZLES

When two unconfined liquid jets meet, a liquid sheet is formed which disintegrates into droplets. Extensive studies have been made of the sprays formed with two directly opposed liquid jets.[4] An attempt is made here to use a nozzle which will use impinging jets to make a spray and produce a conical spray pattern. A nozzle was designed that causes three axisymmetric liquid jets to meet at a common vertex (Fig. 13).

Nozzles were tested which had jets meet in a cone of varying angles ranging from 20° to 90°. The orifice outlets were symmetrically positioned around a 0.25-in. circle. The orifice diameters were all 0.040 in. except the 70° nozzle,

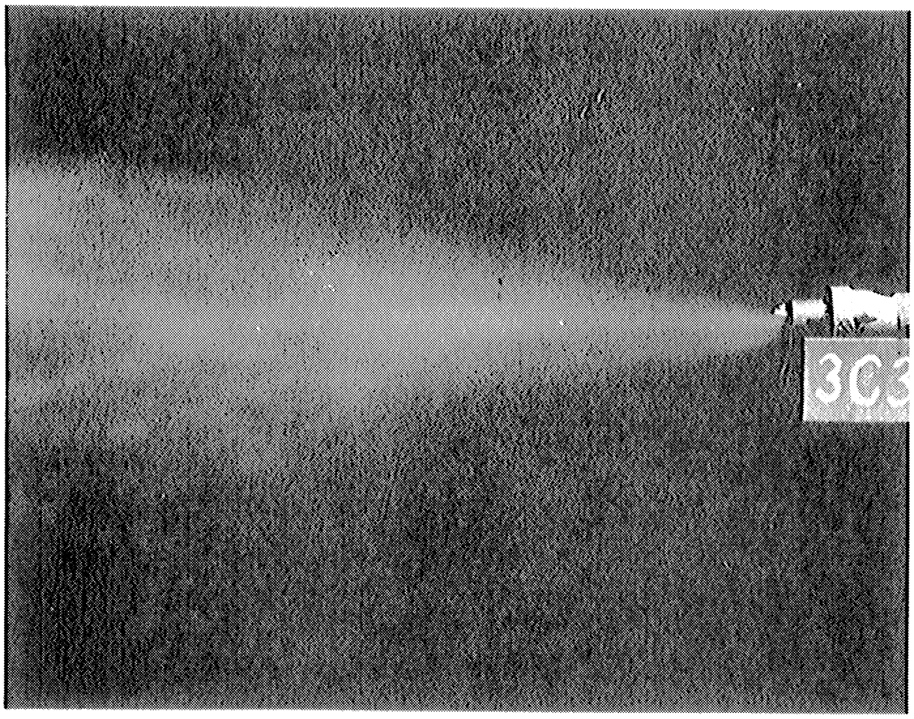

Fig. 12. Flashing with a cone nozzle.

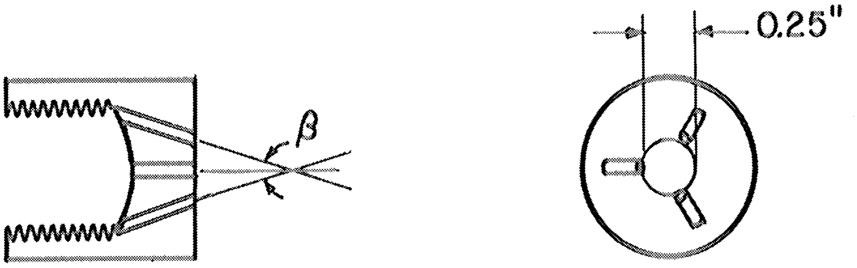

Fig. 13. Impinging jet nozzles.

which was 0.031 in. All the nozzles with angles up to 80° formed a solid conical spray pattern. Figure 14 is a photograph of the spray from the 60° nozzle with an injection pressure of 87 psia.

For nozzles with an angle of over 80°, a considerable portion of the water is sprayed back toward the nozzle. This causes water to run from the nozzle face.

