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Experimental Study of the Spray Characteristics of a Research Airblast Atomizer

Waldo A. Acosta
Propulsion Laboratory
AVSCOM Research and Technology Laboratories
Lewis Research Center
Cleveland, Ohio

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Waldo A. Acosta
Propulsion Laboratory
AVSCOM Research and Technologies Laboratories
Lewis Research Center
Cleveland, Ohio

ABSTRACT

An experimental study of airblast atomization was conducted using an especially designed atomizer in which the liquid first impinges on a splash plate, then is directed radially outward and is atomized by the air passing through two concentric, vaned swirlers that swirl the air in opposite directions. The effect of flow conditions, air mass velocity (mass flow rate per unit area, $\rho_A U_A$) and liquid to air ratio on the mean drop size was studied. Seven different ethanol solutions were used to simulate changes in fuel physical properties. The range of atomizing air velocities was from 30 to 80 m/s. The mean drop diameter was measured at ambient temperature (295 K) and atmospheric pressure.

NOMENCLATURE

D_p prefilmer diameter, m

PE peak of the weight distribution

Re Reynolds number, $\rho DU/\mu$

SMD Sauter mean diameter, m

U velocity, m/s

W mass flow rate, kg/s

W' width of the weight distribution

We Weber number, $D_p \rho U^2/\sigma$

ρ density, kg/m^3

Γ gamma function

σ surface tension, kg/s^2

μ dynamic viscosity, kg/ms

φ efficiency factor

Subscripts:

A air

L liquid

INTRODUCTION

The fuel spray characteristics have a great influence on the performance of gas turbine combustors. A change in the flow conditions or in the physical properties of the fuel produces a change in the spray characteristics of the fuel injector. The latter will have a greater influence in the future when the supply of high-quality fuels cannot be satisfied and fuels with different physical properties must be used. During the past few decades many reseachers have studied the effect of liquid properties and flow conditions on atomization and found empirical equations for the type of fuel injector investigated.

The work of Radcliffe (1) showed that for a swirl atomizer the degree of atomization depends on the viscosity, surface tension, mass flow rate and pressure drop of the fuel. He found the exponents 0.6, 0.2, 0.25, and -0.4 for the surface tension, viscosity, mass flow rate, and pressure drop, respectively. Jasuja (2) worked on fuels having surface tension ranging in viscosity from 1.0×10^{-6} to 93.0×10^{-6} m^2/s finding a different power for the viscosity, 0.16. He observed the same power for the surface tension, 0.6, but the variation was only 20 percent and was accompanied by a large variation in viscosity.

Simmons and Harding (3) studied the atomizing performance of six simplex pressure-atomizers using water and kerosene, liquids with almost the same viscosity, a 30 percent difference in density and a water surface tension three times higher. They concluded that any difference in Sauter Mean Diameter (SMD) was due to the difference in surface tension rather than density. It was found that the power for the surface tension is 0.16 for a constant liquid pressure and 0.19 if the mass flow rate was held constant.

Merrington and Richardson (4) found that the SMD for a plain-orifice atomizer was proportional to the viscosity of the fuel raised to the 0.2 power and inversely proportional to the fuel velocity. For liquid jets injected cross stream from simple orifices into axial-flow airstreams, Ingebo (5) found that the mean drop diameter was proportional to the product of the Weber and Reynolds numbers (WeRe) raised to the 0.25 power for WeRe < 10^6 and proportional to the 0.4 power for WeRe > 10^6.

Fraser, Dombrowski and Routley (6) studied the rotary atomizer. Their studies showed that the SMD is a combination of a constant plus a term including the effects of surface tension, kinematic viscosity, mass flow rates and relative velocity between the air and the fuel. The powers 0.5 and 0.21 were found for surface tension and kinematic viscosity, respectively. Using a large range of disc types, Friedman, Gluckert and Marshall (7) correlated their results for SMD in terms of the operating and liquid variables in dimensionless groups. These groups present the viscosity raised to the 0.2 power and the surface tension and density raised to the 0.1 power.

After studying the experimental data on prefilming types of airblast atomizers Lefebvre (8) concluded that for liquids of low viscosity the main factors governing SMD are liquid surface tension, air density and air velocity, whereas for liquids of high viscosity, the SMD is more dependent on the liquid properties, especially viscosity. This fact had been observed by Nukiyama and Tanasawa (9), Kim and Marshall (10), Lorenzetto and Lefebvre (11), Rizkala and Lefebvre (12), El-Shanawany and Lefebvre (13), and Jasuja (2). They expressed the SMD as the sum of two terms, the first dominated by air density and velocity, and the second by liquid viscosity.

An experimental investigation was conducted to study the effect of mass velocity (mass flow rate/unit area, $\rho_A U_A$), liquid to air ratio, and liquid properties on the spray characteristics of two fuel injector modules designed for high temperature and high pressure combustors. The experiment was conducted in an open duct facility. The SMD of the spray was measured at ambient temperature (295 K) and atmospheric pressure. The liquids used were different aqueous solutions of ethanol.

The measured SMD was plotted against the air mass velocity, liquid to air ratio, and prefilmer diameter for both fuel module injectors. The data were correlated using a basic equation derived by Lefebvre (8).

APPARATUS AND PROCEDURE

Test Facility

A schematic of the test facility is shown in Fig. 1, and a photo in Fig. 2. The fuel injector module was mounted on a 0.635-cm-thick plate and installed on the end of a 15.25-cm-diameter pipe. Air was supplied by the Lewis Research Center's air system with a range of test flow rate from 0.0169 to 0.0684 kg/sec and a maximum pressure of 1.171×10^5 Pa at the fuel module location. A pitot tube was located about 22.5 cm upstream of the injector and connected to a manometer board which was used to set the pressure differential across the module.

