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Department of Chemical and Metallurgical Engineering
Multi-Phase Fluids Laboratory

Progress Report

EXPERIMENTS ON THE EFFECT OF FLASHING ON SPRAY FORMATION

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SUMMARY

Water at a temperature higher than its boiling temperature at one atmosphere was injected into air through an orifice nozzle and a swirl nozzle. The upstream pressure was kept constant and the liquid temperature was varied to change the fraction of liquid which flashes. A photographic record of the results is presented. The sprays formed when flashing takes place have a much smaller drop size than cold liquid sprays. The spray pattern also undergoes a considerable change.

Flow rates at constant inlet pressure and various percentages of flashing are measured. The flow rate of the orifice nozzle decreases 20% below the cold-water flow rate when 10% of the liquid is flashing, as may be expected from the effect of expansion when flashing is taking place. If all the flashing had taken place within the throat of the nozzle, the reduction in flow rate would have been much greater. However, in all nozzles with small length-to-diameter ratios, most of the flashing takes place after the nozzle, and the flow rate decreases only a small fraction of that predicted. Using a sharp-edged orifice, there is no decrease below the cold-water flow rate, as all the flashing takes place after the liquid has passed the nozzle throat.

The results of these experiments lead to recommendations for more intensive study of this method of spray formation.

INTRODUCTION

It has been suggested that an extremely fine spray might be produced by the flashing of a portion of a liquid jet as it issues from an orifice. This report presents the results of some preliminary experiments made to test the possible practical value of such a method of spray formation.

There are a number of means which might be employed to promote the flashing of a liquid jet flowing through an orifice. The method chosen for these experiments was the injection of water at a temperature higher than its boiling temperature at the receiving pressure. Two other possible methods are the introduction of a dissolved gas into the liquid, or local heating of part of the liquid at the orifice. The particular method of these experiments may not be the most practical in many spraying applications, but the effect of the flashing on the spray formed should be similar to the effect resulting from other methods of producing flashing.

The sprays are injected into air at one atmosphere. The sensible heat of the water provides the latent heat for vaporization of a fraction of the water. Water is available at 120 psig and at its saturation temperature (350°F). The water is cooled by a heat exchanger before its injection through the nozzle. The fraction vaporized is controlled by varying the temperature of the water. A photographic study of the spray formed is made at various inlet water temperatures. A simple orifice nozzle and a swirl nozzle are tested.

To our knowledge, these are the first experiments that have been made of this type for the purpose of producing spray. A common application of flashing for spray formation is aerosol pressure dispensers. Measurements have been made on the flow metering of hot* water through orifices. Bottomley[1] was the first to discuss the prediction of flow of flashing water through orifices. Benjamin and Miller[2] present results of the measurement of flow of hot water through sharp-edged orifices. Silver and Mitchell[3] measure the flow of hot water through a number of orifices with varying ratios of length-to-throat diameter. These and numerous other investigators have been concerned with the problem in connection with evaporator design. The prediction and possible limitations of the flow-metering with reference to the spraying application will be discussed further in a later section of this report.

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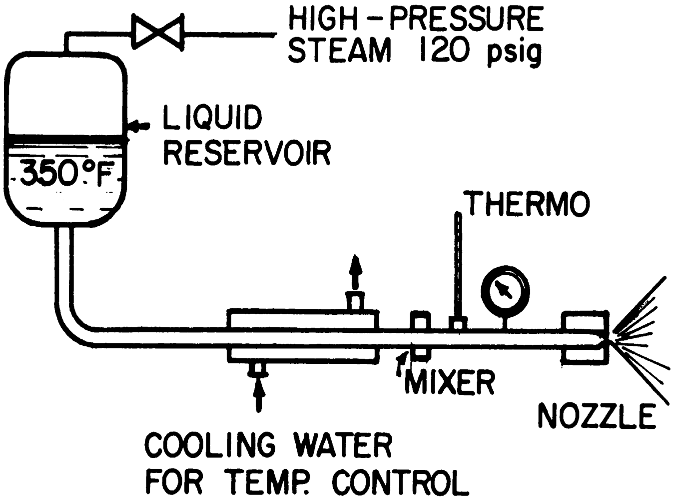
*Meaning, throughout this report, water above the saturation temperature at one atmosphere (above 212°F).

APPARATUS AND PROCEDURE

The injection system consists of a feed tank fitted with a steam line such that 120-psig steam can be bubbled through a water charge until the water reaches its saturation temperature. The water from the feed tank passes through a double-pipe heat exchanger, where it can be cooled to the desired temperature. A mixer is placed in the line after the heat exchanger. There is a pressure gauge and a thermowell in the line between the mixer and the nozzle. The pressure gauge is a Jas. P. Marsh Mastergauge type 103, range 0-160 psi. The thermowell is filled with mineral oil and a thermometer that can be read to the nearest 0.5°C is placed inside. A diagram of the injection system follows.



Flow rates are measured by injecting the spray into an Erlenmeyer flask wrapped in wet towels for about one minute. The time is measured with a stopwatch. In those cases in which there is a relatively high fraction vaporizing, a measured amount of cold water is placed in the flask to minimize the steam loss from the mouth of the flask.

Photographs are taken using Kodak Super-Panchro Press Type B film at f-4.5 and an exposure of 1/100 second. The camera is approximately 3 ft from the spray and on a horizontal with it. Two Ken-Rad photoflood lamps are used for lighting. The lights are placed above and below the spray when photographing the spray from the orifice nozzle. When photographing the spray from the swirl nozzle, the overhead light is placed behind the nozzle and in the direction of flow.

The orifice nozzle consists of a 0.02-in.-diameter hole drilled in a 1/2-in. pipe cap. The orifice length-to-diameter ratio is about 6. The swirl nozzle used was a Kopp No. 10.00 designed to give a flow rate of 9.5 gallons/hr at a pressure of 120 psig with a 90° cone angle.

RESULTS OF THE PHOTOGRAPHIC STUDY

A. THE ORIFICE NOZZLE

Figures 1 to 6 are photographs of the spray from the orifice nozzle. The injection pressure was 120 psig and the temperature was varied. The photographs will serve to illustrate the observations made here.

Using cold water, a liquid stream comes out of the orifice and disintegrates mainly by the surface-tension mechanism about 6 ft from the nozzle. A striking change in the liquid jet takes place within 1° of 212°F. The jet is no longer straight but begins to spread with a definite cone angle. The water concentration is considerably greater on the edges of the spray cone. This indicates that the flashing occurs in the center of the liquid stream. As the temperature of the liquid is raised, the effects become more pronounced. The angle increases further and the spray becomes finer. Eventually the straight boundaries of the spray zone become less well-defined and a homogeneous mist of water and steam is ejected from the orifice. This condition is illustrated in Figs. 5 and 6. The nozzle is about 3 ft above the ground, and when the water temperature is above 250°F, it appears that all the water has vaporized before reaching the ground. The penetration of the spray is considerably less as all the mist has vaporized by the time it reaches a point approximately 3 ft from the orifice.

B. THE SWIRL NOZZLE

Figures 7 to 13 are photographs of the spray from the swirl nozzle. The inlet pressure was also 120 psig and the temperature was varied. The photographs will again illustrate the following observations.

