Quick Response Initiative Final Report on Small Heavy Fuel (JP-8) Engine Development

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ABSTRACT

The US Army Vehicle Technology Directorate (VTD), in response to an Army Research Laboratory (ARL) request, acquired and tested a small, 1.5 kW (2 HP) class Intermittent Internal Combustion (IIC) engine and developed procedures allowing the operation of this engine on JP-8 jet fuel. Extensive instrumentation coupled with system modeling using a widely used IIC software package[2] allowed for detailed evaluation of the engine operation.

INTRODUCTION

For a number of years the United States Army has had the stated goal of transitioning all engine systems to use only one fuel, JP-8. This “one fuel forward” initiative simplifies logistical issues, improves safety, and increases combat effectiveness.

During the current Iraq operation, the Army has increasingly relied upon unmanned vehicles, both ground and air, to provide additional capabilities to the soldier, such as communications and battlefield observation. These vehicles are powered by commercially available power plants that use a variety of fuels. Higher volatility fuels currently used in today’s IIC engines are not only inherently less safe, they significantly complicate logistical operations.

The Vehicle Technology Directorate has the mission to explore and develop new propulsion technologies and has promoted new concepts for small propulsion and power systems for many years. However, the increased emphasis on small propulsion systems, resulting from the Army’s increased reliance on unmanned systems, has resulted in the decision of the VTD to develop a much larger and more focused in-house capability in this area. While the initial focus was to explore the difficulties inherent in running a small powerplant on JP-8, the long term emphasis is to develop new technologies such as hybrid engine concepts, new engine cycles, and fuel injection technologies.

This paper will focus primarily on the initial efforts to develop an in-house research capability and the results of the first test project using a commercially available model aircraft engine[3]. This initiative required the development of technologies and procedures for operation of very small engines on JP-8 and a demonstration of such a capability. This has been accomplished.

JP-8 fuel is essentially kerosene with additives to reduce static electric buildup, improve lubricity, and prevent water separation in the fuel[4]. As with kerosene, JP-8 also lacks the light, short hydrocarbon chains contained in 87 octane gasoline that provide the volatiles for ignition, particularly when the engine is cold.

THE POWERPLANT

The team chose a powerplant that would fulfill the mission requirements set forth in the C4ISR (Army communication field exercise) briefing of 2006[5], which require an aircraft and propulsion system very similar in capabilities to the Buster Unmanned Aerial Vehicle (UAV). These requirements drove the power size class selected. Further, the relatively short window (~12 months) for executing the QRI essentially required the modification of an existing engine design, if possible.

The Army requirement for a single fuel in the battlespace has been interpreted by the team to mean that there will be no additives to the fuel beyond the available JP-8. Most small reciprocating engines are 2-cycle and lack an independent lubricating system. Instead, lubricating oil is added to the fuel. Previous work has highlighted the difficulties of converting such a system to operate without additive lubrication oil. Given these previous efforts, it was clear that any engine used would require an independent lubricating system to operate.

The team decided that the spark ignition (Otto) cycle with normal aspirated carburetion would be the most conducive cycle for operating such a small engine on JP-8. There were several reasons for this selection:

1. Normally these small engines operate using glow plugs to accomplish the fuel ignition. However, conversion to another less volatile fuel would raise serious questions about ignition timing.
2. The Diesel cycle offered a number of serious difficulties ranging from the problem of fuel injection to combustion speed.
3. