

Mapping of Fuel Anti-Knock Requirements for a Small Remotely Piloted Aircraft Engine

Joseph K. Ausserer,¹ Marc D. Polanka,¹ Jacob A. Baranski,² and Paul J. Litke³

¹Air Force Institute of Technology, USA

²Innovative Scientific Solutions, Inc., USA

³Air Force Research Laboratory, USA

Abstract

Small remotely piloted aircraft (10-25 kg) powered by internal combustion engines typically operate on motor gasoline, which has an anti-knock index (AKI) of >80. To comply with the single-battlefield-fuel initiative in DoD Directive 4140.25, interest has been increasing in converting the 1-10 kW power plants in the aforementioned size class to run on lower AKI fuels such as diesel and JP-8, which have AKIs of ~20. It has been speculated that the higher losses (short-circuiting, incomplete combustion, heat transfer) that cause these engines to have lower efficiencies than their conventional-scale counterparts may also relax the fuel-AKI requirements of the engines. To investigate that idea, the fuel-AKI requirement of a 3W-55i engine was mapped and compared to that of the engine on the manufacturer-recommended 98 octane number (ON) fuel. The knock limit was established to be a peak-pressure rise rate of 5 bar/deg or a maximum amplitude of pressure oscillations of 5 bar for 1% of 400 consecutive cycles, whichever was more conservative. The 3W-55i engine was able to develop full power at all speeds above 6000 rpm (which included the peak power of 5 kW between 6500 and 7000 rpm) running on a 20 ON primary reference fuel (PRF) blend. Below 6000 rpm engine performance was knock-limited on the 20 ON PRF blend, resulting in up to a 30% decrease in power at some operating points. The results validate the speculation that losses in small engines can permit a direct conversion to low-AKI fuel with minimal impact on engine performance.

History

Received: 04 Jan 2019
 Accepted: 04 Feb 2019
 e-Available: 08 Nov 2016

Keywords

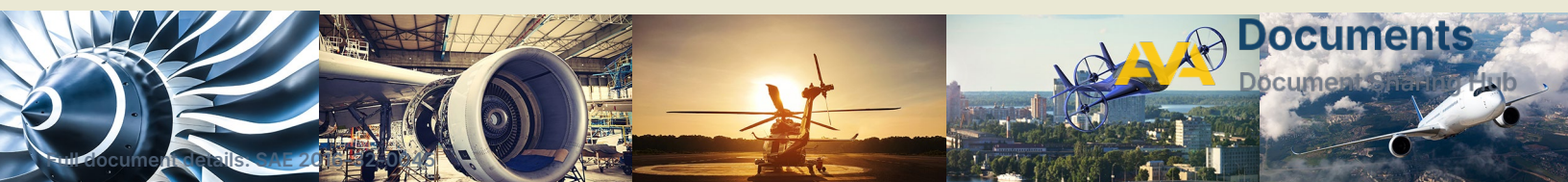
Anti-Knock, Internal
 Combustion Engines, Two
 Stroke, Heavy Fuel
 Conversion

Citation

Ausserer, J., Polanka, M.,
 Baranski, J., and Litke, P.,
 "Mapping of Fuel Anti-
 Knock Requirements for a
 Small Remotely Piloted
 Aircraft Engine," *SAE Int. J.*
Aerosp. 12(1):5-21, 2019,
 doi:10.4271/2016-32-0045.

ISSN: 1946-3855
 e-ISSN: 1946-3901

This paper was presented at SETC 2016 and is the recipient of the 2016 SAE Charles M. Manly Memorial Medal.



Introduction

Most small (10-100 cm³) internal combustion engines (ICEs) for remotely piloted aircraft (RPAs) are hobbyist and utility engines designed to run on high anti-knock index (AKI) fuels between 80 octane number (ON) and 100 ON. These commercial-off-the-shelf (COTS) engines are appealing for such applications because of their low cost (relative to the entire platform) and off-the-shelf availability. DoD Directive 4140.25 [1] encourages the transition of all Department of Defense (DoD) platforms to a single battlefield fuel, in this case JP-8 for aircraft and diesel for vehicles. These fuels have lower AKI ratings, typically about 20 ON. To comply with this DoD Directive, interest has been increasing in converting small COTS engines to run on low-AKI fuels instead of motor gasoline.