With cold water, the spray is formed into a hollow cone with a 90° cone angle. The cone terminates about 2 ft from the nozzle as the droplets curve back towards the nozzle. There is no very striking change around 212°F as with the orifice nozzle. However, as the temperature rises somewhat above that point, the spray distribution changes. Some spray can be observed in the center of the cone. This is probably because of the passage of steam through the vortex of the swirl chamber. As the temperature rises above 230°F, the flow in the center of the cone is strong enough to change the pattern of the spray. The spray begins to penetrate more. As the temperature continues to rise, the penetration becomes greater and the spray does not spread as far perpendicular to the flow axis. Eventually, the cone angle begins to decrease as partial mixing of liquid and vapor takes place in the swirl chamber. When the water temperature has reached 300°F, the cone has broken down completely, and a homogeneous mist of water and spray issues from the nozzle. This condition is illustrated in Figs. 12 and 13. Until this point there has been some separation of the phases in the swirl chamber. When over 9% of the liquid is flashing, the swirl nozzle acts quite like the orifice nozzle. The drop size is considerably smaller than for a cold spray—in fact, one cannot see any discrete drops, just a mist.

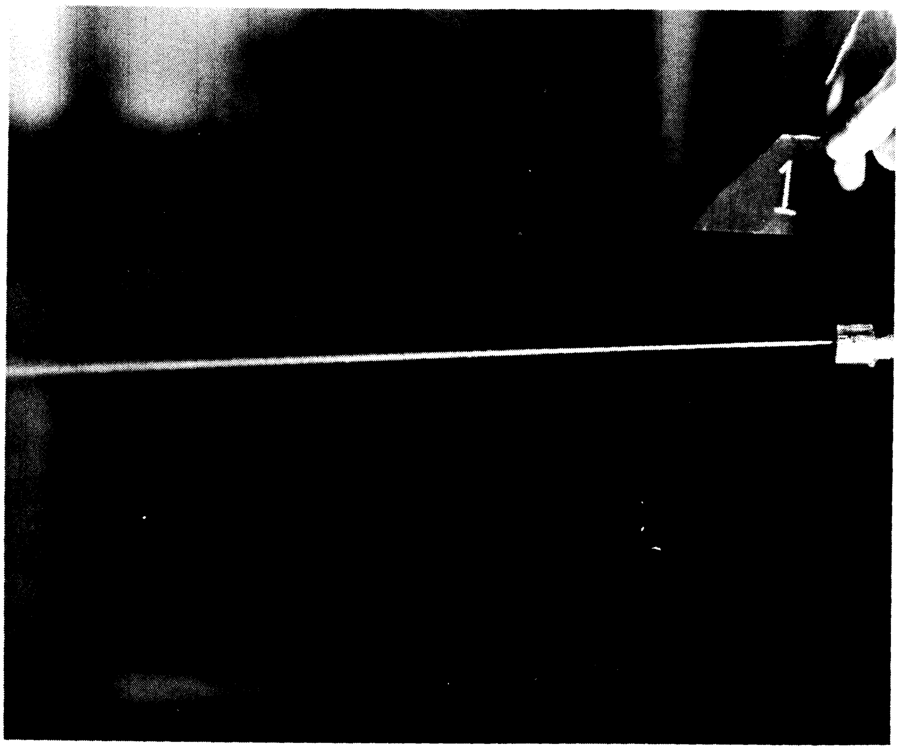


Fig. 1. Orifice nozzle, cold spray.

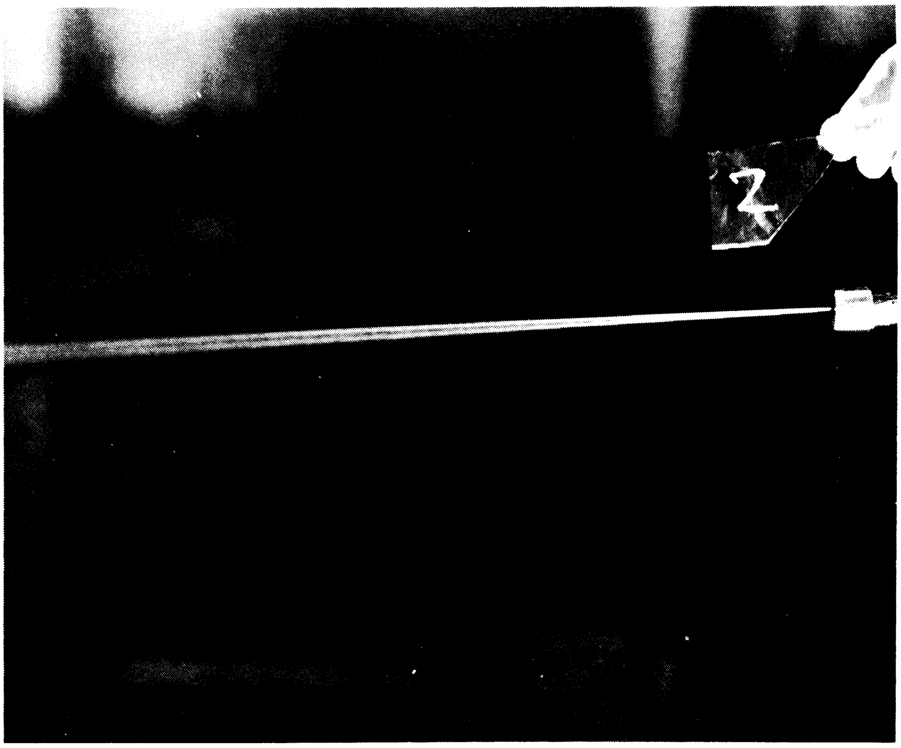


Fig. 2. Orifice nozzle, just below 212°F.

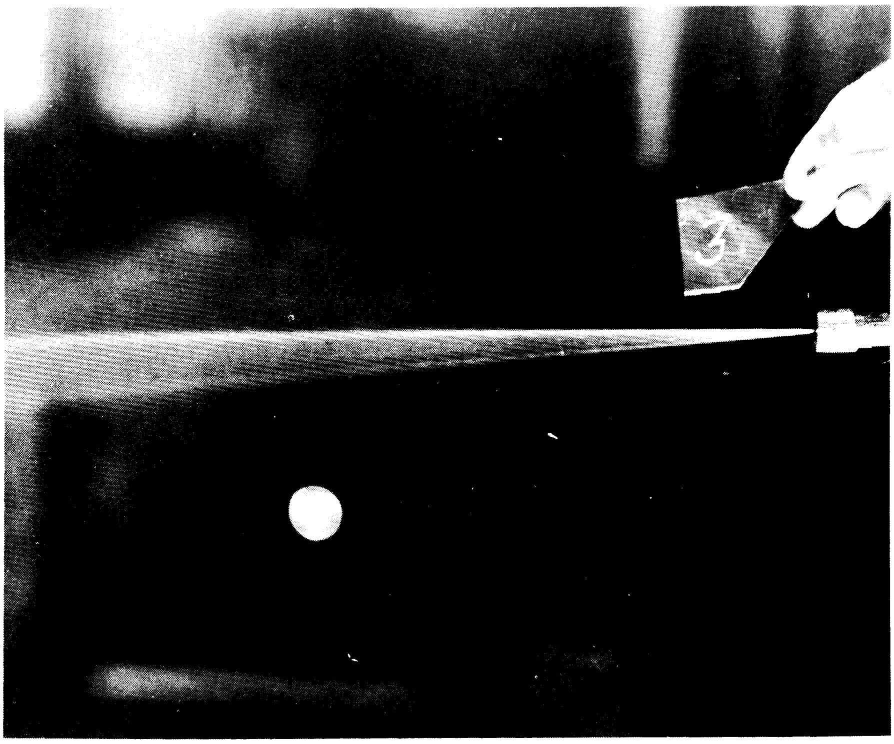


Fig. 3. Orifice nozzle, just above 212°F.

