Air-Assisted Injection System for Aviation Heavy Fuel Engine

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Abstract. According to the system requirement of a certain type of aviation piston engine, the reconstruction and matching of fuel injection system is carried out. The schematic design of the air-assisted injection assembly and the improvement of pressure regulator assembly are completed. After that, the air-assisted direct injection system is studied experimentally. The results reveal the effect of injection parameters and injection pressures on the system flow characteristics and spray characteristics. The effects of gasoline and kerosene on the actual engine performance are compared. The test results show that the self-designed air-assisted direct injection system can meet the system fuel injection requirements. In addition, the effect of injection pressure on the spray width is more noticeable than other spray characteristics.

1. Introduction
With the advantages of low fuel consumption, light weight, high power-to-weight ratio and easy maintenance, piston engines have become the satisfactory choice for small aviation propulsion system [1-2]. Over the years, most piston-type aircraft engines use carburetor as fuel supply system. However, carburetor-type engines have the disadvantages of long response time, low control accuracy, uneven combustible mixture and high-altitude fuel condensation. In addition, there is also a growing requirement for lightweight high-performance piston engines capable of operation with aviation kerosene as well as maintaining the capability of running on regular gasoline [3]. Compared with gasoline, kerosene has a high flash point since it is less volatile and therefore shows higher safety [4-5]. However, after fueled with kerosene directly, the overall performance of engine will decline [6]. In-depth research and power performance matching of aviation kerosene engines are needed.

In-cylinder direct injection (DI) technology has developed rapidly in recent years [7-8]. As a key component of in-cylinder DI technology, high-pressure injection will easily cause spray wall-impingement which may lead to incomplete combustion, poor emission and power loss [9-10]. The low-pressure air-assisted direct injection system was mainly applied to two-stroke gasoline engines in the early years, which can reduce the short-circuiting of fuel-air mixture during scavenging of two-stroke gasoline engines, improve fuel economy and reduce emissions [11-13]. After that, this technology was applied to four-stroke gasoline engines and LPG engines. The most representative one is the air-assisted in-cylinder direct injection four-stroke spark ignition (SI) engine jointly developed by Orbital and AVL. This air-assisted direct injection system possesses a small spray droplet size, low penetration, and narrow spray cone angle which can effectively improve spray atomization quality at a low pressure [14-16].
The fuel used in this research is aviation heavy fuel (JP-5). Considering the improvement of the fuel injection system of aviation kerosene engines, an air-assisted fuel injection assembly that uses low fuel supply pressure and separate fuel injector and air injector is designed. Compressed air is mixed in the fuel injection process before the air-injection operation [13, 15]. When the mixture of the fuel-air mixture is sprayed together, the expansion of the compressed air will accelerate the fragmentation of the fuel droplets, thereby improving the atomization of the spray [17]. During this process, well-atomized spray can be achieved under a quite low fuel injection pressure. At the same time, the low injection pressure will reduce the risk of leaks in the fuel supply system, helping to improve the reliability of aircraft engines operating in extreme environmental conditions [18, 19].

Based on the system requirement of a certain engine design, this paper develops the overall schematic design of the fuel system. The influence of related parameters on the injection performance of the system is discussed, and the matching of the characteristics of the fuel supply system and the practical engine is completed.

2. Experimental Setup

2.1. Engine specifications

The Rotax-914 aviation engine is a piston engine produced by BRP-Powertrain. The carburetor is selected for fuel supply method. In this study, the carburetor fuel supply system was replaced by an air-assisted fuel injection system. Aviation kerosene was used to fuel the engine. The endurance of this engine and its supporting models may be increased through the optimization of fuel delivery under different working conditions. The technical parameters of the original engine are shown in Table 1. The figure 1 shows a layout diagram of the test bench of the improved Rotax engine.

| Table 1. Rotax-914 Engine |
|---------------------------|
| Version                   | EQD180N-20                      |
| Type                      | Four-cylinder, four-stroke,     |
|                           | water-cooled                    |
| Bore/Stroke               | 79.5mm/61mm                    |
| Displacement              | 1.2L                             |
| Compression ratio         | 9:1                              |
| Firing order              | 1-4-2-3                         |
| Ignition method           | DCDI dual ignition system       |
| Rated power               | 73.5 kW, 5500 r/min             |

Figure 1. Engine test bench
The peak fuel delivery of the engine's fuel injection system is determined according to the actual needs of the engine. Usually, it is calculated based on the rated power, rated speed and effective fuel consumption rate of the original engine as

$$m_s = \frac{1000P \cdot b_e}{60nZi}$$

where \(P\) is 73.5 kW according to table 1 and \(b_e\) is the effective fuel consumption rate with the value of 285 g/(kW*h) at rated power. \(n\) is 5500 r/min. \(Z\) is 0.5 and \(i\) represents the number of cylinders. After calculation, the single-cylinder circulating peak fuel consumption \(m_s\) of the engine is around 33.25 mg/cyl.

