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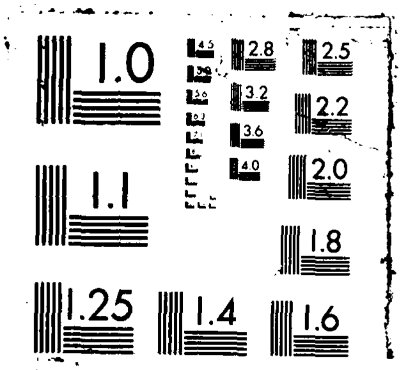
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(4)

J85-21 FUEL NOZZLE ATOMIZATION TESTS

INTERIM REPORT
BFLRF No. 226

By
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Ignition and lean blowout tests were previously conducted at the Naval Air Propulsion Center for a J85-21 combustor using three fuels, JP-5, Suntech A, and NDF. In order to help correlate those tests results, Southwest Research Institute conducted atomization tests with a J85-21 fuel atomizer on the same three fuels over a range of air conditions corresponding to air densities used in the combustor tests. The results of those atomization tests are presented in this report. Some significant conclusions from the atomization tests are as follows.

The J85-21 combustor uses a dual-orifice pressure-swirl atomizer in which fuel flow is restricted to the primary nozzle for flows below about 3.30 grams/s, but flows through both the primary and secondary nozzles at higher flows. This results in

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19. ABSTRACT

a complex relationship between average drop sizes and fuel flow rates. At flows below 3.30 g/s, the drop sizes decrease with increasing fuel flow. As the flow rate increases just above 3.30 g/s, the drop sizes increase as flow begins in the secondary nozzle. At still higher fuel flows the increased pressure drop causes a decrease in drop sizes. This complex relationship between fuel flow rate and drop sizes may complicate the interpretation of the ignition and blowout tests. In future tests this complication could be avoided by restricting flow to the primary or secondary nozzle only.

Fuel property effects on atomization were significant only at the lowest fuel flow rates, where the NDF and Suntech A exhibited degraded atomization relative to JP-5. Increases in air density tended to decrease the drop-sizes due to increased air friction forces.

FOREWORD/ACKNOWLEDGEMENTS

This work was performed by the Belvoir Fuels and Lubricants Research Facility (BFLRF) located at Southwest Research Institute (SwRI), San Antonio, Texas under Contract No. DAAK70-85-C-0007 with the Belvoir Research, Development and Engineering Center (BRDEC). The work was performed during May 1986 through May 1987. Funding was provided by the Naval Air Propulsion Center (NAPC) through a Military Interdepartmental Purchase Requisition. Mr. P.A. Karpovich, Mr. James J. Zidzik, and Mr. Anthony Klarman were the principal NAPC staff members providing program direction. Mr. F.W. Schaekel of BRDEC (STRBE-VF) served as the Contracting Officer's representative, and Mr. M.E. LePera, Chief of Fuels and Lubricants Research Division (STRBE-VF) as the project technical monitor.

Mr. R.C. Haufler and Mr. M.G. Ryan conducted the experimental measurements. Ms. S.J. Hoover performed the manuscript preparation with the assistance of Mr. J.W. Pryor. Dr. C.A. Moses, Mr. S.J. Lestz, and Mr. J.P. Cuellar, Jr. provided assistance in contract management.

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INTRODUCTION

A series of ignition and lean blowout tests were previously performed with a J85-21 combustor at the Naval Air Propulsion Center (NAPC). These tests were conducted at a constant air temperature of 241°C (465°F) and fuel temperature of 18.3°C (65°F), but at air pressures ranging from 101 to 517 kPa (14.7 to 75 psia). Fuel flow rates ranged from 0.94 to 19.95 grams/s (7.5 to 158.3 lbm/hr) using JP-5, Suntech A, and Navy distillate fuel (NDF).

The results from these ignition and blowout tests will be correlated by NAPC personnel or their contractors using the characteristic time model.(1-5)* One critical parameter in that model is the Sauter mean diameter (SMD) or D_{32} of the fuel spray, which is a measure of average drop size. Fuel sprays are easier to ignite as the SMD becomes smaller. Atomization tests of the J85-21 fuel nozzle were performed at Belvoir Fuels and Lubricants Research Facility (SwRI) to determine this parameter for the characteristic time model.

Thus, the objective of this program was to measure the atomization characteristics of the J85-21 atomizer using the same fuels and flow conditions as those used by NAPC for the ignition and blowout tests. The test matrix including fuel properties, fuel flow rates, and air conditions was supplied by NAPC. The results of those atomization tests are discussed in this report.

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* Superscript numbers in parentheses refer to the list of references at the end of this report.

EXPERIMENTAL APPARATUS

The J85-21 fuel nozzle atomization tests were carried out at the gas turbine combustor laboratory at Belvoir Fuels and Lubricants Research Facility (SwRI). This facility is capable of supplying air at flow rates up to 1.1 kg/s (2.5 lbm/s) at temperatures to 815°C (1500°F) and pressures to 1620 kPa (235 psia). These conditions spanned those required to duplicate the test conditions used at NAPC for the ignition and blowout tests.

The test section used for the atomization tests is shown schematically in Fig. 1 and described in detail in Ref. 6. The test section consists of a type 316 stainless steel pipe, 168.3 mm OD, 125.0 mm ID, 21.7 mm wall thickness, with quartz windows on each side having a clear aperture of 92 mm by 67 mm. A smooth transition section 55 mm long is provided on each end of the windows to reduce recirculation zones. Each window is purged by air on both top and bottom. Air is supplied to each window by a total of 10 tubes of nominal 0.635 cm OD and then diffused and exhausted by a convergent section parallel to the window surface. The J85-21 fuel atomizer was mounted about even with the upstream edge of the windows. Drop-size measurements were performed through the centerline of the spray at an axial distance of 42.7 mm (1.68 in.) downstream of the atomizer tip. This dimension was supplied by NAPC personnel and corresponds to the axial distance between the atomizer and igniter in a J85 combustor. The fuel line was water-cooled to maintain a constant fuel temperature of about 29°C (85°F).

