Fuel Thermal Stability Effects on Spray Characteristics

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The propensity of a heated hydrocarbon fuel toward solids deposition within a fuel injector is investigated experimentally. Fuel is arranged to flow through the injector at constant temperature, pressure, and flow rate and the pressure drop across the nozzle is monitored to provide an indication of the amount of deposition. After deposits have formed, the nozzle is removed from the test rig and its spray performance is compared with its performance before deposition. The spray characteristics measured include mean drop size, drop-size distribution, and radial and circumferential fuel distribution. It is found that small amounts of deposition can produce severe distortion of the fuel spray pattern. More extensive deposition restores spray uniformity, but the nozzle flow rate is seriously curtailed.

Introduction

MODERN aircraft turbines subject fuels to a range of thermal stresses. Advanced turbojet engines employ high compression ratios and high turbine inlet temperatures, which means that heat must be extracted from the lubricating oil, using the fuel as a heat sink. The fuel experiences a further temperature rise as it flows through the burner feed arm just prior to entering the nozzle. The continuing trend toward higher engine compression ratios has greatly increased this heat input, since an increase in compression ratio raises both the pressure and temperature of the air flowing over the burner feed arm. Another consequence of higher compression ratios is additional heat loading on the fuel nozzle due to higher rates of radiative heat transfer from the flame. The combined effect of these heat inputs is a considerable elevation in the temperature of the fuel before it is sprayed into the combustion zone.

From a combustion standpoint, this increase in fuel temperature is beneficial. It raises the specific energy of the fuel, improves atomization, and accelerates fuel evaporation. Unfortunately, these advantages are accompanied by certain drawbacks. For example, the heat acquired by the fuel stimulates oxidation reactions that lead to the formation of gums and other insoluble materials. This is clearly undesirable if it produces lacquer formation on heat exchangers and control surfaces. However, deposition within the fuel nozzle is potentially more harmful. Deposits can distort the fuel spray pattern which, in turn, can lead to local overheating of liner walls, turbine blades, and nozzle guide vanes.

The deposits formed in fuel lines and on other heated surfaces are a manifestation of thermal degradation of the fuel.[1-3] Fuels that have a high thermal stability also have a low tendency to form deposits. Current aircraft turbine fuels do not present a major problem with regard to thermal stability,[4] but reports of tendencies to form deposits in some engines have been received, even with today's fuels, where a margin of stability exists within specification limits.[3] The magnitude of the problem is due to a complex combination of variables such as engine model, length of flights, fuel contamination, and the average stability of the fuel used.[5] However, the problem seems likely to assume added importance in the future due to the anticipated higher fuel temperatures in nozzles and to the more widespread use of fuels having broadened properties. The dependence of deposition on fuel temperature and composition has been studied for some time and is still being actively investigated, but comparatively little is known of the effects of nozzle deposition on fuel spray characteristics.

The problems outlined above are of special importance to the small gas turbine. To a large extent, the basic difficulty is one of geometric scale. As the power level is reduced, the dimensions of various engine components must also decrease. This is especially disadvantageous for the fuel injector because it embodies small internal passages that are especially prone to plugging and blockage.

Previous Work

Several methods have been developed to evaluate fuel thermal stability due to its growing importance. These methods fall into three general categories: static tests, scaled dynamic tests, and full-scale fuel system simulators.

Static tests generally take a small sample of the test fuel and heat it in an enclosed container for a specified time. The fuel is then cooled and analyzed for gum and insoluble formation and its chemical composition compared to that of the unheated fuel. Static tests investigate primarily the effect of heating on the fuel itself. General advantages include small sample size, short testing time, and easily quantifiable results. Their main drawback is that they do not simulate the prevailing conditions in the fuel system of a turbojet engine.[6-8]