### 2.2. Air-assisted injection system

Air-assisted fuel injection system consists of injection block assembly (air injector, fuel injector, etc.), fuel-air pressure regulation assembly (fuel pressure regulator, pressure difference regulator, pressure relief valve, etc.), low-pressure fuel pump, fuel filter, fuel pipe, compressed air cylinder, ECU and other components. Figure 2 is the physical diagram of the air-assisted injection assembly and the pressure regulation assembly. Both of the injectors are under the control of the solenoid coil to achieve precise control of opening and closing time. The fuel injector is in the upper part of the air injector. Before the air injector is opened, liquid fuel was injected into the premixing chamber. In this process, the fuel is delivered to the premixing chamber filled with compressed air (0.6 MPa) with a certain injection pressure of 0.7 MPa. The pressure difference between the fuel and air (0.1MPa) is maintained by the fuel-air pressure regulating valve, which is reliable and conducive to the precise control of the fuel injection quantity. Then the air injector is open and the mixture of fuel and air was injected into the combustion chamber. The control signal timing is shown in figure 3.

![Figure 2. Injection system assembly (left) and pressure regulator assembly (right)](image)

![Figure 3. Injection control signal timing](image)

The injection quantity of fuel and air is determined by their respective injection durations. \(T_f\) \((T_f + T_a)\) represents the fuel injection duration and \(T_a\) \((T_f + T_a)\) represents the air injection duration. \(T_i\) and \(T_j\) is the opening duration of injector while \(T_a\) and \(T_a\) represent the holding duration. \(T_{fa}\) is the fuel-air injection interval. Different combinations of injection durations of \(T_f\) and \(T_a\) will affect the fuel
concentration in the spray, which in turn affects the spray characteristics, atomized droplet size of the spray and the quality of combustible mixture subsequently formed in the cylinder.

2.3. Test system description
Figure 4 illustrates the schematic of the test system layout. The system mainly includes: fuel supply and air supply system, synchronization system and high-speed image system. The compressed air in figure 4 is provided by a high-pressure air cylinder and the air pressure is controlled by a regulating valve. The fuel supply system consists of fuel tank, fuel filter, fuel pump and a hydraulic pressure regulating valve. The high-speed camera is FASTCAM SA2 (from Photron Inc.) with the shooting frequency set by 3600 frames per second (fps) and image resolution of 1024×1024 pixels. The test ambient temperature is 25 °C and ambient pressure is 101 kPa.

3. Results and analysis
3.1. Injector flow characteristics
During each measurement, 1,000 injections are conducted. The average value of the three measurements is taken to get the mass flow rate of a single injection. The injected fuel is collected by a container sealed with the injector. The fuel pressure is maintained at 0.7 MPa during the measurement. The $T_{fa}$ is 1.0 ms and the air injection duration $T_{a}$ is 2.5 ms. Figure 5(a) is the fitting curve of the injection quantity of the fuel injector. The approximate relationship is $Q_{inj}=2.6524\times\Delta T_f +1.61615$. Here, $Q_{inj}$ is the fuel injection quantity and $\Delta T_f$ is the duration of the fuel injection.

The mass flow characteristic of the air injector is measured by the drainage method. During the measurement, the air injector is driven separately and the air pressure is maintained at 0.6 MPa. The average value of multiple injections is obtained. Here the air density is selected as 1.293 g/m$^3$. $T_f$ is 5.5 ms and $T_{fa}$ is 1.0 ms. Figure 5(b) shows the fitting curve of $Q_{inj}=8.3214\times\Delta T_{fa} -11.6936$ where $Q_{inj}$ is the injection quantity of the air, and $\Delta T_{fa}$ is the air injection duration.

Figure 5. Flow characteristics of (a) fuel injector and (b) air injector
3.2. Fuel injection characteristics

The time from when the fuel injector is closed to when the air injector is opened is called the fuel-air injection interval, which is recorded as $T_{fa}$. During this interval, the fuel emerging from the nozzle is fully mixed with the compressed air in the premixing chamber. Here the $T_{fa}$ is set to -0.5 ms, 0.0 ms, 0.5 ms and 1.0 ms. Figure 6(a) shows the effect of different $T_{fa}$ on the fuel injection quantity when $T_a$ is set to 1.0 ms. It can be seen that when $T_{fa}$ is 0.5ms, the fuel injection quantity of the air-assisted injection system is the largest. When the $T_{fa}$ is -0.5ms, the fuel injection quantity is the smallest. When $T_{fa}$ is greater than 1.0 ms, the fuel injection quantity does not change significantly.

Figure 6(b) shows the change of fuel injection quantity of air-assisted injection system under different air injection duration $T_a$ when $T_{fa}$ is 0.5 ms. It can be seen that with the increase of $T_a$, the system fuel injection quantity gradually decreases but small differences exist for all cases. When the $T_a$ is 0.5 ms, the system fuel injection quantity reaches the largest. In addition, the fuel injection quantity is close to 33 mg when $T_f$ is 11.5 ms. This means that the fuel injection quantity of the air-assisted injection system can meet the peak fuel consumption requirement of the engine by appropriately increasing the fuel injection duration.

