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

Progress Report

THE INFLUENCE OF FLASHING AND CAVITATION ON SPRAY FORMATION

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UMRI Project 2815

under contract with:

DELAVAN MANUFACTURING COMPANY
WEST DES MOINES, IOWA

administered by:

THE UNIVERSITY OF MICHIGAN RESEARCH INSTITUTE ANN ARBOR

October 1959

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FOREWORD

The project is following two related but somewhat different paths in its study of spray mechanisms. Different investigators have been carrying the main effort in each path; this report is therefore divided into Part I, on flashing, and Part II, on cavitation. The flashing studies have been conducted by Ralph Brown, and the cavitation studies by E. Y. Weissman (during the summer months). Dr. M. R. Tek and Dr. J. L. York have been working on both programs to coordinate them and avoid duplication of effort.

A considerable amount of qualitative information has been obtained in both programs in their respective areas. Quantitative studies of the promising techniques are now being made in both programs, along with theoretical analyses to interpret results and give direction to future work.

PART I

THE EFFECT OF NOZZLE DESIGN ON THE FLASHING MECHANISMS OF CYLINDRICAL WATER JETS

The studies of the effect of flashing on spray formation are being restricted to the break-up of cylindrical liquid jets. The break-up of a liquid jet is probably considered the most fundamental means of making a spray and has wide application. There are, however, other important reasons for studying cylindrical jets. One is that the break-up of cylindrical jets has been both theoretically and experimentally studied by many investigators. Therefore, the results obtained with flashing can be compared to the information available concerning ordinary jet disintegration. Another reason is that the nozzle design for producing cylindrical jets is very simple—a circular orifice. Simplicity of nozzle design is important in all break-up studies as the design often has a profound effect on the break-up mechanism. It is particularly important in this case as the design will affect the manner in which flashing contributes to the jet break-up. With an orifice nozzle the design parameters which govern the break-up are easily controlled. The purpose of this study is to determine the effect of the design on the flashing mechanism.

The manner in which flashing occurs when a liquid jet is subject to flashing has a direct effect on the properties of the spray and the flow-metering. For example, if the flashing is initiated within the orifice of the nozzle, the mass flow rate can be considerably less than when flashing occurs downstream of the orifice. This reduction in flow rate has been discussed in previous reports. The flashing must occur throughout the body of the liquid jet rather than on the surface alone in order to shatter the jet effectively. It would thus be advantageous to control the flashing mechanism by nozzle design, if possible.

EXPERIMENTS AND RESULTS

Two flashing mechanisms have been observed in previous experiments. When hot water at 120 psig was injected through a 0.02-in.-diameter nozzle having a length-to-diameter (L/D) ratio of 6, flashing was initiated within the orifice. That is, no portion of intact liquid jet could be observed ejecting from the nozzle, just a mixture of droplets and steam. A fine spray resulted but the characteristic reduction in flow rate was experienced. When water at the same temperature was injected into the atmosphere through a smooth rounded orifice with a 0.025-in. diameter, flashing took place about 0.5 in. downstream from the orifice. The flashing effectively shattered the jet, producing a fine, although nonuniform, spray. The experiments undertaken here were planned to study the effect of L/D ratio and nozzle diameter on the flashing mechanism.

Brass nozzles were made with orifice diameters of 0.02 and 0.031 in. and L/D ratios varying from 0.7 to 5. The orifices were made with drills so the surfaces can be considered comparatively rough, estimated in the neighborhood of 200 µ rms.

With the 0.02-in.-diameter nozzle, L/D of 1, water was injected at pressures of 80 psig and 120 psig. Temperatures varied from 140-221°F for the low- and 140-300°F for the high-pressure runs. Flashing occurred at temperatures above 212°F, but apparently only on the surface of the liquid jet. A fine mist was observed around the jet. This mist was somewhat more extensive at the higher temperatures. There was a slight hissing sound. The surface flashing did not seem to contribute in any way to the jet break-up. The break-up length was essentially the same as when cold water was injected. The results were identical with the same diameter orifice and L/D ratio of 2. In this nozzle and those with larger L/D ratios the lower pressure was 90 psig and the corresponding temperature ranges about 140-270°F. When the L/D ratio was 3, the flashing began to take place within the body of the jet about 1 in. downstream from the orifice. There was a louder noise than with the shorter orifices. The flashing was slightly more violent at the higher temperatures and the observations were the same at the both pressures. Although flashing occurred within the jet, it was not violent enough to contribute greatly to the jet break-up. When the nozzles had L/D ratios of 4 and 5, flashing occurred in the orifices at the higher injection pressures. In these cases, a fine spray issued from the nozzles. When the pressure was 90 psig with these nozzles, flashing still occurred outside the orifice but was not violent enough to contribute effectively to the jet break-up.

The shortest nozzle with a 0.031-in. diameter had an L/D ratio of 0.7. The injection pressures for this and other 0.031-in.-diameter nozzles were 100 and 120 psig. The temperature ranges at both pressures were about 190-310°F. The results with nozzles having L/D ratios of 0.7 and 1 were identical. At temperatures above 212°F, the flashing occurred outside the orifice and on the surface of the jet. Above temperatures of about 260°F, it was very violent and made a loud noise. Moreover, the jet was completely disintegrated and a fine spray resulted. The spray formed seemed uniform and appeared to have a remarkably uniform pattern. In previous experiments with the smooth round-edged orifice, the spray had not appeared as uniform and the pattern was erratic and fluctuating. With the 0.031-in.-diameter nozzles having L/D ratios of 2 and 3, the flashing was initiated within the orifice for both pressures and at all temperatures above 212°F. The sprays were fine and uniform.

High-speed photographs were taken of a portion of the liquid jet from the 0.031-in.-diameter brass nozzle with an L/D of 1. The injection pressure was 120 psig and photographs were taken at various injection temperatures. The photographs (Figs. 6-10) represent a 10X magnification. The camera lens was an Argus with a focal length of 50 mm and a between-the-lens aperture setting of f-3.5. The lens was positioned so that the photographs show a 1.25-cm portion of the jet starting about 0.5 cm from the nozzle. Lighting was from the rear of the jet facing into the camera as shown in Fig. 11. A General Electric Photolight Cat. No. 9364688G1, which provides a high-intensity flash for approximately 1 µsec, was employed. Photographs were taken with Kodak Contrast Process Ortho film.

Figures 6 and 7 show the liquid jets at injection temperatures of 230°F and 248°F, respectively. The jet remains intact although some vapor bubbles are being evolved at the surface, as can be seen in Fig. 7. In Fig. 8 and subsequent photographs, the 1-µsec flash was insufficient to "stop" the breakup action entirely. Although the photographs are not sharp, it is easy to see that the injection temperature of 266°F in Fig. 8 is high enough so that the evolution of vapor breaks up the liquid jet. The jet is disintegrated even more violently when the injection temperatures are 284°F and 302°F as in Figs. 9 and 10. In those cases where the jet was disintegrated by the vapor evolution as in Figs. 8-10, a fine spray resulted.

Flow-rate data were obtained for all the runs. The flow rate was measured upstream by a Fischer-Porter variable area flow meter. The flow rates for the runs with the 0.02-in.-diameter nozzles are plotted in Figs. 1-5. The flow rates are given in gallons per minute at 60°F, and so represent a mass flow rate. The flow-rate curves for the larger nozzles are omitted here since they would have illustrated the same principles.

DISCUSSION

As in previous experiments, flashing occurs in one of two distinct ways, inside or outside the orifice. One of the questions that these experiments were expected to answer was: "Which variable in nozzle design governs where flashing will take place?" In particular, "Does orifice length or surface roughness determine whether flashing will initiate inside or outside the orifice?" In these experiments flashing took place outside the orifice at an injection pressure of 120 psig with L/D ratios of 1 and 2 for the 0.02-in.-diameter orifices and L/D ratios of 0.7 and 1 for the 0.031-in.-diameter orifices. These orifices were drilled and as a result had rough metal surfaces and sharp edges. A smooth superheated liquid jet was still formed by them before flashing was able to occur. This was the same result that was observed in the case of the smoothly machined, round-edged orifice with a 0.025-in. diameter. This shows that flashing can occur outside the orifice even though the surface is rough, provided that the orifice length is small enough.

