Recent Progress in Heavy Fuel Aviation Piston Engine

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Abstract: Heavy fuel aviation piston engines (HF-APEs) refer to the engine using fuels with high flash point, such as kerosene or light diesel. Here technique specifications of some classical foreign HF-APEs (Hirth3503, Zanzottera 498) are introduced. Recent progress and trend of fuel injection, fuel ignition, working cycle, intake charging, thermal management and electronic control of HF-APE are compared and summarized. Emphases are put on the technological difficulties, solutions and development tendency in the design, retrofitting and manufacturing of HF-APE aiming to provide references for the research of related area and the development of prototype HF-APE in China.

Key words: heavy fuel; aviation piston engine; direct injection; electronic control

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0 Introduction

Aviation piston engines (APE) generally consists of two ignition types: spark-ignited and compression-ignited. The former employs gasoline and kerosene as fuels with the assistance of a spark plug to provide ignition energy. The later enables compression ignition for fuels by increasing the compression ratio.

Compared with gasoline, heavy fuel (aviation kerosene) has lower volatility, higher flash point and lower flame propagation speed which is hard to be ignited[1]. Meanwhile, for turbo-charged HF-APE which requires more fuel supply during each working cycle at high engine speed and load, higher requirements are put forward to mixture formation and ignition in terms of fuel spray and ignition energy due to the limited duration for fuel evaporation. Therefore, the breakthroughs of heavy fuel injection, ignition and super (turbo) charging technologies, etc, are key factors for research and development of HF-APE.

With concerns of safety, simplicity of logistics and cost-effective, abundant works were conducted on HF-APE which were vigorously promoted in UAV in foreign countries around 1990. In 1988, the development guideline of aviation piston engine issued by NASA and Department of Defense (DoD) pointed out that the fuel of piston engine for military use should be single heavy fuel ("Single Fuel on the Battlefield"). Furthermore, FAA published in 1994 regulated that general aviation must use heavy fuels[2]. Under such circumstance, more efforts were put on the research of HF-APE during the last decades and series of breakthroughs were made. Spark-ignited and compression-ignited HF-APE were successfully developed and gradually expanded in aircraft application.

1 Significance of Developing HF-APE

With the rapid development of industrial technology and the acceleration of military revolution, great attention is paid on the development of HF-APE, especially for the world's premier military power, US. There are mainly two reasons:

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for one thing, JP-5, JP-8 and other heavy fuels have higher flash point which is not easy to be ignited in order to fulfill the requirement of single fuel on battle; for another, gasoline is hard to transport and easy to explode. However, due to the technology limits, the development of HF-APE is disturbed for a long time until 1989[3]. To date, HF-APE has been successfully applied to UAVs in US, such as MQ-5B Hunter, Warrior, ScanEagle and KillerBee[4].

1.1 Variation of aviation fuel for US army

The serial number of aviation kerosene is F-XX and JP-XX for North Atlantic Treaty Organization (NATO) and US air force, respectively.

Aviation kerosene, JP-4 (F-40) and JP-8 (F-34), were firstly used to avoid catching fire which occurred in the Vietnam War. The superiority of JP-8 refers to its low volatility and condensation temperature. The aviation kerosene was changed from JP-4 (F-40) to JP-8 (F-34) for USAF based in UK in 1979. JP-8 was also applied by USAF in EU in 1988, as well as in Japan and South Korea in 1991[5].

The aviation kerosene used in EU, Jet A-1 (NATO F-35) can transfer to JP-8 (F-34) by adding frozen-inhibitor, corrosion-inhibitorand lubricant. Jet A aviation kerosene was used by continental US which is similar to NATO F-35. Compared with JP-8 (F-34), Jet-A has higher condensation temperature and high flash point range, leading to denser fuel spray and higher evaporation temperature[6].