A pressurized tank, a 15.25-cm-diameter schedule 40 stainless steel pipe 1.22 m long, was used to supply the ethanol solutions to the fuel injector modules. A pressure regulator was used to keep the pressure of the nitrogen in the tank constant at 5.15×10^5 Pa. The liquid mass flow rate was measured using a rotameter previously calibrated for each solution at the appropriate working temperature.

The exhaust and liquid collection systems consisted of a 0.16-cm-thick stainless steel duct about 38.7 cm in diameter and 3.8 m long, an air operated flow amplifier was used to increase the velocity of the exhaust, a water spray was installed in the duct to dilute the ethanol solutions and avoid any flammable mixture, and a 200 L tank was used to collect the solutions.

Fuel Injector Modules

The fuel injector module designs used in these tests are shown in Fig. 3. Each fuel injector module consisted of two concentric, vaned air-swirlers that swirl the air in opposite directions to create a zone of high shearing action. All vanes were at an angle of 45° to the axial direction. The liquid was supplied to each module by a tube located in the central cavity of each module. The liquid flows from the fuel tube through an 0.084-cm-diameter discharge opening and impinges on a splash plate mounted on the downstream face of each module. This splash plate breaks up the fuel jet and directs it radially outward, where the fuel is further atomized by the air passing through the inner swirler. Additional fuel atomization occurs in the shearing region between flows exiting the counter rotating air swirlers.

Drop Size Measurements

Drop sizes were measured using a Malvern S.T. 1800 Particle and Droplet Size Distribution Analyzer. The Malvern instrument is a nonintrusive optical system based on the Fraunhofer diffraction of a parallel monochromatic light beam scattered by moving droplets. The transmitter portion of the Malvern instrument houses the 2-mW helium-neon laser and beam expander, which emits an approximately 9-mm-diameter beam. The receiver consists of a focusing lens (Fourier transform lens), a multielement photoelectric detector, beam alinement knobs, lamps, and an indicator. A computer with an 8 K memory receives, stores, and processes data inputs from the detector. A teletype with a hard copy printer is used for data output. The output is discussed in the appendix. Two data points were taken at each condition and stored in the computer memory. Measurements were made at the center line of the spray at a distance of 7.62 cm downstream of the fuel injector module.

RESULTS AND DISCUSSION

Mass Velocity

The effect of mass velocity (mass flow rate per unit area, $\rho_A U_A$) on SMD for the fuel injector modules investigated is clearly shown in Figs. 4 and 5. These figures show in general that the SMD decreases with an increase in the mass velocity. The same effect was observed for both modules. Changes in mass velocity were obtained by changing the total air flow rate through the injector modules while keeping the available flow area (including both swirlers) constant. The range of mass velocities was from 37 to 112 kg/m^s and the calculated flow area was 6.420×10^{-4} m^2 for injector module 1 and 4.519×10^{-4} m^2 for injector module 2. The area was calculated at the upstream side of the injector modules.

Liquid To Air Ratio

Tests were conducted to study the effect of liquid to air ratio on SMD. These tests covered a range of liquid to air ratios from 0.0147 to 0.0462 for module 1 and from 0.0202 to 0.0636 for module 2. Figures 6 and 7 show no effect of the liquid flow rate on SMD when the air velocity rate is kept constant at different concentrations of ethanol.

Liquid Properties

Many tests were made to determine the atomizing performance of two especially designed fuel injector modules operating with liquids of different physical properties. A number of aqueous solutions of ethanol were prepared representing the following range of liquid properties:

surface tension = 0.0290 to 0.0555 kg/s^2
dynamic viscosity = 0.001226 to 0.002684 kg/ms
density = 890.7 to 988.0 kg/m^3

Samples of the solutions were analyzed using standard laboratory techniques to measure surface tension, viscosity and density. Table I presents the results of those measurements.

The effect of ethanol concentration on SMD for the fuel modules studied is shown in Fig. 8. Both figures show a decrease in the SMD with an increase in the ethanol concentration, i.e., decrease in surface tension.

Figure 8 shows a comparison between data from Ref. 12 for an airblast atomizer and data from this investigation. Both fuel injector modules produced smaller droplets than the airblast atomizer for the same air velocity, 60 m/s. The only difference is the liquid flow rate, but Figs. 6 and 7 showed the SMD is not affected by changes in the liquid to air ratio. This figure shows the benefits created by the high shearing action between the flows exiting the counter rotating air swirlers compared with the airblast atomizer of Ref. 12. Note that the liquid surface tension was used as a parameter because the liquid used in Ref. 12, aqueous solutions of Butan-2-ol, have almost the same physical properties.

Linear Scale

Two identically designed fuel injector modules were used in this investigation. The only difference was the size and the number of swirler vanes (Fig. 3). Module 2 is approximately 20 percent smaller in diameter than module 1, having a prefilmer diameter, Dp, of 1.2 and 1.5 cm, respectively. The influence of atomizer scale on SMD is illustrated in Fig. 9. This figure shows module 2 producing smaller droplets than module 1 under the same operating conditions.

Data Analysis

The experimental data gathered in this investigation were correlated using the basic equation derived by Lefebvre (8) with the experimental constants of Ref. 13

$$SMD = \left\{0.073\left(\frac{\sigma_L}{\rho_A U_A^2}\right)^{0.6}\left(\frac{\rho_L}{\rho_A}\right)^{0.1} D_p^{0.4} + 0.015\left(\frac{\mu_L^2 D_p}{\rho_L \sigma_L}\right)^{0.5}\right\}\left(1 + \frac{W_L}{W_A}\right) \qquad (1)$$

As stated in Ref. 13, the experimental constants 0.073 and 0.015 may have to be modified by an efficiency factor, φ, whose values will depend on the atomizer design and will take into account the presence of extraneous devices, such as air swirlers, and the different methods of drop size measurement. Figures 10 and 11 compare the SMD measured in the present investigation with values predicted by Eq. (1). Good agreement is shown in Fig. 11 for a value of φ of 0.59. Figure 10 shows good agreement in the high velocity region for the same value of φ, but does not describe the experimental data very well in the intermediate to low velocity region i.e., less than 60 m/s, corresponding to drop sizes greater than 60 μ.

