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ABSTRACT

Axial and swirling airflows were used to break up water jets and sheets into sprays of droplets to determine the overall effects of orifice diameter, weight flow of air, and the use of an air swirler on fineness of atomization as characterized by mean drop size. A scanning radiometer was used to determine the mean drop diameter of each spray. Swirling airflows were produced with an axial combustor, 70° blake angle, air swirling. Water jets were injected axially upstream, axially downstream and cross stream into the airflow. In addition, pressure atomizing fuel nozzles which produced a sheet and ligament type of breakup were investigated. Increasing the weight flow rate of air or the use of an air swirling markedly reduced the spray mean drop size. Test conditions included a water flow rate of 68.0 liter per hour and airflow rates (per unit area) of 3.7 to 25.7 g per square cm per sec, at 293 K and inlet-air static pressures of 1.01×10^5 to 1.98×10^5 N/m^2.

INTRODUCTION

Experimental tests of water jet and sheet break up were conducted in axial and swirling airflows to determine in each case the effect of orifice diameter and airflow rate (flowrate/unit area, or airstream momentum, ρV) on mean drop size and, from these data, to detmonstrate the overall effect of an air swirler on fuel injector performance. Water jets produced by multiple orifice spary bars were injected cross stream, into a 7.6 cm diam duct, with and without the use of an air swirler, at airflow rates (per unit area) of 3.7 to 25.7 gm/cm^2-sec and a water flow rate at 68.0 liters/hr. In addition, similar tests were conducted for axial upstream and downstream injection with single tubes, and for axial downstream and cross stream injection with pressure atomizing fuel nozzles A scanning radiometer that measured the forward scattered light was used to determine the mean drop diameter of the spray at each test condition.

Air swirlers are often used to enhance the rapid mixing of fuel and air in the primary zone of gas turbine combustors to improve combustor performance and reduce exhaust emissions, as indicated in ref. (1). Thus, tests were made with and without the use of an air swirler to determine the overall effect of the air swirler on injector performance as characterized by the man drop diameter obtained in axial and swirling airflows. Such data are needed in the design of advanced fuel injectors for high performance gas turbine combustors. In the present investigation, an air swirler and two fuel nozzles were tested that had been used in previous combustor studies as described in ref. (2). With this equipment, data for the fineness of atomization, as characterized by mean drop size, was obtained with and without the use of an air swirler. Also, data obtained for the breakup of water jets were compared with data obtained for the breakup of water sheets.

APPARATUS AND PROCEDURE

Air drawn from the laboratory supply system was at ambient temperature (293 K) and pressures in the tests section were varied from 1×10^5 to 1.98×10^5 N/m^2. As shown in fig. 1, airstream flow rate was controlled with the valve directly downstream of the air orifice. The test section, also shown in fig. 1, was a 7.6-centimeter inside diameter duct 15.2 cm in length and mounted, with a bellmouth, inside of a 15.2-cm inside diameter duct 5 m in length. The top of each test injector was located at the duct exit and a distance of 11.4 cm upstream of the center line of the 7.5-cm diameter laser light field. The air swirler was located at a distance of 7.6 cm upstream of the duct eixt for all of the tests except those in which swirler location was varied from zero to 7.6 cm upstream of the duct exit. A scanning radiometer was mounted near the end of the open duct test facility as shown in fig. 1.

SCANNING RADIOMETER

The scanning radiometer, shown in fig. 2, was used to determine the mean drop size of water sprays produced at each test condition. The optical system shown in fig. 2 consisted of a 1-mW helium-neon laser, a 0.003-cm-diameter aperture, a 7.5-cm-diameter collimating lens, a 10-cm diameter converging lens, a 5-cm-diameter collecting lens, a scanning disc with a 0.05 x 0.05-cm slit, a timing light and a photomultiplier detector. A complete description of the scanning radiometer and the method of determining mean particle diameters are given in ref. (3). Calibration tests of the instrument were performed as discussed in ref. (4).

AIR SIWRLER AND TEST INJECTORS

The 70° blade-angle axial air swirler and the pressure atomizing fuel nozzles used in this investigation are shown in fig. 3. As shown in fig. 1, the air swirler was mounted 7.6 cm upstream of the fuel nozzle which was positioned at the duct exit.