At the 120-psig injection pressure the transition from flashing outside to inside the orifice took place between L/D ratios of 3 and 4 or orifice lengths of 0.06 and 0.08 in. for the 0.02-in.-diameter orifices. For the larger diameter orifices, the transition took place between L/D ratios corresponding to orifice lengths of 0.031 and 0.062 in. Since the velocity of the liquid in the orifices was the same in both cases, flashing occurred sooner in the liquid after passing the orifice entrance in the larger diameter nozzles. This can be explained by the higher degree of turbulence in the larger diameter nozzles. At the injection pressure of 120 psig and with liquid at 212°F, the Reynolds numbers in the large and small orifices are 124,000 and 80,000, respectively. Turbulence aids in the initiation of flashing by shortening the time it takes for nucleation of the bubbles.

When flashing occurs inside the orifice, a fine spray generally has resulted but with the usual reduction in mass flow rate. When flashing takes place outside the orifice, the flashing affects the break-up in varying degrees. The photographs of the liquid jets from the 0.031-in.-diameter nozzle show cases in which the vapor evolution has relatively no effect on the jet and cases in which the jet is disintegrated. The jet was not shattered until the liquid reached a minimum temperature, corresponding to about 5 weight percent of the liquid vaporizing. These experiments have shown that good sprays can be produced when flashing occurs outside the orifice. If the temperature, pressure, or orifice diameter is too small, however, the flashing will be ineffectual in shattering the liquid jets.

The appearance of bubbles on the surface of a hot liquid jet (see Fig. 7) provide a hint as to the mechanism by which vapor is evolved. This apparently takes place by bubble nucleation. The liquid ejected by the orifice is superheated with respect to the pressure of the receiving medium, which is atmospheric. Its temperature must drop down to the equilibrium value of 212°F. The heat given up by the liquid in this approach to the equilibrium temperature provides the heat for the vaporization of a portion of it. If vaporization is taking place on the surface of the jet, the liquid near the surface is cooled, and heat flows from the central portion of the jet to the surface. If a bubble is forming, the liquid immediately surrounding the bubble is cooled, and heat flows from the body of the liquid to the bubble surface. In both these mechanisms, a definite amount of time must pass for the heat to be transferred through the liquid to the surface of the jet or bubble and then to vaporize some of the liquid. A bubble is initiated either at or some point after the spot in the orifice where the pressure has decreased to the vapor pressure of the liquid at its injection temperature. The nucleus of this bubble may be a bubble of air that has come out of solution. It then takes a certain time for it to grow to proportions of the same magnitude as the jet, where it will burst. The bubbles in Fig. 7 are about 1/2 in. from the orifice and the jet velocity is about 140 ft/sec. The time for the bubbles to grow to about half the jet diameter is therefore about 300 μsec.

We can see from the photographs that, when enough of these bubbles are being formed and breaking, the jet is totally disintegrated. In Figs. 8-10 this disintegration has occurred within about 300 μsec, a time shorter than that required for aerodynamic forces to tear apart the jet. This shows that the disintegration of the jet into a fine spray is primarily a result of the flashing.

The mass flow-rate data points in Figs. 1-5 show that in all cases the flow rate is reduced as the injection temperature is raised. In the case where flashing occurs downstream of the orifice, this reduction is a result of the decreased density of the liquid passing through the orifice as the temperature is raised. The straight lines in the plots show the flow-rate curves predicted from this density difference, based on the experimental value of the lowest temperature point. The higher temperature points on these curves are calculated by multiplying the low-temperature flow rate by the ratio of the density of the liquid at the higher temperature to its density at the low temperature point. The data points lie on or close to these theoretical curves in the plots with L/D ratios of 1, 2, and 3, those cases in which flashing occurred outside the orifice. The three highest temperature points for the 90-psig injection pressure in Fig. 3 are disregarded in this discussion. The runs are made by slowly raising the injection temperature. It is believed that this comparatively large reduction over such a small temperature range may have been caused by some dirt clogging the orifice.

In the nozzles with L/D ratios of 4 and 5 and an injection pressure of 120 psig, where the flashing took place inside the orifice, note that the data points fall below the theoretical curve at the higher injection temperatures. This added reduction in flow rate is a result of the small percentage of vapor in the orifice. The presence of this vapor greatly increases the specific volume of the liquid-vapor mixture and results in a decrease in the flow rate.

WORK IN PROGRESS

A quantitative measure of the effect of flashing on spray quality is being obtained through drop-size analyses from the nozzles described here. More high-speed photographs under a variety of lighting conditions are being taken to obtain more revealing pictures. Attempts to "stop" the break-up action more effectively in the higher temperature jets will be made by positioning the camera to face the jet at an acute, rather than at a right angle. The results of such photographs will help support or refute the notion that the break-up is mainly caused by bubble formation and break-down.

Theoretical studies are in progress on predicting the time for the growth of a bubble in a superheated liquid jet given the physical, geometric, and flow conditions. We could then predict whether flashing would begin inside or outside the nozzle for a given set of conditions.

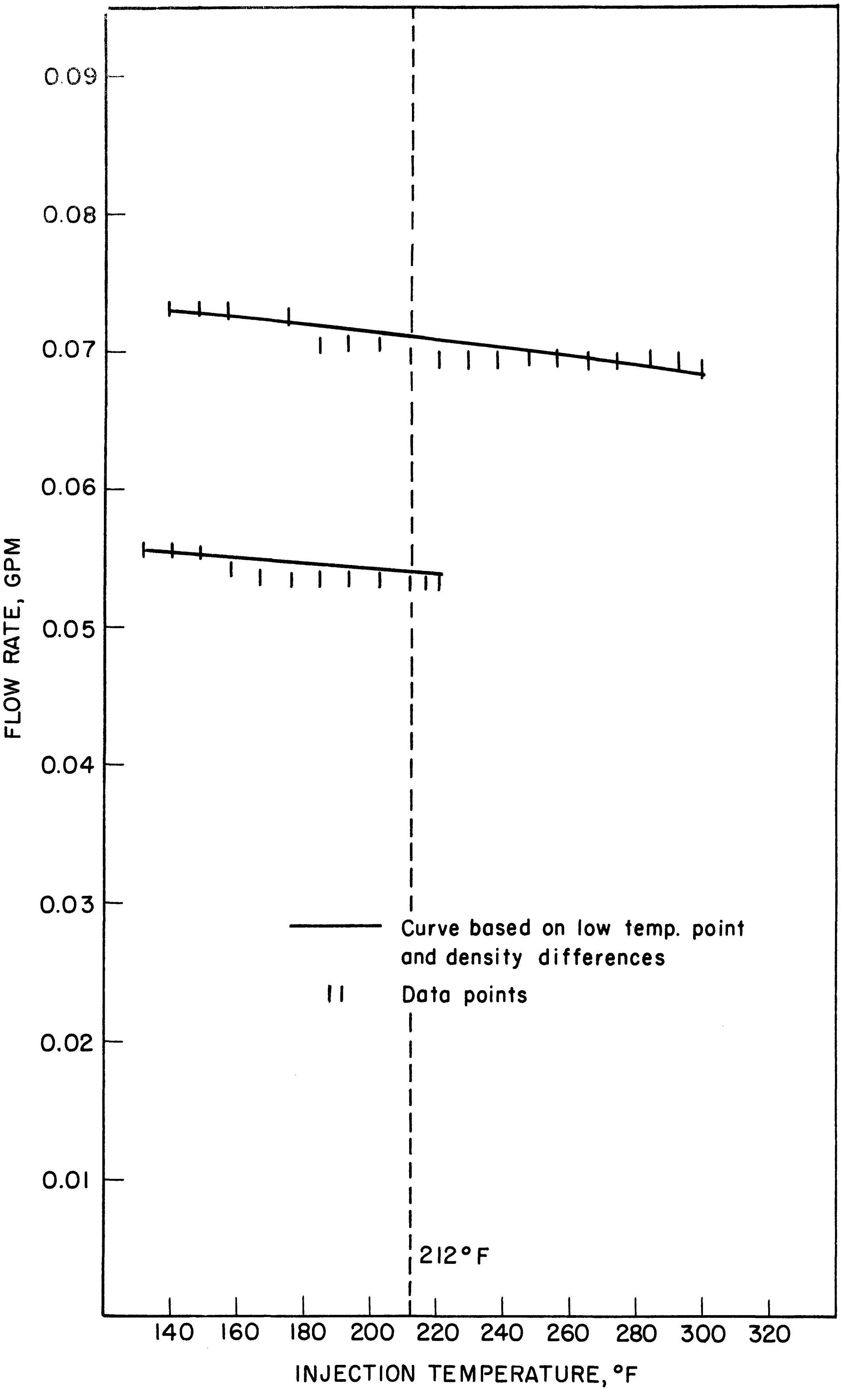

Fig. 1. Brass orifice nozzle; D = 0.020 in.; L/D = 1.