The flash point (35 ℃, 100 ℉) is low for Jet A, F-34 and F-35. F-40 consists of 60% naphtha and 40% kerosene and its flash point is between −23 ℃ and −12 ℃ (−10—+10 ℉), therefore, it is easy to vaporize. JP-5 (NATO F-44) is the main fuel for navy which has low flash point (60 ℃, 140 ℉) and low volatility[7].

1.2 Development program of HF-APE in US

In the early 1990s, US proposed the development program of HF-APE requiring the technique targets as shown in Table 1.

Based on the feature of HF-APE, the advanced technologies consist of the following aspects:

(1) Advanced in-cylinder direct injection

In order to combine the superiority of lean burn mechanism and fuel-efficiency of diesel engine, a direct injection technology is applied.

Table 1 Technique target of HF-APE

Parameter	Value
Maximum power/kW	37
Fuel consumption rate/ $(kg \cdot kW^{-1} \cdot h^{-1})$	0.31
Maximum weight (not including starter, generator and screw shaft)	23
Working endurance/h	300
Required altitude of cold-starting	2 286
Altitude range/m	0—4 572
Fuel temperature range/℃	−32—52
Fuel type	JP-5, JP-8, diesel fuel

(2) Stratified lean-burn combustion

The knocking of piston engine has a bad effect on indicated thermal efficiency and also limits the compression ratio. Therefore, high intense turbulence and stratified lean-burn technology are developed. The lean-burn technology reduces the knocking tendency which enables the increase of compression ratio to 12—14. In addition, at part of full engine load, the engine combustion can be adjusted like diesel engines, which contributes to an increase of thermal efficiency by 15—20%. The lean-burn technology is also coupled with turbo-charging and applied to piston engine.

(3) Fuel additives can change the physical properties of fuel, eg. flash point.

(4) The research and test of reliability of engine structure is critically important at the premise of R&D period.

(5) The design consists of computer simulation, assembling and testing experiment, including sea-level and high-altitude experiments[8].

The design of engine satisfying the requirement of navy needs to have low weight and high fuel efficiency. The combustion mode of shaft turbine is continuous and has high fuel consumption. Compared with shaft turbine, the combustion mode of HF-APE is intermittent. Due to the technology reason, the program of HF-APE is delayed. Until the late 1990s, US navy had been increasingly interested in developing HF-APE with low weight and high fuel efficiency which can work stably at 40 000 feet high. The program is then carried out competitive biddings domestically. After that, 13 competitive bidding were received and three proposals were finally chosen as shown in Table 2.

Table 2 Proposals of three competitive companies

Competitive company	Competitive engine
Southwest Research Institute	Two-stroke engine
AAI	Wankel engine
DGII	Wankel engine

In April, 1992 and January, 1993, the US navy chose the prototype engines for bench test. The results are shown in Table 3. From Table 3, it can be found that the three prototype engines cannot fulfill the requirement of US navy[9].

Table 3 Experimental results

Parameter	AAI	DGII	Southwest Research Institute
Maximum power	24 kW (5 898 r/min)	Satisfied	26.3 kW (5 000 r/min)
Fuel consumption rate	Satisfied	Unsatisfied	Acceptable
Maximum weight (not including starter, generator and screw shaft)	Unsatisfied (32 kg)	Unsatisfied	Unsatisfied
Stable working time	Without experimental validation	Without experimental validation	Without experimental validation
2 286 m cold starting	Satisfied	Unsatisfied	Satisfied (Without experimental validation)
Altitude range	Satisfied	Satisfied	Satisfied (Without experimental validation)
Fuel temperature range	Satisfied	Satisfied	Satisfied
Fuel requirement	JP-5	Unsatisfied	Satisfied

Table4 Difference between spark ignited and compression ignited HF-APE

Ignition method	Compression ratio	In-cylinder gas temperature	Fuel consumption rate	Power/ weight ratio
Spark ignited	<10	Low	High	High, around 1
Compression ignited	>14	High, >400 ℃	Low, 30%—40% reduction	Low, around 0.4

1.3 Summary of experience

The way to realize heavy fuel combustion can be summarized as follows (differences are listed in Table 4):

(1) Compression ignition aviation piston engine, such as diesel engine

The engine parts need to have high strength and stiffness since the in-cylinder gas pressure is high and aluminum cannot be used. Meanwhile, due to the different mixture preparation method, engine speed is limited. Therefore, the size and weight/power ratio of compression ignition engine is higher than that of spark ignition engine.

