Investigation of High-Altitude Ignition Performance of Several Chinese Jet Fuels With Different Properties

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ABSTRACT

Investigation of high-altitude ignition performance of several Chinese jet fuels with different properties has been conducted at a simulated altitude facility. Jet fuels were tested in a small pilot combustion chamber taken from an existing aeroengine. The fuels consist of Da-Qing oil, Da-Gang oil, Nan-Jing oil, Gu-Dao oil (so called as high density fuel) as well as a compound oil. Test results show that the lower the fuel density (its viscosity is also lower, but vapour pressure is higher), the better the high-altitude ignition performance. The high-altitude ignition performance of high density fuel is rather bad, but can be significantly improved by mixing it with a small quantity of low density oil (about 10 percent). Using a small flow number atomizer may obviously improve the weak ignition limit of the high density fuel, but the ignition velocity-pressure limit and the rich ignition limit are shrunk. Test results also show that prevailing theory model for spark ignition is feasible.

INTRODUCTION

The purpose of this study is to demonstrate the effects of Chinese aviation turbine fuel property variations on the high-altitude ignition performance. It is well-known that the fuel property variables expected to have the greatest influence on atomization, ignition and combustion of gas turbine mainly include: 1. viscosity 2. volatility 3. hydrogen content (aromatics). Generally speaking, the higher the fuel density, the higher the viscosity and the lower the volatility as well as the lower the hydrogen content. For this reason, high-altitude (low pressure) ignition behavior of jet fuels of different properties inevitably differs from each other to a considerable extent attributed to the diversity of atomization and evaporation. However, this diversity in the high-altitude ignition performance of various jet fuels can not be calculated by means of thematical models at the present. It is also very difficult and prohibitively expensive to measure under real flight condition. The most effective, precise and economic approach is to conduct comparative tests for various jet fuels at a simulated high-altitude facility. Through these tests, qualitative differences in the low pressure ignition performance among these various fuels can be found, and various means to improve low pressure ignition performance may be initiated.
It is predicted that high quality aviation kerosene will become less available in the near future and the low-grade fuels will have to be utilized. The serious obstacle that hampers the application of inferior fuels is their ignition capability at low pressure and low temperature. Therefore, it is necessary to understand and study the ignition capability of inferior fuels at low pressure.

EXPERIMENTAL SET-UP

The layout of the low pressure ignition test rig is shown in Fig. 1. The ignitor(5), taken from an existing engine, is essentially a small combustion chamber with a tiny swirl fuel atomizer and two electrodes. Air is drawn in from the atmosphere by a vacuum pump(2). The pressure and the air flow rate in the ignitor can be controlled to the desired values by adjusting the regulator valve(1) and inlet throttle valve(7).

The small combustion chamber is mounted at the top of the low pressure plenum chamber. The exhaust system includes a low pressure plenum chamber (6420·12mm, 415mm high) with quartz glass windows on both sides for observation and photography. At the outlet of the plenum chamber is the flame arrestor for safety consideration. A drainage valve(10) is installed at the lowest position of the system to avoid any fuel accumulation in the exhaust pipe. The electrodes are connected to the induction ignition coil. The spark energy is close to 50 mj and spark frequency is 350-800 cycles per second.

The air flow rate is measured by float

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The air flow rate is measured by float