SUMMARY AND CONCLUSIONS

An experiment was conducted at atmospheric pressure to determine the effect of liquid physical properties and flow conditions on the Sauter Mean Diameter, SMD, using two geometrically-similar research airblast atomizers designed for high pressure and temperature combustors.

After studying the effects of the different variables involved in this investigation it is found that:

1. The SMD of the spray decreases with increases in ethanol concentration due to changes in the physical properties as shown in Table I.

2. Increasing the air velocity decreases the SMD which varied inversely with air velocity, of all the variables, air velocity has the most dominant effect on the atomization process of the fuel injector modules investigated.

3. An increase in atomizer scale increases the mean drop diameter.

4. The air to liquid ratio has no measurable effect on the SMD of sprays produced by any of the two fuel injector modules.

5. The SMD performance of the airblast atomizers, when spraying in stagnant air at atmospheric pressure, is predicted with a reasonable degree of accuracy by the correlation:

$$SMD = \left\{0.1237\left(\frac{\sigma_L}{\rho_A U_A^2}\right)^{0.6}\left(\frac{\rho_L}{\rho_A}\right)^{0.1} D_p^{0.4} + 0.0254\left(\frac{\mu_L^2 D_p}{\rho_L \sigma_L}\right)^{0.5}\right\}\left(1 + \frac{W_L}{W_A}\right) \qquad (2)$$

for the following range of test conditions

Surface tension = 0.0290 to 0.0555 kg/s^2
Dynamic viscosity = 0.001226 to 0.002684 kg/ms
Liquid density = 890.7 to 988.0 kg/m^3
Air velocity = 30 to 80 m/s
Liquid to air ratio = 0.0147 to 0.0776
Air density was not varied appreciably.

REFERENCES

1. Radcliffe, A., "The Performance of a Type of Swirl Atomizer," Proceedings, Institution of Mechanical Engineers, Vol. 169, 1955, pp. 93-106.

2. Jasuja, A.K., "Atomization of Crude and Residual Fuel Oils," Journal of Engineering For Power, Vol. 101, No. 2, Apr. 1979, pp. 250-258.

3. Simmons, H.C., and C.F. Harding, "Some Effects of Using Water as a Test Fluid in Fuel Nozzle Spray Analysis," Journal of Engineering for Power, Vol. 103, No. 1, Jan. 1981, pp. 118-123.

4. Merrington, A.C., and Richardson, E.G., "The Break-Up of Liquid Jets," Proceedings of the Physical Society, Vol. 59, Part 1, No. 331, Jan. 1, 1947, pp. 1-13.

5. Ingebo, R.D., "Capillary and Acceleration Wave Breakup of Liquid Jets in Axial-Flow Airstreams," NASA TP-1791, 1981.

6. Fraser, R.P., Dombrowski, N., and Routley, J.H., "The Production of Uniform Liquid Sheets from Spinning Cups"; "The Filming of Liquids by Spinning Cups"; The Atomization of a Liquid Sheet by an Impinging Air Stream," Chemical Engineering Science, Vol. 18, No. 6, June 1963, pp. 315-321, 323-337, 339-353.

7. Friedman, S.J., Gluckert, F.A., and Marshall, W.R., Jr., "Centrifugal Disc Atomization," Chemical Engineering Progress, Vol. 48, No. 4, Apr. 1952, pp. 181-191.

8. Lefebvre, A.H., "Airblast Atomization," Progress in Energy and Combustion Science, Vol. 6, 1980, pp. 233-261.

9. Nukiyama, S. and Tanasawa, Y., "Experiments on the Atomization of Liquids By Means of Air Stream," Transactions of Society of Mechanical Engineers, Japan, Part I, Vol. 4, No. 14, Feb. 1938, pp. 86-93; Part II, Vol. 4, No. 15, May 1938, pp. 138-143; Part III-IV, Vol. 5, No. 18, Feb. 1939, pp. 63-75; Part V, Vol. 6, No. 22, Feb. 1940, pp. II-7-15; Part VI, Vol. 6, No. 23, May 1940, pp. II-18-28.

10. Kim, K.Y., and Marshall, W.R., Jr., "Drop-Size Distributions from Pneumatic Atomizers," American Institute of Chemical Engineers Journal, Vol. 17, No. 3, May 1971, pp. 575-584.

11. Lorenzetto, G.E., and Lefebvre, A.H., "Measurements of Drop Size on a Plain Jet Airblast Atomizer," AIAA Journal, Vol. 15, No. 7, July 1977, pp. 1006-1010.

12. Rizkalla, A.A., and Lefebvre, A.H., "Influence of Liquid Properties on Airblast Atomizer Spray Characteristics," Journal of Engineering for Power, Vol. 97, No. 2, Apr. 1975, pp. 173-179.

13. El-Shanawany, M.S., and Lefebvre, A.H., "Airblast Atomization: Effect of Linear Scale on Mean Drop Size," Journal of Energy, Vol. 4, No. 4, July-August 1980, pp 184-189.

APPENDIX - OUTPUT FROM THE MALVERN S.T. 1800 PARTICLE AND DROPLET SIZE DISTRIBUTION ANALYZER

The Malvern instrument is a nonintrusive optical system based on the laser diffraction principle. This instrument uses the Rosin-Rammler weight distribution model. The Rosin-Rammler distribution is defined as follows

$$P(x) = \frac{W' x^{W'-1}}{PE^{W'}} \exp\left\{-(x/PE)^{W'}\right\}$$

where $P(x)$ is the weight or volume fraction of particles in the range x to $x + dx$ where x is in microns. The parameters PE and W' characterize the peak of the weight distribution and its width. PE is in microns and W' is a dimensionless number usually in the range from one for very wide weight distributions to 10 for very narrow weight distributions. The values of the two parameters, PE and W', which give the minimum error, E, define the size distribution. Using the values of PE, W' and the gamma function the Sauter Mean Diameter (SMD) can be calculated. The following formula is used

$$SMD = \frac{PE}{\Gamma\left(1 - \frac{1}{W'}\right)}$$

where SMD is in microns and Γ is the tabulated gamma function.