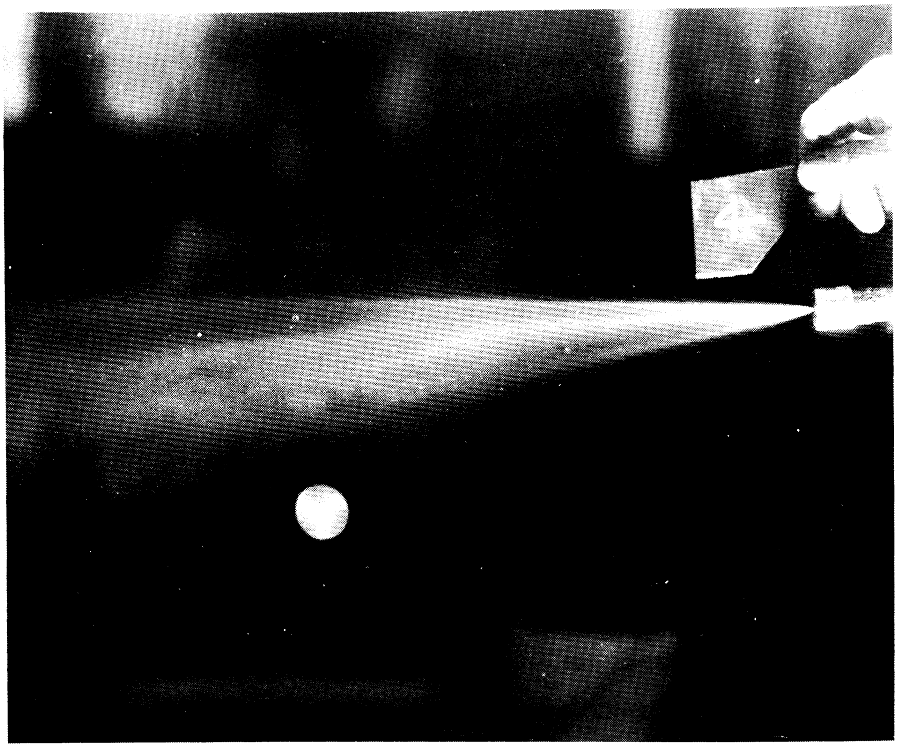


Fig. 4. Orifice nozzle, 128°F - 1.8% flashing.

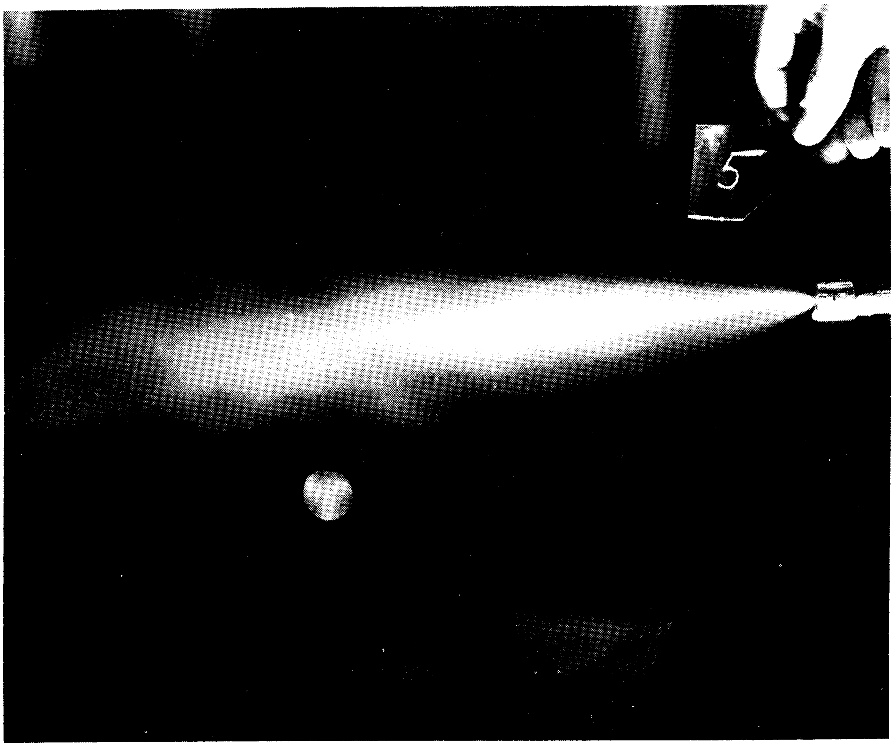


Fig. 5. Orifice nozzle, 256°F - 4.5% flashing.

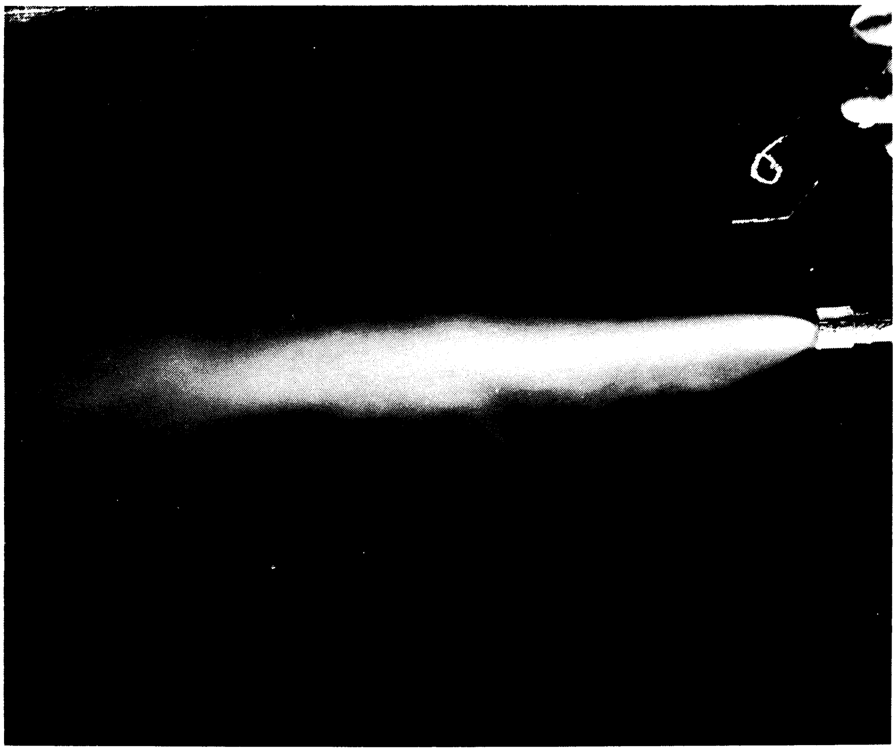


Fig. 6. Orifice nozzle, 295°F - 8.5% flashing.