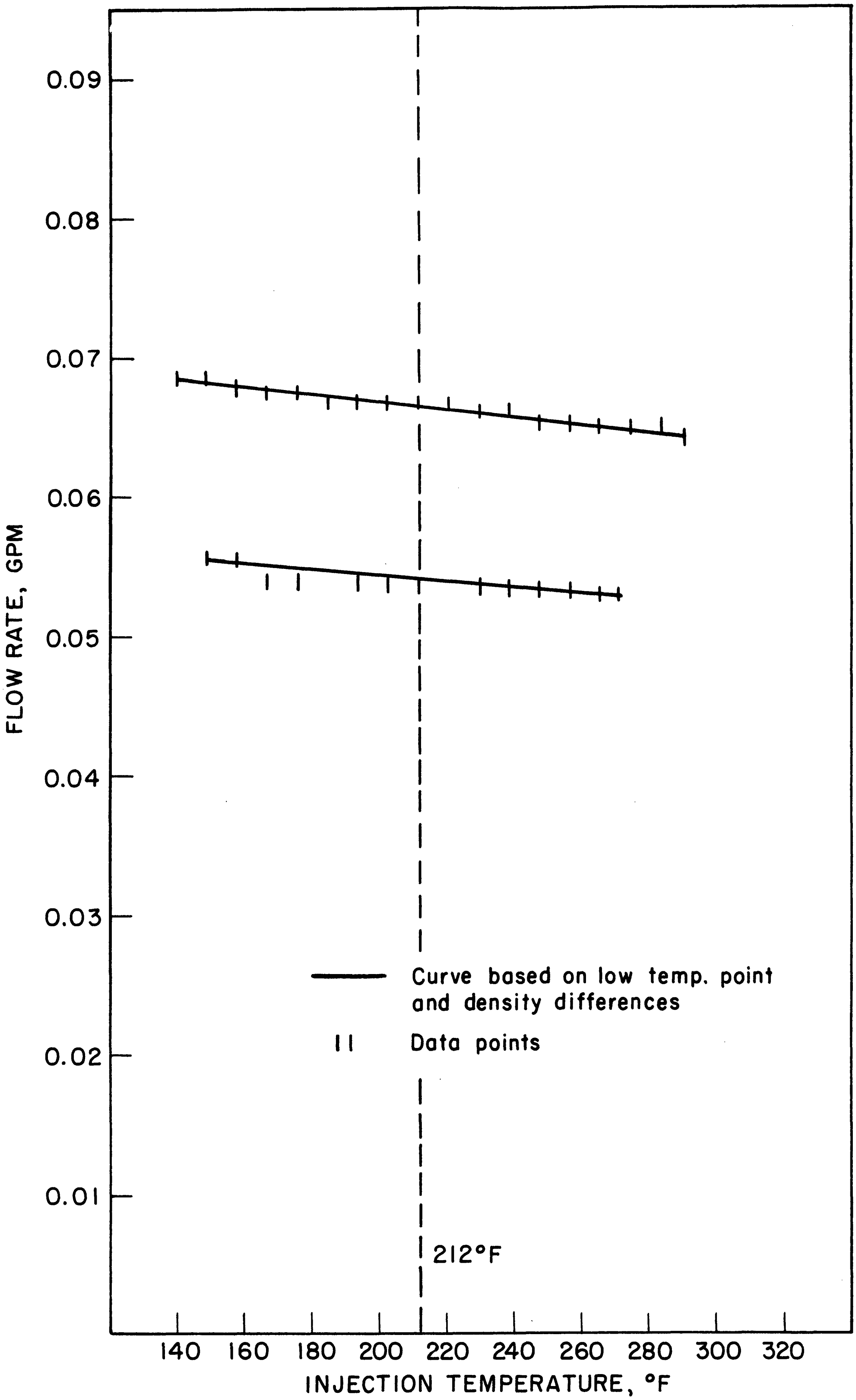

Fig. 2. Brass orifice nozzle; D = 0.020 in.; L/D = 2.

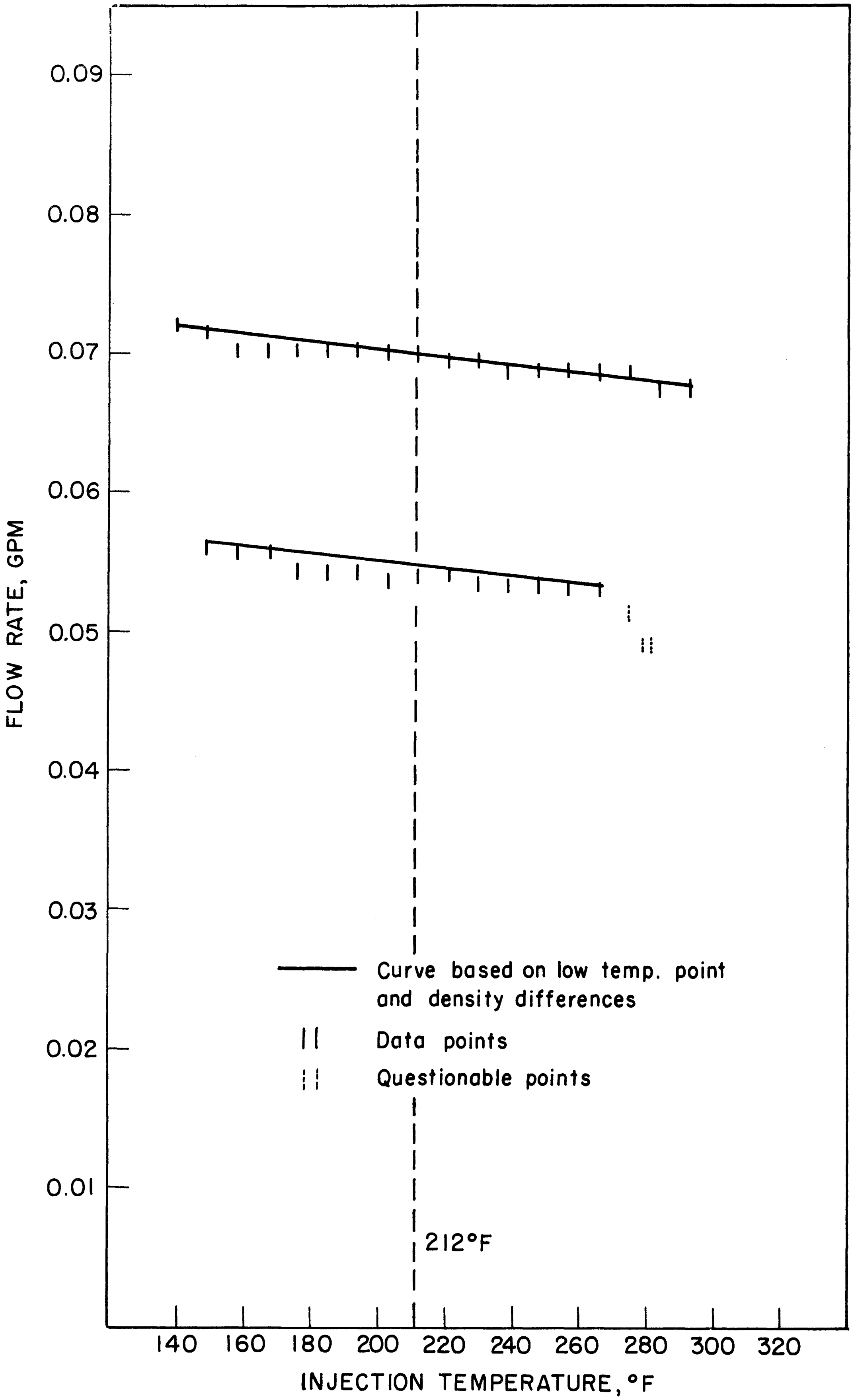

Fig. 3. Brass orifice nozzle; D = 0.020 in.; L/D = 3.