Figure 13 shows an example of the output. The first line of output is the peak PE, width W', and error E of the distribution. The first column gives the droplet size ranges in microns. The next three columns are the spray distributions as percent weight fraction, cumulative percent by weight, and normalized percent by number density. The last two columns are the calculated and actually measured energy distributions.

TABLE I. - LIQUID PROPERTIES

Level tested	Solution, percent ethanol	μ, kg/ms	σ, kg/s^2	ρ, kg/m^3
1	5	0.001226	0.0555	988.0
2	7.5	.001264	.0530	985.3
3	10	.001438	.0485	980.8
4	20	.001973	.0395	969.4
5	30	.002488	.0340	952.4
6	40	.002684	.0325	936.0
7	60	.002424	.0290	890.7

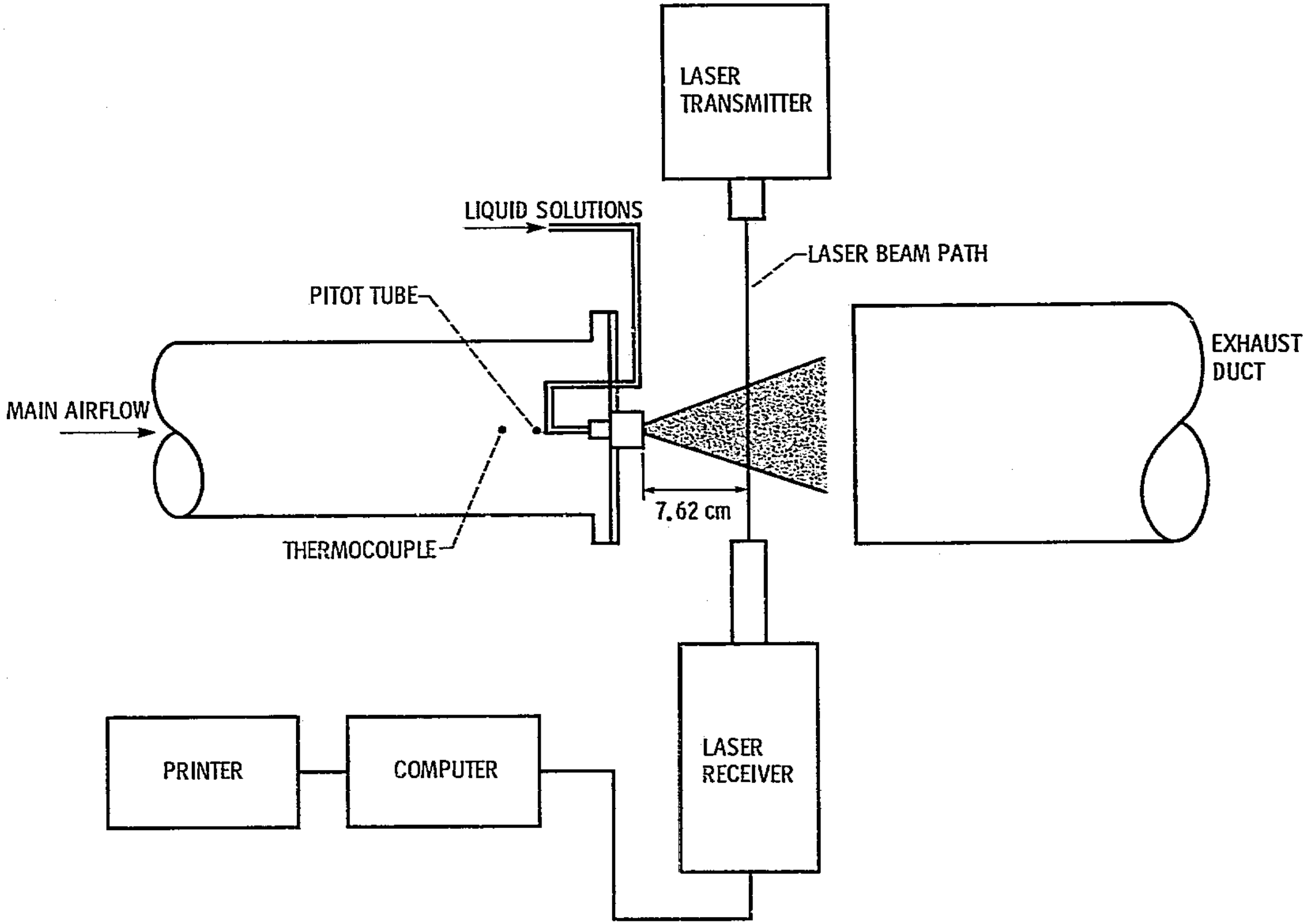


Figure 1. - Test facility schematic. (Not to scale.)

