

Low Volatility Fuel Cold Start Experience with a Stepped Piston UAV Engine to Address Single Fuel Objectives

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ABSTRACT

This paper reports on the research and development challenges experienced from dynamometer testing of a spark ignition UAV engine operating on heavy fuel. The engine is a segregated scavenging two stroke engine with air charge delivery by means of integral stepped pistons overcoming durability issues of conventional crankcase scavenged engines. A key element of the experimental study builds upon performance development to address the need for repeatable cold start on low volatility fuel thereby eliminating gasoline from UAV theatres of deployment. Lubrication challenges normally associated with crankcase scavenged two stroke engines are avoided by the integrated re-circulatory lubrication system. The fuel explored in this study is kerosene JET A-1.

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INTRODUCTION

Amongst the array of items of military equipment utilising internal combustion engines for propulsion and/or power generation several examples are capable of operating on a common fuel and therefore meet the requirements of the single fuel policy [1]. Whilst many items can operate on low volatility fuels there are key equipment areas for which the ability to operate on less conventional fuels (other than those for which they were originally designed) presents a considerable challenge. Such areas have included marine outboard engines, motorcycles/all-terrain vehicles and perhaps most challenging Unmanned Aerial Systems [2] or Unmanned Air-Vehicles (UAVs). If all such power systems could be developed to operate effectively on a single low volatility fuel, key safety and supply logistical objectives would be addressed.

Very few UAVs operate with compression ignition (CI) engines which would offer a solution to the need to be able to operate on low volatility fuels such as diesel, AVTUR, NATO F34, JET A-1, JP-5 or JP-8, however the mass penalty of CI engines usually precludes their use except for larger aircraft. There are cases of CI engines requiring additives to JET A-1 [3][4] to overcome lubricity problems within the fuel injection system. This is not normally an issue with conventional diesel fuelled systems due to the inherent lubrication properties within diesel. Turbine power plants could offer an alternative solution but these are usually limited to larger high altitude UAVs [5] such as Global Hawk. For smaller medium to low altitude UAVs the loitering or cruise speed of turbine propelled UAVs can present a limiting factor [6]. For these reasons, spark ignition gasoline engines are still the predominant source of UAV power plants due to their high power to mass ratio, relatively good thermal efficiency and ability to allow low loiter speeds over the target.

Research and development studies have considered a range of engine types. Several studies have centre-ed on two stroke engines [7, 8, 9, 10, 11, 12, 13, 14, 15, 16] including conversion of existing engines such as the work of Duddy *et al* [7] and Cathcart *et al* [9], whilst others consider dedicated UAV powerplants using stepped piston charging [8][12], cylinder head excitation methods [10] and opposed piston scavenging [11]. Some studies have focussed on four stroke engines as demonstrated by the work of Cathcart *et al* [17], Groenewegen *et al* [18], Wilson *et al* [19] and Zhang *et al* [20]. Research has also been considered using Wankel rotary combustion engines [21][22] with work performed on SI UAV engines to explore performance characteristics of "Heavy Fuel" operation. The thermodynamic properties of the fuels in question are well understood [23, 24, 25], however for many such as JET A-1, their operation under spark ignition is less clear. Furthermore, in order to eliminate gasoline based fuels from the area of UAV deployment, and to replace these with lower volatility fuels it is essential that the engine propulsion unit is capable of achieving repeatable cold start and indeed hot start without the need of a gasoline supply. The research of Tartovsky *et al* [26] explores the use of ultrasonic oscillation to excite heavy fuels such as diesel to try to create small fuel particles thereby enhancing combustibility. This study examines a number of cold start assistance methods applied to the SPV580 stepped piston UAV engine, an engine that has been successfully developed to operate on kerosene JET A-1 [6]. The SPV580 engine was originally designed and developed by Bernard Hooper Engineering Ltd for spark ignition operation on gasoline. By virtue of it segregated charge scavenging system, it is able to operate on neat fuels without added lubricant, unlike conventional two stroke cycle engines.

This work builds upon research and development reported by Hooper [13][14] focussing on experience using a crankcase scavenged two stroke UAV engine.

Charging Principle of the Stepped Piston Engine

To date all V4 cylinder stepped piston charged engines prototyped comprise two banks of paired cross-charging cylinders and the SPV580 follows this arrangement with a 90° V4 configuration. Odd numbered cylinder configurations (e.g. single, inline three cylinder, etc.) are possible and have been the subject of research and development projects. The principle operating method for inlet air charge transfer utilised in the SPV580 and most other even numbered cylinder stepped piston engines is shown schematically for reference in Fig 1.

Air is induced into the pumping annulus via a non-return valve or other form of flow control valve. On ascending the cylinder, the pumping section of the piston transfers the air through a charge crossover system to the power or working cylinder. Above the power cylinder piston, the engine operates in a similar method to a Schnürle [27][28] loop scavenged two-cycle engine but with major key differences. The crankcase isolation offered by the stepped piston enables fundamental operational advantages and enhanced durability.