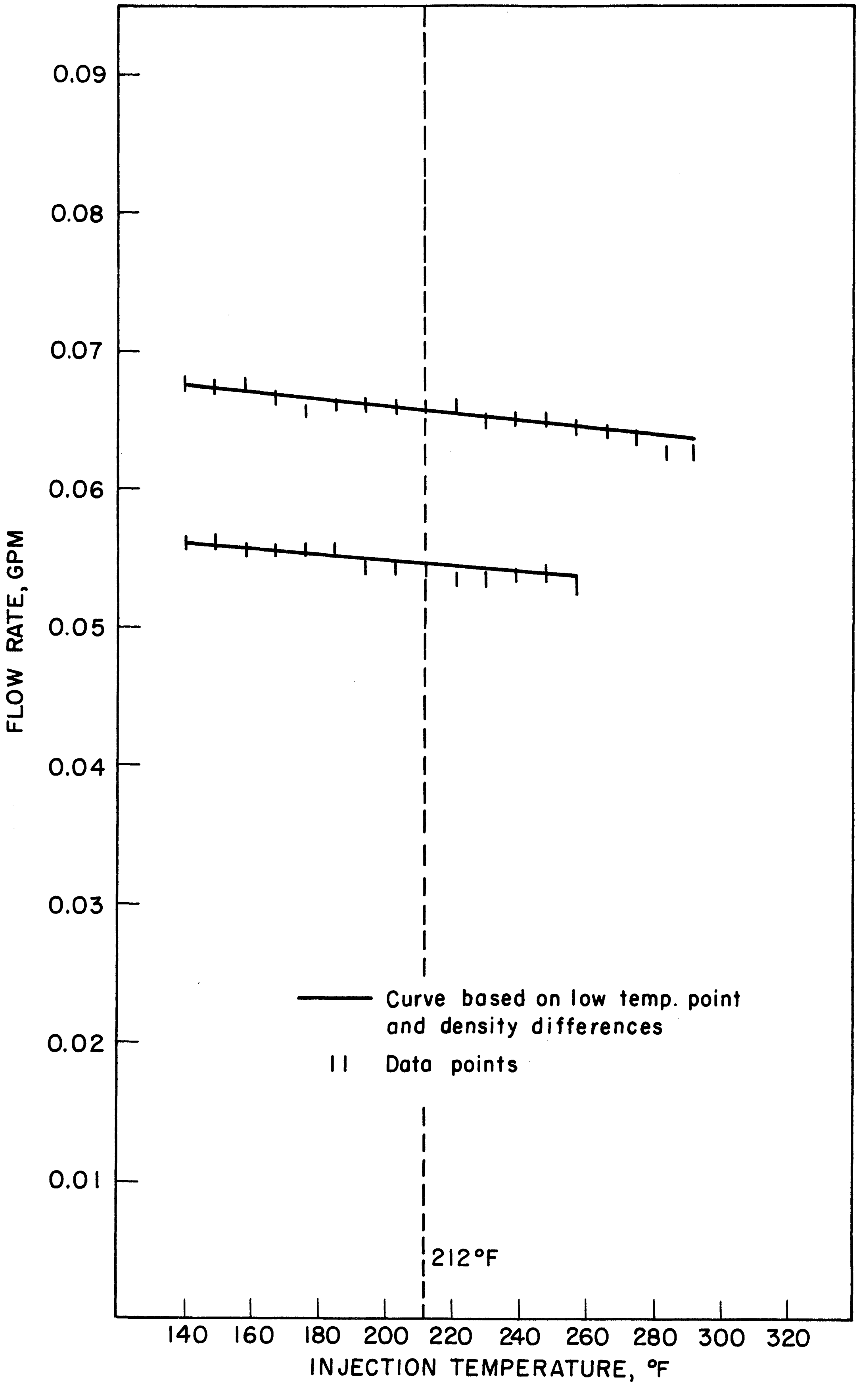

Fig. 4. Brass orifice nozzle; D = 0.020 in.; L/D = 4.

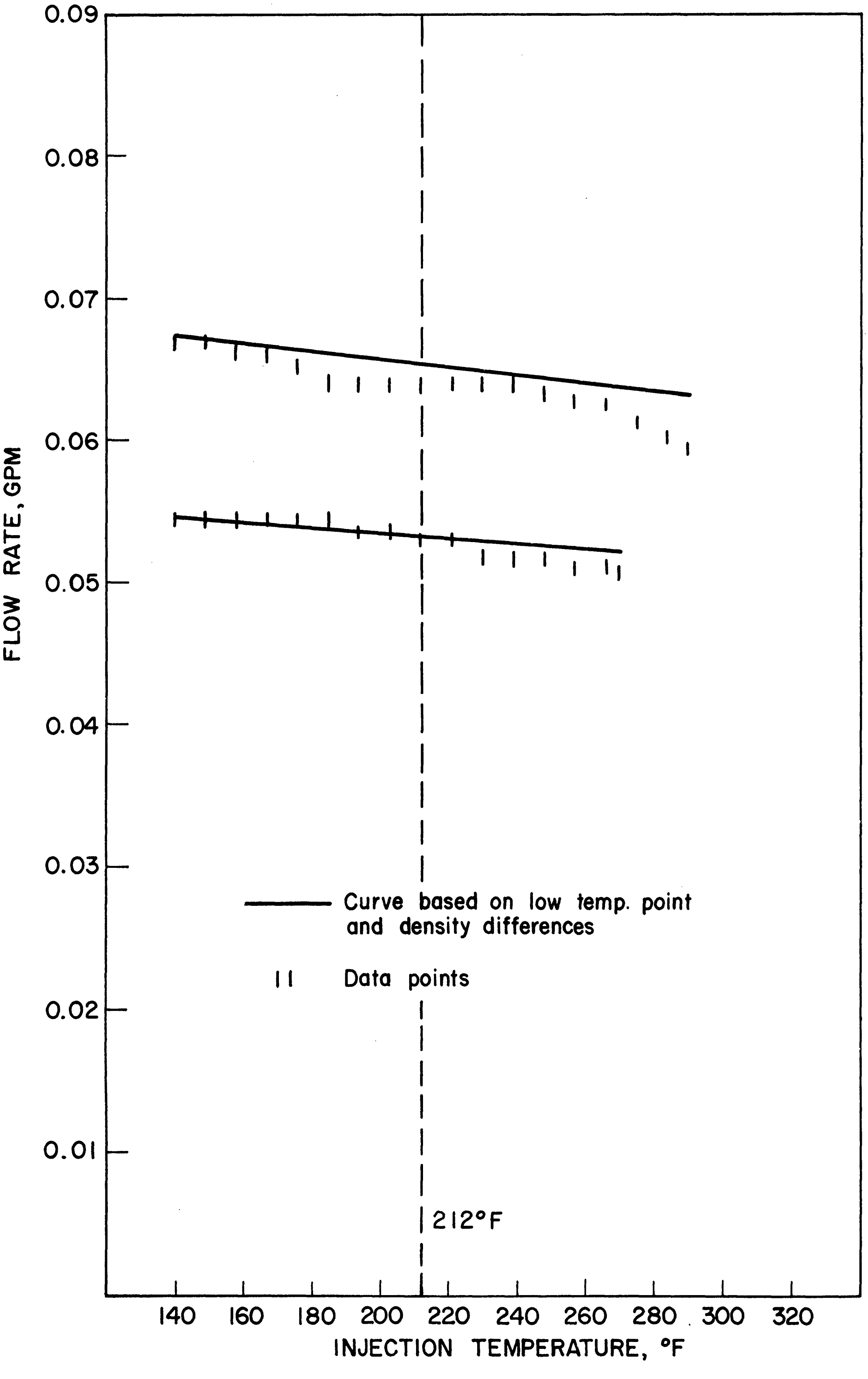

Fig. 5. Brass orifice nozzle; D = 0.020 in.; L/D = 5.