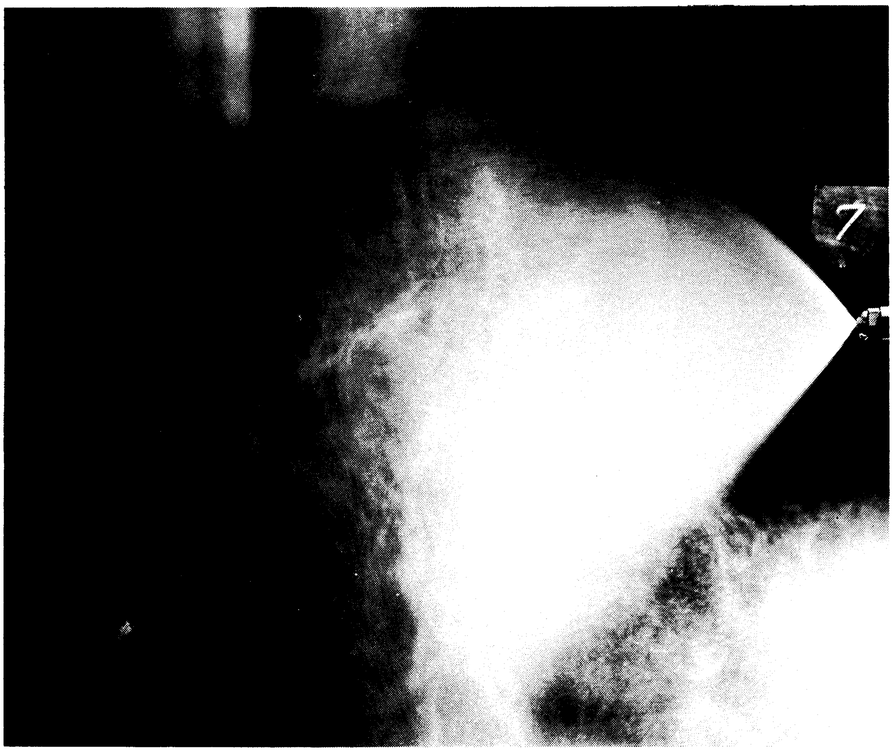


Fig. 7. Swirl nozzle, cold spray.

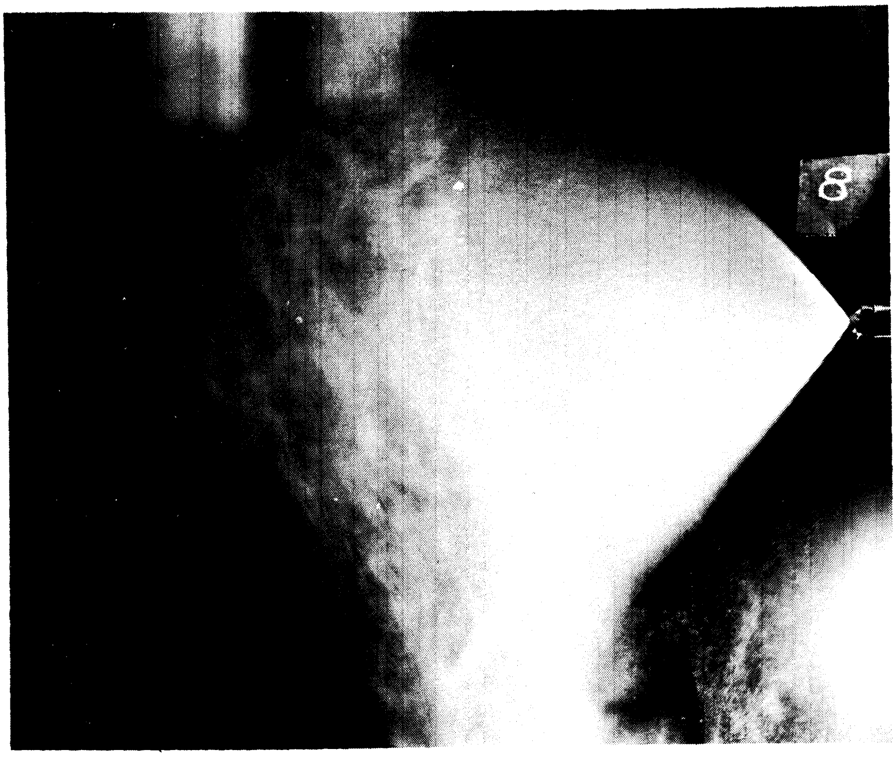


Fig. 8. Swirl nozzle, just below 212°F.

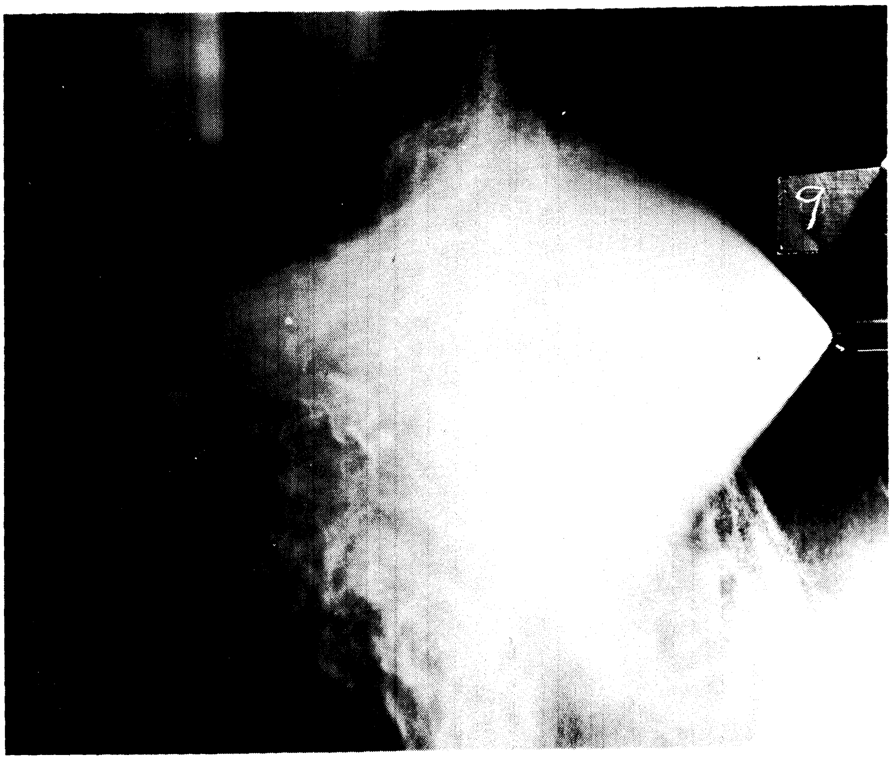


Fig. 9. Swirl nozzle, 235°F - 2.3% flashing.