The compression ignition piston engine needs high compression ratio and hence heavier crankshaft. Therefore, it needs more metal and accordingly increases the fabricating cost.

The density of heavy fuel is higher than that of gasoline such that the fuel tank can store more diesel fuel.

However, due to the requirements of high power per liter, high power/weight ratio, low vibration, the diesel fuel piston engine is hard to be realized. Therefore, spark ignited kerosene piston engine was widely proposed. It is now reported that there is still no four-stroke spark ignited HF-APE application in UAV.

(2) Spark ignited HF-APE

There are two methods for fuel evaporation. The fuel can be vaporized outside the cylinder by a carburetor and can also be directly injected into the cylinder[10].

In foreign countries, the development of HF-APE was based on the prototype engine, such as Hirth (Germany) and Orbital (Australia). Based on Hirth 3503E, the first military-used 45 kW in-line two-stroke HF-APE and the technique specification are shown in Table 5. Zanzottera (Italy) developed the horizontally-opposed two-stroke HF-APE based on 498 prototype.

Due to the bad fuel spray, low evaporation, low ignitability, low antiknocking quality and low reaction rate and flame propagation speed, the development of HF-APE in China encountered many problems, for instance, difficulty in cold-starting, spark plug submerging, unstable working condition at low engine speed and load, scuffing of cylinder bore, etc. It is pointed out that fuel spray improvement, increased ignition energy, optimization of heavy fuel combustion can solve these aforementioned problems[11].

Table 5 Technical specification of Hirth3503E/3503HF engine

Type	Hirth 3503E	Hirth 3503HF
Layout	In-line two stroke gasoline engine	In-line two stroke heavy fuel aviation piston engine
Displacement	625 cm^3	625 cm^3
Stroke	69 mm	69 mm
Bore	76 mm	76 mm
Compression ratio	9.5 : 1	9.5 : 1
Rated power	51.5 kW /6 500 r · min^{-1}	45 kW /6 500 r · min^{-1}
Maximum torque	77.6 N · m/6 000 r · min^{-1}	67.5 N · m/6 000 r · min^{-1}
Mixture preparation	MPFI	Orbital AADI
Intake system	Leaf valve	Leaf valve
Ignition system	PVL programmable CDI	PVL programmable CDI
Power of generator	250 W/12 V	250 W/12 V
Cooling method	Water-cooling	Water-cooling
Mass	36 kg (without muffler)	30 kg (without muffler)
Weight/power ratio	1.43 kW · kg^{-1}/6 500 r · min^{-1}; 82.4 kW · L^{-1}	1.50 kW · kg^{-1}/6 500 r · min^{-1}; 72 kW · L^{-1}
Starting device	Electric starter	Electric starter
Lubrication	1 : 50 mixing of lubricating oil and Gasoline	Lubricating oil injection
Fuel	Gasoline (>RON-95)	JP5(F44)/JP8 (JetA/F30)
Exhaust temperature	<680 ℃	<680 ℃

2 Recent Progress of HF-APE

2.1 Stratified fuel injection and combustion

The direct fuel injection and combustion were developed from wall guided, charge motion guided modes to fuel spray guided mode, as shown in Fig. 1.

For wall guided and charge motion guided direct injection methods, the injector is not close to the spark plug. In case of submerging of the spark plug, the fuel spray needs to avoid touching the spark plug. Proper mixture formation is necessary so as to fulfill the ignition requirement of the spark plug. Therefore, high intense tumble and turbulence is indispensable. However, the engine cannot keep stable when engine speed is varied[12].