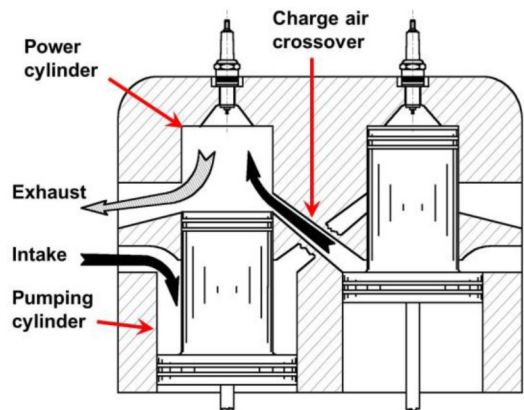


Figure 1. Stepped piston engine twin cylinder charging principle (schematic) (image courtesy of Bernard Hooper Engineering Ltd)

Piston cooling is significantly improved when stepped piston charging is employed, compared to the typically high piston thermal loading found in a crankcase scavenged two stroke engine. The underside of the stepped piston is cooled by the oil supply from the sump and if necessary further cooling can be directed by oil jets as employed in four stroke engines. Most SI engines developed to date have worked satisfactorily with splash feed from the big end bearings but more positive directional cooling is available as a development option as thermal efficiency levels increase beyond the current levels established for IC engines. This facility is of course not readily possible with a crankcase scavenged engine design.

These key advantages highlighted the technology for future UAV power plant development and resulted in the design and development of the SPV580 engine to meet the following design objectives set out by UK Ministry of Defence.

Principal UAV Engine Design Objectives

- Low engine mass
- High reliability and life
- Minimum vibration and torque fluctuation
- Minimum noise and heat signature
- Good fuel consumption
- Operating attitudes to accommodate bank, climb and dive angles up to $\pm 35^\circ$

The piston of a stepped piston engine is naturally heavier than a conventional piston of the same power piston (smaller) diameter. However; the mass increase is limited due to a number of factors. The positive cooling available from copious amounts of lubricating oil together with charge air cooling effects means that the piston crown can be thinner than that applied to conventional crankcase scavenged two stroke engines. Furthermore the flange stiffening effect of the multi diameter or step allows thinner skirt sections and further mass savings. The current state of the art pistons are around 20% heavier than conventional engines. This increase can be reduced to below 15% if composite methods of piston construction are used.

On first consideration it is possible to come to the conclusion that the larger pumping cylinder diameter has a consequential effect on increasing cylinder centre distance. However; if a conventional loop scavenged engine arrangement is considered, the required flow area of transfer port ducts feeding the cylinder have a similar effect on centre distance in conventional two stroke engines. As discussed by Hooper [29] there is no negative effect on increasing cylinder centre distance with larger pumping cylinder diameters offering delivery ratios of up to 1.1:1. The comparable crankcase scavenged engine can of course only displace a unity ratio from this perspective.

A further advantage of a segregated scavenging engine such as the stepped piston engine is offered by the integral sump re-circulatory lubrication system. This is advantageous not only in terms of improving durability but particularly in the context of Heavy Fuel operation when considering two stroke cycle operation. Conventional crankcase scavenged two stroke cycle engines for UAV application often operate on gasoline via inlet fuel delivery methods, with lubricant as an integral part of the gasoline supply. Such engines utilising premixed oil within the gasoline rely on the vapourisation of the lighter fuel fractions thereby leaving the lubricating oil to deposit on bearings and surfaces. Whilst heavy fuels such as JET A-1, JP-5, JP-8 and DF2 could hold two stroke oil in suspension the higher density and surface tension of fuels such as kerosene JET A-1 make this form of lubrication method, which is often marginal, unlikely to work as effectively. Therefore to operate on low volatility fuels conversion to fuel injection delivery methods further downstream from the inlet is usually required. This means that the oil cannot be supplied via the fuel and must therefore be delivered via a precision metering system, supplying oil at a rate proportional to engine load and speed from an additional reservoir. This type of technology is not uncommon on conventional two stroke engines for automotive or marine applications. However; for UAV applications it can present challenges in terms of mass and volume increase of the propulsion system. The stepped piston engine is designed to overcome this

problem as discussed by Hooper *et al* [6][12] and Stone [30] and all stepped piston engines developed so far have been operated on neat fuel. Monograde or multigrade oil is stored in the integral sump system usually beneath the engine as is commonly applied in four-stroke cycle engine practice. The oil delivery system consists of an automotive gerotor or gear type pump delivery system avoiding the cost and requirements for precision metering. The majority of the oil supplied to critical areas of the engine is re-circulated to the sump unlike the conventional crankcase scavenged where it is mostly consumed on a total loss basis. Wankel type UAV engines also use the lubrication methods typically adopted by conventional two-stroke cycle engines.