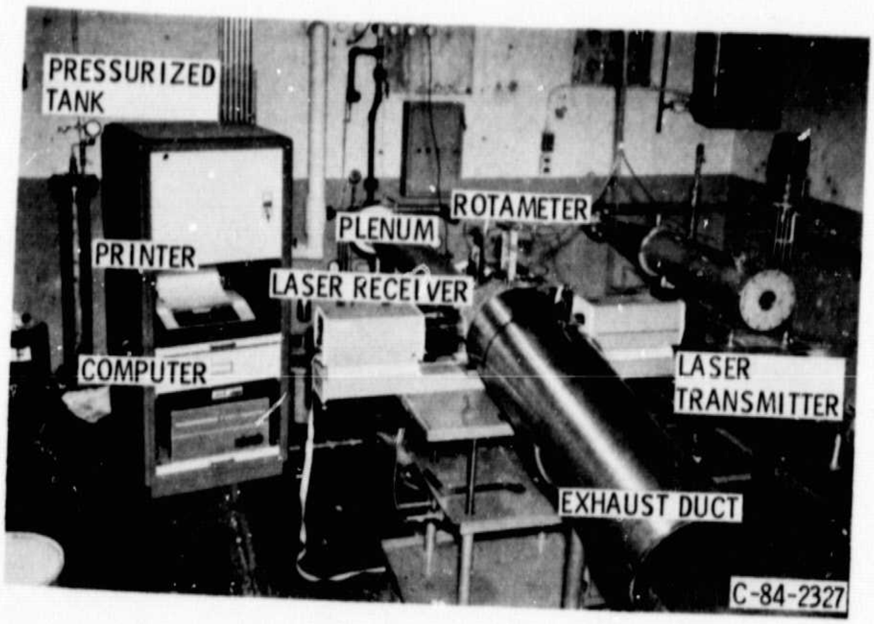
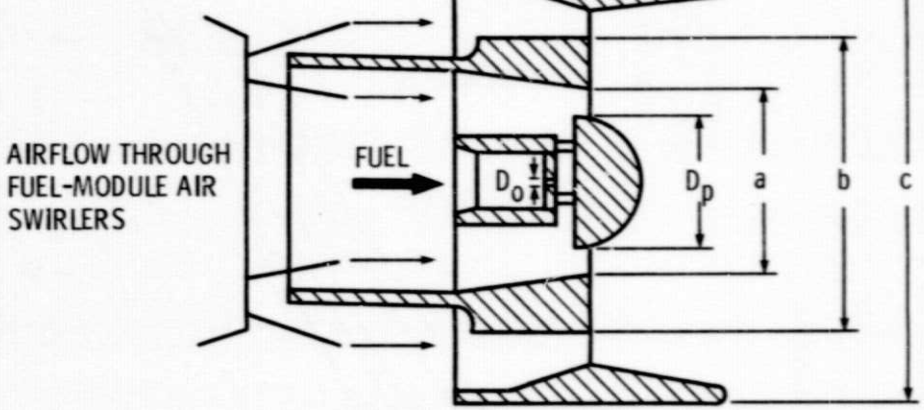


Figure 2. - Test facility.



DIMENSION, cm	D_p	D_o	a	b	c
MODULE 1	1.5	0.084	2.2	3.6	5.2
MODULE 2	1.2	.084	1.8	2.9	4.2

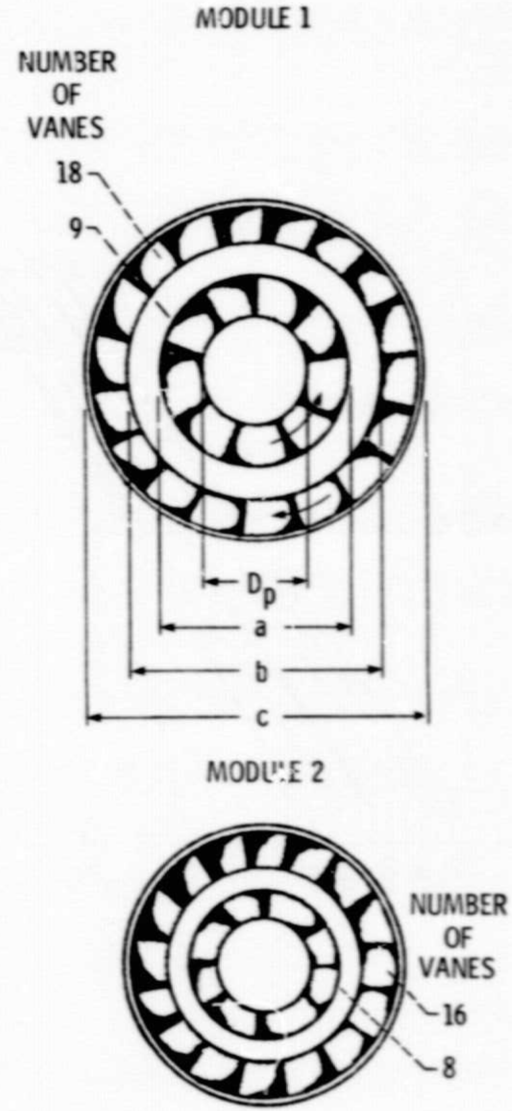


Figure 3. - Schematic of fuel modules.

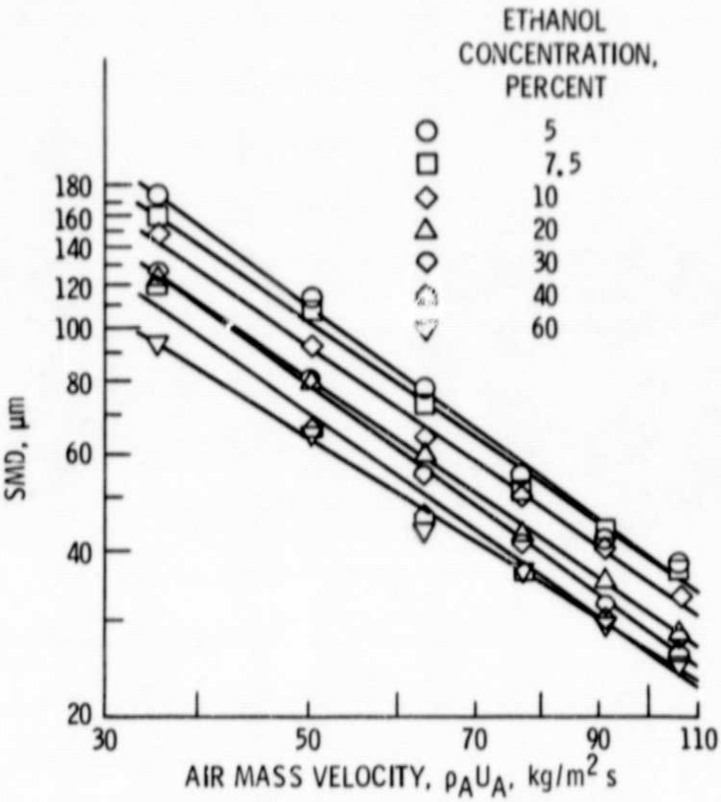


Figure 4. - Relationship between SMD and mass velocity for different concentrations of ethanol for Module 1.