The fuel injection pressure of air-assisted injection system is adjusted by the air pressure combined with the fuel-air pressure regulating valve. The fuel injection pressure is a key parameter of the air-assisted fuel injection system, which plays an important role in the stability and reliability of the engine operation. In the test, the injection pressure was set to 0.7 MPa and 0.6 MPa respectively. The injection control parameters are: $T_{fa}$ is 0.5 ms and $T_a$ is 2.5 ms. Figure 6(c) shows the fuel injection quantity of the air-assisted injection system under different injection pressures. It can be seen from the figure that as the fuel injection pressure increases, the fuel injection quantity of the system increases. Therefore, under the condition of ensuring reliability and safety, the air supply pressure can be appropriately increased to increase the fuel injection pressure to ensure the circulating fuel injection required for the engine.

![Fuel injection characteristics under different conditions](image)

3.3. Spray characteristics

The study of macro spray characteristics helps to optimize the structural design of the combustion
chamber to reasonably match the in-cylinder airflow organization, which will contribute to improving the mixture formation, combustion and power of the engine.

The spray width and penetration length are important parameters reflecting the macroscopic development of the spray. The spray dispersion rate can directly indicate the diffusion degree of the spray in a certain space. The default environmental parameters and injection control parameters are: ambient back pressure is 0.1 MPa, ambient temperature is 25 °C, injection fuel injection duration is 5.5 ms, air injection duration is 2.5 ms and fuel-air injection interval is 0.5 ms. The spray development images after start of injection (ASOI) of the air-assisted injection system at different injection pressures is shown in figure 7. The change of the injection pressure will not affect the pressure difference (0.1 MPa) between the fuel and air. The fuel injection quantity will not change. The change of injection pressure will cause the actual pressure difference to the ambient to change and thus to affect the spray characteristics.

The spray raw images were processed with Matlab to obtain the spray penetration, width and dispersion rate (ratio of spray pixels to image pixels). In this process, the spray image background was first removed by image subtraction. Then the image contrast was enhanced appropriately to highlight the spray area after converting the RGB image into grayscale image. After that, the intensified grayscale image was binarized with the gray threshold based on Ostu’s method to obtain spray edge [19]. Figure 8(a) shows the comparison of the spray penetration and dispersion rate at different injection pressures. It can be seen that before 3.0 ms, the penetration of 0.6 MPa and 0.7 MPa are close. After 3.0 ms ASOI, the penetration of 0.7 MPa exceeds that of 0.6 MPa but the difference is quite insignificant. For the spray dispersion rate, the value of 0.6 MPa and 0.7 MPa are also very close during the whole injection process. Figure 8(b) shows the spray width under injection pressure of 0.6 MPa and 0.7 MPa at 2.0 ms ASOI. It shows that the spray width of near-nozzle field of 0.7 MPa is less than that of 0.6 MPa while the spray width of far-nozzle field of 0.7 MPa is greater than 0.6 MPa. This indicates that higher injection pressures cause the spray to tend to spread laterally at the far-nozzle field.
Figure 8. Spray characteristics under different fuel injection pressures

4. Engine test result

Engine test of improved Rotax engine with air-assisted injection system is conducted. A cylinder pressure sensor was installed on the cylinder body. The figure 9 shows the comparison of maximum IMEP value of gasoline and kerosene at each speed on this test bench. When the engine is fuelled with gasoline, the maximum IMEP is 13.8 bar. After switching to aviation kerosene, the engine can still run stably in the speed range of 2500 r/min to 5500 r/min, but the maximum IMEP can only reach around 6.3 bar. This conclusion is similar to the conclusion of the National Research Council and the U.S. Air Force Research Laboratory Promotion Agency for Rotax-914 retrofitting burning kerosene JP-8. Due to different physical and chemical properties, the aviation kerosene burns at a slower rate than gasoline. The cylinder pressure is lower than that of the original gasoline-fuelled engine. In general, the self-designed air-assisted fuel injection system basically meets the operating requirement of the engine with kerosene. The next research work will focus on the optimization of control parameters to achieve the power output increase of kerosene-fuelled engines.

Figure 9. Comparison of gasoline and kerosene

5. Conclusions

This study mainly involves the development of an air-assisted fuel injection system using kerosene as alternative fuel for a carburetor-type aviation gasoline engine. The scheme design of the air-assisted injection assembly and the regulator assembly was carried out before the experimental research of the air-assisted injection system was conducted. The effects of injection control parameters and pressure on the system flow characteristics and spray characteristics were studied, and the matching verification of the fuel system and the engine was completed. The test results show that the self-designed air-assisted injection system meets the system fuel injection requirements. The influence of injection pressure on spray penetration and spray dispersion rate is small, but its impact on spray width is large. The using of air-assisted injection helps to improve the spray atomization of the engine. At the same
time, reasonable injection pressure and fuel and air injection timing will be critical to the stable operation of the system.

Acknowledgements
This research was financially supported by Beijing Institute of Technology Research Fund Program for Young Scholars (grant no. 2019CX04031) and Foundation research funds of Ministry of Industry and Information Technology (grant no. JCKY2019602D001).

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