<table>
<thead>
<tr>
<th>Fuels</th>
<th>Da-qing oil</th>
<th>Da-Gang oil</th>
<th>Nan-Jing oil</th>
<th>Gu-Dao oil</th>
<th>Compound oil</th>
</tr>
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<tbody>
<tr>
<td>Properties</td>
<td>RF-2</td>
<td>Rp-3</td>
<td>RF-5</td>
<td>RF-6</td>
<td>(RF-6)+(RF-2)</td>
</tr>
<tr>
<td>Density g/cm³, 20c</td>
<td>0.7759</td>
<td>0.8079</td>
<td>0.8194</td>
<td>0.8389</td>
<td>0.8236</td>
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<td>Initial Point c</td>
<td>140</td>
<td>169</td>
<td>187</td>
<td>197</td>
<td>166</td>
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<tr>
<td>10%</td>
<td>155</td>
<td>179</td>
<td>197</td>
<td>207</td>
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<td>90%</td>
<td>217</td>
<td>218</td>
<td>228</td>
<td>262</td>
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</tr>
<tr>
<td>98%</td>
<td>227</td>
<td>229</td>
<td>243</td>
<td>280</td>
<td>273</td>
</tr>
<tr>
<td>Flash point, c</td>
<td>32</td>
<td>51</td>
<td>61</td>
<td>68</td>
<td>55</td>
</tr>
<tr>
<td>Viscosity mm²/s, 40c</td>
<td>1.4</td>
<td>1.67</td>
<td>1.96</td>
<td>1.96</td>
<td>2.73</td>
</tr>
<tr>
<td>40c</td>
<td>5.27</td>
<td>7.57</td>
<td>13.46</td>
<td>27.53</td>
<td>27.27</td>
</tr>
<tr>
<td>Carbon/Hydrogen</td>
<td>5.73</td>
<td>6.04</td>
<td>6.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low heat value KJ/Kg</td>
<td>43500</td>
<td>43065</td>
<td>43044</td>
<td>43019</td>
<td></td>
</tr>
<tr>
<td>Flame height without smoking, mm</td>
<td>34</td>
<td>23</td>
<td>22</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Aromatic hydrocarbon % by weight</td>
<td>7.14</td>
<td>16.08</td>
<td>17.3</td>
<td></td>
<td></td>
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<tr>
<td>Crystallization point, c</td>
<td>-52.8</td>
<td>-59</td>
<td>-56</td>
<td>-48</td>
<td>-50.2</td>
</tr>
</tbody>
</table>
gas meters. The fuel flow rate is determined by the pressure drop of the fuel swirl atomizer with experimentally calibrated fuel swirl atomizer characteristic curve (mass flow rate vs pressure drop). Since the air flow Mach number in the ignitor is rather low (<0.1), the air velocity at the electrodes can be determined by the measured air static pressure, temperature, air mass flow rate and the flow area at the electrodes.

TESTED FUELS AND THEIR PHYSICOCHEMISTRY

The fuels tested in the present research consist of five species. They are Chinese aviation kerosene: Da-Qing oil (RP-2), Da-Gang oil (RP-3), Nan-Jing oil (RP-5), Gu-Dao oil (RP-6) as well as a compound oil [(RP-6) + (RP-2)] which is a mixture of Gu-Dao oil with a small quantity of Da-Qing oil (with a ratio of 9 to 1 by mass). Their main physico-chemistry properties are shown in table 1. It is obvious from table 1 that fuel viscosity increases with increase of fuel density. Without doubt, their volatility and vapour pressure should be decreased with increase of density.

Well-known prevailing thermal theory model of spark ignition by Subba Rao and Lefebvre(1973) shows that passage of the spark creates a kernel in which high gas temperature are attained, partly resulting from the energy supplied in the spark, but also from the heat liberated by the rapid combustion of the smallest fuel drops. This initial high temperature then falls as heat is lost by diffusion to the fresh mixture in contact with the outside surface of the kernel, and to the remaining fuel drops undergoing evaporation within the kernel. The key factor governing ignition is whether or not these drops can evaporate and generate heat quickly enough to compensate the heat loss to the surrounding fresh mixture before the kernel has shrunk below its minimum critical size.

When ignition is achieved, the burning drops continue to produce heat and raise the temperature of the surrounding unburned mixture. The vapour produced diffuses outwards and the flame rapidly spreads to all regions where the air and fuel vapour are in combustible proportions.

According to above thermal theory model of spark ignition in the spray, it is believed that fuels of different properties would have different ignition performance at high-altitude because there is such large difference of atomization and evaporation performance among these fuels.

IGNITION PERFORMANCE CRITERIA AT LOW PRESSURE AND TEST PROCEDURES

To evaluate ignition performance of various jet fuels at low air pressure simulating high-altitude condition, following four criteria are selected:

1. Ignition pressure-velocity limit for the given fuel atomizer at constant fuel supply pressure.

2. Ignition pressure-velocity limit for the given fuel atomizer at optimum fuel supply pressure, namely at optimum air fuel ratio.

3. Weak ignition limit for the given fuel atomizer at constant air pressure and velocity.

4. Rich ignition limit for the given fuel atomizer at constant air pressure and velocity.

To acquire above various relationships, test procedures are as follows:

1. At constant fuel supply pressure of $P_f = 1.96 \times 10^5 N/m^2$, a series of vacuums of 0.133, 0.267, 0.4, 0.533, 0.6$ \times 10^5 N/m^2$ in the low pressure plenum chamber are kept respectively, so the corresponding absolute pressure in the low pressure plenum chamber approximately are 0.88, 0.746, 0.613, 0.48, 0.413$ \times 10^5 N/m^2$ respectively. The maximum air flow rates of ignition are measured by float meter.