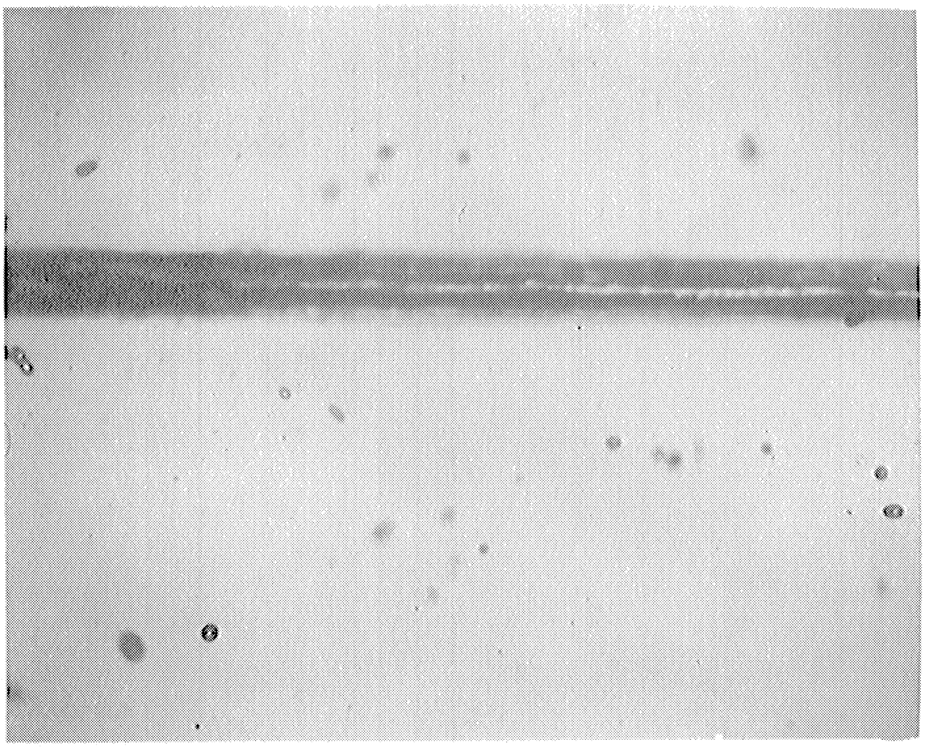

Fig. 6. Brass orifice nozzle; D = 0.031 in.; L/D = 1, T = 230°F; 10X.

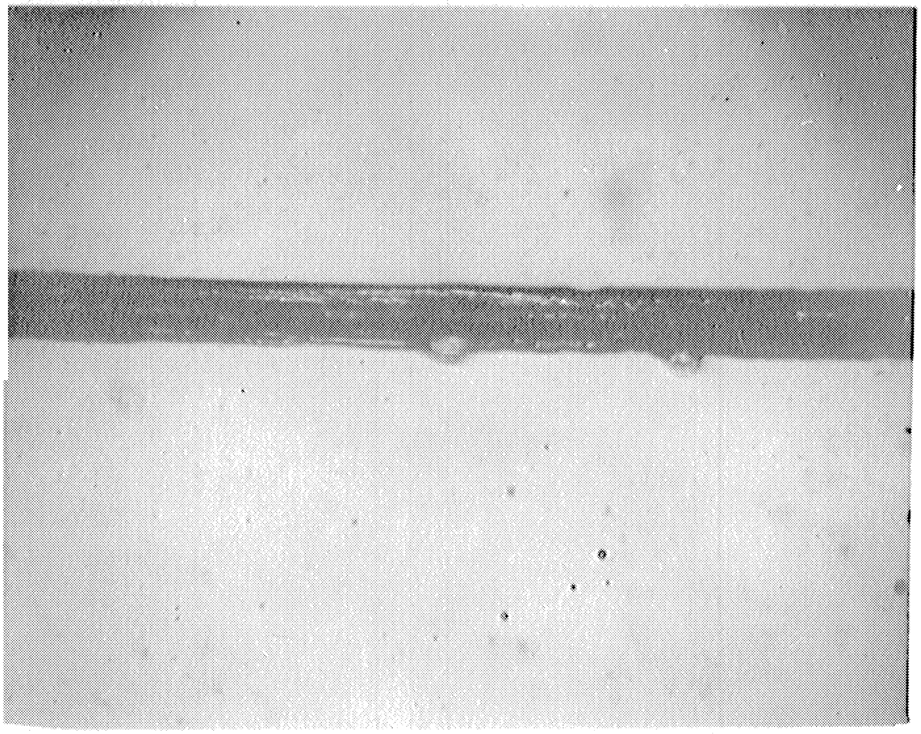

Fig. 7. Brass orifice nozzle; D = 0.031 in.; L/D = 1, T = 248°F; 10X.

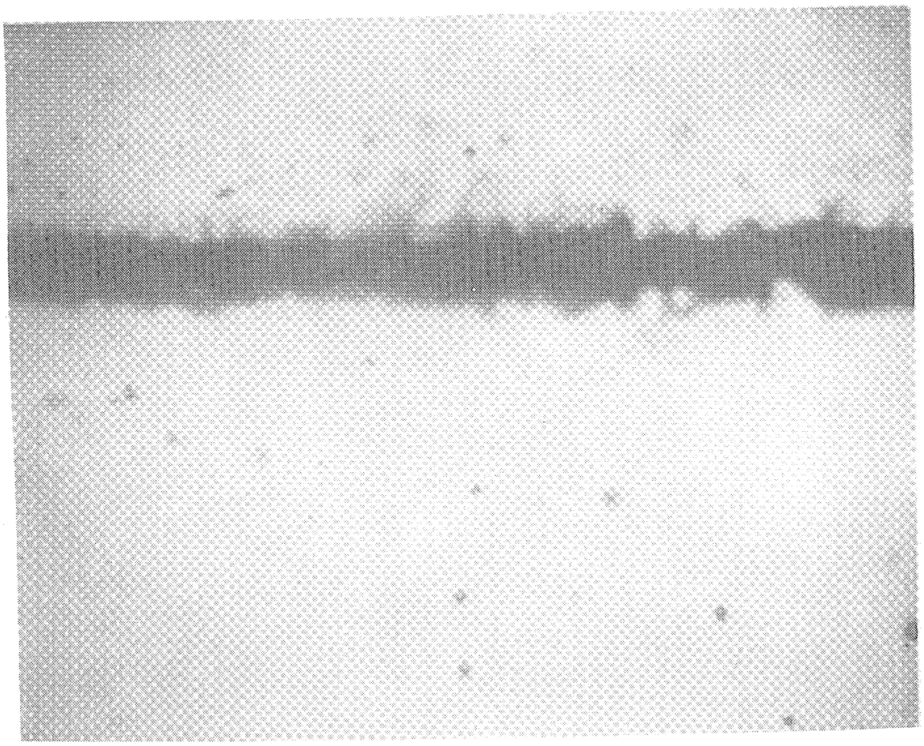

Fig. 8. Brass orifice nozzle; D = 0.031 in.; L/D = 1; T = 266°F; 10X.

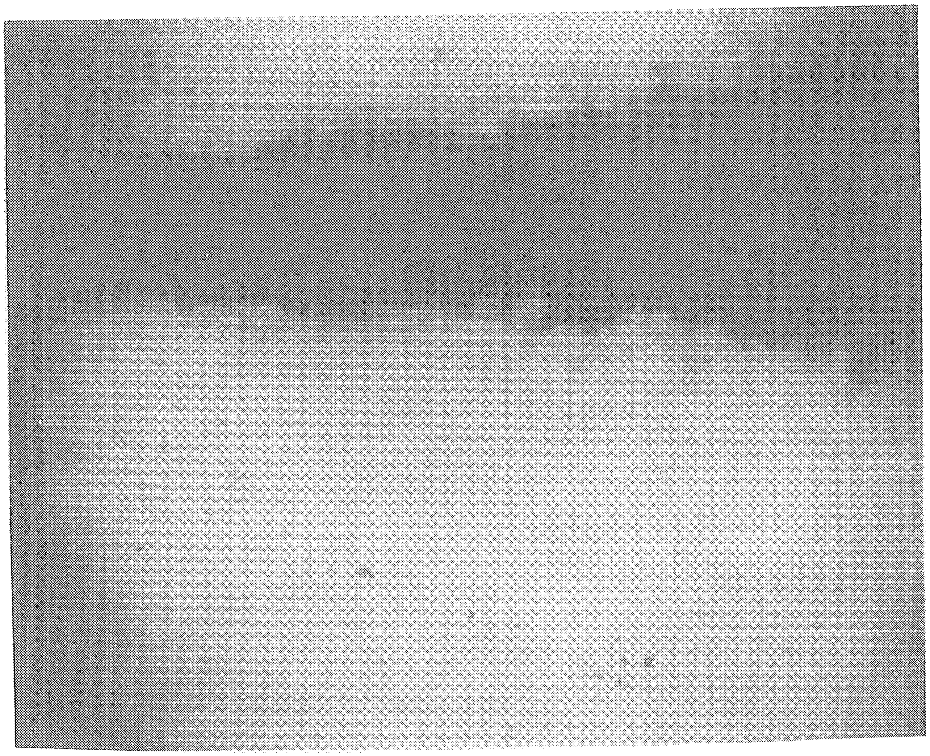

Fig. 9. Brass orifice nozzle; D = 0.031 in.; L/D = 1, T = 284°F; 10X.