Drop size data were obtained with a Malvern Model 2200 Particle Sizer based on principles of forward light scattering or Fraunhofer diffraction. When illuminated by a beam of monochromatic, coherent, collimated light from a HeNe laser, the smaller drops diffract light at larger angles to the optical axis than the larger drops, and a unique diffraction pattern is formed. Detection is accomplished with a 30-annular ring set of solid-state detectors. Detector outputs are multiplexed and the data signal averaged with a Commodore PET computer. A computer routine is used to interpret the light-scattering pattern of the polydisperse drop systems and to compute the drop-size distribution. The drop-size distributions are available in two general formats. For the first format, the size distribution is assumed to be monomodal (single-peaked) and to follow a Rosin-Rammler, log-normal, or normal distribution, at the choice of the operator. In the second case, no assumption is made about the shape or the number of peaks in the distribution. In that case, called the model-independent analysis, the size distribution is presented as a histogram divided into 15 size classes. A 300-mm focal length f/7.3 lens was used to collect the scattered light. The laser beam diameter was 3 mm.

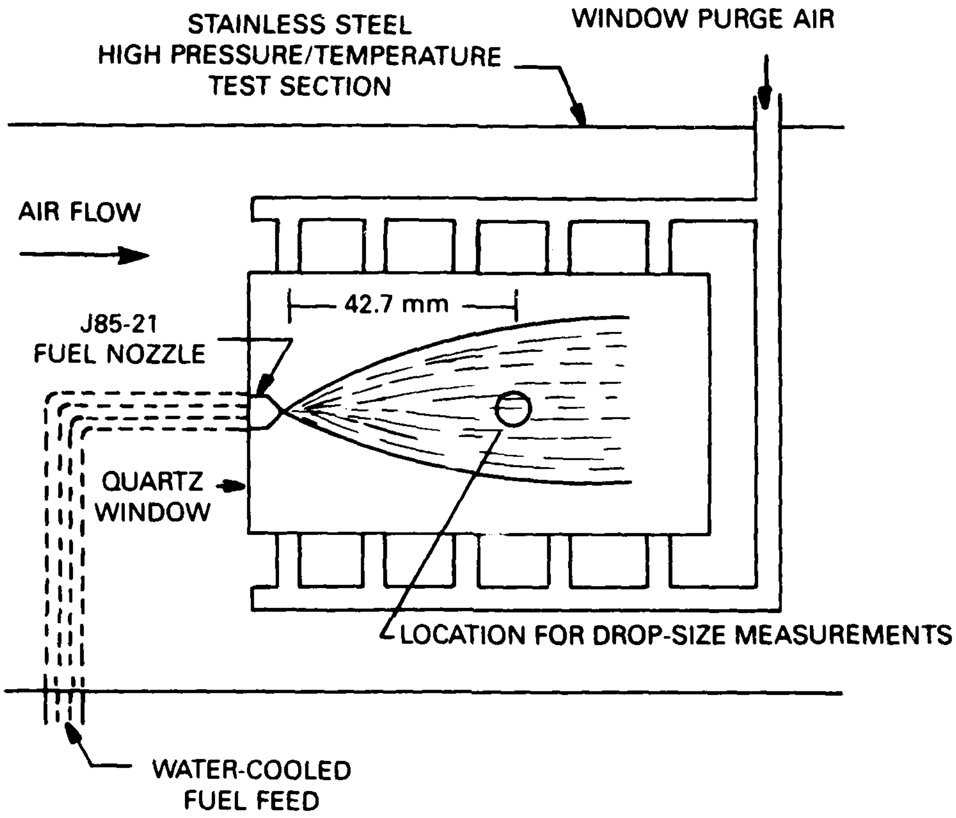

Figure 1. High pressure/temperature test section

A standard J85-21 dual-orifice pressure-swirl atomizer was supplied by NAPC for these tests. TABLE 1 shows identifying numbers found on the atomizer. The flow rate characteristics of this atomizer were measured at SwRI with a Micro Motion Model D6 (Coriolis-effect) flowmeter and are shown in Fig. 2. The abrupt change in flow characteristics at a pressure differential of about 820 kPa (120 psia) is due to the opening of the flow-divider valve and the resulting fuel flow to the secondary nozzle of the atomizer. This corresponds to a mass flow rate transition point of about 3.30 g/s (26.2 lbm/hr). The flow characteristics shown in Fig. 2 agree closely with those published by Oller, et al.(7)

