FUEL SPRAY CHARACTERISTICS OF GAS TURBINE FUEL INJECTORS AT COLD START CONDITIONS

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ABSTRACT

Engine starting at extremes of cold ambient and fuel temperatures are a concern to both military and commercial operators of jet engines, but the military in particular needs the capability to quick start under very cold conditions. The ongoing worldwide conversion to JP8 fuel is compromising this ability for older engines developed for use on wide-cut JP4 fuel. The greatly reduced volatility and increased viscosity of JP8 fuel significantly impacts fuel spray angle and droplet size at start conditions resulting in over-long and aborted starts in cold climates.

A program was carried out by Pratt & Whitney and Textron Fuel Systems to investigate and improve the spray qualities of a dual orifice pressure atomizing fuel injector of a commonly used military jet engine in the start to low power range. The primary fuel injector portion was modified to produce a finer droplet size and wider spray angle. A hybrid design with an aerating secondary was also tested. Droplet diameter and spray angles were measured to -40°F (-40°C) temperatures. Variations in fuel flow rate and fuel type were also investigated. It was found that cold fuel had an adverse effect on spray qualities for the all pressure atomizing nozzles, but the hybrid injector was less affected and produced superior sprays at all conditions on the primary portion. Improvements in the all pressure atomizing design resulted in lesser but still significant benefits.

NOMENCLATURE

Ax Cross-Sectional Area
B/M Bill of Material
d0,D0 Orifice Diameter
FN Flow Number, Fuel Rate/√ΔPL
Re Reynolds Number
ΔPL Pressure Loss Across Liquid Injector
SMD Sauter Mean Diameter, Microns
V Velocity
WL Fuel Flow Rate
ρ Density
σ Surface Tension
v Kinematic Viscosity
μ Viscosity
Θ Spray Angle

Subscripts
L Liquid
O Orifice

INTRODUCTION

The United States Air Force (U.S.A.F.) has long used JP4 as its standard jet fuel. More recently, however, considerations of the environment, safety factors, and commonality has led the U.S.A.F. and other air forces of the world to commit to JP8 fuel as their current and future standard. The use of JP8 is estimated to reduce fuel loss by vaporization by millions of gallons per year within the United States alone, and, with a flash point at least 120°F (49°C) higher than JP4, it will be a considerably safer fuel with which to work. As the standard fuel in all NATO countries, JP8 will be more generally available.
Fuel conversion of the current aircraft fleet is not a straightforward process. Studies (References 1 and 2) have been made to conclude that losses in starting capability, emission/smoke performance, and hot section durability are inevitable. Some performance can be regained through fuel schedule and control adjustments, but hardware modification will be required to regain others. One specific requirement of P&W TF33 engines is to start and operate in arctic conditions to -40°F (-40°C). Testing has revealed that cold start capability of these engines is greatly compromised with JP8 fuel and would need improvement.

The U.S.A.F. requested Pratt & Whitney to suggest means of improving the cold start capability of TF33 engines. One promising approach considered was improvement in the fuel injector spray quality to reduce droplet size and increase fuel distribution at start conditions. Pratt & Whitney combined with the injector manufacturer, Textron Fuel Systems, to design and test improved fuel nozzle concepts. Testing was carried out in Textron's unique cold spray rig facilities in Zeeland, Michigan. This paper describes those facilities and the results of testing carried out on several fuel injector designs at fuel and air temperatures ranging from 70°F (21°C) down to -40°F (-40°C). Data from an injector of a Swedish Air Force engine which was similarly modified for improved cold start is also included.

PREVIOUS WORK

The problems and detail effects of gas turbine combustor cold temperature ignition with less volatile and more viscous fuels have been studied by various investigators. In Reference 3, Dodge and Naegeli, after conducting a number of controlled viscosity and volatility fuel tests in a cold air temperature environment with a gas turbine combustor, concluded the following important criteria affected cold temperature ignition:

- Fuel viscosity is more important than volatility in the ignition process. The effect of viscosity was particularly apparent with less volatile fuels such as JP5 and JP8. Volatility effects are more apparent in JP4 and fuels containing gasoline.