Scaled dynamic tests are designed to model specific components of a gas turbine fuel system. Usually, a single tube is used to simulate a part of the turbine's oil-cooling heat exchanger, but sometimes a filter is employed to represent the small passages and orifices in control valves and fuel nozzles. Heated fuel is supplied to the test system, and changes in fuel composition, filter pressure drop, and surface characteristics of the tube or filter are examined. The results obtained are sometimes difficult to quantify, but scaled dynamic tests are extremely versatile and widely accepted as among the best means of studying the general mechanisms involved in thermal deposition. Examples of scaled dynamic tests include the ASTM CRC fuel coker[9-11] and the jet fuel thermal oxidation tester (JFTOT).[12-19]

The United Technologies Research Center has developed a unique dynamic test device that simulates a gas turbine fuel nozzle and support strut assembly.[8,19,20] The system components are fuel supply and preconditioning, test section, and automatic control and data acquisition. Metal test disks,

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mounted in the flow channel, can be removed for detailed deposit analysis and a pressure-atomizing fuel nozzle is located at the discharge end of the test section to control the flow rate and allow visual examination of the fuel spray. The method has proved very effective in determining the effects of the fuel system environment on thermal deposition. However, no pertinent results on the influence of this deposition on spray characteristics have been acquired, because no discernible changes in spray pattern have yet been observed.

In the present research, attention is focused on the effects of deposit formation occurring within fuel nozzle flow passages on fuel spray characteristics. Several different fuels are employed in this study, but no attempt is made to assess the influence of fuel chemistry on thermal deposition. The only purpose in testing a variety of fuels is to find one that can reproduce the same type of deposition as a conventional aircraft fuel, but in a much shorter time.

Measurement of Spray Characteristics

The apparatus used for studying spray characteristics is shown schematically in Fig. 1. The main component is a cylindrical vessel, 200 cm long and 25 cm in diameter, which is mounted vertically. The atomizer is located at the top of the cylinder and sprays downward. Two nitrogen lines are connected to the tank. One line protects the optical windows from any contamination by fuel drops or mist. The other provides a gentle downdraft of nitrogen through the tank to minimize droplet recirculation.

Spray characteristics are measured using a Malvern 2600 particle sizer. This instrument is widely used and is considered to be one of the most accurate available. It uses a forward light-scattering technique to determine the Sauter mean diameter (SMD) of the spray and the Rosin-Rammler drop-size distribution parameter q. Note that a higher value of q denotes a more uniform distribution of drop sizes in the spray. For a monodisperse spray, $q=\infty$.

A "patternator" is used to measure the radial fuel distribution. It comprises 29 sampling tubes spaced 4.5 deg apart on a 10-cm radius. The patternator is mounted below the test nozzle with the nozzle axis located at the center of curvature. After spraying fuel through the nozzle for a set period of time, the volume of fuel in each tube is measured. Each nozzle can be rotated on its axis to measure the radial distribution of fuel at different angular locations. The results of the tests for a given nozzle are then plotted and a contour map is generated to depict distribution of liquid flux in the spray. Figure 2 is typical of the results obtained by this method for a clean, deposition-free nozzle. In this and subsequent figures, the number assigned to each contour line represents the liquid flow rate—the higher the number, the higher the flow rate. Thus, for a circumferentially uniform spray, the contour map becomes a series of concentric circles. If the spray is also radially uniform, then each contour line will carry the same number.

Circumferential patternation is also measured using a plexiglass cylinder divided into 16 equal wedges. Fuel is sprayed into the patternator until it nears the top of one of the cells. The level of the fuel in each cell is then measured and recorded. The values are normalized against the average of the levels in all the cells, and the standard deviation of the normalized values is calculated. This yields a normalized standard deviation σ, which is indicative of the irregularity of the nozzle spray.

Thermal Stability Rig

The main features of the fuel thermal stability rig are shown schematically in Fig. 3. It is a closed-loop system, designed to recirculate fuel over wide ranges of temperature, flow rate, and pressure. The purpose of the system is to study the rates at which deposits are formed in fuel nozzles when high-temperature fuel flows through the nozzle. The major components are the pump, flow meter, electrical heaters, fuel nozzle, thermocouple, and the pressure-drop meter. Each of the components is capable of operating at the maximum conditions of 4.1 MPa (600 psi), 2.5 liters/min (39 gal/h), and 650 K. All components exposed to the test fluid are made of stainless steel to minimize the chemical interaction between the components and the fuel. High-temperature ceramic insulation is used throughout to minimize the amount of power required to maintain the desired fluid temperature.