TABLE 1. Identification Numbers on J85-21 Fuel Nozzle Tested

1 S/N P 7367
71895 37751
99207
5007T85P06
P

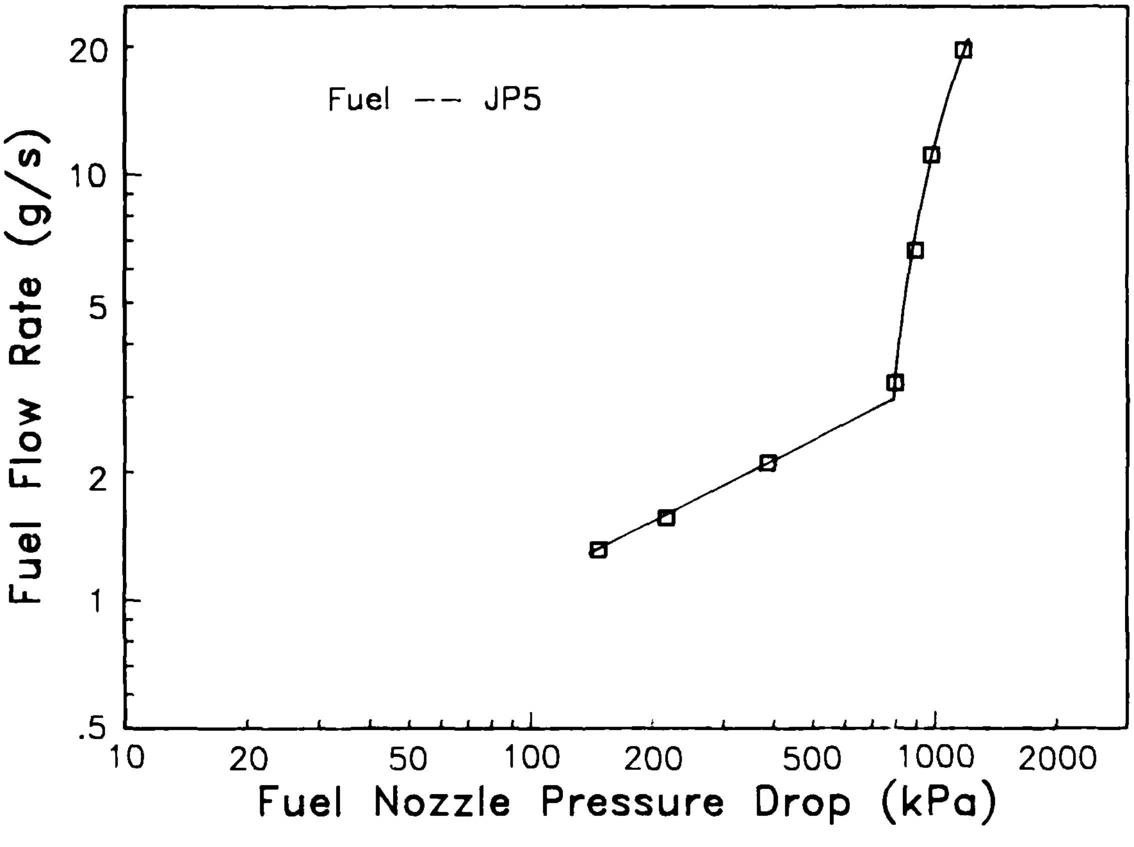

Figure 2. Flow characteristics of J85-21 fuel atomizer

The fuels were supplied by NAPC and consisted of a standard JP-5, a high-energy density liquid fuel (Suntech A), and a Navy distillate fuel (NDF) with properties as specified in TABLE 2. The Suntech A had the interesting characteristics of a viscosity similar to JP-5 but a surface tension and specific gravity closer to the NDF.

TABLE 2. Fuel Properties

Fuel	Viscosity at 40°C (cSt)	Viscosity at 20°C (cSt)	Surface Tension at 24°C (dyn/cm)	Specific Gravity (at 0° C)
JP-5	1.56	2.17	27.56	0.8179
Suntech A	1.95	2.90	29.30	0.8628
NDF	3.24	5.24	29.70	0.8468

The experimental test matrix, which was defined by NAPC, is shown in TABLES 3 (metric units) and 4 (common usage units). The chamber air temperature for these tests was specified by NAPC to be 241°C (465°F). The initial test conditions corresponded to those conditions that were used for the J85 combustor tests conducted at NAPC. As discussed in the Results section, there were problems interpreting the drop-size distribution data at elevated air temperatures for this nozzle. Therefore, tests were also conducted at ambient temperatures but at an air density equivalent to the high-temperature test condition.

The equivalent air density test conditions at a temperature of 29°C (85°F) are also shown in TABLES 3 and 4. Note that for the higher pressure test conditions, the densities at the high- and low-temperature conditions are equivalent. At the two lowest pressure conditions, an equivalent density could not be obtained due to limitations of the combustor test facility. For these conditions, the densities at the ambient temperature test condition were higher than at the elevated temperature test condition.

The test matrix shown in TABLES 3 and 4 includes the addition of an extra mass flow rate condition (3.30 g/s) beyond that specified by NAPC at each chamber pressure. This point was included to better define the drop size as a function of mass flow rate, since it represented the transition point between operation of the fuel nozzle on primary-only and primary-plus-secondary flows. This point corresponded to a minimum for the average drop size at the various conditions.

TABLE 3. Tests Conditions and Atomization Results (Metric Units)

Desired Test Conditions at 241°C		Actual Test Conditions at 29°C			Sauter Mean Diameter (micrometers)		
Air Pressure (kPa)	Air Density (kg/m^3)	Air Pressure (kPa)	Air Density (kg/m^3)	Fuel Flow Rate (g/s)	JP-5	Suntech A	DFM
517	3.53	303	3.51	1.35	77.4	129.2	155.4
517	3.53	303	3.51	1.60	62.2	78.8	99.5
517	3.53	303	3.51	2.10	48.0	55.2	65.2
517	3.53	303	3.51	3.30	35.2	38.2	36.8
517	3.53	303	3.51	6.83	124.1	137.4	123.3
517	3.53	303	3.51	11.34	134.0	167.4	171.6
517	3.53	303	3.51	19.95	101.7	122.7	127.6
414	2.82	241	2.79	0.94	139.4	202.5	241.2
414	2.82	241	2.79	1.35	74.6	95.2	137.1
414	2.82	241	2.79	1.60	60.8	81.0	97.7
414	2.82	241	2.79	3.30	33.1	35.6	36.3
414	2.82	241	2.79	6.83	123.4	125.2	100.1
414	2.82	241	2.79	11.34	132.6	152.0	145.5
414	2.82	241	2.79	19.95	109.0	116.2	119.8
331	2.26	193	2.24	1.60	72.5	77.3	122.1
331	2.26	193	2.24	3.30	39.1	36.5	40.7
331	2.26	193	2.24	6.83	90.8	129.6	101.6
331	2.26	193	2.24	11.34	99.1	149.5	159.6
331	2.26	193	2.24	17.22	88.8	88.0	95.2
331	2.26	193	2.24	19.95	90.9	87.6	104.5
207	1.42	138	1.60	0.58	335.8	395.0	336.8
207	1.42	138	1.60	1.21	159.9	159.0	187.6
207	1.42	138	1.60	3.30	38.9	34.8	42.8
207	1.42	138	1.60	6.83	106.6	128.8	122.0
207	1.42	138	1.60	11.34	120.6	137.8	158.1
207	1.42	138	1.60	14.01	86.0	84.2	138.4
101	0.69	110	1.27	1.35	103.9	126.9	187.1
101	0.69	110	1.27	1.60	76.9	96.4	132.9
101	0.69	110	1.27	3.30	49.8	42.1	46.5
101	0.69	110	1.27	6.83	98.6	147.2	124.9
101	0.69	110	1.27	8.61	125.2	180.0	143.6
101	0.69	110	1.27	11.34	84.6	152.8	170.1