- Ignition depends more strongly on achieving a critical average drop size (SMD) than on reaching the lean-limit fuel-air ratio.

In Reference 4, Gauthier et al. developed a theoretical/phenomenological model combining a heterogeneous flame propagation model and a multi-component fuel volatility model. In this reference, “the combined model has been used to investigate the effect of fuel properties and injection system performance on minimum ignition energy, blowout velocity, lean extinction limits, and related aspects for cold temperature starting.” The three fuels studied in this reference included JP4, Jet A1, and diesel fuel. The temperature range considered in the model evaluation of cold start conditions spanned -40°F (-40°C) to 104°F (+40°C). The basic assessment in successful cold temperature starting “implies that both the spark ignition energy must exceed the minimum (energy) required and that the air velocity in the spark zone must remain below the blowout limit during start-up.” In terms of minimum ignition energy considerations, the relative energy relationship developed in Reference 4 indicates that smaller droplets of the less volatile fuels could be specified so as to allow the same ignition energy to be used with equal effect. For example, the less volatile Jet A1 fuel droplets would require an approximately 19% reduction in size at -40°F (-40°C) to achieve the same ignition energy level as needed for JP4 fuel.

In addition to the minimum energy consideration, the model in Reference 4 indicates that blowout velocity is affected only to a small degree by the level of the fuel volatility over the temperature range of -40°F (-40°C) to +104°F (+40°C). Moreover, the results of the overall evaluation of the cold start process by the model in Reference 4 reveal the following generalizations for ignition:

- It is in the conditions (fuel type, droplet size, trajectory, etc.) leading up to combustion that differences in fuel characteristics are significant.

- In comparison of JP4 to Jet A1 ignition and flame propagation characteristics, it is clearly evident that the injection system must deliver substantially smaller droplets for the less volatile fuel in order to achieve comparable cold temperature combustion capability.

In addition to the acknowledged effect of viscosity and surface tension on the atomization performance of simplex fuel nozzles, there is the influence of viscosity on the effective spray angle. A narrower spray angle can significantly influence the cold temperature ignition performance of a given combustion system by reducing the available fuel-air mixture in the zone of the igniter. According to Chen et al. in Reference 5, the effect of a nearly 12-fold increase in viscosity due to temperature and/or physical properties is to reduce the spray angle of a simplex nozzle by approximately 44%. Chen et al. also noted a further decrease of spray angle with liquid pressure drop across the simplex fuel nozzle as fuel viscosity increases.

Based on the previous investigations with viscous fuels described above, this current paper addresses the simplex fuel nozzle design changes required to improve the atomization performance as well as spray cone angle when using cold JP8 fuel in place of JP4 fuel. This paper explores beyond previous publications the range of very low air and fuel temperatures which approach the region of near freezing point of the fuels.

FUEL CONSIDERATIONS

Significant properties of military and commercial gas turbine fuels which can affect the pumpability, spray nozzle atomization, and combustion performance, have been adequately documented by organizations such as the Coordinating Research Council (Reference 6). Two significant properties of gas turbine fuels which greatly affect the ignition and combustion stability at cold temperature start-up
conditions are viscosity and vapor pressure. The kinematic viscosity and true vapor pressure of JP4 and JP8 gas turbine fuels are shown in Figures 1 and 2. The viscosity of JP8 and the similar Jet A1, Figure 1, is significantly higher than JP4, up to three-fold at -40°C.

Fuel surface tension, not shown, is another property associated with spray atomization quality but varies only about 10% between JP4 and JP8 fuels in the region of interest. Thus, it has little influence on differences in cold starting capability.

In this paper, the development effort utilized MIL-C-7024 calibration fluid to simulate the atomization characteristics of JP4 fuel. The utilization of MIL-C-7024 fluid in place of JP4 fuel was entirely for safety reasons. JP4 fuel kinematic viscosity at 80°F (27°C) ranges from 0.88 centistoke to 1.05 centistoke (Reference 6 and NAC technical note 3276) while MIL-C-7024 fluid is documented at 1.15 centistoke at 80°F (27°C). This discrepancy was considered satisfactory for use as a reference fluid in this development effort.