Two spray bars were tested. A schematic diagram of the spray bar consisting of 12, 0.033-cm-diameter, orifices is shown in fig. 4. A similar spary bar consisting of 3, 0.132-cm-diameter, orifices was also tested. The spray bar was positioned at the duct exit and the water jets were injected cross-stream into the airflow. For the axial downstream and axial upstream injection test of the breakup of single jets of water, two tubes having inside diameters of 0.102 and 0.216 cm, respectively, were used. Physical characteristics of the test injectors are given in Table I.

RESULTS AND DISCUSSION

Mean drop diameters were determined for sprays produced by axial upstream, axial downstream and cross-stream injection of water jets into airstreams with and without the use of air swirlers. Also, to determine the effect of swirling airflow on the breakup of water sheets, similar tests were made with pressure atomizing fuel nozzles. Test conditions for airflow rate (or airstream momentum) and water flow rates are given in Table II.

The first type of injector tested was the spray bar shown in fig. 4. Two different spray bars having orifice diameters of 0.033 and 0.132 cm, respectively, were used for the study of cross-stream injection of water jets. The effect of air flow rate on mean drop diameter is shown in fig. 5. Good agreement was obtained with ref. (4). A marked decrease in mean drop diameter was obtained as airflow rate was increased from 3.7 to 18.3 gm/cm^2-sec. Mean drop size was further reduced when a swirling airflow was used to atomize the water jets. With axial airflow, decreasing orifice diameter by a factor of 4 decreased the mean drop diameter approximately 20 percent. In a swirling airflow, the similar fineness of atomization of small and large water jets was attributed to a greater penetration of the larger jets into the swirling airflow which would provide a larger liquid surface area for breakup. At a relatively high airflow rate, the use of an air swirler gave a reduction in mean drop size of 20 percent with the large orifice spray bar. A decreasing percent reduction in mean drop size was obtained with both spray bars as airflow rate was increased.

In the next set of tests, single jets of water were injected axially downstream through two different tubes having inside diameter of 0.102 and 0.216 cm, respectively, as shown in fig. 1. With an axial airflow rate of 7.3 gm/cm^2-sec, as shown in fig. 6, the mean drop diameter was approximately 20 percent less for the large diamter tube as compared with the small tube. This was attributed to the fact that the liquid jet velocity was much lower for the large tube than the small tube, i.e., 5.2 and 23.3 m/sec respectively. A lower jet velocity made the velocity difference between airstream and jet greater and hence the momentum transfer rate was higher for the large diameter jet as compared with the small jet. At a high airflow rate (25.7 gm/cm^2-sec), mean drop size was nearly the same for both tube sizes since velocity difference was nearly the same in each case. By using an air swirler, the man drop diameters obtained with both the large and small tube injectors were decreased approximately 50 percent. Also, comparison of figs. 5 and 6 shows that mean drop sizes were considerably larger for axial downstream injection than those obtained with cross-stream injection in axial flow airstreams. However, when an air swirler was used, both types of injection gave nearly the same mean drop size at high airflows.

In the final tests of liquid jet breakup, single water jets were injected axially upstream (contrastream) into axial and swirling airflows. By reducing orifice diameter approximately 50 percent, as shown in fig. 7, mean drop size was decreased 15 percent with breakup in axial airflow. When an air swirler was used, dreasing the orifice diameter decreased mean drop size by approximately 40 percent. Of all the methods tested in the injection of water jets, axial upstream injection from a 0.102-cm-diameter tube orifice into a swirling airflow gave the smallest mean drop diameter, i.e., 10 μm at the highest airflow rate. Also at this condition, it was difficult to obtain data since the orifice froze up if the water flow rate was not preset before setting the airflow rate at 18.3 gm/cm^2-sec. This was attributed to the very rapid rate of atomization and evaporation cooling produced by a high concentration of small drops being blown back over the injector tip.