Drop-size data are given in Fig. 15 for those nozzles spraying water with an injection pressure of 87 psig. The sprays were photographed in the center of the spray axis as the spray pattern appeared uniform throughout the conical spray zone. As might be expected, the drop size decreases as the angle of impingement is raised. At the wider angles, a larger percentage of the kinetic

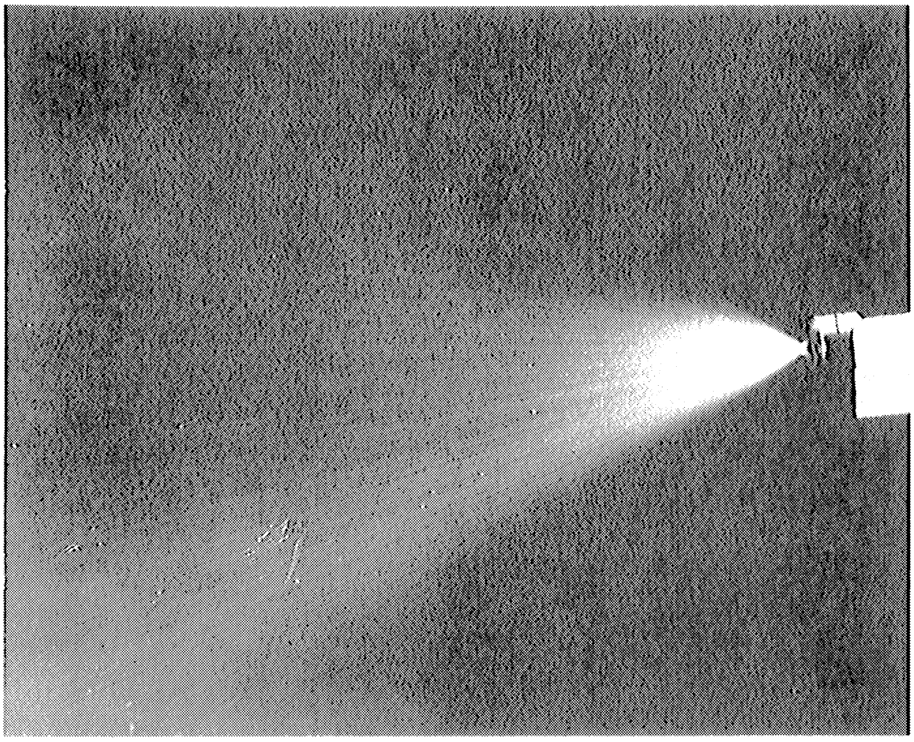

Fig. 14. 60° impinging jet nozzle.

energy of the jet contributes to the shattering of the jets, and a smaller percentage to the forward motion of the liquid after the jets have made contact. The drop size for the spray from the nozzle with the smaller orifices lies below the curve of the other nozzles. One can observe that the ratio of the drop size from this nozzle with 0.031-in. orifices and the drop size from this curve for nozzles with 0.04-in. orifices is approximately the same as the ratio or orifice diameters. This hints that the drop size may be proportional to the liquid jet diameter.

The use of this nozzle has enabled us to obtain a solid conical spray pattern of small drop size. The few preliminary experiments have indicated that good control of drop size may be obtained through design of the nozzle.

ORIFICE-TUBE NOZZLE

This nozzle consists of a simple orifice nozzle with a short tube of larger diameter than the orifice at the exit end (Fig. 16). The tube may or may not have holes in the sides of it.

The nozzle enabled us to try several principles that may improve the atomization of a liquid jet. One is boundary-layer stripping which is the removal of the low-velocity liquid film surrounding a liquid passing through a pipe and obtaining a flat velocity profile before it issues from an orifice. The simple