For fuel spray guided direct injection method, the injector is close to spark plug, which is benefit for the ignition of heavy fuel. The wall wetting effect can be avoided when the injector is located at central of the combustion chamber. Low tumble ratio and intake port without generating turbulence is necessary to limit the influence

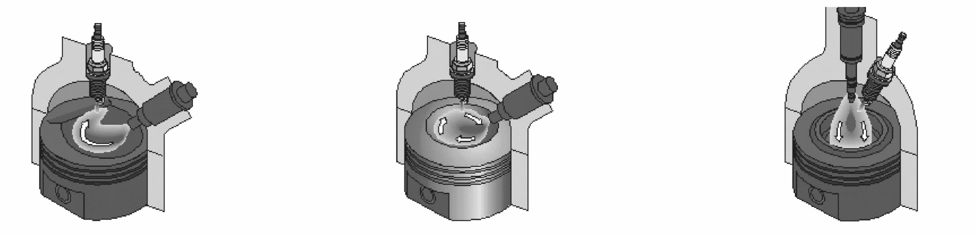

Fig. 1 Three combustion modes of in-cylinder direct injection

of charge motion on the fuel-air mixture. To date, fuel spray guided direct injection and combustion technology has been widely adoped in foreign countries for HF-APE, for instance, the OCP technology proposed by Orbital[13].

2.2 Heavy fuel injection system

The electronic heavy fuel injection control system consists of fuel tank, fuel pump, pipeline, injector and control unit, where the injector and the control unit are the key parts affecting the heavy fuel spray. According to the foreign heavy fuel injection system, the electronic injection control systems can be classified two categories: the high pressure common rail injection system and the air assisted direct injection system[14]. The latter is shown in Fig. 2.

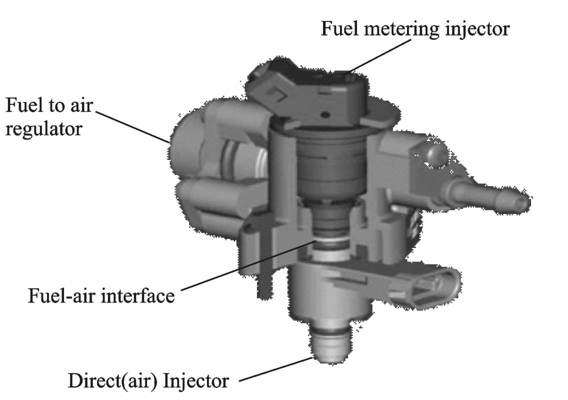

Fig. 2 Air-assisted fuel injector

For compression ignition engine, the compression ratio is high, as well as the load of the engine parts. However, the compression ratio has to be low for spark ignition in an engine with the direct injection system. Hence one should contemplate the compromise. Furthermore, the problem of igniter oscillation is to be solved too.

2.3 Heavy fuel ignition system

The companies, such as Hirth, Orbital and XRDi, use the ignition system of gasoline aviation piston engine as basis. After retrofit and re-calibration of the system, especially the combination and optimization of the best ignition angle and the combustion characteristics of heavy fuel, it can fulfill the requirement of heavy fuel ignition[15-16].

2.4 Supercharging system

The supercharging system is vital for APE which consists of intake system, supercharger, intercooler, etc. Multi-stage supercharging technology is successfully adopted in APE in US. Numerous research programs are conducted by NASA to investigate the effect of Reynold number on the supercharger performance, the design techniques and the matching among multi-stage superchargers, as well as between supercharger and APE[17].

2.5 Thermal control of key parts

The HF-APE designed by Hirth and Zanzottera choose the water-cooled cylinder and cylinder head of prototype as retrofit targets since the slow combustion rate of heavy fuel that accelerates the temperature increase of cylinder wall may result in cylinder bore scuffing and gluing.