Fig. 10. Swirl nozzle, 253°F - 4.1% flashing.

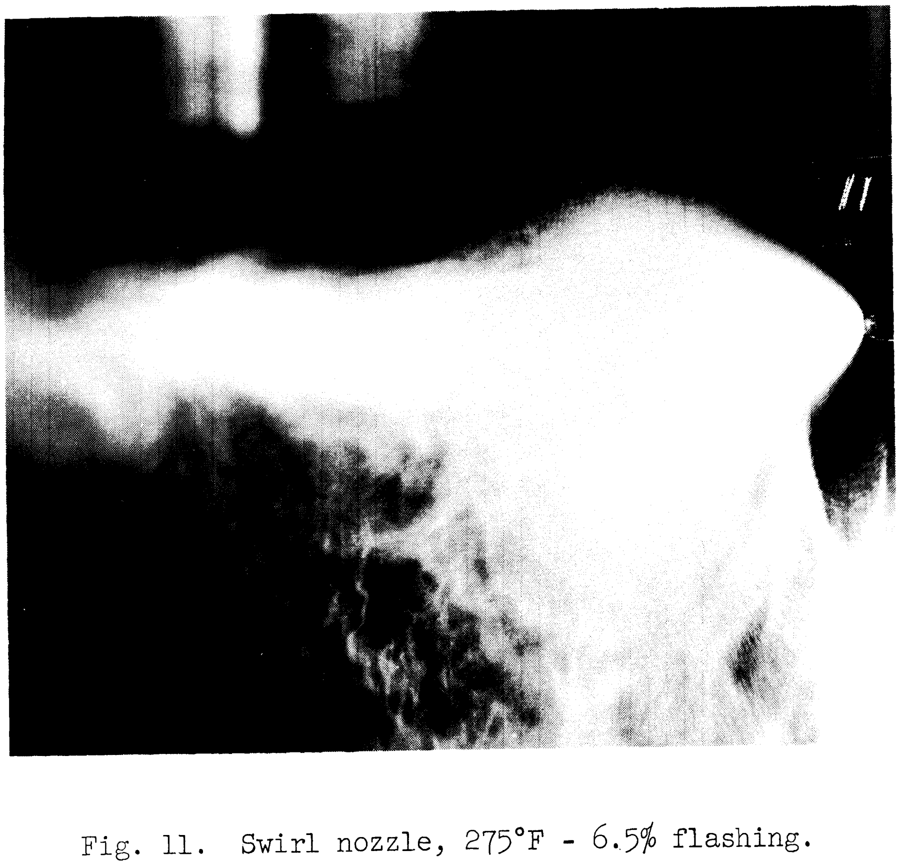


Fig. 11. Swirl nozzle, 275°F - 6.5% flashing.

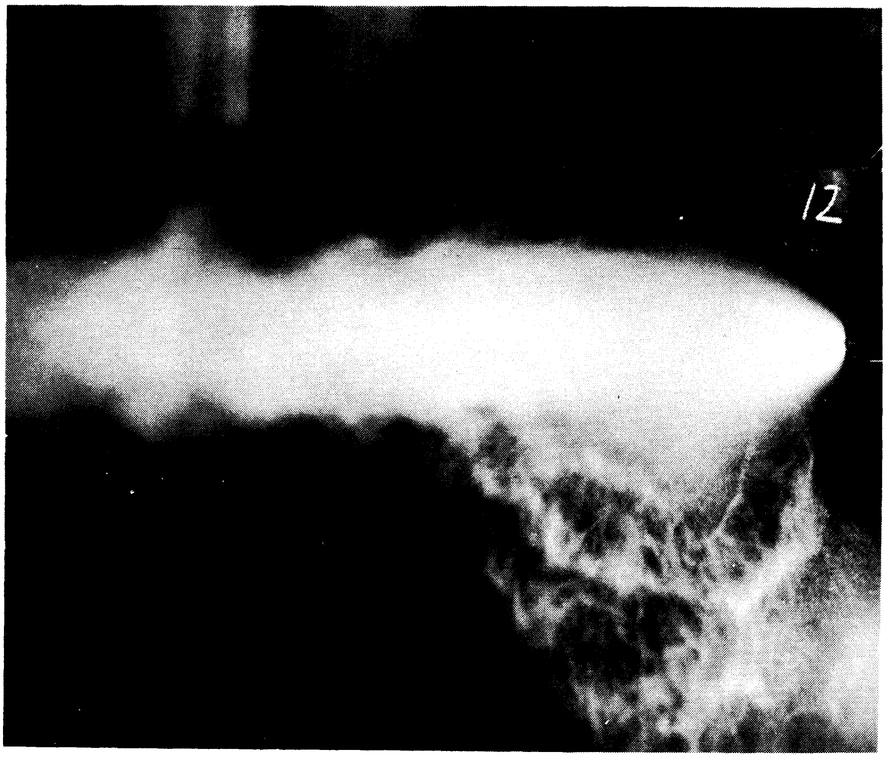


Fig. 12. Swirl nozzle, 302°F - 9.3% flashing.

Fig. 13. Swirl nozzle, 324°F - 11.7% flashing.

FLOW-RATE STUDIES: RESULTS AND DISCUSSION

The result of the flow-rate study is plotted in Fig. 14. The flow rate is plotted versus the percent flashed. The percent flashed is calculated from the inlet water temperature. Assuming that no heat is lost, the sensible heat of the liquid provides the latent heat for the vaporization of a portion of it. The thermodynamic properties of water and steam for the calculation are obtained from Keenan and Keyes.[4] In this range of temperature, the percent flashed is a linear function of temperature; therefore the scales are interchangeable.

A. THE THEORETICAL FLOW RATES

The flow rate of water through an orifice can be predicted from the familiar orifice equation:

$$Q = \frac{A}{v} C \sqrt{2gv\Delta P} \tag{1}$$

where:

Q = mass flow rate,
C = orifice coefficient,
A = cross-sectional area of orifice throat,
v = specific volume of fluid,
g = conversion factor from absolute to engineering units, and
ΔP = pressure decrease across orifice.

The relation is derived from the flow equation after having made the following assumptions:

(1) The upstream velocity is much smaller than the downstream velocity.
(2) The effects of friction are negligible.
(3) The change in specific volume is negligible.

When a portion of the liquid is flashing as it goes through the orifice, the variation in specific volume is quite large, and the flow equation must be solved without the use of assumption 3. Two further assumptions are made, however. Thermodynamic equilibrium is assumed. That is, the liquid temperature is never above its saturation temperature at the pressure at any point in the orifice. The liquid and vapor are also assumed to move with the same average velocity, u. The validity of these assumptions will be discussed later in view of the experimental results that have been found.

Consider water at its saturation temperature. If there is no heat loss or change in level of the inlet and outlet streams, the flow equation can be written as:

$$- v dP = \frac{u}{g} du \tag{2}$$

where u = velocity of fluid.

Integrating the equation and solving for the velocity:

$$u = \left(-2g \int_{P_1}^{P_2} v dP \right)^{1/2} \tag{3}$$

The integral $-\int vdP$ can be computed graphically to any given pressure in the nozzle throat. The specific volume used for the calculation is computed assuming a homogeneous mixture of liquid and vapor:

$$v = x v_g + (1 - x) v_l \tag{4}$$

where:

subscript g refers to vapor,
subscript l refers to liquid, and
x = mass fraction vapor.