The effect of distance between air swirler and orifice on mean drop size is shown in fig. 8 for the case of water injected axially upstream from a 0.216-cm-diameter orifice. Minimum mean drop diameters were obtained at an optimum distance of 3.8 cm. At high airflow rates, the spacing between air swirler and orifice had only a small effect on mean drop diameter. However, the effect increased markedly as airflow was decreased. Thus, particularly at lower airflow, the location of the air swirler relative to the orifice would appear to be a very important criteria in the design of fuel injectors.

In the final tests, water sheets produced by pressure atomizing nozzle were injected axially downstream and also cross-stream into airstreams with and without the use of an air swirler. As shown in fig. 9, the two pressure atomizing nozzles gave approximately the same mean drop size for axial downstream injection into an axial airflow. This was attributed to a collapsing of the spray cone as airflow was increased which provided a smaller liquid surface area for breakup. However, when the air swirler was used, the mean drop diameter was approximately 10 percent less for the nozzle with a small orifice diameter (0.23 cm) as compared with the nozzle having a larger orifice diameter (0.34 cm). By using swirling instead of axial airflow the mean drop diameter was decreased by 30 and 40 percent with the large and small nozzles, respectively, at a high airflow rate (18.3 gm/cm^2-sec).

Mean drop size data were obtained for cross stream injection of water sheets into axial and swirling airflows as shown in fig. 10. In the case of axial airflow, the small orifice nozzle produced a 15 percent smaller mean drop diameter than the large orifice nozzle at low airflow rates (7.3 gm/cm^2-sec) and approximately the same mean drop size at high airflow rates (18.3 gm/cm^2-sec). When the air swirler was used with a high airflow rate, mean drop size was reduced approximately 30 and 35 percent for the large orifice and small orifice nozzles, respectively. Cross stream and axial downstream injection with pressure atomizing nozzles as shown in figs. 9 and 10, gave approximately the same mean drop size in high flowrate, swirling airflows. The cross stream method of injection into airstreams was investigated since it is occasionally used in agricultural aviation spray applications.

The mean drop diameter data given in Table III were obtained for all injector types and orientations, with an airflow rate of 18.3 gm/cm^2-sec. Reproducibility of mean drop size measurement was ±5 percent. Since a mean size of less than 10 μm could not be measured, the smallest mean size was indicated as being ≤10 μm. Comparing liquid jet and liquid sheet breakup data for cross stream injection shows that mean drop size was decreased to approximately the same value of 24 μm when an air swirler was used. For this condition, orifice diameter appeared to have a negligible effect on mean drop size.

SUMMARY OF RESULTS

At the same airflow rates, injector performance was consistently improved as characterized by a reduction in mean drop size by using swirling instead of axial airflows to breakup water jets and sheets. The greatest reduction in mean drop diameter (55 percent) and the smallest mean drop diameter (10 μm or less), were obtained by axial upstream injection of a water jet at a velocity of 23.3 m/sec from a 0.102-cm-diameter tube orifice into a high flow rate swirling airflow. For the breakup of water sheets, the best results were obtained with a 0.23-cm-diameter orifice pressure atomizing nozzle injecting water axially downstream into a high flowrate swirling airflow. This configuration gave a mean drop diameter of 22 μm, i.e., a reduction of 44 percent in mean drop diameter with swirling instead of axial flow.

REFERENCES

1. Ingebo, R. D., Doskocil, A. J., and Norgren, C. T., "High-Pressure Performance of Combustor Segments Utilizing Pressure-Atomizing Fuel Nozzles and Air Swirlers for Primary-Zone Mixing," NASA TN D-6491, 1971.

2. Ingebo, R. D., and Norgren, C. T., "High Pressure Combustor Exhaust Emissions With Improved Air-Atomizing and Conventional Pressure Atomizing Fuel Nozzles," NASA TN D-7154, 1973.

3. Buchele, D. R., "Scanning Radiometer for Measurement of Forward-Scattered Light to Determine Mean Diameter of Spray Particles," NASA TM X-3454, 1976.

4. Ingebo, R. D., "Effect of Airstream Velocity on Mean Drop Diameters of Water Sprays Produced by Pressure and Air Atomizing Nozzles, NASA TM-73740, 1977.