**FUEL NOZZLE DESIGN**

A study was initiated through Pratt & Whitney by the Air Force to determine the necessary modifications to the TF33 primary simplex fuel nozzle to ensure comparable JP4 fuel cold start-up performance with JP8. As illustrated in Figure 1, JP8 has a significantly higher viscosity relative to JP4, especially at very low temperatures. It is well established that increased viscosity results in a reduction in atomization quality with simplex pressure atomizer nozzles, as well as a reduction in fuel spray angle. The coarser droplet spray and reduced angle results in significantly diminished ignition performance as indicated by References 3 and 4, especially for a reduced volatility fuel such as JP8.

Spray angle is additionally affected by reduction of liquid pressure drop across the nozzle, as shown in Figure 3. Reduced pressure drop is a result of increased viscosity. Work by Lefebvre et al. (References 9 and 11) indicate the effect of viscosity is to reduce the liquid swirl velocity component within the swirl chamber of the nozzle and increase the thickness of the liquid film within the orifice, thereby increasing the exit orifice discharge coefficient. Measurements of liquid pressure drop as a function of viscosity revealed the pressure drop across the orifice decreasing as much as 50% at constant fuel flow for a small 0.0220" (0.564 mm) orifice as viscosity was increased from 1.5 to 9.5 centistokes. A lesser effect was seen for a larger 0.0325" (0.833 mm) orifice where pressure drop decreased only 21% for the same viscosity change.
Various investigations (References 5, 7, 8, 9, 10, and 11) have demonstrated the effects of geometric design and operational conditions on the spray performance of simplex pressure swirl fuel nozzles. These investigations indicate that certain geometric design changes within the nozzle’s internal flow path can offset the adverse effect of fuel viscosity on spray quality and enhance ignition performance. These include: increased swirl chamber length to diameter ratio, reduced orifice length to exit diameter ratio, increased liquid pressure drop (lower flow number), and maximized liquid swirl velocity within the swirl chamber. In addition to these internal changes, additional droplet atomization forces can be supplied by the incorporation of external air flow introduced in close proximity to the liquid film exiting the nozzle orifice.

Based on the general knowledge of fuel injector behavior, the following approaches were utilized in the current development program to obtain improved low temperature spray quality:

- Increased nozzle pressure loss
- Internal modification of swirl slots and exit orifice
- External swirl air flow

A cross-section of the baseline TF33 fuel injector is shown in Figure 4a. It is characterized by two straight slots in the primary pintle and straight air addition holes in the nozzle nut. The purpose of the pintle slots is to channel the fuel into the conical swirl chamber and can be used to vary the swirl and flow distribution into that chamber. The first nozzle design approach employed in the development program was to modify the primary injector of the baseline for increased pressure drop and swirl, as shown in Figure 4b. The pintle slots were given inclination for swirl, increased to three in number for improved flow distribution and reduced in total cross-sectional area for increased pressure drop. The exit orifice was also reduced for the increased pressure drop. In total, flow number was reduced...
by 25% to 2.1 from 2.8. Comparisons of the design parameters of the B/M baseline and modified high pressure loss nozzles are shown in Table I.

The second design approach employed is shown in Figure 4c with details also in Table I. The all-pressure atomized dual orifice baseline was replaced with a hybrid design where the main fuel injector becomes an air blast atomizer. This also provides additional air flow over the primary portion, which remains a pressure atomizer. Pressure loss of the primary was also increased as in the modified B/M, Figure 4b, and both two and three swirled pintle slot configurations were tested. Observations of the primary spray cone of the hybrid nozzles indicated the effect of the surrounding air flow was significant. While the nozzle nut air flow of the baseline and modified B/M nozzles tend to aerodynamically pinch the envelope of the spray cone, the swirling core of the air flow in the hybrid nozzle reverses that trend and counters the effects of higher fuel viscosity and reduced hydraulic pressure drop seen with low temperature, highly viscous fuels.