The pump is a packed-plunger, positive-displacement pump whose displacement can be varied from 0–2.5 liters/min at an inlet pressure of 0.69 MPa (100 psi) and outlet pressures of up to 2.76 MPa (490 psi). The pump is water-cooled to prevent overheating of the packing. The flow meter has a radial piston transducer with a digital readout. It can measure flows up to 7.5 liters/min. The heaters are 800-W electrical resistance heaters that are wound around the tubing. The desired fluid temperature is maintained by a temperature controller, which also protects the heaters from overtemperature operation. The fuel nozzle is inserted directly in the fuel line and simply sprays into the fuel line. Any type of nozzle can be configured into the apparatus. The pressure-drop meter includes a variable-reluctance, differential-pressure transducer, and a digital indicator.

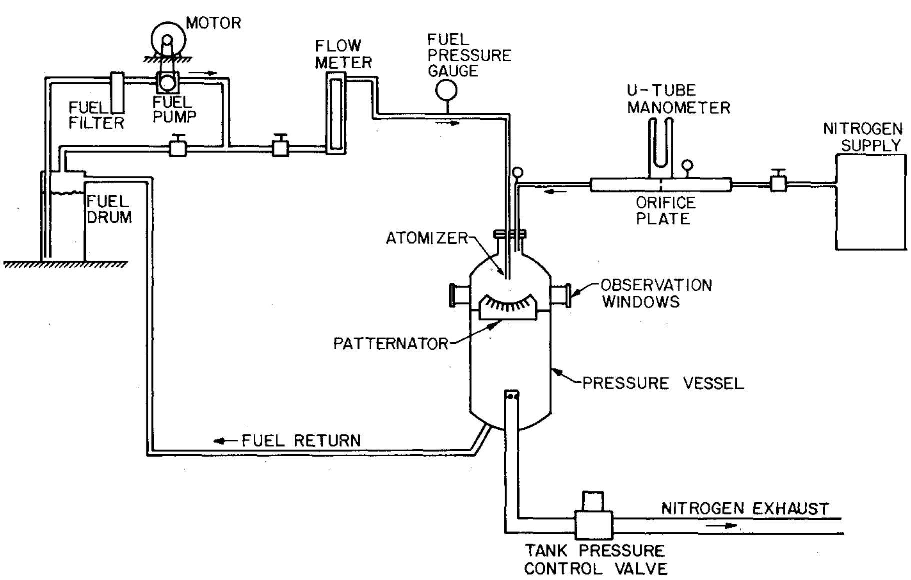

Fig. 1 Basic test facility for atomization and patternation studies.

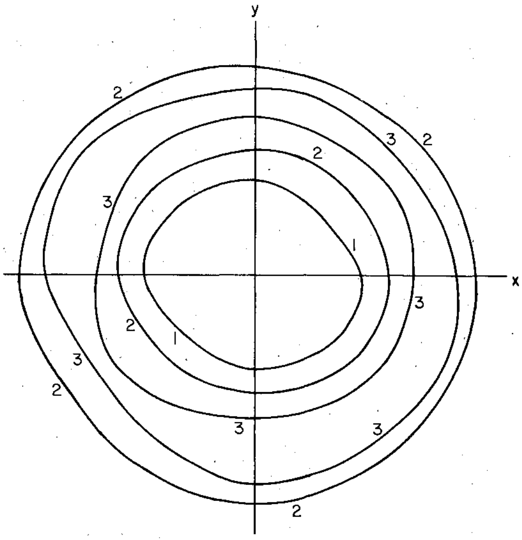

Fig. 2 Graphs illustrating variations in local fuel flow rate within the spray at a fixed distance downstream of the nozzle (nozzle 664, before deposition).