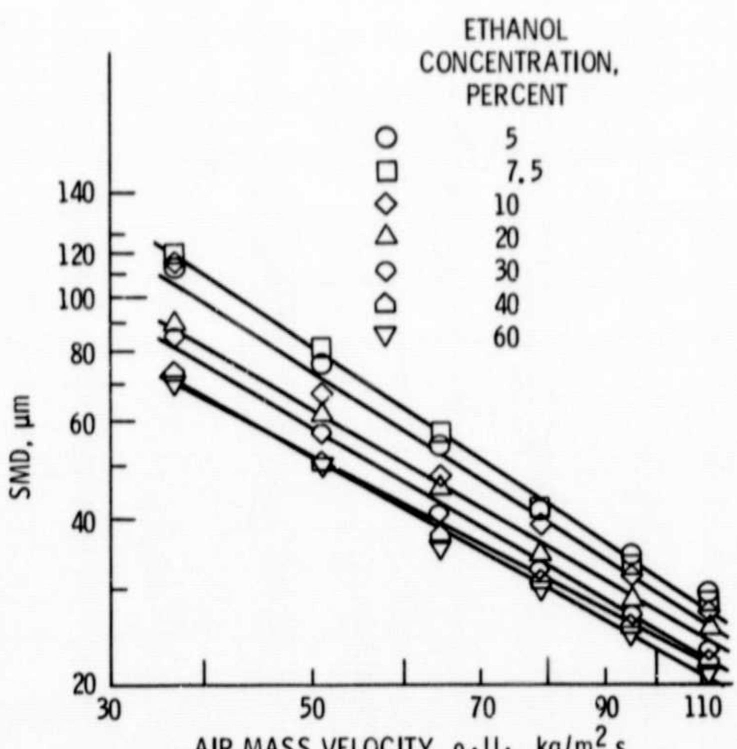


Figure 5. - Relationship between SMD and mass velocity at different concentrations of ethanol for Module 2.

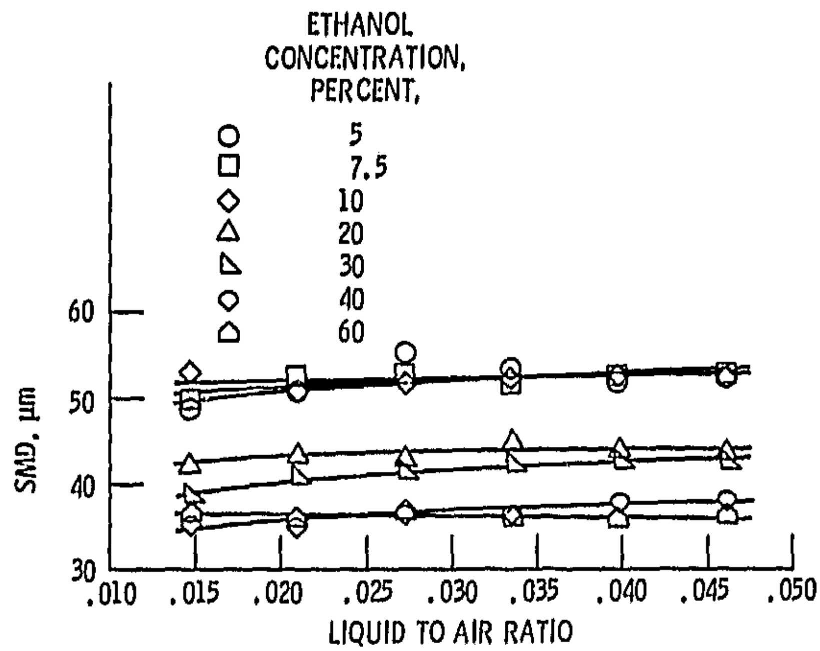


Figure 6. - Variation of SMD with liquid to air ratio at a constant atomizing air velocity for Module 1. U_A = 60 m/s.

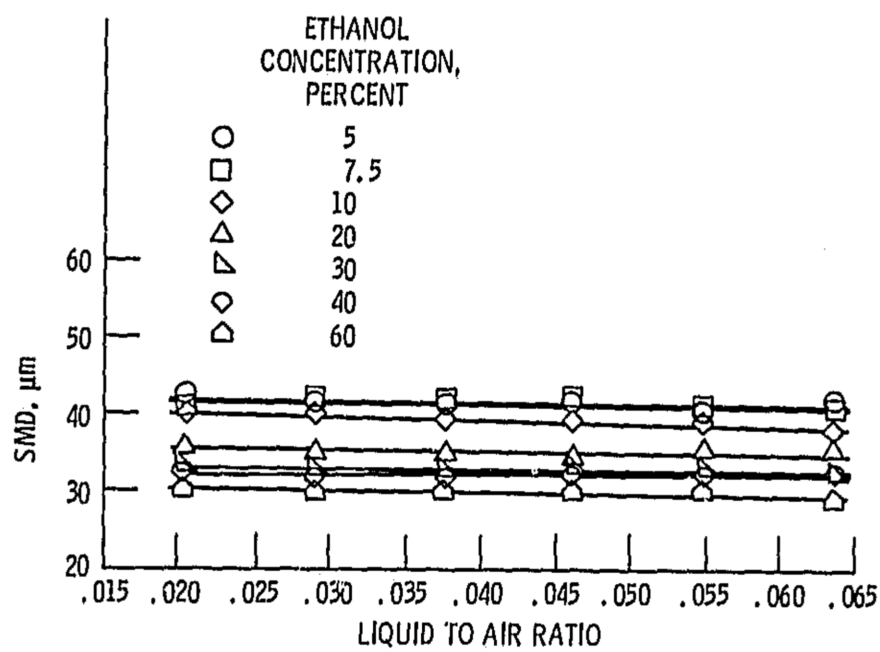


Figure 7. - Variation of SMD with liquid to air ratio at a constant atomizing air velocity for Module 2. U_A = 60 m/s.