TABLE 4. Test Conditions and Atomization Results (Common Usage Units)

Desired Test Conditions at 465°F		Actual Test Conditions at 85°F			Sauter Mean Diameter (micrometers)		
Air Pressure (psia)	Air Density (lbm/ft^3)	Air Pressure (psia)	Air Density (lbm/ft^3)	Fuel Flow Rate (g/s)	JP-5	Suntech A	DFM
75.0	0.219	44.0	0.218	1.35	77.4	129.2	155.4
75.0	0.219	44.0	0.218	1.60	62.2	78.8	99.5
75.0	0.219	44.0	0.218	2.10	48.0	55.2	65.2
75.0	0.219	44.0	0.218	3.30	35.2	38.2	36.8
75.0	0.219	44.0	0.218	6.83	124.1	137.4	123.3
75.0	0.219	44.0	0.218	11.34	134.0	167.4	171.6
75.0	0.219	44.0	0.218	19.95	101.7	122.7	127.6
60.0	0.175	35.0	0.173	0.94	139.4	202.5	241.2
60.0	0.175	35.0	0.173	1.35	74.6	95.2	137.1
60.0	0.175	35.0	0.173	1.60	60.8	81.0	97.7
60.0	0.175	35.0	0.173	3.30	33.1	35.6	36.3
60.0	0.175	35.0	0.173	6.83	123.4	125.2	100.1
60.0	0.175	35.0	0.173	11.34	132.6	152.0	145.5
60.0	0.175	35.0	0.173	19.95	109.0	116.2	119.8
48.0	0.140	28.0	0.139	1.60	72.5	77.3	122.1
48.0	0.140	28.0	0.139	3.30	39.1	36.5	40.7
48.0	0.140	28.0	0.139	6.83	90.8	129.6	101.6
48.0	0.140	28.0	0.139	11.34	99.1	149.5	159.6
48.0	0.140	28.0	0.139	17.22	88.8	88.0	95.2
48.0	0.140	28.0	0.139	19.95	90.9	87.6	104.5
30.0	0.088	20.0	0.099	0.58	335.8	395.0	336.8
30.0	0.088	20.0	0.099	1.21	159.9	159.0	187.6
30.0	0.088	20.0	0.099	3.30	38.9	34.8	42.8
30.0	0.088	20.0	0.099	6.83	106.6	128.8	122.0
30.0	0.088	20.0	0.099	11.34	120.6	137.8	158.1
30.0	0.088	20.0	0.099	14.01	86.0	84.2	138.4
14.7	0.043	16.0	0.079	1.35	103.9	126.9	187.1
14.7	0.043	16.0	0.079	1.60	76.9	96.4	132.9
14.7	0.043	16.0	0.079	3.30	49.8	42.1	46.5
14.7	0.043	16.0	0.079	6.83	98.6	147.2	124.9
14.7	0.043	16.0	0.079	8.61	125.2	180.0	143.6
14.7	0.043	16.0	0.079	11.34	84.6	152.8	170.1

EXPERIMENTAL RESULTS

Drop-size measurements were performed initially for all three fuels for all conditions listed in column 1 of TABLE 3 (metric units) and TABLE 4 (common usage units). However, at the elevated air temperature of 241°C (465°F), gradients in temperature and fuel vapor concentration caused the laser beam to be deflected randomly in passing through the evaporating spray. This deflection resulted in erroneous signals on the inner detectors of the Malvern laser-diffraction instrument. A correction procedure was previously developed to overcome this problem.(8) However, that procedure is only applicable for relatively fine sprays that are monomodal (having one maxima in the drop-size distribution). When operating at higher flow rates with flows through the primary and secondary nozzles, the sprays were bimodal, quite broad in size distribution, and relatively coarse as can be seen in comparing Figs. 3(a) and 3(b). The size bands shown in Figs. 3(a) and 3(b) are defined in TABLE 5. Therefore, the correction procedure previously developed(8) could not be applied accurately, and two alternative approaches to the experiment were considered. (Note that the size bands listed in Table 5 are not of uniform width, but rather, are logarithmically spaced and sized. To compensate for that, the weight distributions in Figs. 3(a) and 3(b) are expressed per unit micrometer of size range. Thus, for the weight percentages of Figs. 3(a) and 3(b) to sum to 100 percent, the values must be multiplied by the width of the size bands from Table 5.)