Several challenges are associated with operating an engine on a low-AKI fuel; these challenges may be grouped into three categories. The first is creating a vaporized fuel and a well-mixed air-fuel mixture. Creating a viable mixture, especially during starting, is difficult because of the low volatility of heavy fuels such as JP-8, diesel, and kerosene relative to regular gasoline. This challenge is well documented in the literature and almost universally addressed using a fuel injection system [2, 3, 4, 5, 6, 7, 8]. The second issue is that the lubricity of JP-8 (and diesel) differs from that of gasoline [9:64]. For two-stroke engines where oil is premixed into the fuel, this problem may be solved by adjusting the amount of oil added to the fuel. The third challenge and the focus of this work involves abnormal combustion due to the low-AKI nature of heavy fuels and the impact on engine operation and power output.

Heywood describes abnormal combustion as “a combustion process in which a flame front may be started by hot combustion chamber surfaces [or compression of the end gas] either prior to or after spark ignition (SI), or a process in which some part or all of the charge may be consumed at an extremely high rate” [10]. This highlights the relationship between abnormal combustion and temperature and pressure within the cylinder; given sufficient residence time, this relationship causes autoignition of the end gas. This relationship is frequently described with the Livengood-Wu integral [11], which proposes that the time constant governing autoignition is a function of temperature and pressure and that when the time integral of that relationship reaches unity, autoignition occurs [12]. It has been established that 10-100 cm³ COTS two-stroke engines have higher losses [13] and run at higher speeds (4000-8500 rpm) than larger engines. Increased losses such as short-circuiting offer a charge cooling effect, while higher operational speeds decrease the residence time of fresh charge in the cylinder prior to spark-initiated combustion. Therefore, abnormal combustion may be less of an obstacle to COTS heavy-fuel conversion of 10-100 cm³ engines than to conventional-scale engines.

Research Objectives

This work is part of a larger effort to examine how fuel-AKI requirements change with engine size in 10-100 cm³ two-stroke engines and to link those requirements to engine size and loss pathways. This article is focused on describing the methodology and initial results from examination of the first of three engines, a 3W Modellmotoren 55 cc SI two-stroke. Most of the previous efforts described in the literature [2, 3, 4, 5, 6, 7, 8] were focused on the technology of heavy-fuel conversion and, in most cases, demonstrating that running their specific SI engine on heavy fuel was feasible, at least with some compromises in power, efficiency, or design. The present study, on the other hand, assumes that using throttle-body fuel injection will permit the engine under study to run on low-AKI fuel and focuses on the abnormal-combustion aspect of the conversion. As shown by Baranski et al. [14], a 20 ON primary reference fuel (PRF) blend of iso-octane and n-heptane is representative of the knock resistance of JP-8 and diesel;

therefore, PRF blends were used in the present study to maintain a consistent and repeatable fuel composition.

The overall effort of which this study is a part is focused on quantifying the degree to which abnormal combustion is an obstacle to heavy-fuel conversion for 10-100 cm³ two-stroke engines. The present work, which was focused on describing the test methodology and results for one specific engine, had three objectives: (1) to map knock-limited performance of the engine for PRF blends ranging from 0 ON to 98 ON; (2) to investigate the impact of lower AKI fuel on engine power and fuel-conversion efficiency, specifically for converting an engine from 98 ON to 20 ON fuel; and (3) to investigate which engine controls were most effective at controlling knock and creating an additional power margin for knock-limited operation on 20 ON fuel.