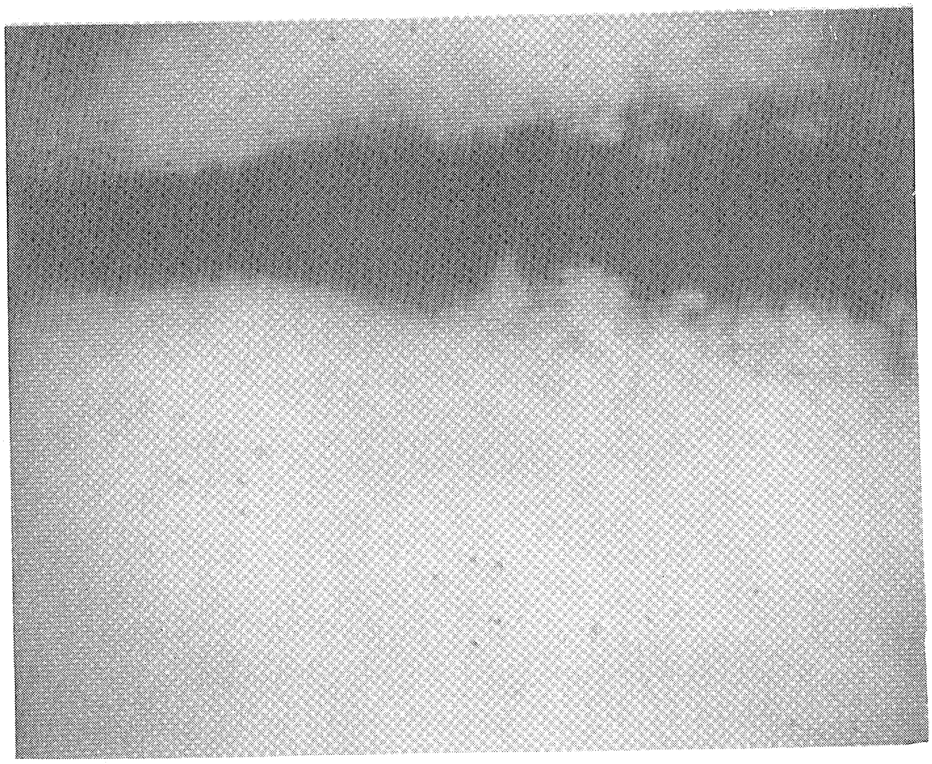

Fig. 10. Brass orifice nozzle; D = 0.031 in.; L/D = 1, T = 302°F; 10X.

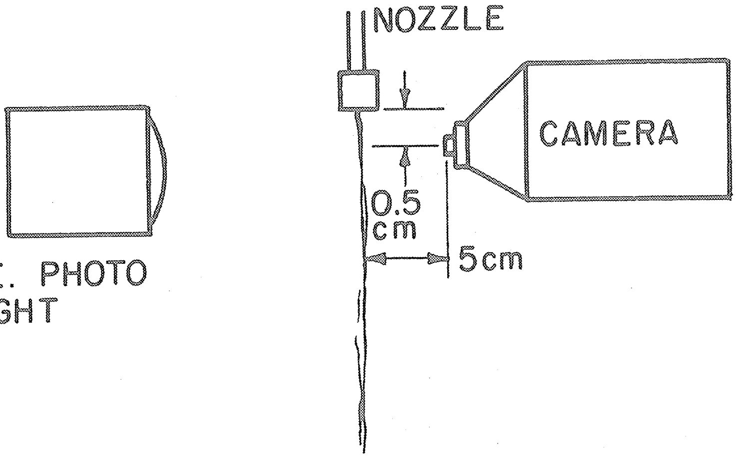

Fig. 11. Camera arrangement for high-speed photographs.

PART II

EFFECT OF CAVITATION ON SPRAY FORMATION

SUMMARY AND CONCLUSIONS

A series of systematic experiments with 16 specially designed nozzles were performed to investigate the effect of cavitating flow on the formation of spray. The nozzles were designed to induce cavitation by means of suitable obstructions placed on the inside wall. A summary of the experimental work is given in Table I.

From the results and observations obtained so far in cavitation studies, the following conclusions may be drawn:

1. It is possible to promote cavitating conditions by a suitable design of flow obstruction placed some point upstream through the orifice passage.

2. The necessary condition for cavitating flow and the nature and strength of the observed cavitation appears to depend critically on the L/D ratio of the orifice and the location of the obstruction in the orifice.

3. The properties of spray, particularly the cone angle, penetration, and probably the particle size distribution are influenced appreciably when the cavitation is present.

4. The experiments to date definitely point to a need for further data on metering characteristics, quantitative information relating to the effect of cavitation on particle size distribution, and more elaborate instrumentation for cavitation detection.

5. In the experiments conducted so far, the bulk of the liquid was preheated to a saturation pressure above the nozzle exit pressure to facilitate inception of cavitation. This resulted in flashing in all cases, along with cavitation in many. The intended objective of the cavitation program, however, is to bring about nucleation-cavitation phenomena in an undersaturated liquid by local pressure differences sufficient to promote cavitation with no flashing.

TABLE I

SUMMARY OF EXPERIMENTS ON THE EFFECT OF CAVITATION ON SPRAY FORMATION

Remarks	No.	ID, in.	L/D	Material of Construction	Obstruction					
					Shape	No.	Arrangement	Height, in.	Diam. of Base, in.	Position from Inlet End of Nozzle, in.
No cavitation Inlet and exit of nozzle were not well centered (on a common axis)	1	0.02	10	nozzle: iron obstr.: steel	sphere segment	1	-	2/5 D	0.02	0.08
No cavitation	2	0.02	10	nozzle: iron obstr.: steel	cone	1	-	2/5 D	0.02	0.08
No cavitation	3	0.035	23	nozzle: brass obstr.: steel	sphere segment	1	-	2/5 D	0.02	0.105
No cavitation	4	0.035	21	nozzle: brass obstr.: steel	cone	1	-	2/5 D	0.02	0.07
No cavitation	5	1/32	384	nozzle: brass obstr.: steel	sphere segment	1	-	2/5 D	0.02	0.08
No cavitation	6	1/16	192	nozzle: brass obstr.: copper	sphere segment	1	-	2/5 D	0.04	0.12
Strong cavitation	7	1/16	192	nozzle: brass obstr.: copper	sphere segment	3	same cross-sectional plane, symmetrical	0.015-0.02	0.04	0.06
Some cavitation*	8	1/16	192	nozzle: brass obstr.: copper	sharp-edged orifice*	1	-	-	-	0
Some cavitation	9	1/16	192	nozzle: brass obstr : copper	sphere segment	2	one in front of the other (longitudinal)	2/5 D	0.04	1st: 0.12 2nd: 1.12
Strong cavitation	10	1/16	192	nozzle: brass obstr.: copper	cone	3	see no. 7	1/3 D	0.04	0.4
Some cavitation	11	1/16	192	nozzle: brass	none	-	-	-	-	-
Some cavitation	11-2	1/16	192	nozzle: brass	none	-	-	-	-	-
No cavitation "poor" jet appearance	12	1/16	7.6	nozzle: brass obstr.: copper	cone	3	see no. 7	1/3 D	0.04	0.1
No cavitation "poor" jet appearance	13	1/16	7.6	nozzle: brass obstr.: copper	sphere segment	3	see no. 7	1/3 D	0.04	0.1
No cavitation	14	1/16	7.6	nozzle: brass	none	-	-	-	-	-
No cavitation	15	1/32	384	nozzle: brass	none	-	-	-	-	-
Strong cavitation	16	1/16	192	nozzle: brass obstr.: copper	sphere segment	2	same cross-sectional plane, symmetrical	0.02	0.04	0.75

*Initially of 0.02 in. diam., when cavitation occurred; subsequently increased to 0.031, 0.04 in.; no cavitation in last cases.