TABLE 5. Size ranges for Malvern Drop Sizer

Drop Size Band Number	Drop Size Range (micrometers)	
	lower	upper
1	5.8	7.2
2	7.2	9.1
3	9.1	11.4
4	11.4	14.5
5	14.5	18.5
6	18.5	23.7
7	23.7	30.3
8	30.3	39.0
9	39.0	50.2
10	50.2	64.6
11	64.6	84.3
12	84.3	112.8
13	112.8	160.4
14	160.4	261.6
15	261.6	564.0

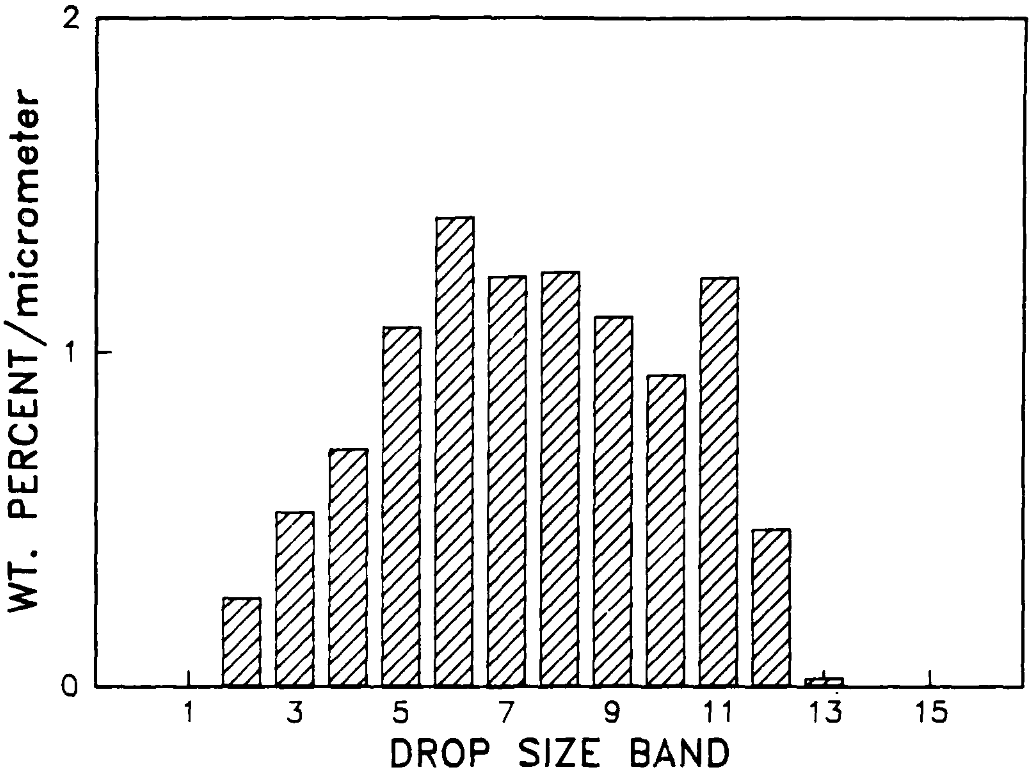

Figure 3(a). Drop-size distribution for J85-21 atomizer operating on primary nozzle only (3.30 g/s flow of JP-5). See Table 5 for definition of size bands.

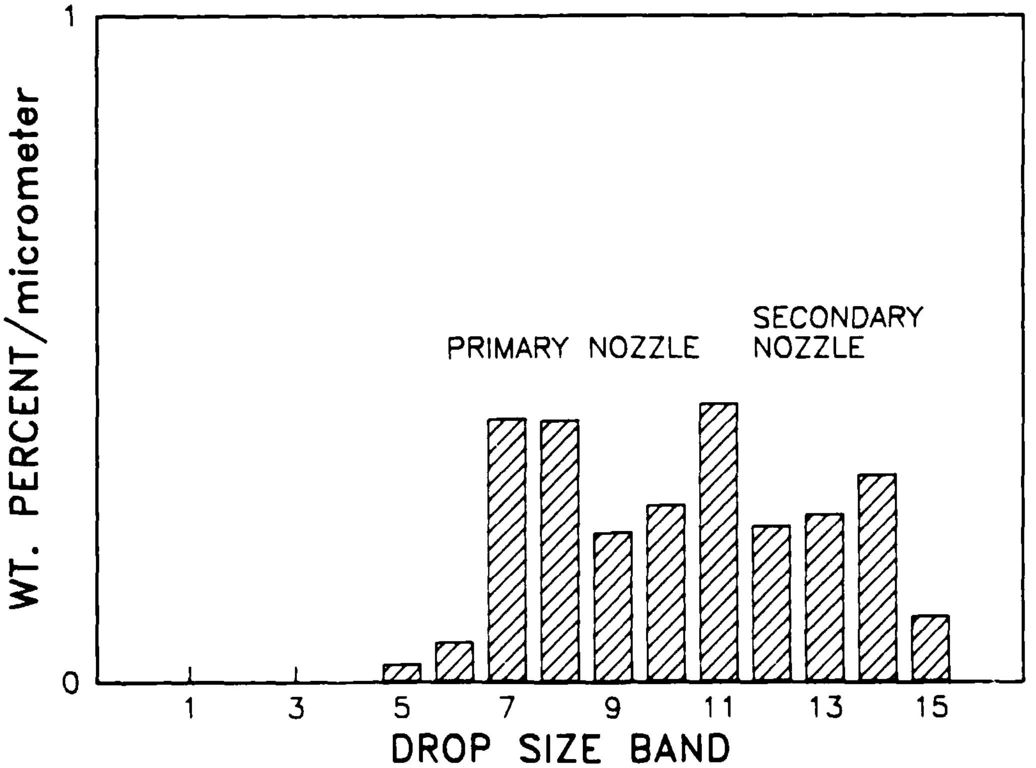

Figure 3(b). Drop-size distribution for J85-21 atomizer operating on primary and secondary nozzles (6.83 g/s flow of JP-5). See Table 5 for definition of size bands.