TABLE I. - INJECTOR CHARACTERISTICS

Injector	Orifice diameter, cm	Injection velocity, m/sec*
Spray bar		
12 orifices	0.033	18.4
3 orifices	.132	4.6
Single tube		
Small orifice	.102	23.1
Large orifice	.216	5.2
Pressure atomixing		
Small orifice	.230	4.6
Large orifice	.340	2.1

*Measured at a water flowrate of 68.1 liter/hr.

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TABLE II. - AIRFLOW TEST CONDITIONS

Airflow rate per unit area, gm/cm^2-sec	Inlet-air static pressure	
	Without air swirler, N/m^2	With air swirler, N/m^2
3.7	1.01×10^5	--------
4.6	1.01	--------
5.5	1.01	--------
6.4	1.01	--------
7.3	1.08	1.15×10^5
11.0	1.12	1.39
14.7	1.17	1.67
18.3	1.24	1.98
22.0	1.32	--------
25.7	1.43	--------

TABLE III. - MEAN DROP DIAMETERS, M, FOR BREAK UP WITH

AIRFLOW RATE OF 18.3 gm/cm^2-sec

Injector	Conventional airstreams			Swirling airflows		
	Cross stream injection	Axial injection		Cross stream injection	Axial injection	
		Downstream	Upstream		Downstream	Upstream
Spray bar						
Small orifices	[a]24	---	---	23	---	---
Large orifice	31	---	---	23	---	---
Single tube						
Small orifice	---	45	22	---	25	[b]<10
Large orifice	---	41	27	---	19	17
Pressure atomizing						
Small orifice	35	39	---	23	22	---
Large orifice	35	39	---	25	28	---

[a]Mean drop diameter, μm.
[b]10 μm or less.

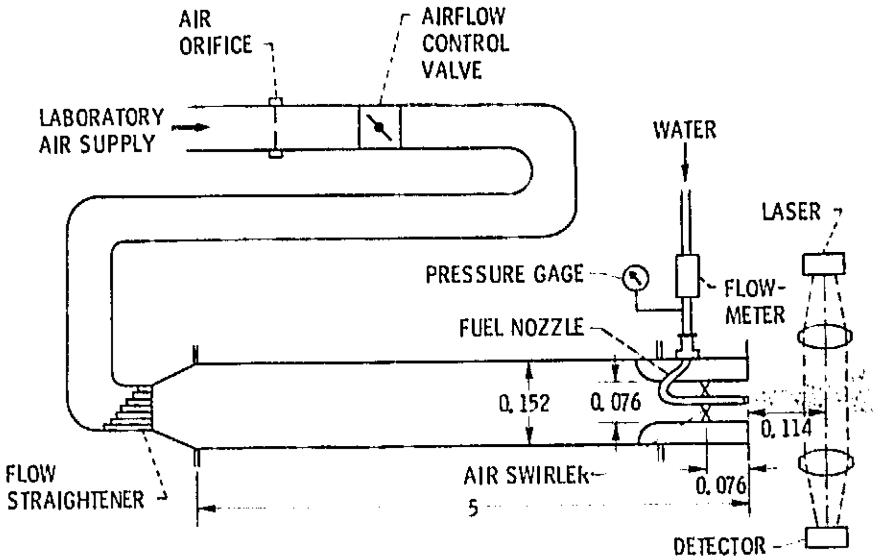

Fig. 1 Test facility and auxiliary equipment. (Dimensions are in meters.)

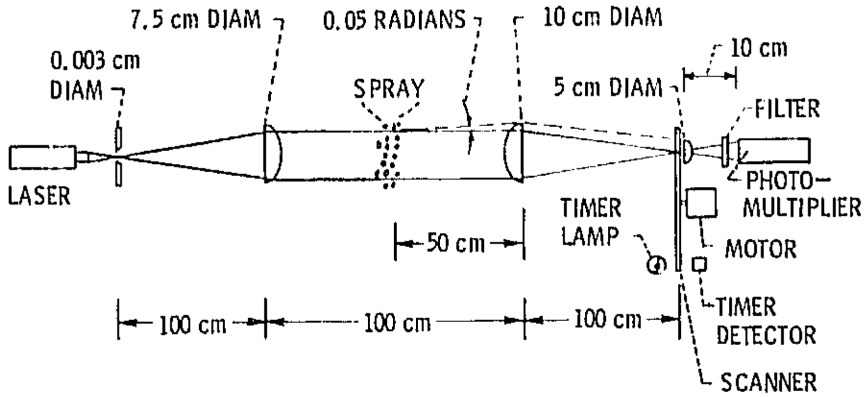

Figure 2. - Scanning radiometer optical path.