Background

Studies on the use of kerosene in SI engines date back to at least the 1970s. In 1974 Tankaria and Ghosh [15] reported that peak power with kerosene was lower than that with gasoline when used in air-carbureted engines. They also concluded that an air-carbureted system may not provide sufficient atomization to mix kerosene sufficiently for efficient combustion. In 1984 Gupta and Ganesan [16] published similar results. As early as 1990, the DoD was interested in heavy-fuel conversion for small military aircraft. Lawton [17] authored a proposal to the US Navy for the development of a 37.5-56.25 kW heavy-fuel engine for use on naval RPAs. It is not clear whether any of the proposed engines were successfully tested; however, the proposal does highlight the need for DoD-driven technology development of small ICEs since COTS parts cannot fulfill the mission requirements.

In 1991 Suhy et al. [18] investigated the feasibility of converting a 390 cm³ Mercury Marine two-stroke engine to run on heavy fuel. Similar to the 3W engine considered in the present effort, their engine had a trapped compression ratio of 7.57, reed-valve induction, and Schnürle-loop scavenging. These researchers addressed the problem of poor vaporization of the heavy fuel in the carburetor by equipping the engine with a vortex atomizer. Preheating was required to start the engine, and the authors state, “a cold spark ignited engine with either a carburetor or fuel injection [system] will not start on kerosene. Presumably insufficient vapor is available.” The data show that kerosene produced higher indicated mean effective pressure (IMEP) than gasoline and reduced the burn time by 8° crank angle (CA) at low throttle and about 30° CA at medium throttle when the atomizer was used (under non-knocking conditions). When the carburetor was used, gasoline and kerosene exhibited comparable burn times for a given throttle setting, indicating that mixing and fuel preparation were critical for heavy-fuel operation. At wide open throttle (WOT), kerosene showed 60-80% higher specific fuel consumption (SFC) because of the retardation of spark timing required to combat knock. For conditions where the kerosene spark timing could be maintained, the SFC of gasoline and kerosene were comparable. The authors concluded that the major challenges to heavy-fuel conversion were knock limitations and preheat requirements.

By 2005, Orbital Engineering [7] had developed an air-assisted direct-injection system called the FlexDI[®] system that used high-pressure air to inject fuel directly into the cylinder of a two-stroke engine. Cathcart et al. [3] investigated the use of the FlexDI[®] system on three two-stroke engines with 50 cm³, 625 cm³, and 700 cm³ displaced volumes to enable the use of heavy fuel in aircraft SI engines. Orbital's FlexDI[®] system was designed to enable heavy-fuel operation through better mixture and phasing control coupled with variable spark timing. The air-injection system excelled at creating a combustible mixture, even with low volatility JP-5. In fact, the atomization was too effective and actually increased the tendency for the engine to knock compared to the stock configuration engine. To compensate for this, Cathcart et al. [3] retarded the spark timing. As a result JP-5 delivered 5-15% lower output torque across the WOT

operating range. The lower power output caused gasoline to outperform JP-5 and kerosene from a fuel-consumption standpoint.

In a manner similar to the Cathcart et al. [3] test of the FlexDI[®] system, in 2011 Duddy et al. [4] tested a system manufactured by SONEX [5] for converting 15-30 kW SI engines to run on JP-8 for use on unmanned platforms. The SONEX system managed heat losses from the engine, increasing the thermal mass of the engine head to provide additional energy for vaporizing incoming fuel. The researchers reported that the IMEP was unchanged for the stock and modified engines and that the cylinder-head temperature (CHT) decreased with operation on JP-8. The authors also stated that knock did not occur in the engine. In a related effort, Lee et al. [19] investigated the lubrication issues raised by converting the engine to run on JP-8. They determined that for an SI gasoline two-stroke engine using premixed oil, about 2% two-stroke oil by volume was required to provide sufficient lubricity of the JP-8 [19]. That amount of oil was comparable to the amount required when running on gasoline.