To solve the problem mentioned above, the analysis of both heat transfer and design of high-efficiency cooling system are important to the thermal load control of the key parts. In addition, new type of heat-resisting, thermal insulating and wear-resisting materials can be adopted, such as ceramic (SiC) piston, cylinder, etc[18].

3 Trend of HF-APE

The trend of HF-APE can be summarized as follows: (1) Multi heavy fuel adaptability is required, such as kerosene, JP-5, JP-8 and Jet-A. (2) Low compression ratio is preferable. It is depending on the ignition system of gasoline and diesel fuel. (3) Fuel additives should be developed to make the heavy fuel easily ignited. (4) Separated use of Gasoline and heavy fuel is expected. Due to the variation of flash point of gasoline and heavy fuel, the heavy fuel is hard to be applied to spark ignition engine. Generally, heavy fuel is applied to compression ignition engine but hardly used in spark ignition engine. It is proposed that gasoline can be used at the engine start and when the in-cylinder gas temperature reaches the flash point of kerosene and the fuel is thus switched to kerosene fuel. (5) Pre-heating system is also needed. Heavy fuel is hard to be ignited compared with gasoline. Meanwhile, heavy fuel spray is likly to coagulate, thus forming big droplets when encountered cool air. It is unfavorable to combustion and will easily cause carbon deposits. Therefore, pre-heating system is necessary to enable smooth cold-starting and complete combustion.

In brief, the requirements for modern HF-APE involve heavy-fuel, spark ignition, low compression ratio, high efficiency, low weight and compact. However, in China, urgent action is needed to fill the gap in four-stroke APE and the following technologies have to be developed.

3.1 Four-stoke operation

Super-charged engine usually equipped by medium/high-altitude, high-endurance UAV is featured by its high power, low fuel consumption, excellent altitude performance and high reliability. So far, the power of APE in China has been in a range of 11.025—40.425 kW, always generated by two-stroke natural aspirated aviation piston engines. It can only fulfill the requirement of low-altitude, short-endurance UAV[19].

Due to the limit of cylinder number and engine cooling condition, it is hard to further improve the engine power. Meanwhile, according to the characteristics of intake and outtake systems, turbo charging is also difficult to be realized and thus cannot meet the requirement of long endurance.

Therefore, the four-stroke aviation piston engine, especially the small-sized APE (58.8—117.6 kW) needs to be developed.

3.2 Electronic control

Electronic fuel injection technology can accurately control the air-fuel ratio under various engine working conditions in order to keep the engine operating with best performance. Power, fuel efficiency and working stability are improved to fulfill the requirement of aviation reliability and boost the endurance. Meanwhile, the electronic fuel injection system employs a micro-computer to implement intelligent control which may increase the flexibility of working and operating mode. In foreign countries, the electronic control technology is applied to small-sized aviation piston engine. However, for engine in UAVs, especially the small-displacement engine, electronic control technology still faces such problems as the weight and size of electronic devices, the minimization and integration of the assembles, etc.

3.3 Supercharging and turbocharging systems

Turbocharging is wildly applied in foreign countries and also investigated in China. Many problems still exist when turbocharging is used in small-displacement typed UAV engine, for instance, the weight, size and wearing during high speed rotation of turbine, and the transient response of turbo-charged engine.

4 Conclusions

To meet the requirement of fuel unification for navy and air force, this paper gives a full picture of the recent progress and trend of heavy-fuel aviation piston engine. The development of HF-APE is usually based on the original APE. The retrofit is focused on the re-design and re-construction of fuel injection and ignition, intake charging systems and electronic control unit. It is urgent to develop fuel injection and ignition system which is particularly suitable for heavy fuel. Ai-assisted fuel injector, high pressure direct injector, high energy spark plug are good references. The fuel injector and ignition systems need to be coupled with appropriate mixture formation strategy, such as wall-guided, charge motion guided, etc. To adapt severe environment (high altitude, low pressure/oxygen content), intake gas heating, supercharging and turbocharging are necessary for HF-APE to maintain the engine output power and avoid misfiring.

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