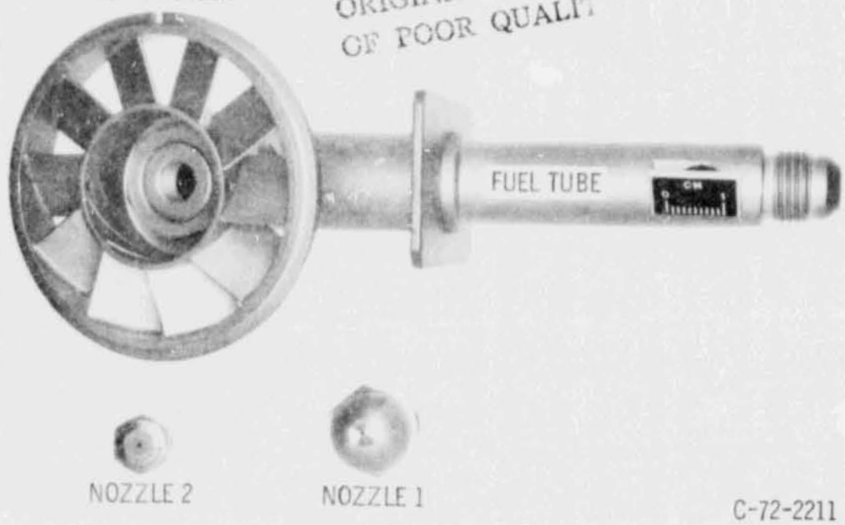

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Figure 3. - Pressure-atomizing nozzles with airswirler and fuel tube.

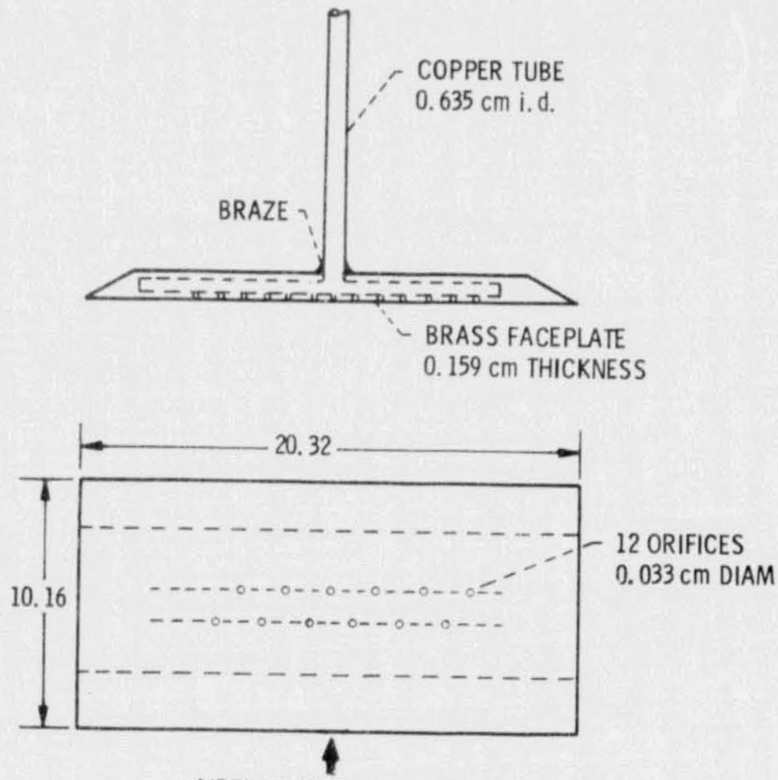

Figure 4. - Schematic diagram of multiple-orifice spray-bar. (Dimensions are in centimeters.)