First, SwRI has another drop-sizing instrument, an Aerometrics phase/Doppler Particle Analyzer, that is not adversely affected by measurements in evaporating sprays. However, the existing test section does not allow sufficient optical access to use that instrument. Therefore, this first alternative was considered beyond the financial resources of this program.

The second alternative approach to the experiment was to perform the atomization tests at room temperature but at air densities matching those used at NAPC. Previous tests at SwRI have indicated that initial atomization depends most strongly on air density rather than air pressure or temperature.(9) This approach was selected as the most expedient and cost-effective solution to the laser-beam-steering problem caused by the hot gases.

Drop-size measurements were repeated at room temperature (29°C or 85°F) with the air pressures adjusted to match the densities used for the NAPC tests. The resulting air pressures and densities are shown in columns 3 and 4 of TABLES 3 and 4. Because of facility limitations, the air densities at the two lowest pressure conditions could not be matched exactly to those used at NAPC. The measured Sauter mean diameter (SMD) for each fuel at each test condition is shown in TABLES 3 and 4. These values represent the average of two repeat tests at the 29°C (85°F) test conditions. On the average the variability of the two measurements was approximately 6 percent of the mean value.

These data are plotted versus mass flow rate for each fuel in Figs. 4 through 6. As indicated in the figures, there are two distinct regions corresponding to the primary and secondary flow regions. At a mass flow rate below 3.30 g/s, flow is through the primary nozzle only. In this region, the SMD decreases with increases in mass flow rate. Above a mass flow rate of 3.30 g/s, there is an increase in the SMD corresponding to the point where fuel begins to flow through the secondary nozzle. With flow through both the primary and secondary nozzles, the fuel spray is actually bimodal or consisting of two distinct sprays (one primary, one secondary) each having a drop-size distribution and a characteristic SMD. Thus as the mass flow rate increases and a greater amount of fuel flows through the secondary nozzle, the average drop size of the spray tends to be weighted toward the larger drops of the secondary nozzle. At much higher flow rates (10 to 20 g/s), the greater pressure drop across the nozzle results in better atomization of the spray from the secondary nozzle and a corresponding decrease in the SMD.