The velocity in the throat of the orifice will reach a maximum value corresponding to a critical velocity which is the velocity of sound. This will correspond to the velocity computed by evaluating the integral $-\int vdP$ to a pressure which is approximately 58% of the upstream pressure. The existence of a critical pressure for the flow of a mixture of liquid and vapor has been validated by many experimental investigators.[2,3]

The mass flow rate for this case can then be calculated from the relation:

$$Q = \frac{uA}{v} \tag{5}$$

where:

u = velocity at the throat from Eq. (3), and
v = specific volume at throat from Eq. (4).

The flow rates calculated for a flashing liquid will therefore be less than those for a cold liquid because of the greater specific volume in the denominator of Eq. (5). Figure 15 presents a comparison of the predicted flow rates versus inlet pressure for cold water and water at the upstream saturation temperature. In the experiments in this study, the feed water was somewhat below the upstream saturation temperature. This simply means that flashing does not occur until the pressure in the flowing liquid is reduced to the saturation pressure at the water temperature. The evaluation of Eq. (3) is carried out as with liquid at saturation temperature except that in this case the specific volume is constant for a certain pressure range.

B. COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

The results of these experiments as well as of those reported in the literature have shown that the flow rates for flashing liquids through orifices are far in excess of the predicted theoretical ones. Benjamin and Miller[2] have shown that the flow rates for flow through sharp-edged orifices are essentially those predicted for cold water. As the length-to-diameter ratio of a nozzle is increased, the flow rates will decrease below those for cold water. Figures 16 and 17 are plots of the data taken by Silver and Mitchell.[3] Water at various pressures and at the upstream saturation temperature was used. The results show that the flow rates decrease with increasing length-to-throat-diameter ratios. Comparison of the curves for the 3/16-in.-diameter nozzle and the 1/2-in.-diameter nozzle show that the effect of increasing the length-to-diameter ratio is much greater for larger diameter nozzles. Flow rates have been found to approach the theoretical limit only when hot water flows through long pipes.

The large discrepancy between the experimental and theoretical results can easily be explained by the fact that thermal equilibrium is not reached at every point in the nozzle. The fact that the flow through a sharp-edged orifice is the same as that for cold water demonstrates that no flashing takes place until the liquid has passed the orifice throat. With a longer nozzle, there is more time for a given slug of liquid to flash; therefore the flow rate will decrease with increasing nozzle length. The effect of the diameter on the flow rate shows that the higher turbulence in a larger orifice promotes the approach to thermal equilibrium.

The assumption that flashing would take place instantaneously and thermal equilibrium be reached at every point in the nozzle is actually quite erroneous. Consider first the nucleation of a vapor bubble. The pressure of the vapor inside a small bubble is slightly greater than the liquid surrounding it due to the compression effect of surface tension. Therefore, in order that water molecules be transferred into the vapor bubble, the liquid surrounding it must have a higher vapor pressure than the pressure in the bubble and thus be slightly superheated. The rate of heat transfer from the body of the liquid to the surface of the bubble must be finite. If equilibrium is assumed to be reached instantaneously, this implies an infinite rate of heat transfer from the liquid to the bubble surface.

The results in this experiment show that there is a 20% decrease in flow rate below the cold-water flow rate with the orifice nozzle when there is 10%

flashing. The theoretical decrease is about 80% of the cold-water flow. The length-to-diameter ratio is 6. The flow rate of the swirl nozzle remains at the cold-water rate to a much higher degree of flashing than the orifice nozzle. This can be explained by the fact that there is a separation of phases in the orifice nozzle. The fact that a small portion of the liquid is vaporizing does not affect the flow of the liquid on the walls of the swirl chamber. When the phases do mix and the photographs show the spray as a mixture of water and steam, the flow rate does decrease. The data for the high flashing percentages on this nozzle are somewhat erratic because of the unsteady condition between mixing and no mixing of the phases in this range.

In view of the experimental results in this and previous investigations, the theoretical values for the flow of flashing liquid are of little value in predicting the flow rate. The theoretical flow rates, however, do provide a lower limit on the flow rate expected from a nozzle. The values for the flow of cold water provide us with the upper limit on the flow rate.

CONCLUSIONS

Although no drop-size measurements have been made, qualitative observation has shown that a small degree of flashing has a tremendous effect on the spray formed. The most striking demonstration of this is the spray formed from an orifice nozzle just as the temperature is increased enough for flashing to take place. When there is no flashing, the drops formed are on the order of magnitude of the diameter of the liquid jet. With a small degree of flashing, less than 1%, a spray of fine drops is formed. Comparison of the effect of flashing with a more efficient spraying mechanism, the swirl nozzle, again shows the formation of a finer spray when flashing occurs. The introduction of flashing in a swirl nozzle also changes the spray pattern.

The possibility of a serious flow-metering problem is apparent. For a given nozzle the flow rate can be predicted only within a wide range of values when the liquid is flashing. This problem can be solved by noting that, by use of a short length or sharp-edged orifice nozzle, the flow rates for a flashing liquid will be identical to those for a cold liquid.

RECOMMENDATIONS FOR FURTHER STUDY

The flashing of a liquid jet has been shown to be an effective way of producing a fine spray. It is now appropriate to provide a quantitative measure of the effectiveness of flashing by measuring drop sizes.

Future studies should also be concerned with the means by which flashing would be promoted in practice. It is probably more practical to produce flashing in a fuel-injection system by the introduction of a dissolved gas into the fuel which would flash at the nozzle. Drop-size measurements should be made when flashing is being promoted by the same means that might be used in practice.