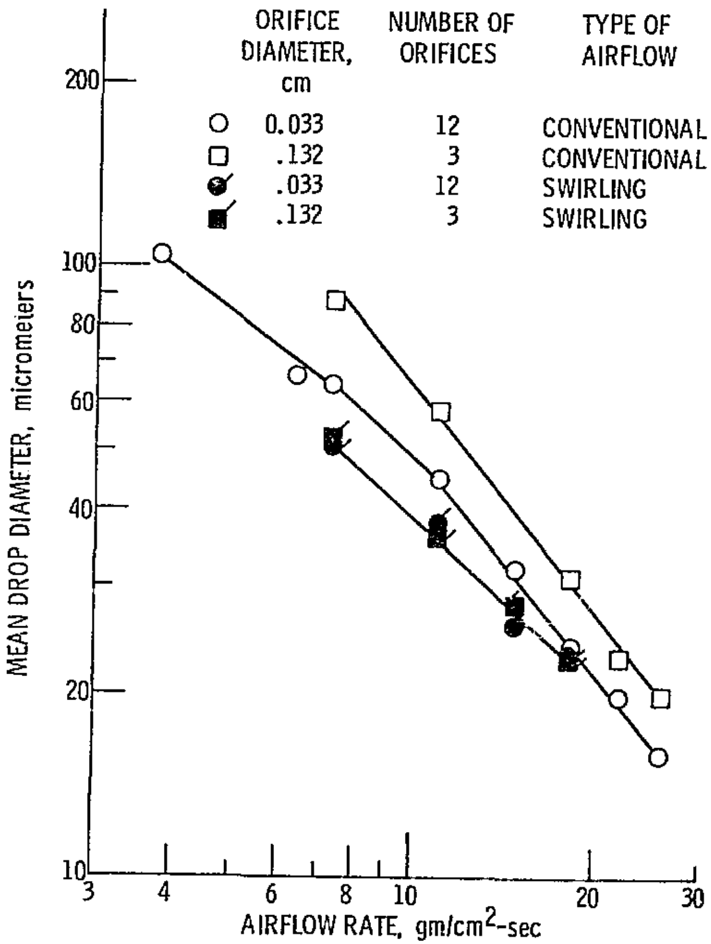

Figure 5. - Variation of mean drop diameter with air-stream momentum for cross stream injection with spray bars.

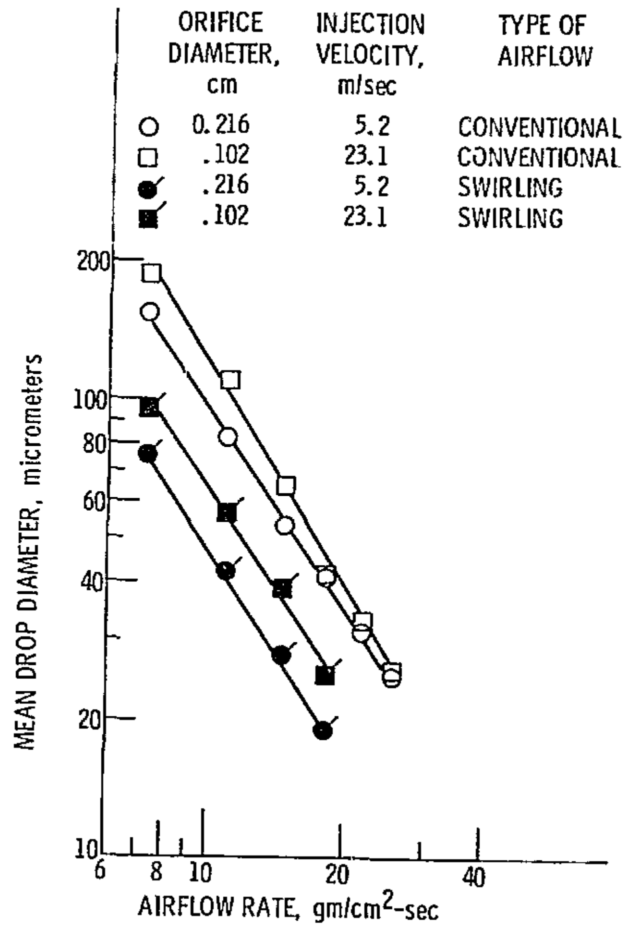

Figure 6. - Variation of mean drop diameter with airstream momentum for axial downstream injection with single tubes.