2. A series of vacuums of 0.4, 0.533, 0.667, 0.8$ \times 10^5 N/m^2$ in the low pressure plenum chamber are kept respectively, so the corresponding absolute pressure in the low pres-
ure plenum chamber are 0.613, 0.48, 0.343, 0.213 \times 10^5 \text{N/m}^2 \text{ respectively}. The fuel supply pressure is changed in order that maximum air flow rate of ignition can be measured by float meter.

3. A series of vacuums of 0.133, 0.267, 0.4, 0.533, 0.667 \times 10^5 \text{N/m}^2 \text{ in the low pressure plenum chamber are kept respectively, so the corresponding absolute pressure in the low pressure plenum chamber approximately are 0.88, 0.746, 0.613, 0.48, 0.346 \times 10^5 \text{N/m}^2 \text{. For above each vacuum a series of air volume rate of 4, 6, 8, 10, 12, 14, 16 \text{m}^3/\text{H} \text{ are kept respectively, and ignition minimum fuel supply pressure are measured by gauge for each vacuum and air volume rate respectively.}}

4. A series of vacuums of 0.4, 0.533, 0.667 \times 10^5 \text{N/m}^2 \text{ in the low pressure plenum chamber are kept respectively, so the corresponding absolute pressure in the low pressure plenum chamber approximately are 0.613, 0.48, 0.343 \times 10^5 \text{N/m}^2 \text{. For above each vacuum a series of air volume rate of 4, 6, 8, 10, 12, 14, 16 \text{m}^3/\text{H} \text{ are kept respectively, and ignition maximum fuel supply pressure are measured by gauge for each vacuum and air volume rate respectively.}}

The criterion for successful ignition is that after the electrical spark has been turned off, a stable flame is self-sustained continuously. But the maximum ignition operation time is 20 seconds.

According to the above required condition, the inlet throttle valve and regulator valve are adjusted, or the fuel supply pressure is changed so that the above various relationships can be obtained experimentally.

A number of references (2-4) have pointed out that improvements in fuel atomization during the ignition sequence may significantly improve the ignition performance at low pressure corresponding to high-altitude windmilling condition in combustion chamber. Therefore, a small flow number (Note: flow number = fuel flow in litres per hour/(fuel injection pressure in N/m$^2$)$^{0.5}$) atomizer for high density Gu-Dao oil is tested in order to understand its effectiveness for improving low pressure ignition performance. Flow number of original atomizer is $0.0216 \frac{\text{L/H}}{(\text{N/m}^2)^{0.5}}$, but flow number of a small atomizer is $0.0121 \frac{\text{L/H}}{(\text{N/m}^2)^{0.5}}$.

RESULTS AND ANALYSIS

1. Figure 2 shows ignition pressure-velocity limits for various fuels at constant fuel supply pressure of $P_f = 1.96 \times 10^5 \text{N/m}^2 \text{.}$ Ignition velocity limits of various fuels increase in direct proportion with decreasing air pressure in the testing pressure range which is generally that of high-altitude relight in combustion chamber under windmilling condition, about 0.343-0.88 $\times 10^5 \text{N/m}^2 \text{.}$ While air flow pressure decreases, oxygen concentration in air flow decreases. The general rate expression governing a chemical reaction can be expressed in terms of Arrhenius form:

$$W = \frac{dn}{dt} = K_o e^{-E/RT} n_a^n n_o^b$$

where $W$ is the chemical reaction rate, $K_o$ is the chemical reaction rate constant, $E$ is the activation energy, $T$ is the reactant temperature, $n_a$ and $n_o$ are the reactant concentrations, and $t$ is the reaction time.

Chemical reaction rate $W$ will decrease in direct proportion with decrease of reactant concentration.
oxygen concentration, so release heat rate by chemical reaction will decrease with decrease of air pressure. Obviously, it is very harmful to the ignition. On the other hand, at constant fuel supply pressure pressure drop in atomizer increases with the decrease of air flow pressure, so atomization quality to be improved is particularly beneficial to the ignition (2-4). At the same time, air flow Re number will be decreased due to decreased pressure so that quenching effect of air flow on hot kernel will be decreased, it is also beneficial to the ignition. In addition, low air flow pressure also promotes fuel evaporation which would be particularly beneficial to the ignition.