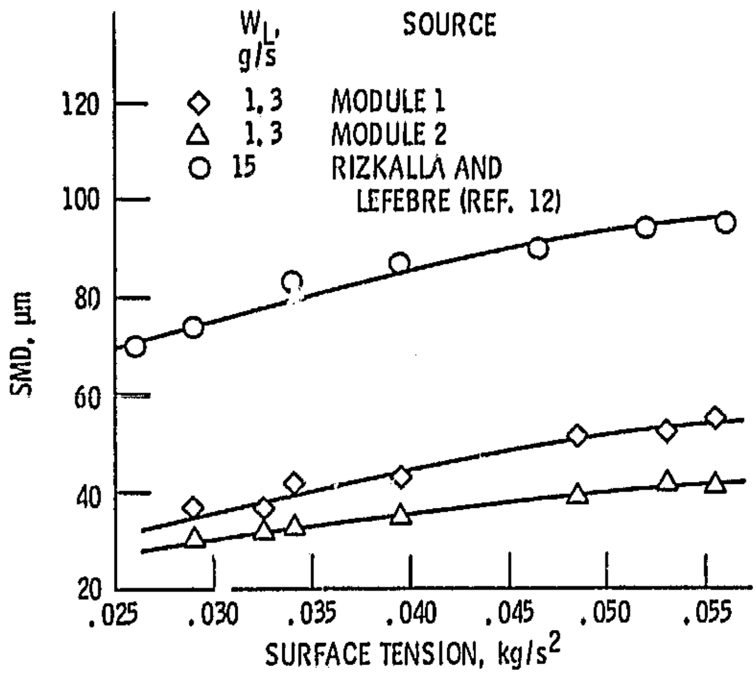


Figure 8. - Comparison between an airblast atomizer and the fuel injector modules. U_A = 60 m/s.

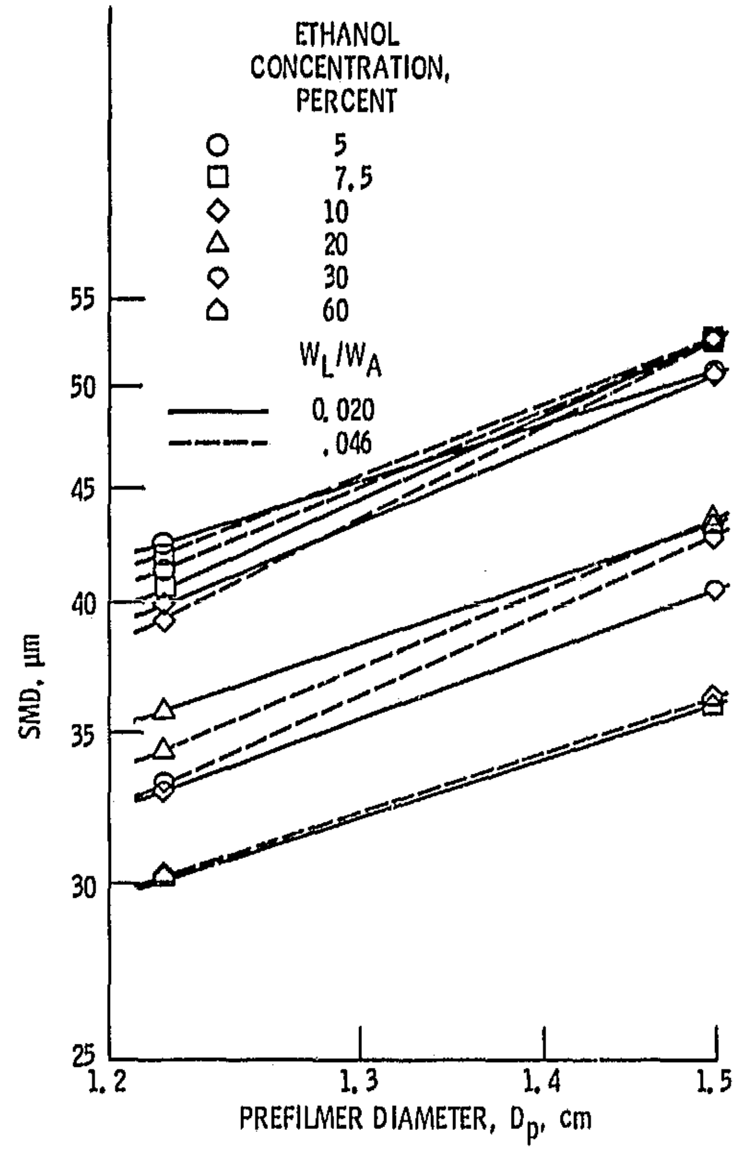


Figure 9. - Effect of linear scale on SMD. U_A = 60 m/s.