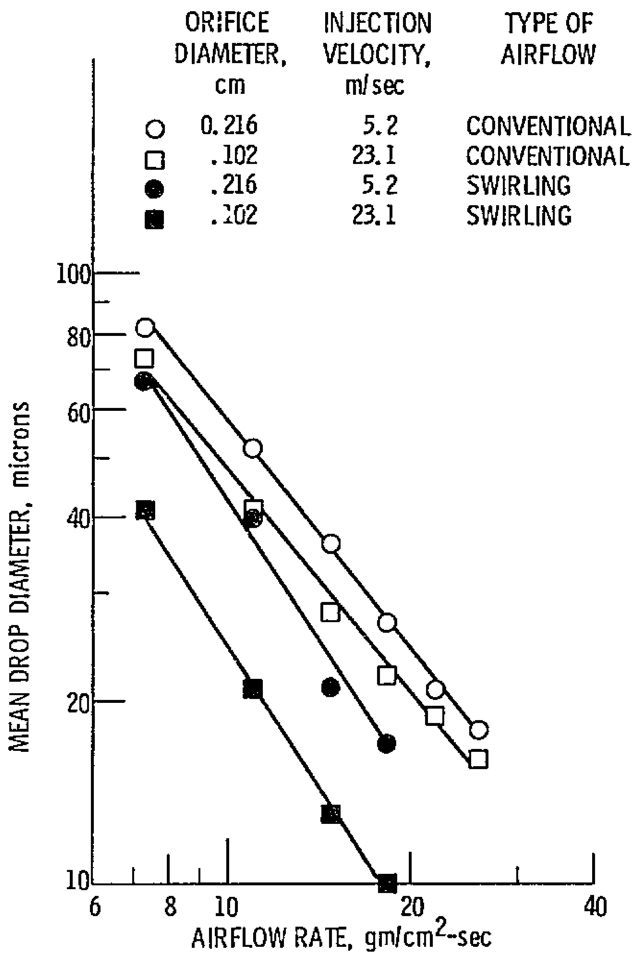

Figure 7. - Variation of mean drop diameter with airstream momentum for axial upstream injection with single tubes.