DISCUSSION OF EXPERIMENTS ON CAVITATING NOZZLES

To promote cavitation, several nozzles with special design characteristics were tested by water previously heated by steam at 120-psig pressure to various water inlet temperatures. Table I summarizes the detailed geometric and shape properties of the nozzles and the flow obstructions designed to promote the local pressure drops necessary for the cavitation.

Construction of obstruction.—The shape of the obstruction used during the experiments varied between spherical segments and cones. Figure 12 is a sketch illustrating the construction of the flow obstruction. After the orifice hole corresponding to the desired (L/D) ratio was drilled, a perpendicular channel usually having the same diameter as the nozzle was drilled from one side of the plug at a spot determined by the location of the protuberance. A cylindrical plug (a) of the diameter hole h was then snugly fitted into the hole. The tip of the cylindrical plug having a previously machined shape (spherical or conical) was adjusted to the desired depth of protrusion into the main flow channel with the aid of a magnifying glass. The height of obstruction thus adjusted varied between 2/5 and 1/3 D. Once the adjustment was made, the plug was soldered in place and the excess length sawed off.

Observations on cavitation experiments.—The length of the orifices used in these experiments varied between 7.6 and 384 diameters. Most of the nozzles constructed were made up of brass mainly because of the ease in machining the interior surfaces to a smooth finish. The location of the obstruction from the inlet edge of the orifice hole varied from 0 to 0.75 in. Steel and occasionally copper wire were selected for materials of obstruction.

Nozzle no. 7 was built with three round-shape obstructions of 0.015- to 0.020-in. height made up of copper wire 0.04 in. in diameter and arranged in a cross-sectional flow plane 120° apart from the center. This nozzle indicated particularly strong cavitating effects when tested with water at 160-170°C. The cavitating runs on this nozzle have been associated with rapid series of bursts with strong vibrations and a high-pitched (almost unbearable) noise.

In nozzle no. 8 an attempt was made to discern the effect of continuous circular flow obstruction in the shape of a smaller diameter sharp orifice. The nozzle proper was the same type of tubing as nozzles 6 or 7. Figure 13 is a sketch of the nozzle and its terminal circular obstruction.

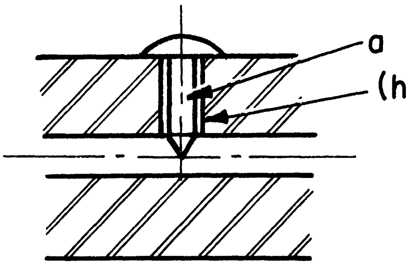

Fig. 12. Sketch illustrating the construction of the flow obstruction.

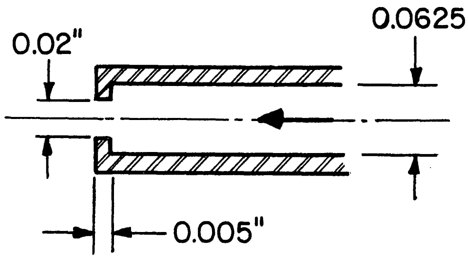

Fig. 13. Sketch of nozzle no. 8.

With nozzle no. 8 using relatively cold water (70 to 80°C) the shortest length of water jet was observed. Upon heating the liquid to a temperature beyond saturation at exit pressure (100°C), the jet lengthened appreciably and an extremely fine spray was obtained. When a throttle valve upstream of the nozzle was fully open, no cavitation effect was observed. When throttling, upstream from the nozzle, took effect along with flashing, spurts of vibrating and noisy flow suggested the co-presence of cavitation. Repeated experiments with this nozzle indicated that, once cavitation was initiated by partially closing the throttle valve, it remained remarkably stable even when the initial normal operating conditions were re-established. When the throttle valve was reopened completely, the flow remained noisy and cavitating. In some of the runs with this nozzle the cavitating condition persisted even to some extent after cooling off the liquid supply. It is believed that the effect of throttling the hot water supply upstream from the nozzle is twofold in promoting the cavitation:

1. Reduction in pressure resulting in lower local pressures in the neighborhood of flow obstructions.

2. By creating a turbulent disturbance which probably nucleates the formation of cavitating bubbles from the unstable undersaturated state.

In nozzle no. 9 two obstructions in the direction of flow, one in front of the other, were tested. The first of these was located 2 diameters from the inlet end of the orifice passage and the second 1 in. downstream from the first one. In this nozzle, slight cavitation was observed with 160°C inlet water temperature. The cavitation was no longer apparent upon cooling but reappeared upon reheating the liquid supply.

The runs on nozzle no. 10 included the study of the effect of 3 conical flow obstructions 120° apart on a plane transverse to flow. The cone angles of the obstructions were about 80° and the height of each was approximately 1/3 orifice diameter. These obstructions were placed 0.4 in. away from the entrance of orifice passage. The cavitation phenomena observed with this nozzle were associated with an apparent increase of the frequency of bubble "implosions" until a high-pitch continuous sound was obtained. Along with the noise some strong and relatively low-frequency vibrations were sensed by pressure gages located upstream from the nozzle. The spray with noncavitating and cavitating flow is illustrated in Figs 14 and 15.

Nozzle no. 11 had no flow obstruction, and its first test exhibited smooth flow and no cavitation. During some additional runs with this nozzle, however, slight cavitation and high-pitched noise were observed during the high-temperature flows. As a result of this unexpected performance, the nozzle was dismantled and a large impurity was found, diametrically obstructing the flow passage. The runs without and with cavitation are illustrated in Figs 16 and 17, respectively.

Nozzle no. 13 consisted of a 12-in.-long, 1/16-in.-diameter brass tubing with two "round" flow obstructions made up of 0.04-in. copper wire arranged in the same cross-sectional plane diametrically opposite. The height of each obstruction was 0.02 in. and they were located 0.75 in. from the entrance of the orifice passage. In testing this nozzle no cavitation was observed with temperatures up to 150°C even after repeated throttlings through an upstream valve. A later experiment with this nozzle, however, indicated extremely violent cavitation which started even with water temperature below 100°C. During this experiment the jet was highly turbulent and unstable. The spray angle was constantly changing. The spray did not conform to a conical shape. Strong pressure fluctuations were observed by the pressure gages.

Additional tests with nozzles nos. 5 and 6 described in Table I indicated cavitating conditions with supply water temperatures, respectively, of 140-145°C and 150-155°C. In these experiments the transition between non-cavitating and cavitating conditions appeared to be around 120-125°C. The 5°C range in the temperature observations was necessitated due to poor thermal inertia of the experimental system. In the future, more accurate runs and more rapid temperature measurements will be attempted through the use of thermocouples instead of mercury thermometers.

Cavitation detection.—In practically all the experiments conducted so far, detection of the presence and intensity of cavitation was more qualitative than quantitative. These tests indicated that some accurate acoustical sensing device to monitor the cavitation effects is badly needed. In the early experiments a screwdriver used in the fashion of a stethoscope could only be used qualitatively. A recent paper, "The Mechanism of Cavitation," by E. G. Richardson, King's College, 1958, reports measurements of the number and size of gaseous nuclei existing in cavitating flow. The detection of these nuclei by the absorption of an acoustic signal produced in a "reverberation vessel" containing the liquid offers some new and quantitative ideas on reliable cavitation detection techniques.

Some investigators claim to have found a correlation between the electric breakdown voltage and presence of gaseous nuclei in organic liquids. A practical evaluation of the reverberation vessel technique and electrical discharge voltage ideas is now under study.