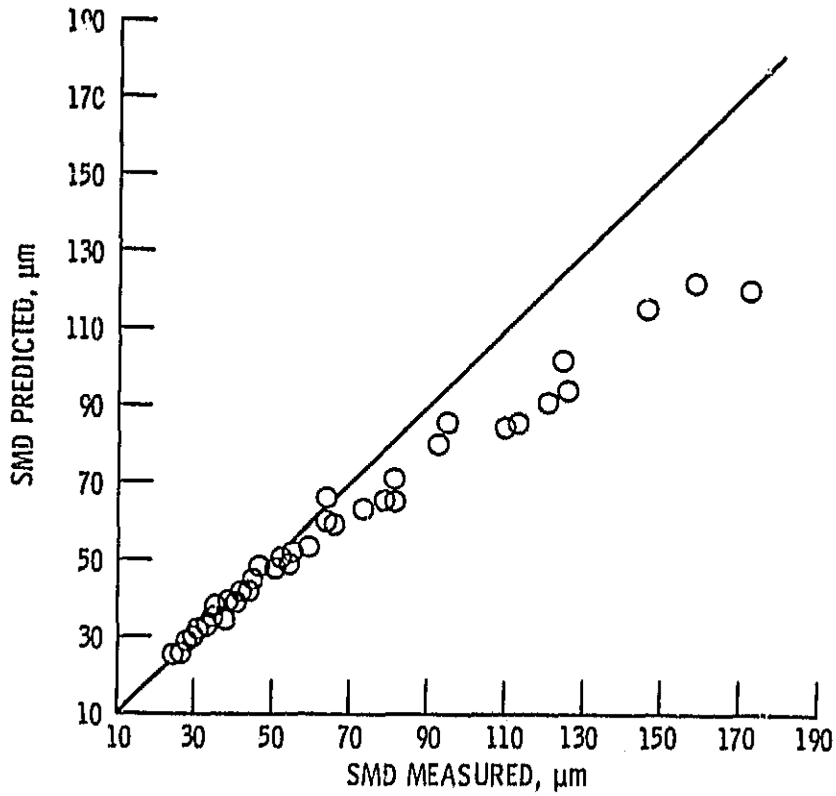


Figure 10. - Comparison of measured and predicted values of SMD from equation (2), Module 1.

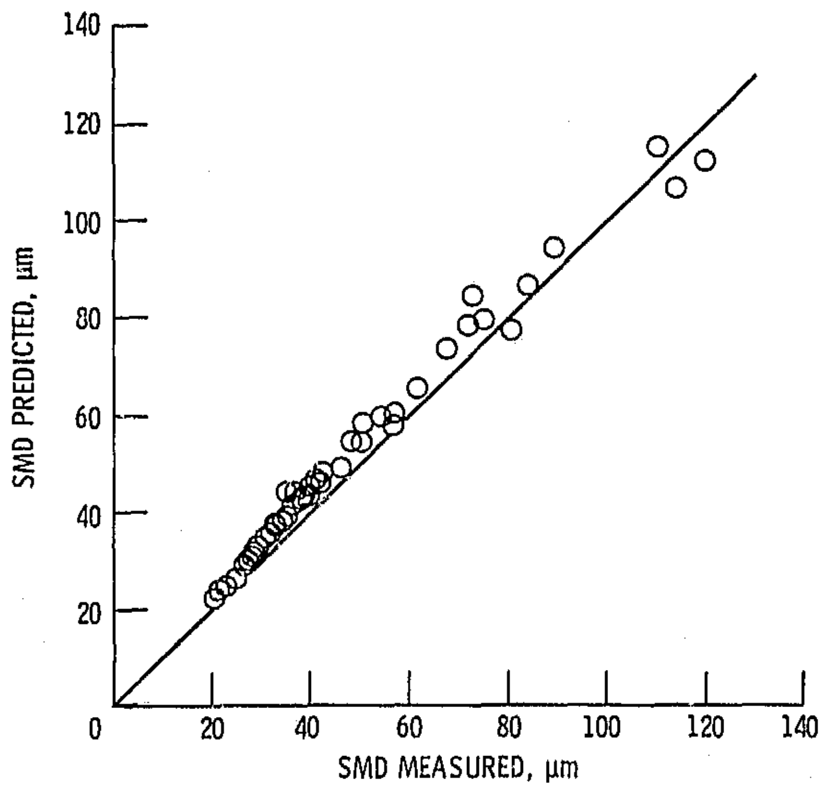


Figure 11. - Comparison of measured and predicted values of SMD from equation (2), Module 2.

> PE = +102.0 W = +2.4 E = 00313752

D = +562.86	> +261.71	P = +0.01%	R = +99.99%	N = +0.00%	C = 0698	A = 0756
D = +261.71	> +160.29	P = +5.18%	R = +94.81%	N = +0.03%	C = 1005	A = 1157
D = +160.29	> +112.86	P = +22.76%	R = +72.05%	N = +0.54%	C = 1380	A = 1424
D = +112.86	> +84.29	P = +25.17%	R = +46.88%	N = +1.60%	C = 1707	A = 1646
D = +84.29	> +64.57	P = +18.50%	R = +28.38%	N = +2.73%	C = 1970	A = 1780
D = +64.57	> +50.29	P = +11.64%	R = +16.74%	N = +3.74%	C = 2044	A = 2002
D = +50.29	> +38.86	P = +7.34%	R = +9.39%	N = +5.05%	C = 1980	A = 2047
D = +38.86	> +30.29	P = +4.11%	R = +5.28%	N = +6.06%	C = 1783	A = 2002
D = +30.29	> +23.71	P = +2.31%	R = +2.97%	N = +7.14%	C = 1542	A = 1869
D = +23.71	> +18.57	P = +1.31%	R = +1.66%	N = +8.42%	C = 1303	A = 1557
D = +18.57	> +14.57	P = +0.73%	R = +0.93%	N = +9.77%	C = 1067	A = 1112
D = +14.57	> +11.43	P = +0.41%	R = +0.52%	N = +11.39%	C = 0867	A = 0623
D = +11.43	> +9.14	P = +0.22%	R = +0.31%	N = +12.08%	C = 0691	A = 0356
D = +9.14	> +7.14	P = +0.14%	R = +0.17%	N = +15.39%	C = 0541	A = 0222
D = +7.14	> +5.71	P = +0.07%	R = +0.10%	N = +16.06%	C = 0419	A = 0178

Figure 12. - Example of output from Malvern particle and droplet size distribution analizer.