For any given fuel, the fuel pressure and flow rate are set at suitable values and the temperature of the fuel is raised to some predetermined value. Once steady-state conditions have been achieved, the rig is run continuously until a small but significant level of solids deposition has occurred within the nozzle flow passages, indicated by an increase in pressure drop across the nozzle. At this point, the nozzle is removed from the rig and its spray characteristics examined. These characteristics are compared with those obtained with the initial "clean" nozzle to ascertain the extent of the deterioration (if any) in spray quality. The nozzle is then returned to the thermal stability rig for a further period of operation at the same conditions. The nozzles are transferred periodically to the spray laboratory for measurements of fuel spray characteristics.

Results

Three distinct phases of the study have been performed. Initially, the thermal stability rig was used solely to study the variations in pressure drop across a simplex pressure swirl nozzle when flowing hot fuel through it over a period of time. Next, various fuels were used in the thermal stability rig to determine which would produce the largest amount of deposits in the shortest time. Finally, the spray characteristics of several nozzles were measured before and after the formation of deposits in the internal passages of the nozzles.

The first phase utilized a straight-run diesel fuel (DF-2) and Delavan simplex pressure-swirl nozzles. The fuel temperature at the nozzle was maintained at 590 K. The system pressure was 2.07 MPa at a flowrate of 30 cm^3/min. The pressure drop across the nozzle was monitored to determine the rates of deposition.

A typical run is shown in Fig. 4. The initial decrease of pressure drop indicated in this figure is attributed to changes in fuel pump characteristics and reduction in fuel viscosity due to increasing the fuel temperature from ambient to normal running temperature. After the heat-up transient, the nozzle pressure drop increased linearly at a rate of 1.45 kPa/min for the remainder of the test, yielding a 63% increase in pressure drop. A layer of black deposits covered the entire nozzle, including the swirler slots and the discharge orifice.

The second phase of the study investigated the deposition rates of various fuels. Small disks with a small central hole were mounted as an orifice plate in place of the pressure-swirl nozzle. Copper disks were used because it is well known that the presence of copper in a hydrocarbon fuel system can greatly accelerate deposition. Each fuel was circulated at 30 cm^3/min for 100 min, with the fuel temperature and pressure maintained at 590 K and 2.07 MPa, respectively. The disk was weighed before and after the run to determine the weight of the deposition.

The fuels used were the following: Shell straight-run DF2 acquired in Alabama, DF2 with winter additives, premium DF2, Amoco No. 2 heating oil and No. 2 fuel oil. The results of the tests are shown in Table 1.

Table 1 Deposition rate of various fuels

Fuel	Mass change, mg	Deposition rate, $\mu g/cm^2$ h
Shell DF2	1.9	600
Winter DF2	3.6	1140
Premium DF2	2.4	760
Amoco No. 2 heating	2.1	670
Fuel oil	4.1	1300
One ring aromatic	1.4	440
Two ring aromatic	0.1	30

The fuel oil and winter blend diesel produced the largest deposition. The Shell straight-run DF2, premium diesel, and Amoco No. 2 heating oil produced about one-half to two-thirds this amount. The aromatic blends produced much less deposition; that of the two-ring aromatic was negligibly small. Based on its high deposition rate in these tests, the fuel oil was chosen for use in the next phase of the study.

The third phase of the study utilized fuel oil in conjunction with Hago simplex pressure-swirl atomizers. Three nozzles of differing flow rate and cone angle were used to determine the effect of nozle geometry on deposition. They comprised a 190 cm^3/min (3 gal/h) 60 deg cone angle nozzle, a 380 cm^3/min (6 gal/h) 60 deg cone angle nozzle, and a 380 cm^3/min (6 gal/h) 90 deg cone angle nozzle, numbered 362, 664, and 691, respectively. The flow rates were reduced to 12 cm^3/min for nozzle 362 and 15 cm^3/min for nozzles 664 and 691. The fuel temperature at the nozzle was increased to 616 K in order to increase the rate of deposition. In addition, the nozzle orifice and swirler slots were electroplated with a very thin layer of copper to augment deposition rates in those specific areas.