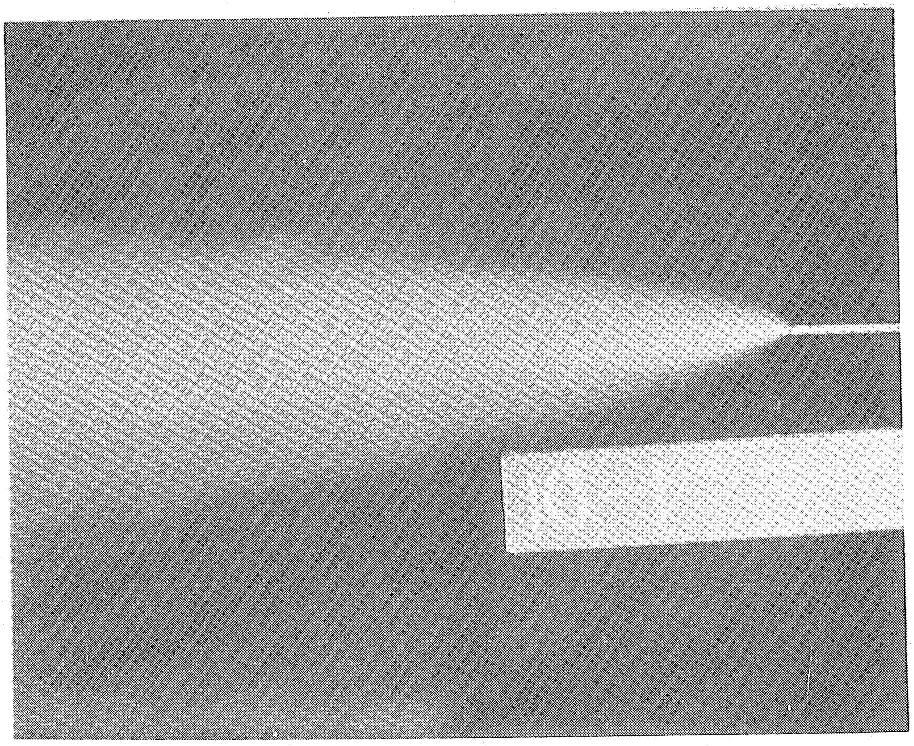

Fig. 14. Nozzle no. 10, noncavitating flow; temperature 129°C.

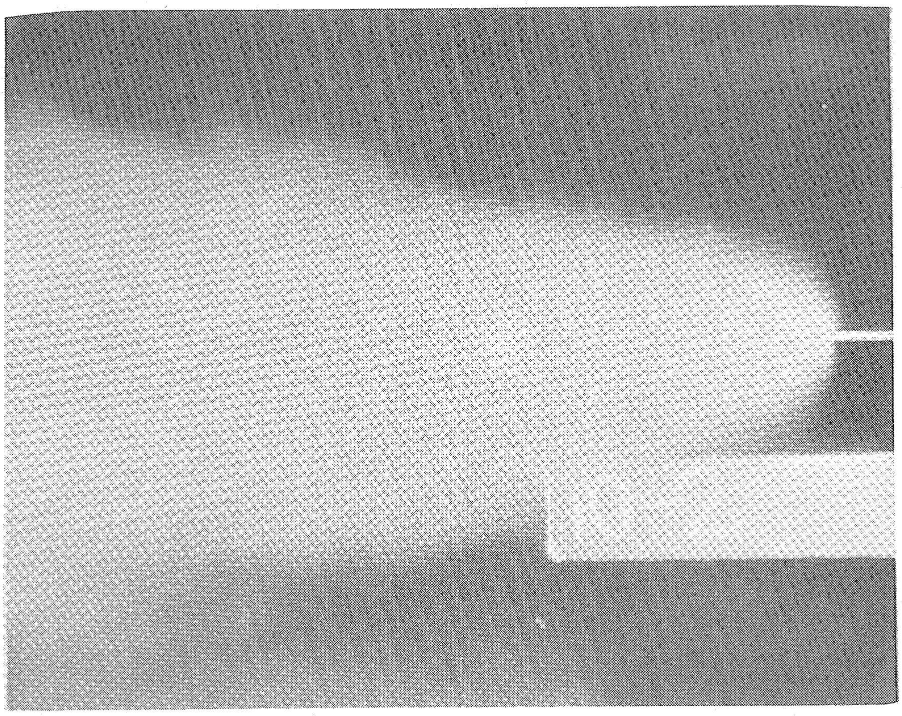

Fig. 15. Nozzle no. 10, cavitating flow; temperature 158°C.

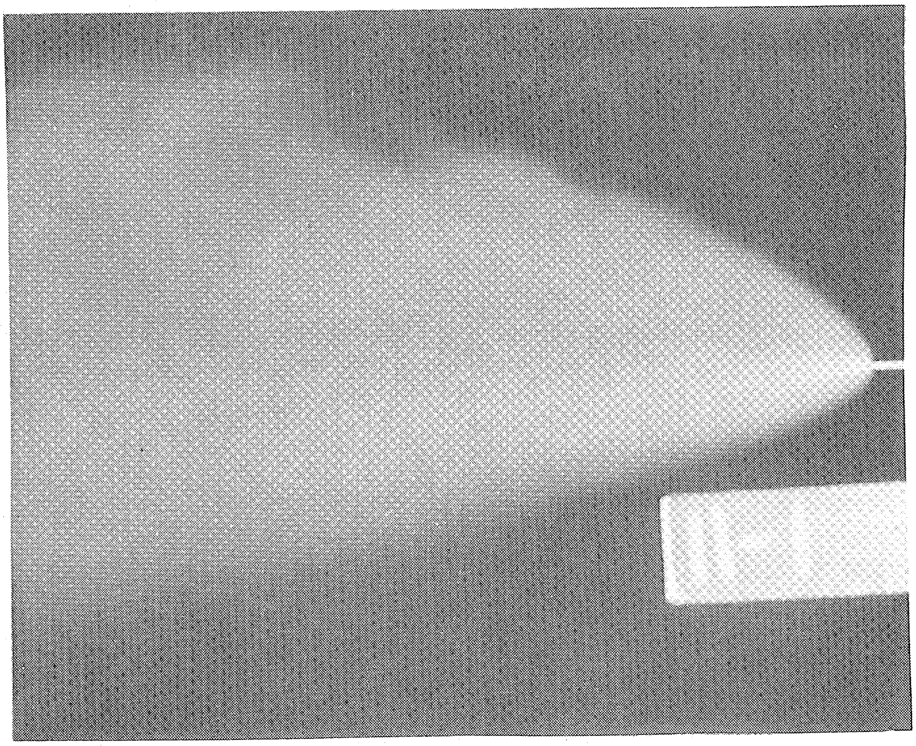

Fig. 16. Nozzle no. 11, noncavitating flow; temperature 136°C.

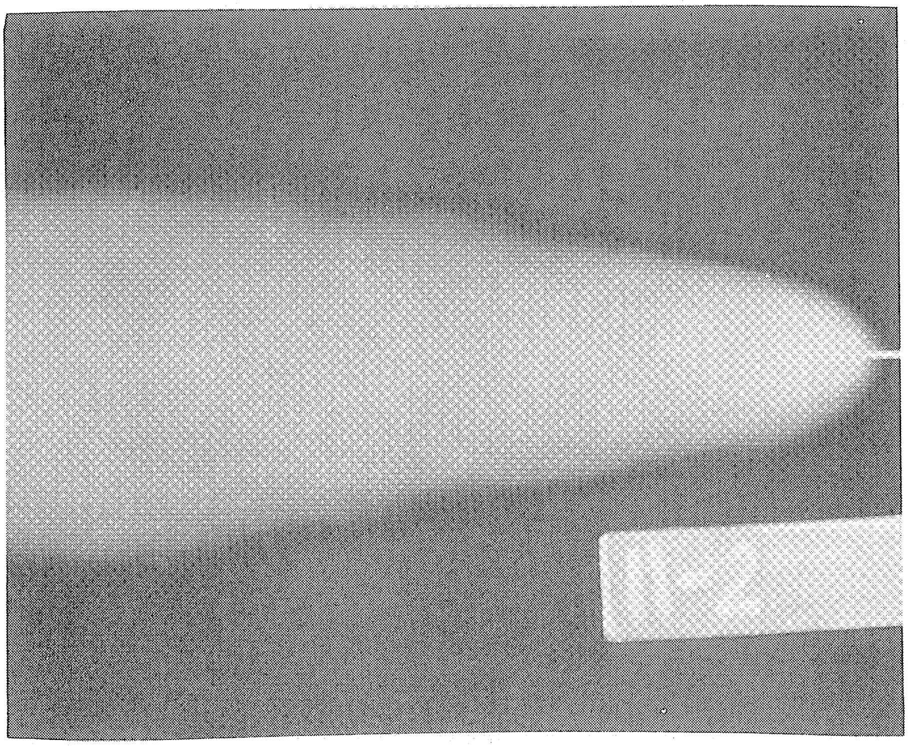

Fig. 17. Nozzle no. 11, cavitating flow; temperature 164°C.

APPENDIX

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