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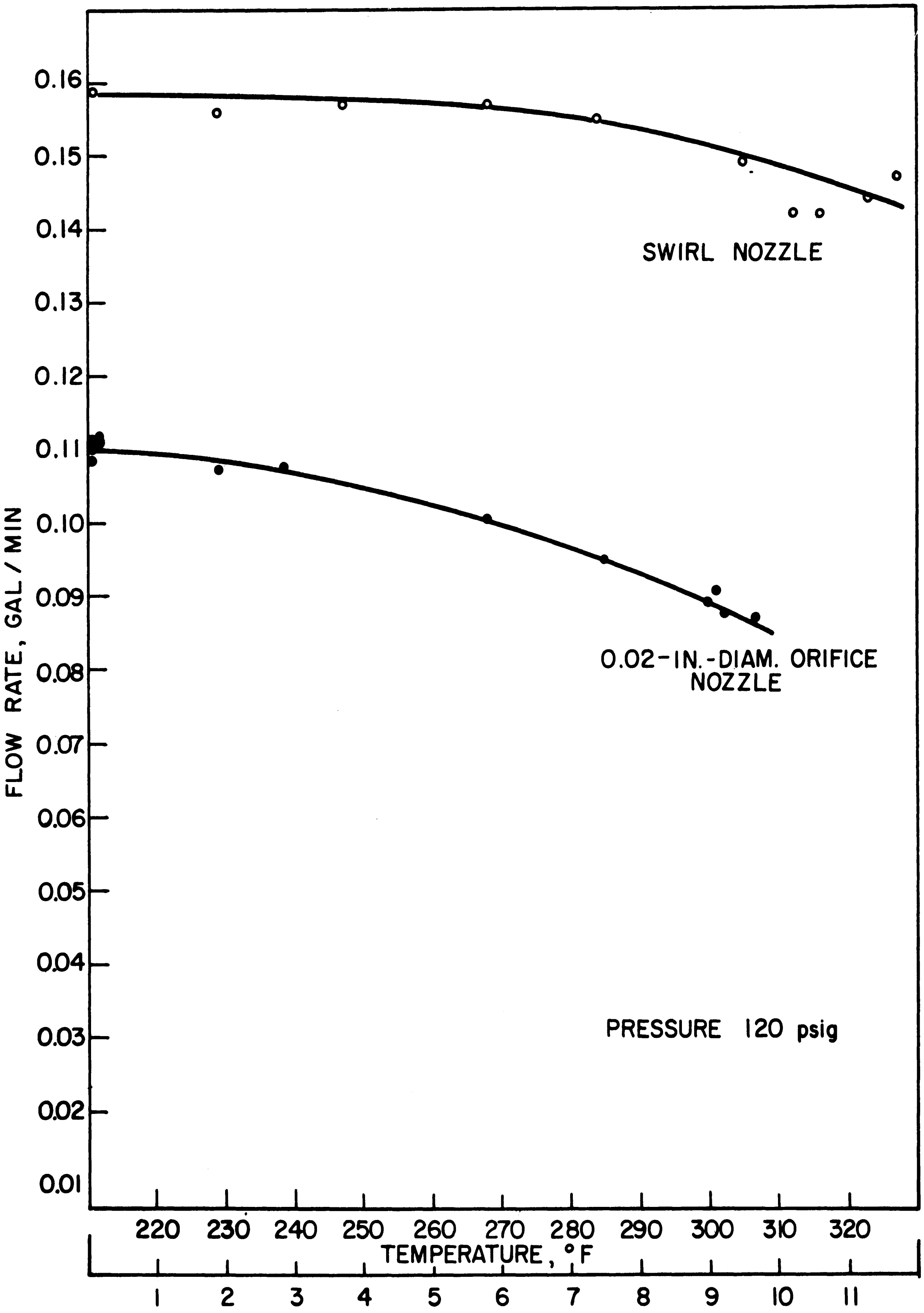

Fig. 14. Flow rates at constant pressure.

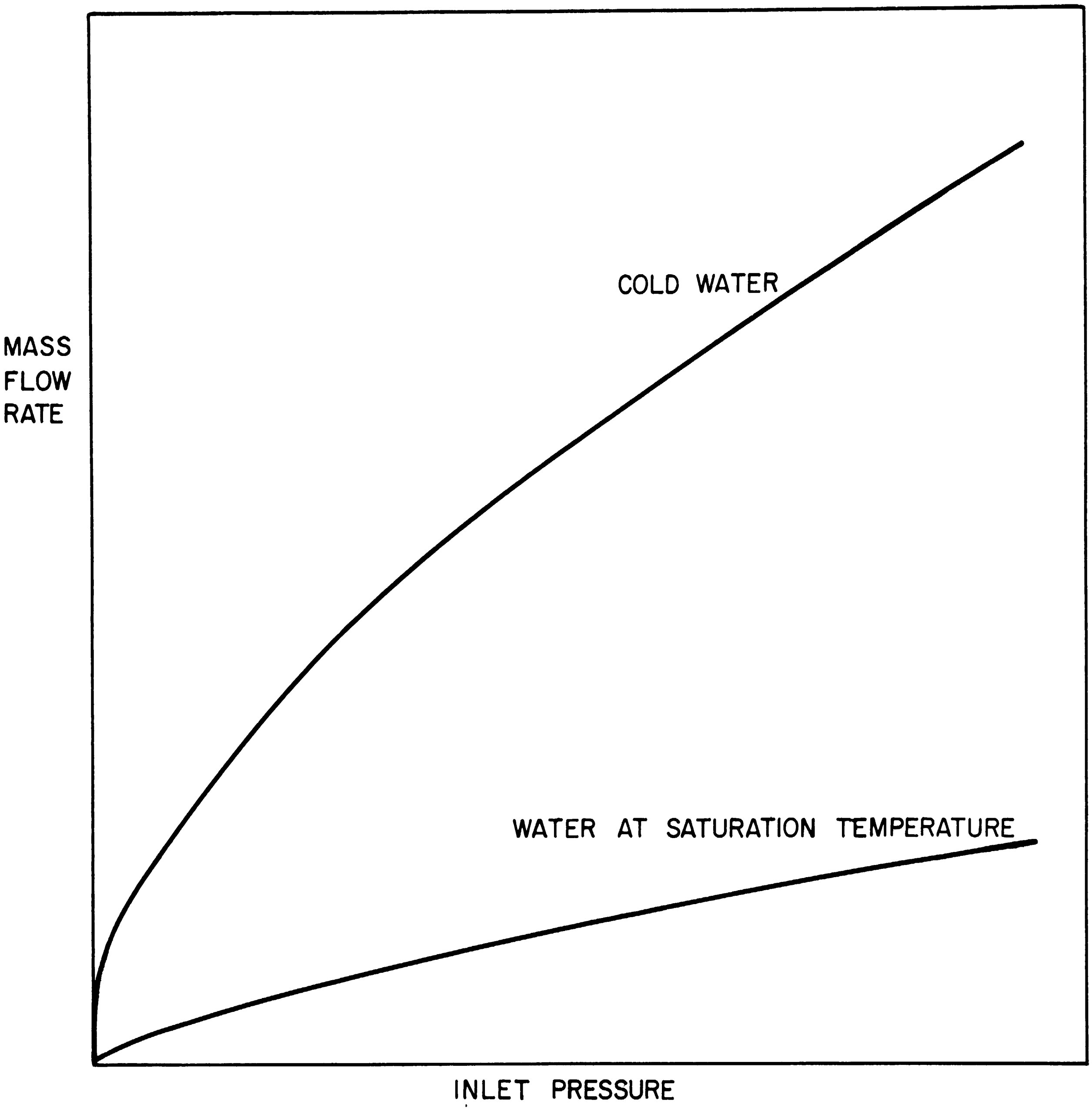

Fig. 15. Predicted cold- and hot-water flow rates through an orifice.