Table 2 Drop sizing summary of new nozzles

Nozzle	Position, deg	SMD, μm	q
362	+0	55.6	2.01
664	+0	54.5	2.27
691	+0	54.8	2.21
691	+90	56.5	2.33

Before forming any deposition on the nozzles, their spray characteristics were measured; the results are shown in Table 2. All the nozzles exhibited fairly uniform sprays, typical of hollow-cone, pressure-swirl atomizers. The SMD values were 54–56 μm and q 2.0–2.3. The circumferential patternation standard deviation σ was 0.05–0.15. After forming deposition in each of the nozzles for 3½ h, the sprays were then reanalyzed. The results are shown in Table 3. In every case, the spray of a nozzle with deposition was much less uniform than that of a new nozzle, the circumferential patternation standard deviation varying between 0.11 and 0.26. The mean drop sizes of the sprays varied over a much wider range, 49–66 μm. Values of q decreased to between 1.8 and 1.9, indicating broader ranges of drop sizes. Another verification of the nonuniform nature of the spray from a nozzle with deposition is the circumferential variation of the mean drop size and drop-size distribution for a given nozzle. Variations of 4–8 μm occur between the axes of a single spray pattern.

In general, with any new fuel, the pressure drop across the nozzle rises continuously with time, indicating a steady rate of

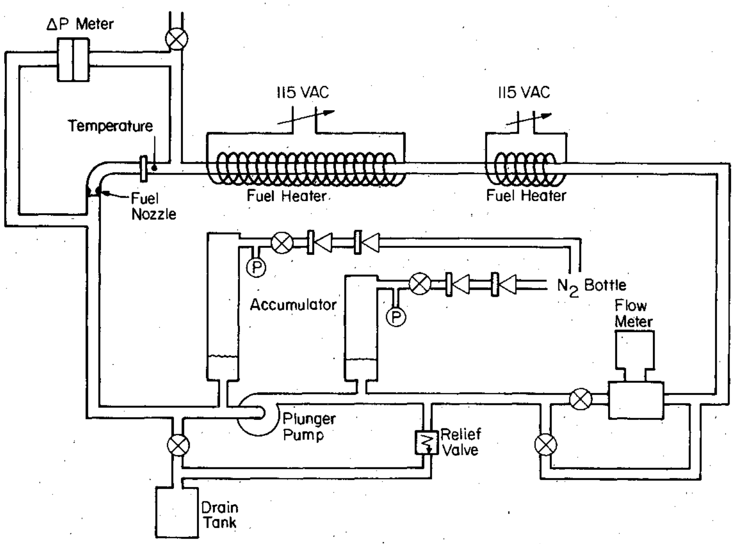

Fig. 3 Fuel thermal stability rig.

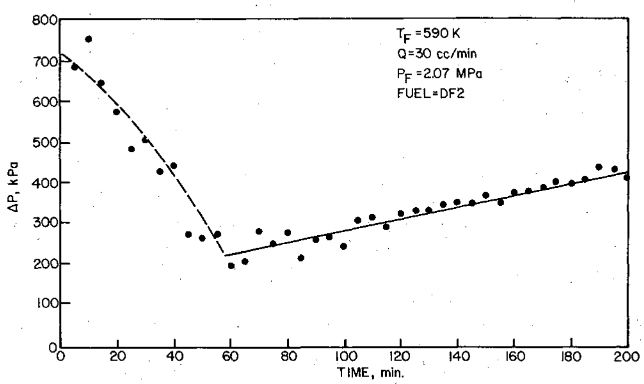

Fig. 4 Typical test run illustrating variation of nozzle pressure differential with time.