In addition to SONEX and Orbital Engineering, as of January 2019 several commercial entities were developing and fielding heavy-fuel-capable engines for small unmanned aircraft. Currawong Engineering [6] manufactured equipment for heavy-fuel conversions in small RPA engines. Their focus was on custom fuel injectors designed for the low flow rate of small engines as well as small, lightweight fuel pumps. The system also included a 3 bar (4 bar for heavy fuel) fuel pump, an engine control unit (ECU), and a custom ignition system. When running heavy fuel, fuel consumption was reduced by 5-10% on Currawong's 28 cm³ engine. Hirthmotoren, a manufacturer of two-stroke engines ranging from 6 to 75 kW, offered an iPower Compression Wave Injection System [20]. Their system uses high-pressure combustion gases captured in a resonance tube to preheat and vaporize the fuel, which is then directly injected into the cylinder. Direct injection also helps to reduce short-circuiting. The system was only available for Hirthmotoren engines. The manufacturer of the family of engines proposed for the current effort, 3W Modellmotoren, opened a heavy-fuel-engine arm in 2013 [8]. The engines were altered to include a second spark plug and a heater on the fuel system. Technical data was limited [8], but based on the available information, it appeared that the heavy-fuel variant consumed an additional 50-100 g/kW-hr, at a lower total power than the stock engine running on gasoline. Northwest UAV approached the low-AKI fuel challenge by designing a new multi-fuel engine system in lieu of converting an existing engine. Their electronic fuel-injected, 44 cm³ displacement engine had logged over 1000 fielded flight hours as of mid-2018 [21].

To date efforts documented in the literature have focused on the technology and feasibility of running engines on heavy fuels instead of the high-AKI fuel on which they were designed to operate. Thus, the ability to use heavy fuel in such an engine was assumed at the onset of this effort, and the work was focused on providing answers to the three questions posed in the "Research Objectives" section.

Methodology

This section is divided into three subsections. The first describes the portion of the research bench necessary to run the engine at the prescribed operating conditions. The second subsection furnishes details of the knock-sensing methodology as well as the criteria selected to define knocking combustion and the rationale for choosing those criteria. The third and final subsection lists the baseline conditions for testing as well as other control variables.

Small Engine Research Bench

The Small Engine Research Bench (SERB) was designed for testing 1-10 kW engines to study how loss mechanisms such as thermal losses and friction vary with engine size and cylinder surface area to displaced volume ratio in the 1-10 kW size range.

The SERB is described in detail in Refs. [22, 23], and key aspects and modifications are reviewed here. For the overall effort, a family of engines that were commercially available and as geometrically similar as possible was chosen. This work was focused on measurements on the 3W-55i engine, and its specifications are given in Table 1.

The engine was loaded using a Magtrol Brand 2WB65 Eddy Current Dynamometer that was rated to 10,000 rpm and 12 kW, with a measurement accuracy of $\pm 0.5\%$ of full scale for torque and speed. The dynamometer was connected to the engine using a belt drive and was controlled remotely using the low-speed data acquisition (LSDAQ) system, with control software written in National Instruments LabVIEW. The engine was started using a pneumatic motor coupled to the system with a clutch bearing. A schematic of the drivetrain and an overhead view that highlights the dynamometer, engine enclosure, and drivetrain are shown in Figure 1. Drivetrain losses were measured at 79 W/krpm for 1000 to 7500 rpm, and a description of the testing methodology is available in Ref. [24]. These losses were combined with the brake power that was measured at the dynamometer to yield the brake power of the engine.

Air-intake temperature was controlled by passing the intake air through a heat exchanger, with the second circuit connected to a Thermo Neslab RTE-211 Recirculating Water Bath. Intake airflow was measured using three TSI 40211 High Performance Linear Mass Flow Meters in parallel that were capable of measuring flow rates up to 300 SLPM (each) with an accuracy of $\pm 3\%$ of the reading. The calibrations on these sensors were verified using a sonic nozzle. The mass flow meters were installed upstream of a 55 gal baffle to damp out flow oscillations [25], with ten diameters of straight runner both upstream and downstream.