**TABLE I... FUEL NOZZLE CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Exit Orifice Diameter</th>
<th>TF33 B/M</th>
<th>TF33 Modified</th>
<th>TF33 Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>DO, Inches (mm)</td>
<td>0.0325</td>
<td>0.0220</td>
<td>0.0175</td>
</tr>
<tr>
<td>(0.833)</td>
<td>(0.564)</td>
<td>(0.385)</td>
<td></td>
</tr>
<tr>
<td>Number of Pintle Slots</td>
<td>2</td>
<td>3</td>
<td>2 and 3</td>
</tr>
<tr>
<td>Pintle Slot Inclination Angle (Degrees)</td>
<td>0</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Flow Number</td>
<td>LBS/HR/PSID</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>(kg/sec/KPa)</td>
<td>(1.34E-4)</td>
<td>(1.07E-4)</td>
<td>(1.07E-4)</td>
</tr>
</tbody>
</table>

![Schematic of Fuel Systems Textron Cold JP8 Fuel Schematic](image)

Fuel nozzle spray quality is measured with a Malvern Model 2600 particle size analyzer utilizing a 300 mm focus lens. Spray data are measured through the centerline of the spray at an downstream apex distance of 1.5 inches. Spray angle measurement is recorded by comparison of the visible edge of the spray as illuminated by the laser beam with a background template scribed with lines angled at 10 degree increments.

Spray radial mass flow patternation measurement was accomplished in the Fuel Systems Textron unique R19 radial patternator. The fuel spray mass flux was measured radially with a square 0.100 x 0.100 inch matrix array indexed circumferentially every 45°. The patternation measurements were collected at a plane 1.5 inches downstream of the fuel nozzle tip.

**TEST PROGRAM**

Two test fluids, MIL-C-7024 (to simulate JP4 fuel) and JP8 fuel, were utilized at liquid bulk temperatures ranging from ambient to below -40°F (-40°C). Spray quality measurements, by the Malvern particle analyzer, were conducted with each primary nozzle modification according to the test matrix shown below. A photographic image of the spray was recorded at each test point to document the resultant spray cone angle. The air pressure drops across the nozzle nut assembly and the fuel flows were chosen to simulate the range of conditions at engine start. Air temperature was matched to fuel temperature.
TABLE II...TEST MATRIX

<table>
<thead>
<tr>
<th>Fuel Flow, PPH (Kgm/sec)</th>
<th>14.3 (1.81E-3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17.9 (2.3E-3)</td>
</tr>
<tr>
<td></td>
<td>21.0 (2.7E-3)</td>
</tr>
<tr>
<td>Fuel Bulk Temperature, °F (°C)</td>
<td>70 (21.1) to -45 (-42.8)</td>
</tr>
<tr>
<td>Fuel Nozzle Air OP, inches H2O (mm)</td>
<td>11 (279.4)</td>
</tr>
<tr>
<td></td>
<td>13 (330.2)</td>
</tr>
<tr>
<td>Fuel Nozzle Air Temperature, °F (°C)</td>
<td>70 (21.1) to -45 (-42.8)</td>
</tr>
</tbody>
</table>

Fuel Nozzle Configurations

- TF33 B/M
- TF33 Modified
- TF33 Hybrid

RESULTS AND DISCUSSION

Fuel Droplet Size

Three of the TF33 injectors are compared, at a typical engine starting fuel and air flow, for droplet size variation as a function of temperature in Figure 6. As shown, the TF33 B/M baseline primary nozzle produces the largest droplet sizes for all temperatures. The modified primary nozzle with higher pressure drop (FN = 2.1) produced smaller droplets as would be predicted by Lefebvre (Reference 11) in his relation for SMD by a simplex injector:

\[ \text{SMD} \sim \sigma_{L}^{0.25} \mu_{L}^{0.25} \rho_{L}^{125} d_{0}^{0.5} \Delta P_{L}^{-0.375} \rho_{A}\text{AIR}^{-0.25} \]

Since fuel and air properties are the same for a given temperature and fuel,

\[ \text{SMD} \sim d_{0}^{0.5} \Delta P_{L}^{-0.375} \]