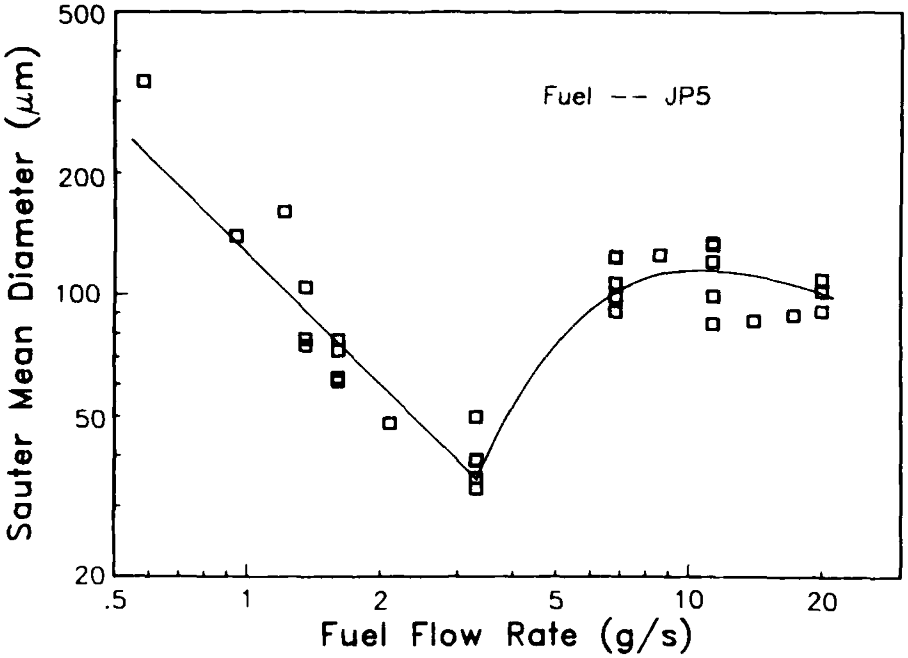

Figure 4. Atomization characteristics of J85-21 fuel nozzle for JP-5

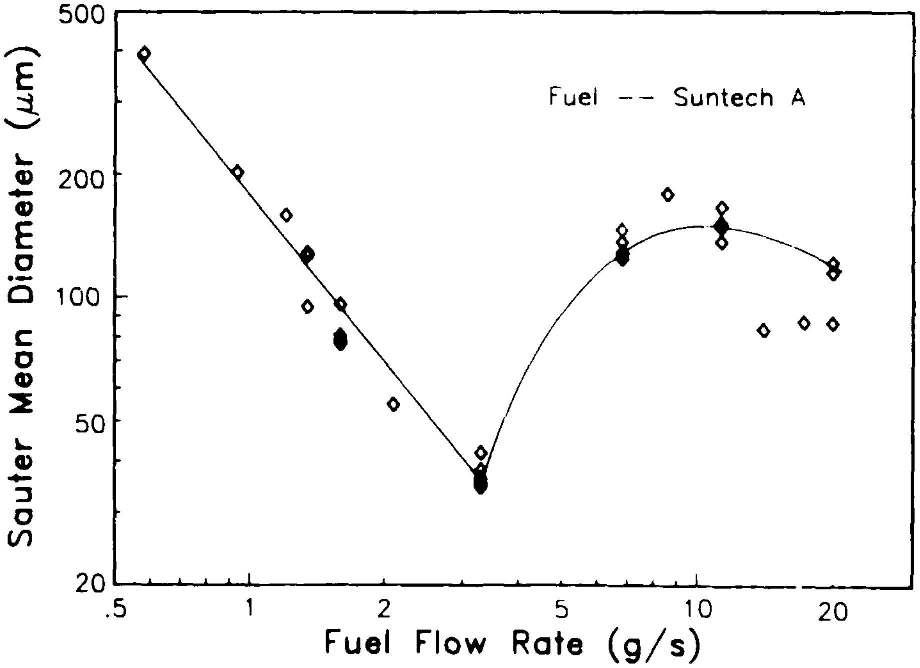

Figure 5. Atomization characteristics of J85-21 fuel nozzle for Suntech A

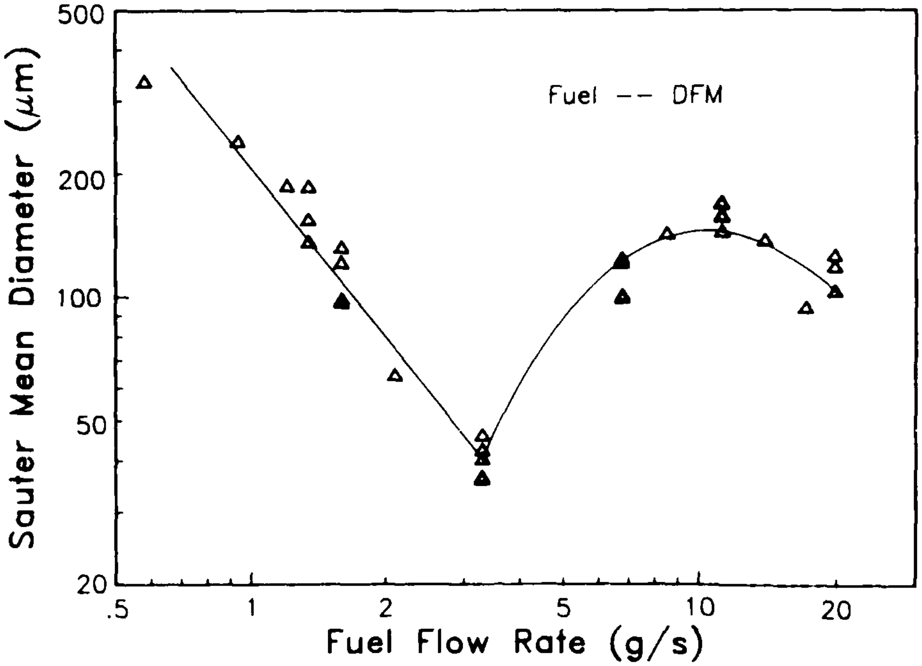

Figure 6. Atomization characteristics of J85-21 fuel nozzle for diesel fuel marine (DFM)

The bimodal nature of the drop-size distribution that occurs with flow through both the primary and secondary nozzles makes the calculation of an SMD less precise. A model independent drop-size distribution routine was used to calculate the SMD's for these cases. Because of the bimodal drop-size distributions, data above the transition flow rate of 3.30 g/s were likely to have a greater error associated with the calculation of the SMD. Thus, fuel property effects and the effects of air density or pressure on the drop-size distribution were more easily examined using data from the primary nozzle only.

The effects of air density on the SMD for each fuel are illustrated in Fig. 7. In this figure, the SMD's are plotted versus chamber air density for each fuel at mass flow rates of 1.60 and 3.30 g/s. As indicated in the figure, the SMD decreased with increases in air density. This effect was similar for each fuel and mass flow rate.

The data presented in Fig. 7 also indicate that there were differences in the drop sizes of the spray from fuel to fuel. The NDF fuel had a higher viscosity than the Suntech A or JP-5 and consequently had a larger average drop size. The Suntech A had a higher viscosity and surface tension than the JP-5 and also tended to have a

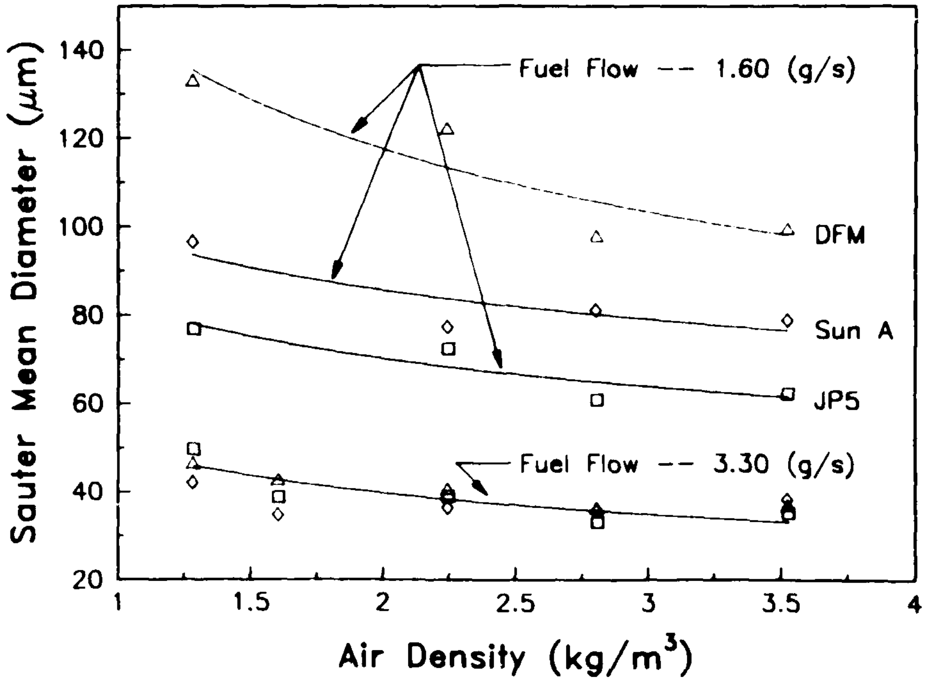

Figure 7. Effects of chamber air density on atomization characteristics of J85-21 fuel nozzle

larger SMD. For the primary nozzle, these differences were greater at the lower flow rates and almost nonexistent at the maximum flow rate for the primary nozzle.