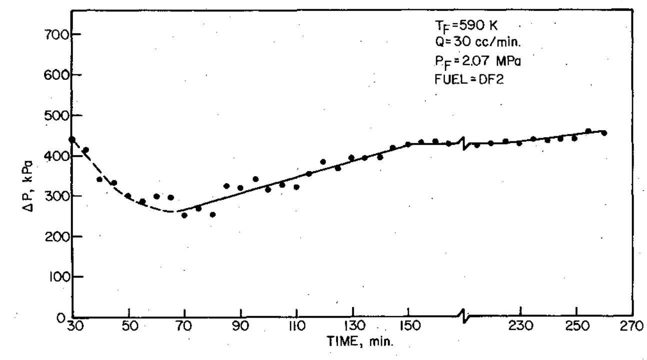

Fig. 5 Illustration of the "plateau" in the variation of nozzle pressure differential with time.

deposition within the nozzle (where deposition occurs preferentially due to the copper plating). Eventually, the increase in pressure drop across the nozzle stops and the curve of pressure drop vs time flattens off, as illustrated in Fig. 5. However, if the rig is allowed to continue running for a long period, then the pressure drop across the nozzle starts to rise again, due to the deposition of particles which have become dislodged from regions upstream. Thus, in practice, once the "plateau" of the pressure drop time curve has been reached, it is customary to drain the system and replace it with fresh fuel.

The spray data obtained with nozzle 664 after each of three layers of deposition are presented in Table 4. The specification flow rate for this nozzle is 380 cm^3/min. As deposition built up in the flow passages, the flow rate at constant fuel pressure

Table 3 Drop sizing summary of nozzles with deposition

Nozzle	Position, deg	SMD, μm	q
362	+0	55.1	1.85
	+45	50.0	2.26
	+90	55.0	1.81
	−45	49.2	1.73
	−90	57.6	1.86
664	+0	65.7	1.92
	+45	64.6	1.82
	+90	60.7	1.89
	−45	64.2	1.92
	−90	61.6	1.93
691	+0	53.9	1.91
	+45	51.2	1.86
	+90	50.0	1.83
	−45	49.4	1.89
	−90	52.2	1.82

Table 4 Nozzle 664 spray summary (deposition with fuel oil)

Characteristic	New	Deposit 1	Deposit 2	Deposit 3
SMD	54.5	63.3	55.0	57.1
$\bar{q}$	2.27	1.86	1.88	2.07
σ	0.045	0.263	0.169	0.043
Q,cm^3/min	384	402	366	162
Cone angle, deg	60	43	51	56

dropped until it was 162 cm^3/min, i.e., 42% of the rated flow. The narrow cone angle and high σ both indicate severe spray distortion after the first deposition. After significant deposition had occurred, both values reversed their trend and returned toward those of a new nozzle.

The spray contour for nozzle 664 after the first layer of deposition, shown in Fig. 6, graphically portrays the irregular spray. The spray along the y axis is heavier on one side, with a 45 deg cone angle. The larger drop sizes along the y axis reflect the heavier spray. The x axis has a narrower, 41 deg cone angle, and the lighter spray produces a 63 μm drop size.

The spray distortion created by the initial layer of deposition, as illustrated in Fig. 6 for the Hago 664 nozzle, was also observed with all the other nozzles tested. For example, Fig. 7 shows the circumferential fuel distribution obtained with Hago nozzle 691 after the first layer of deposition. The severe spray distortion exhibited in Figs. 6. and 7 occurs because the initial deposition does not take place uniformly over the exposed metal surface, but is confined mainly to one of the

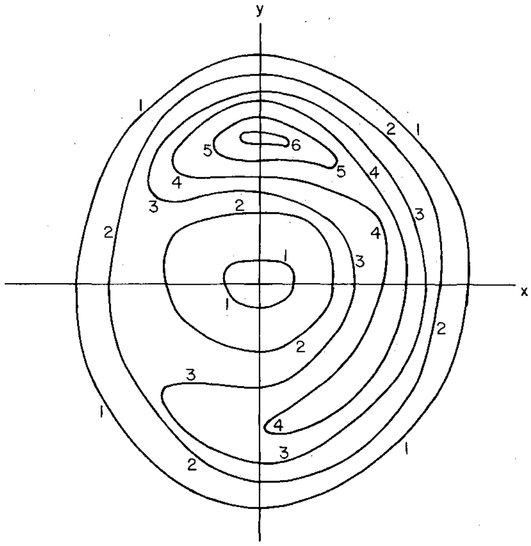

Fig. 6 Spray pattern after first deposition (nozzle 664).