The dashed line in Figure 6 represents the prediction of equation (2) for droplet size of a nozzle with the pressure drop of the modified nozzle relative to the B/M baseline. The actual measured droplet size of the modified high pressure drop primary correlates well in the temperature range of 70°F (21.1°C) to -10°F (-23°C); however, below this temperature, the measured droplet size becomes larger than predicted by the equation.

\[ \text{SMD} \sim \sigma_{L}^{0.25} \mu_{L}^{0.25} \rho_{L}^{125} d_{0}^{0.5} \Delta P_{L}^{-0.375} \rho_{A}\text{AIR}^{-0.25} \]

The fuel and air density variations are relatively small over the range of temperatures of interest, so (3) can be further reduced to

\[ \text{SMD} \sim \sigma_{L}^{0.25} \mu_{L}^{0.25} \rho_{L}^{125} \rho_{A}\text{AIR}^{-0.25} \]

The three-slot pintle alteration of the hybrid TF33 fuel nozzle was tested and compared with the two-slot pintle hybrid shown in Figure 7. While both two and three-slot pintles demonstrate the same low droplet size at 70°F (21.1°C), it becomes apparent that the three-slot pintle is much more sensitive to decreasing temperature and increased fuel viscosity. According to equation (1), if pressure drop and exit orifice size are the same, then:

\[ \text{SMD} \sim \sigma_{L}^{0.25} \mu_{L}^{0.25} \rho_{L}^{125} \rho_{A}\text{AIR}^{-0.25} \]

The predicted variation in droplet size with fuel temperature for JP8 from equation (4) is shown by the dashed line in Figure 7. The three-slot hybrid nozzle shows a greater sensitivity than the two-slot hybrid design. The modified primary simplex, with three slots, also appears more sensitive to fuel and air temperature than the two-slot baseline B/M simplex (Figure 6). This behavior suggests that Reynolds number may have an effect on the pressure swirl atomization process in the low fuel flow, highly viscous regime.

\[ \text{Re} = \frac{\rho_{L} V_{L} D_{0}}{\mu_{L}} \]
Consideration of retaining the same flow number for the simplex two and three-slot pintle designs requires a slight modification to the slot geometries. To maintain a constant cross-sectional area and flow velocity, the hydraulic diameter of the two-slot pintle is approximately 23% larger than the three-slot design. Calculation of the pintle slot Reynolds numbers utilizing very low flows and highly viscous (9.5 centistokes) fuel indicates that the pintle flow is in the turbulent/laminar transition range (1550 - 2500 Re.). Thus, the larger hydraulic diameter of the two-slot pintle will maintain the Reynolds number at a higher value than the three-slot and delay the transition to laminar flow.

The reason for the less than anticipated droplet size reduction for the modified B/M (Figure 6) at low temperatures may also be due to its three-slot design relative to the B/M baseline, which has a two-slot pintle. Early screening tests performed at room temperature eliminated the two-slot modified B/M from the low temperature test program. Analysis of all data now indicates that further revision of the modified B/M to a two-slot design may be beneficial for improved low temperature performance.

The simplex primary nozzle developed for the Swedish Air Force exhibited a very strong increase in droplet size (Figure 8) at fuel temperatures below -40°F (-40°C) in spite of a 40% reduction of primary simplex flow number from the baseline. The dashed line in Figure 8 illustrates the predicted droplet size variation according to equation (4) as fuel temperature is reduced from 70°F (21.1°C). The further increase in droplet size above that predicted by equation (4) is most likely the result of transition into laminar flow as indicated by the Reynolds number effect.

\[
SMD \sim \frac{\Delta P}{V A L^3.75}
\]

Thus, smaller droplet sizes will be produced by the higher injector pressure drop incurred by the increased fuel flow.