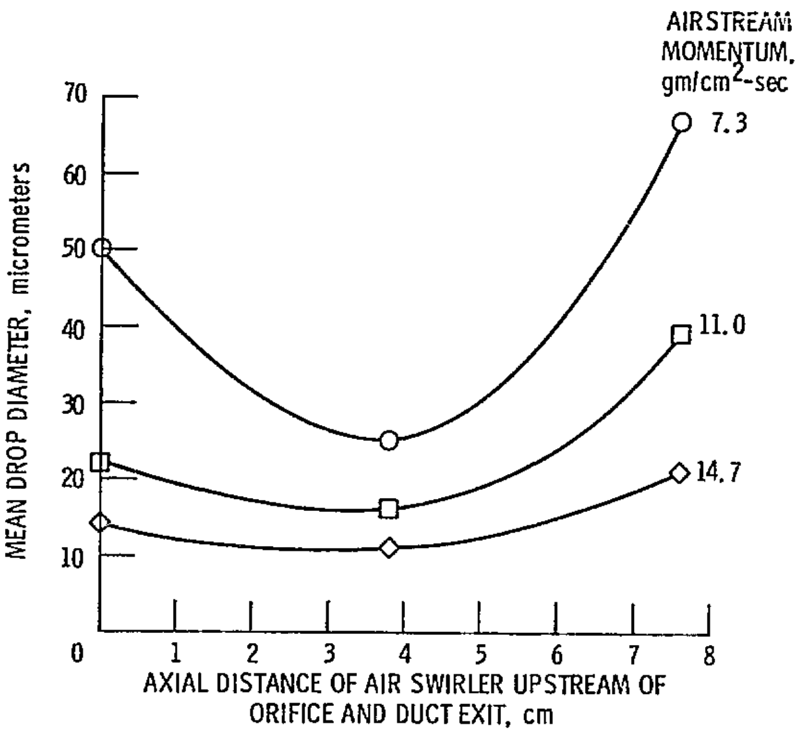

Figure 8. - Variation of mean drop diameter with axial upstream distance between air swirler and injector orifice. Water injected axially upstream with 0.216-centimeter inside diameter tube.

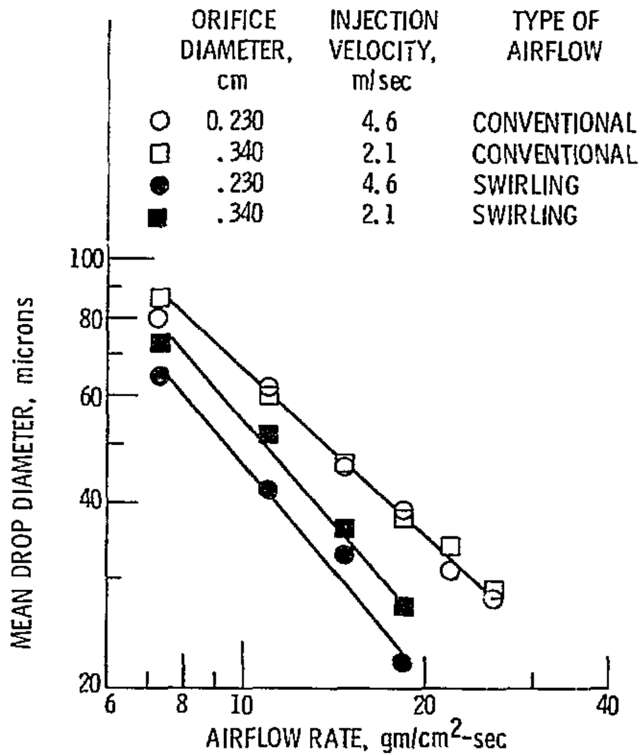

Figure 9. - Variation of mean drop diameter with airstream momentum for axial downstream injection with pressure atomizing nozzles.

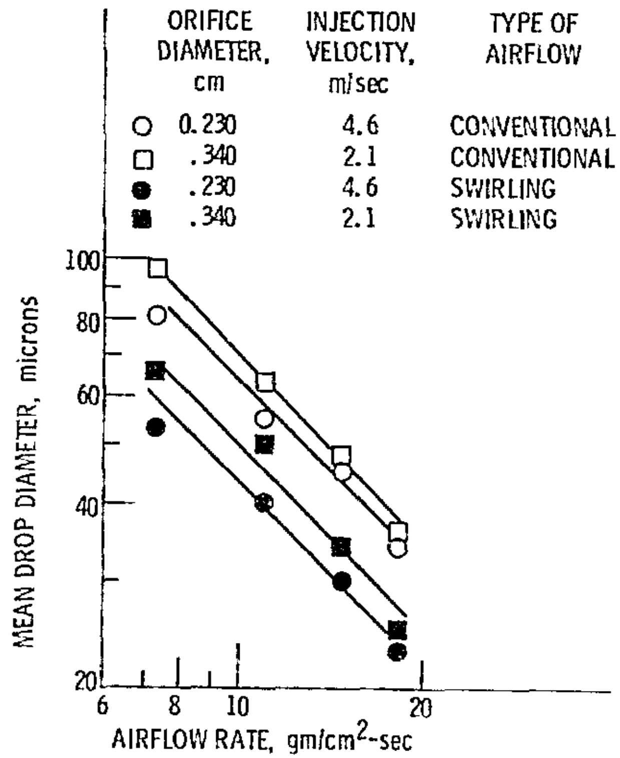

Figure 10. - Variation of mean drop diameter with airstream momentum for cross stream injection with pressure atomizing nozzles.