Methodology

The SPV580 engine uses a 90° V-4 cylinder configuration providing low instantaneous torque fluctuation due to sequential cylinder firing on a two-stroke cycle hence providing 4 equi-spaced pulses per revolution. The engine was originally designed for UK Ministry of Defence for gasoline fuel, and employed air or liquid cooling. General design data for the SPV580 engine is reproduced for reference in Table 1.

Table 1. General Engine data - SPV580 Engine

Charge scavenging system	Segregated using stepped pistons
Swept Volume	580 cm ³
Maximum power	31.6 kW at 5000 rpm
No. of cylinders	4
Cylinder arrangement	90° V-4
Bore	62 mm
Stroke	48 mm
Fuel	95 RON gasoline (No added oil) JET A-1
Lubrication	Monograde or Multigrade
Dimensions (LxWxH) inc generator	360x364x369 mm
Cooling System	Liquid (air option)
Mass	17.45kg (17.22kg)

The air-cooled version of the SPV580 engine arrangement is shown in Fig 2.

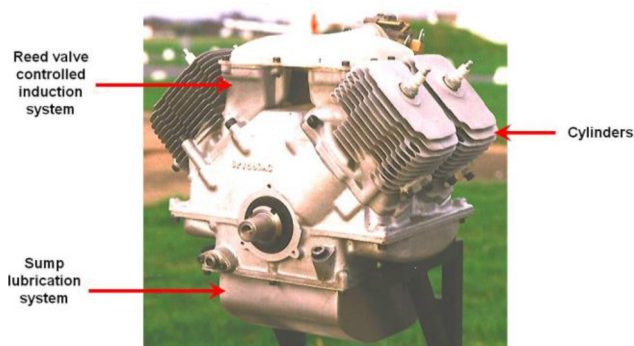


Figure 2. Arrangement of the SPV580 air-cooled engine (image courtesy of Bernard Hooper Engineering Ltd)

Experimental test setup and modifications

Early versions of the SPV580 were designed for inlet fuel delivery methods which are not particularly feasible for low volatility fuel delivery in more sophisticated engine systems. Fuel delivery downstream of the inlet was therefore considered by application of

individual electro-magnetic injectors feeding into the cylinder transfer ports. The engine test facility and control system allowing mapping of fuel injection and ignition advance is shown schematically in Fig 3.

In the interests of mass minimisation fuel system technology capable of relatively low fuel pressures was employed. This comprised conventional electro-magnetic injectors normally applied to multi-point inlet injection in four stroke automotive applications, roller type electrically driven fuel pump and diaphragm pressure regulator maintaining a constant pressure on common supply rails to each bank of cylinders.

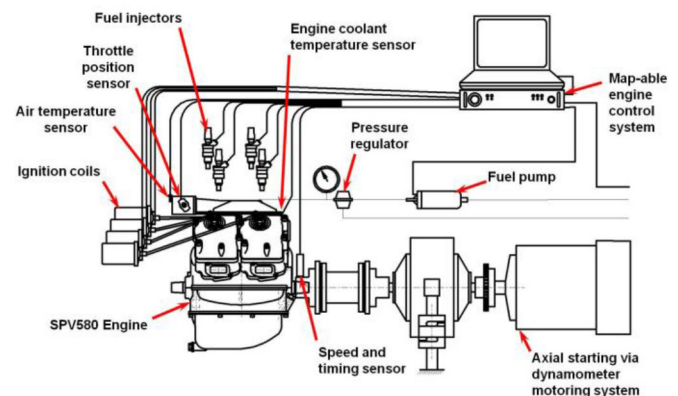


Figure 3. Schematic of the SPV580 engine experimental control and dynamometer test facility

The mapping facility is driven from a computer interface with the mapping module receiving inputs including Hall effect type engine speed/sequential timing reference, throttle position, air intake and engine coolant temperature sensors, barometric pressure and voltage supply sensors. In order to be able to supply kerosene JET A-1 into the cylinders, modifications were made to a liquid cooled SPV580 engine, with injectors installed in the vicinity of the rear transfer ports and fuel delivery around bottom dead centre as shown in Fig 4.

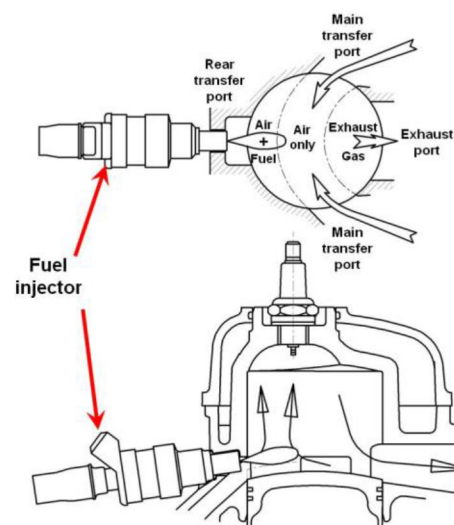


Figure 4. Liquid cooled SPV580 engine cylinder section and injector installation (image courtesy of Bernard Hooper Engineering Ltd)