Between above two functions experimental test shows that beneficial function is more than harmful one to the ignition at the low air pressure. Fig. 2 also obviously shows that in regular orders of low pressure ignition performance for tested fuels are Da-Qing oil, Da-Gang oil, Nan-Jing oil and Gu-Dao oil (namely by ignition velocity at same air flow pressure). These orders are consistent with the orders of the density of tested in Table 1. Of course, it is not by a curious coincidence but agrees with the foregoing statement of theoretical model of spark ignition in the spray: atomization and evaporation play dominant role in the period of ignition.

In addition, low pressure ignition performance of mixed fuel is obviously improved. It is showed that mixing inferior fuel with a small amount of high quality fuel is an effective measure to improve its high-altitude ignition performance.

2. Figure 3 shows ignition pressure-velocity limit for various fuels at optimum air-fuel ratio. Its plot tendency is different from that of in Fig.2. The higher the air flow pressure, the wider the ignition limit. The pressure drop of the fuel atomizer changes a little when maintaining fuel supply pressure constant, but at optimum fuel supply pressure the pressure drop of the fuel atomizer changes greatly as shown in Fig.4. The higher the air flow pressure, the larger the pressure drop of the fuel atomizer. This is because that a large amount of air flow needs more fuel for the ignition so that high fuel supply pressure is needed and atomization quality is greatly improved as well as the ignition can be realized at higher air velocity.

Again as illustrated in Fig.3, in regular orders of low pressure ignition performance for tested fuels are Da-Qing oil, Da-Gang oil, Nan-Jing oil and Gu-Dao oil. Also again show that low pressure ignition performance of mixed fuel may be improved greatly comparing with high density Gu-Dao oil.
3. Figure 5-9 show weak ignition limit of tested fuels at different low pressure. The very strong influence of fuels species on weak ignition limit is clearly demonstrated. Do-Qing oil has the widest weak ignition limit and next are Da-Gang oil, Nan-Jing oil and Gu-Deo oil. The weak ignition limit of compound oil is near that of Nan-Jing oil. Experimental test again demonstrated that prevailing theory model of spark ignition in the spray is rather correct. Oil vapour amount plays the most important part in the course of developing flame kernel. Obviously, the above-mentioned weak ignition limits may be used to evaluate ignition performance at ground low temperature because lacking oil vapour is a key for ignition at low temperature.

To sum up, the foregoing three criteria (ignition limit at constant fuel supply pressure, ignition limit at optimum air-fuel ratio and weak ignition limit) which are used to evaluate high-altitude ignition performance for various fuels will give same results, namely the lower the fuel density, the
This possibly is due to the quenching action of fuel injection on spark kernel with a close distance between the fuel atomizer and the electrodes.

5. Figures 12-15 show difference of low pressure ignition performance between the original and the small flow number atomizer for the high density Gu-Dao oil. Obviously, the ignition pressure-velocity limit at constant fuel supply pressure and optimum fuel supply pressure and rich ignition limit of the small flow number atomizer are shrunk, but the ignition weak limit is significantly extended. By using a small flow number atomizer, a small Sauter Mean Diameter (SMD) in the spray may be obtained because it has a low fuel volume flow $Q_f$ at the same pressure drop $\Delta P_f$.
(reference 1, 90th page). That is why a small flow number atomizer has better weak ignition performance. Although a small flow number atomizer may improve atomization, total fuel flow rate is decreased so that total evaporation rate of the spray is decreased. As a result, weak ignition limit is improved, but other ignition performance are deteriorated.

CONCLUSIONS

Based on the experimental data obtained in the investigation the following conclusion may be drawn:

1. The lower the fuel density (its viscosity is also lower, but vapour pressure is higher), the better the high-altitude ignition performance (except rich ignition performance).

2. The high-altitude ignition performance of high density fuel is rather bad, but can be improved significantly by mixing it with a small quantity of low density fuel (about 10 percent).

3. The high-altitude weak ignition performance of high density fuel may be improved greatly by using a small flow number atomizer, but other low pressure ignition performance are deteriorated.

4. The difference of high-altitude rich ignition performance for tested ignitor and fuels is small and high density fuel is slightly dominant.

5. The experimental data clearly demonstrated that prevailing theory model of spark ignition in the spray is feasible, namely the fuel spray evaporation rate is key in the period of ignition.

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