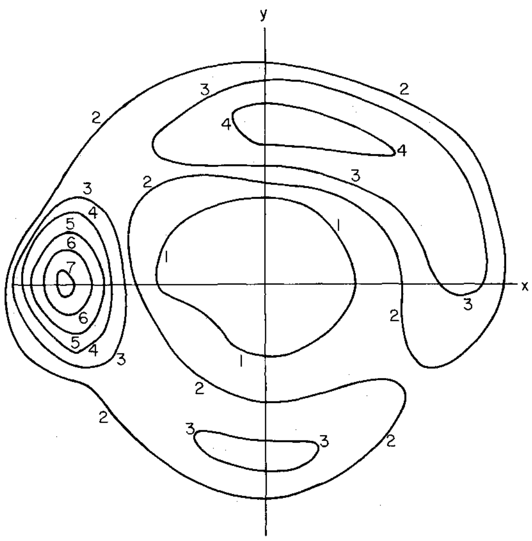

Fig. 7 Spray patternation after first deposition (nozzle 691).

swirl chamber inlet ports. Only after this port has become almost blocked does any appreciable layer of deposition start to build up within the other nozzle passages. Thus, insofar as fuel spray characteristics can affect certain important aspects of gas turbine performance such as lightup characteristics and pattern factor, it is the initial deposition that is the most damaging. Subsequent deposition decreases the cross-sectional area of the flow passages and thereby reduces flow rate, but, at the same time, the spray pattern improves and its symmetry approaches that of a new nozzle.

A series of tests (similar to those with fuel oil) were conducted with the 48%, two-ring aromatic JP-7 blend. Fuels high in aromatics are generally expected to form more deposition. Results of the copper disk tests indicated that this fuel formed negligible deposition at the standard test conditions. Two identically-manufactured 380 cm^3/min (6 gal/h) 60 deg cone angle Hago simplex nozzles were run in repeated tests with fresh fuel for each run to determine the tendency of this high-aromatic fuel to form deposition in pressure-swirl atomizers. Test conditions of 616 K, 15 cm^3/min flow rate, and 2.07 MPa system pressure were maintained, as in previous tests with 380 cm^3/min (6 gal/h) nozzles. The runs for the two nozzles showed that the high-aromatic JP-7 blend has a minimal tendency to form deposition. After two extended runs, the sprays from the two test nozzles exhibited only slight increases in mean drop size.

Conclusions

A main objective of this research was to develop a facility for reproducing the deposition occurring in gas turbine engine fuel nozzles and then use different fuels and nozzles to investigate the varying effects of thermal deposition on nozzle spray characteristics. The conclusions drawn from the work done thus far are:

1) The nozzle pressure drop is an effective indicator of deposit formation within a nozzle.

2) Deposit formation due to fuel thermal stability can be duplicated in the new test facility. Significant amounts of deposition can be formed in a matter of hours rather than thousands of hours as in a gas turbine. Different fuels and nozzles can be used to study a wide range of engine situations.

3) For simplex pressure-swirl atomizers, the size of the flow passages in swirler slots and discharge orifices is important. The adverse effects of deposition on spray characteristics are more pronounced in smaller nozzles.

4) Deposition first forms in isolated patches, causing a narrow cone angle and a highly distorted spray pattern. Continued deposition forms a continuous layer throughout the nozzle, causing the spray to become more circumferentially uniform. At the same time, the nozzle flow rate at constant fuel pressure drops markedly.

5) JP-7 fuel blended for high aromatic content forms less deposition than diesel fuels, heating oil, or fuel oil.

6) Both actual atomizers and small metal disks can be used to study fuel effects. Weighing small disks gives a more quantitative comparison of deposition than measurements of pressure drop on atomizers.

7) Any given quantity of fuel has a limited ability to form deposition. After a period of time, the fuel must be replaced with fresh fuel to effectively renew the supply of reactants. Fuel renewal allows several layers of deposition to be formed within a nozzle.

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