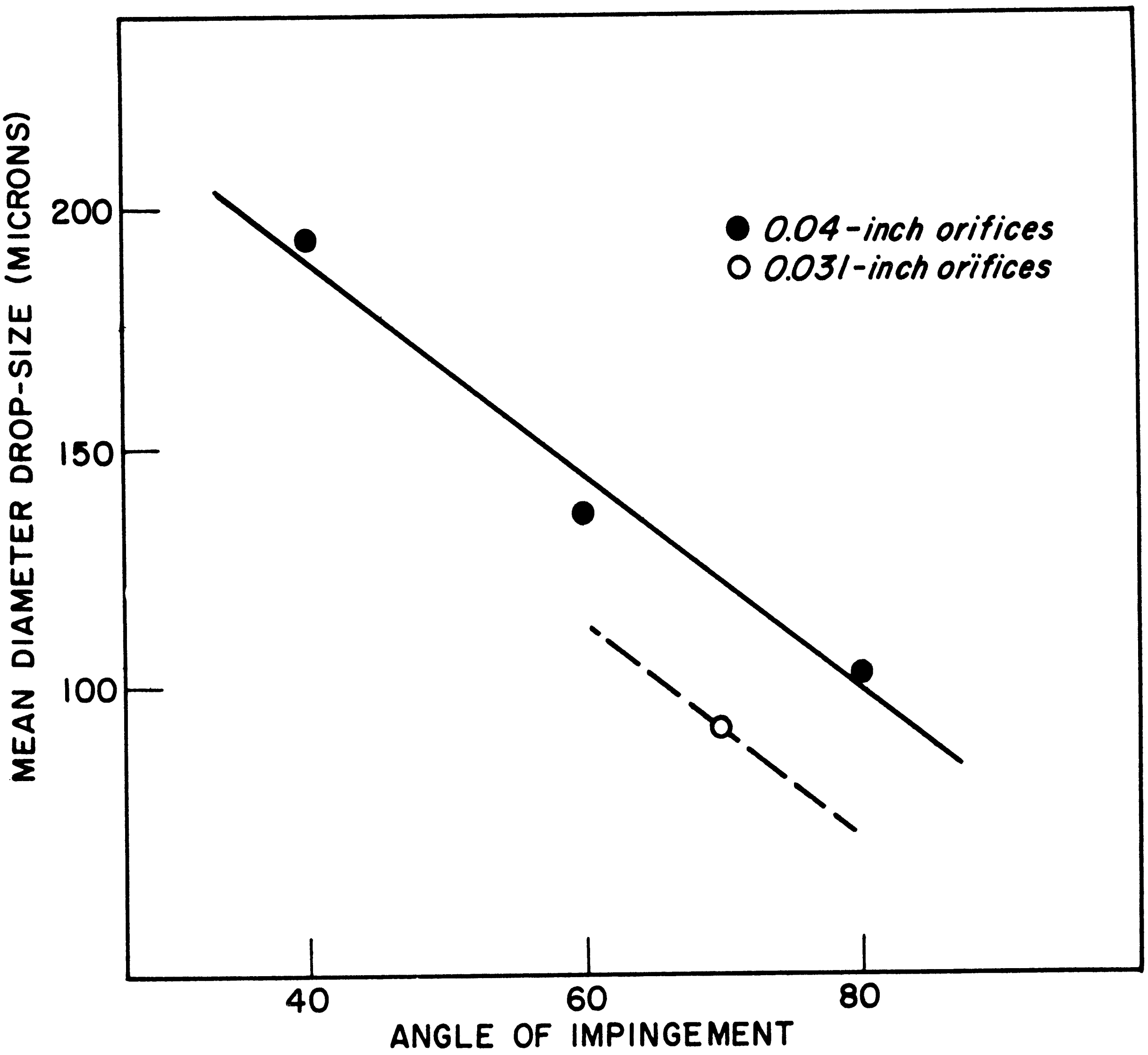

Fig. 15. Drop size for impinging jet nozzle.

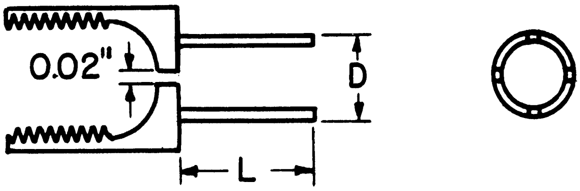

Fig. 16. The orifice-tube nozzle.

orifice in a pipe is probably the most effective way known to obtain a flat velocity profile.[9] The relatively large amount of radial flow as the liquid expands causes this. Although the orifice was not sharp-edged, its rough surface helped flatten the velocity profile of the original set.

Two nozzles were tested having 0.02-in. orifices. The tubes had L/P ratios of 5, and lengths of 0.5 in. and 0.9 in., respectively. Tests were made at injection pressures up to 120 psig. The tubes in the holes were closed. The liquid from the orifice filled the tubes at the lower injection pressures (below 60 psig) and only the smaller tube at the higher pressures. When the tubes were filled the liquid merely dribbled out of the end at a low rate. Apparently, most of the pressure drop across the nozzle was at the orifice and its cross-sectional area limited the flow rate. This being the case, the velocity of the liquid jet coming from the 0.1-in.-diameter tube was only 5.3 fps. To make a meaningful experiment with these nozzles, a much higher velocity jet must come from the tube so higher injection pressures would be necessary. There is also the problem of whether or not the liquid jet from the orifice would fill the tubes when higher injection pressures are employed.

When the holes in the tubes were left open, a straight liquid jet identical with that from a simple orifice nozzle issued from both nozzles under all injection pressures up to 120 psig. We conjecture that, if these holes in the tubes were made small enough, a smaller amount of air than necessary to destroy the partial vacuum in the tube would bleed through the holes. Under this condition, a pulsating pressure may be set up which would perturb the liquid jet passing through the tube. This perturbation of the jet would cause it to break up closer to the orifice and perhaps improve drop sizes. A nozzle must be designed which will allow us to vary the size of the holes in the tubes.

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