Data for the modified primary simplex nozzle comparing droplet sizes at 17.9 and 21.0 PPH are shown in Figure 9. Equation (6) predicts a 12% reduction for the 21 PPH flow rate, which the data confirms. Droplet size measurements for the two-slot hybrid with three fuel flow rates are illustrated in Figure 10. No droplet size trend was observed with fuel flow variation in this concept, thereby indicating the domination of the concurrent swirl air flow incorporated in this design.

#### FIGURE 8...SMD OF SWEDISH INJECTOR

**Fuel Flow Rate.**

A traditional approach to improve gas turbine cold start capability is to increase starting fuel flow rate so as to increase the total amount of available fuel for ignition and flame propagation. Not only is the total mass of fuel increased, but according to the droplet size correlation of equation (1):
Fuel Type.

Spray tests were also performed with cold MIL-C-7024, a calibration fluid whose viscosity and specific gravity sufficiently simulates JP4 fuel. Figure 11 shows a comparison of the droplet sizes obtained with the modified TF33 simplex primary nozzle with JP8 fuel and MIL-C-7024 fluid. As expected, smaller droplet sizes are measured with a lower viscosity fluid as predicted by equation (4). Note that as fuel temperature decreases, a much smaller increase in droplet size is seen with MIL-C-7024 than with JP8. The lower viscosity fluid maintains a higher Reynolds number through the injector and thus the transition to laminar flow is delayed to a lower temperature.

Spray Angle

The observed spray cone angles of three TF33 primary nozzle configuration are shown in Figure 13. Lefebvre in Reference 11 quotes the following dependence of spray cone angle on fluid viscosity.

\[
\tan \theta \sim \nu^{-1.31}
\]

Both the baseline TF33 B/M and modified TF33 simplex nozzles show the anticipated behavior of decreasing spray angle with lower temperature fuel (thereby increased fuel viscosity). The modified TF33 primary simplex initially exhibits a higher spray angle than the baseline, as anticipated in Reference 5 (Chen et al.), for increased pressure drop across the injector. However, as indicated, the difference in spray cone angle between the two simplex primary configurations becomes negligible at the very low fuel temperatures.

Fuel Flow Rate.

Increasing fuel flow rate for the modified TF33 primary simplex resulted in slightly increased spray cone angle as no difference in droplet sizes was observed, thereby substantiating the relative insensitivity of the hybrid concept to fuel viscosity effects.
shown in Figure 14. As anticipated, injector pressure drop is increased with increasing fuel flow thereby exhibiting the same effect on spray cone angle as increased pressure drop by design. The two-slot pintle of the hybrid simplex primary nozzle exhibited no dependency on fuel flow rate (Figure 15) reiterating the absence of pure hydraulic effects on this atomizer concept and the importance of the swirl air.

Fuel Type

Figure 16 shows a 20° spray cone angle increase for the TF33 baseline nozzle with MIL-C-7024 fluid at 70°F (21.1°C); however, at fuel temperatures of 0°F (-17.8°C) and lower, there was no significant difference in spray cone angle between MIL-C-7024 fluid and JP8 fuel. Figure 17 shows the modified TF33 simplex primary nozzle to consistently produce a higher spray cone angle with the lower viscosity MIL-C-7024 fluid as compared to JP8 fuel.

Radial Patternation

While spray cone angle measurements give an indication of the outermost spread of the spray, radial patternation measurements indicate how the fuel mass is distributed within those boundaries. Results of tests of the three TF33 configurations are shown in Figure 18 where the volume of liquid spray accumulated in each collector tube is plotted versus collector tube number from the nozzle centerline outward to the spray boundary. All testing was accomplished at ambient temperatures (21.1°C), but the relative mass flux behavior should persist at the lower fuel temperatures.
simplex nozzle designs. The two-slot hybrid produced the smallest droplet sizes and consistent spray cone angles.

• The modified TF33 primary simplex nozzle (FN 2.1) produced moderate reduction in droplet size and a slightly higher spray cone angle relative to the TF33 baseline primary nozzle (FN 2.8) design.

• The hybrid injector concept designs showed the greatest promise of improving JP8 cold start performance, especially in the two-slot pintle version. The modified TF33 primary simplex injector also should show cold start improvement with JP8 fuel.

REFERENCES