The effect of fuel viscosity on the drop size of the fuel spray is illustrated in Fig. 8 for an air density of 3.53 kg/m^3 and mass flow rates of 1.60 and 3.30 g/s. As indicated by the figure, the SMD at the 1.60 g/s mass flow rate increased from 62.2 to 99.5 micrometers as the viscosity increased from 2.01 to 4.5 cSt (at 25°C). At the 3.30 g/s mass flow rate condition, there was no significant difference in the SMD's of the three fuels. This decrease of fuel property effect on atomization with increased fuel flow rate is typical of many pressure-swirl atomizers.

Attempts were made to correlate the fuel property effects in the standard form of SMD proportional to viscosity raised to a power, etc. However, the results shown in Fig. 8 illustrate that the exponent depends upon the fuel flow rate, and has a larger value (greater dependence of SMD on viscosity) at lower fuel flow rates. The simple correlations with constant exponents are not applicable to this nozzle or many other pressure-swirl atomizers.

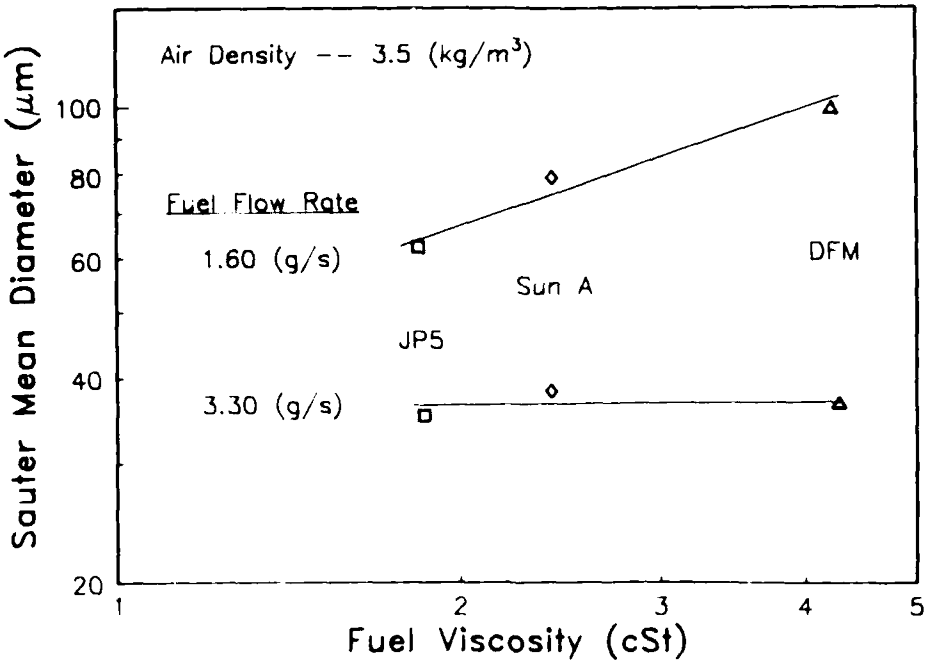

Figure 8. Effect of fuel viscosity on the atomization characteristics of J85-21 fuel nozzle

SUMMARY AND CONCLUSIONS

Drop-size measurements have been completed and reported for three fuels and a variety of air densities approximating those used at NAPC for ignition and blowout tests. These data may be used in a characteristic time model to correlate ignition and blowout test results. Because a dual-orifice atomizer was used in these tests, there was a complex relationship between fuel mass flow rate and average drop size (SMD).

Fuel effects on atomization were most significant at the lowest fuel flow rates on the primary fuel nozzle. The diesel fuel NDF generally produced the largest drops, the JP-5 the smallest, and the Suntech A was intermediate. The Suntech A had a viscosity only slightly larger than JP-5, but the surface tension was close to that of the NDF. These fuel effects are similar to those observed for other pressure-swirl atomizers. Simple correlations of drop size with fuel properties were not possible over the whole range of fuel flows.

The effect of air density on the atomization process was clear for those conditions where the primary nozzle only was operating. Under those conditions, increased air density caused a decrease in average drop size (SMD), i.e., better atomization. With fuel flow through the primary and secondary nozzles, the repeatability and accuracy of the measurements were not sufficient to evaluate the air density effect on atomization.

RECOMMENDATIONS

1. The atomization data supplied in this report may be used by NAPC or one of their contractors to correlate the results of ignition and blowout tests previously performed at NAPC using the characteristic time model.

2. If further ignition or blowout tests are performed at NAPC, consideration should be given to using a simplex (pressure-swirl) atomizer in place of the standard dual-orifice atomizer used in most combustor designs. Alternatively only one stage of a dual-orifice atomizer could be used. This would have the advantage of providing a monotonic relationship between fuel flow rate and the average drop size. Also, the spray characteristics would be more repeatable if the variability associated with a flow-divider valve were removed.

3. In modeling ignition processes, the fuel spray characteristics in the neighborhood of the ignitor are more critical than the overall spray characteristics. Portions of the fuel spray are normally carried to the ignitor by the air stream. SwRI has recently added a capability to measure spray characteristics at a point, such as near the ignitor, through the aquisition of an Aerometrics phase/Doppler particle analyzer. SwRI also has the capability of modeling the process of the air stream picking up part of the fuel spray and carrying it to the ignitor through the use of the FLUENT computer code. These capabilities allow for a more precise evaluation of ignition phenomena. Consideration should be given to utilizing these capabilities for future ignition studies.

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