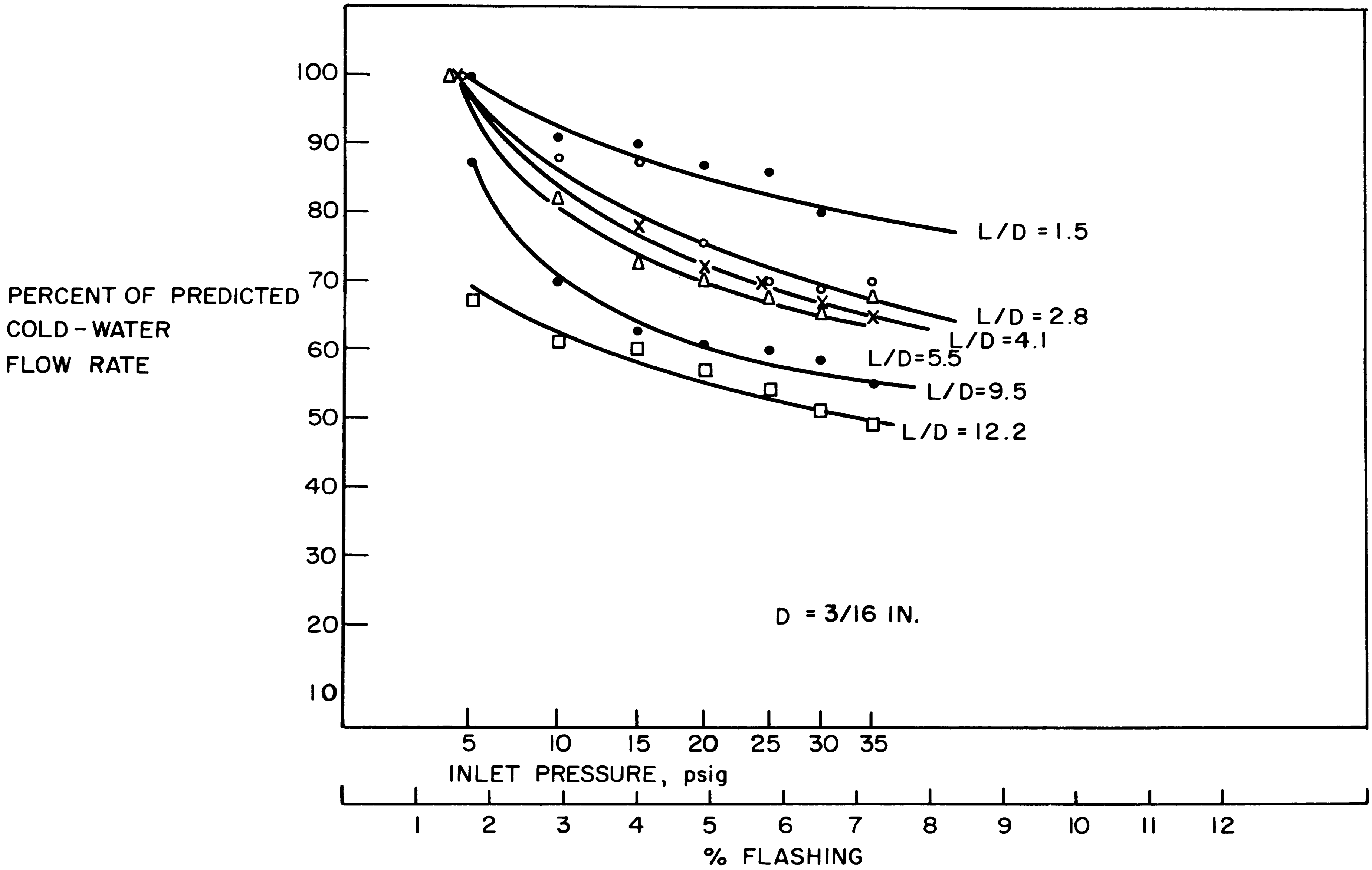

Fig. 16. Flow of flashing water through rounded entrance nozzles.

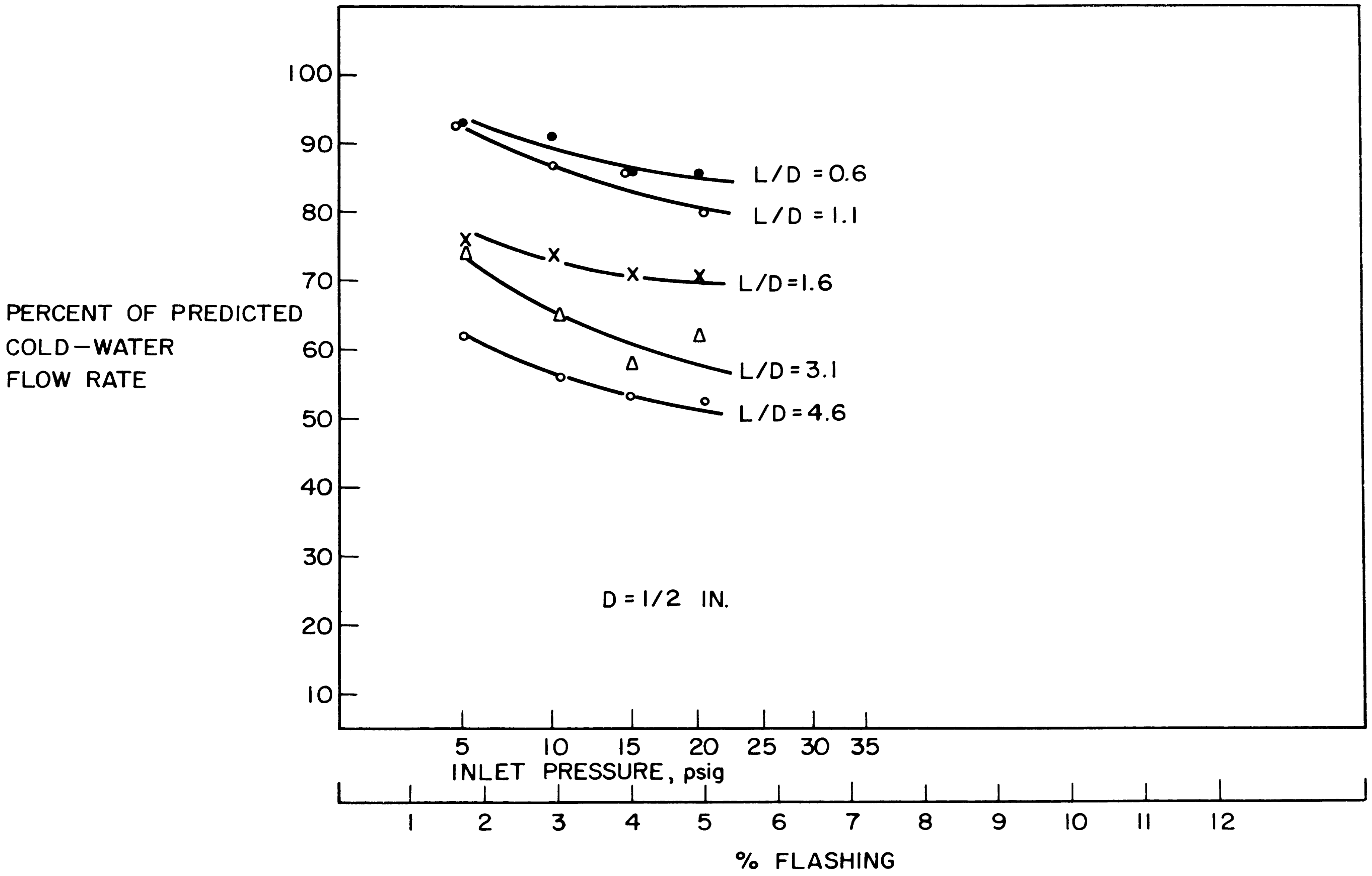

Fig. 17. Flow of flashing water through rounded entrance nozzles.