Engine cooling was provided by a 2.25 kW blower. The engine was mounted inside of an enclosure (visible in Figure 1), and the blower could provide up to 25 m/s of airflow through the enclosure to simulate installation on a pusher-configuration aircraft. Equivalent air speed at the duct exit was varied from 20 to 50 m/s to maintain the external head temperature of the engine at 128–130°C on the intake side. The flow rate of air through the cooling enclosure was measured upstream of the enclosure using an Omega Brand, FMA900-Series Hotwire Anemometer with a range of 0–50.8 m/s and an accuracy of $\pm 2\%$ of full scale. Temperature at the inlet and outlet of the box was measured using three Class A, 100 Ω platinum resistance temperature detectors (RTDs) at each location. Temperature and flow-rate measurements were used to calculate the engine cooling load. Engine temperature was monitored using Class 1, Type J thermocouples mounted to the engine above the exhaust and boost ports.

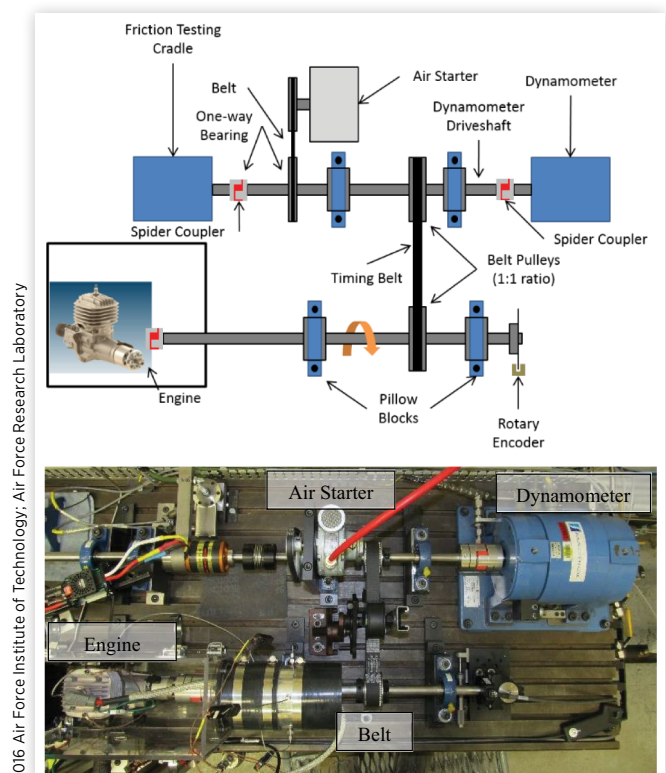
The stock carburetor on the engine was replaced with a Currawong Engineering throttle body and throttle-body injection (TBI) system. The fuel injector was a Siemens Deka 60LB 630 cc High Impedance Fuel Injector with a modified flow plate to reduce the fuel-flow rates to those required by the engine. The throttle plate was controlled using a HiTec high-torque digital servo. Both the throttle servo and the fuel injector were controlled using an in-house engine ECU and control program described in Ref. [26]. Testing revealed that

TABLE 1 Engine specifications.

Displacement	55 cm ³
Manufacturer rated power	3.82 kW
Mass (engine, stock carburetor, and stock ignition module)	1.94 kg
Specific power	1.97 kW/kg
Bore (cm)	4.50 cm
Stroke (cm)	3.51 cm
Compression ratio	10:1
Cylinder surface area-to-volume ratio	1.46 cm ⁻¹
Exhaust port opening	103°aTDC
Exhaust port area	2.15 cm ²
Exhaust area/intake area	0.62

2016 Air Force Institute of Technology; Air Force Research Laboratory

FIGURE 1 Top: Schematic of SERB drivetrain. Bottom: Overhead view of test bench showing dynamometer, engine enclosure, and drivetrain.



the timing of the fuel injection (as opposed to the width of the injection) had no observable effect on the operation of the engine. This observation is consistent with the work of Grasa-Alsina et al. [27], who found that “timing of injection into the inlet duct was of little, if any, consequence.” Fuel flow was measured with a Max Machinery 213 Piston Type Flow Meter with a range of 0-1800 cc/min and an accuracy of 0.2% of the reading. The delivered equivalence ratio was then calculated using the intake airflow and fuel-flow rates and monitored by the operator for the purpose of adjusting the fuel-injector pulse width to achieve the desired equivalence ratio. The engine was run on PRF blends of iso-octane and n-heptane ranging from 0 ON to 98 ON in 10 ON increments. As established by Baranski et al. [14], 20 ON PRF was used to simulate the combustion characteristics of JP-8 and diesel. Two-percent-by-volume AMSOIL SABER Professional Synthetic Two-Stroke Oil was added for lubrication according to the manufacturer’s recommendations.

For indicating pressure measurements, the SERB was equipped with an AVL Indismart combustion analyzer for measuring in-cylinder pressure and calculating IMEP, mass fraction burned, peak-pressure rise rate, and the maximum amplitude of pressure oscillations (MAPO) and for monitoring spark and injection timing. Engine CA was measured using a US Digital Brand E6 Optical Encoder with 1800 counts per revolution. A Kistler 6113B Measuring Spark Plug was installed in place of the stock spark plug for measuring in-cylinder pressure. The in-cylinder-pressure signal was conditioned using a Kistler SCP Charge Amplifier, Chassis Model 2852A12, and Amplifier Model 5064C. During each cycle the baseline of the in-cylinder pressure sensor was set using a 0-103.4 kPa pressure transducer that was accurate to 0.1% of full scale. The pressure transducer was located in the intake runner ~5 cm upstream of the throttle plate.

The exhaust system on the SERB is described in detail in Ref. [23], which discusses sampling of the exhaust using foil sample bags to quantify short-circuiting and incomplete combustion. The exhaust system was not tuned; instead it emulated a straight-pipe configuration. It is acknowledged that tuning of the exhaust runner for a specific speed (and, thus, a specific application) will decrease short-circuiting and increase engine power. Since no specific platform was identified in this work, the engine was operated in an untuned configuration with the understanding it could be tuned later for use on a specific platform. Furthermore, based on a comparison to manufacturer data, the SERB setup did not statistically alter the engine performance (power and brake-specific fuel consumption (BSFC)) significantly relative to manufacturer expectations at the 95% confidence level [13].

Knock-Detection System

The knock limit defines the boundary between acceptable and unacceptable abnormal combustion. In this work two knock limits were established—one based on typical practice for conventional-scale engines and a second intended to prevent damage to the engine. The first limit was 5 bar MAPO for 1% of 400 consecutive cycles, which is the boundary between light and medium knock and commonly used in engine research [26, 28, 29]. Pressure oscillations caused by end-gas knock have a number of oscillatory modes. Of these, the strongest and most commonly detected in a MAPO-type knock analysis is the 1,0 Circumferential Mode [26, 30]. However, detecting the 1,0 Mode requires the pressure transducer to be off-center [31]. On the SERB the pressure transducer was integrated into the centrally located spark plug, which reduced the detected intensity of the 1,0 Circumferential Mode. Therefore, a second knock limit was established to supplement the MAPO limit and prevent damage to the engine. Typically, damage from knock can be traced to two sources: (1) mechanical damage from rapid pressure rise and (2) thermal damage from hot spots (which form because of rapid combustion, which is, in turn, tied to rapid pressure rise). In SI engines, pressure rise rates are typically <2.5 bar per crank angle degree (CAD) [29]. Values of 10 bar/CAD and higher are associated with heavy knock and can lead to rapid engine failure in SI engines [28]. Homogeneous charge compression ignition (HCCI) engines typically operate with peak-pressure rise rates from 3 to 5 bar/CAD, which is on the high end of the typical limit for SI engines [26].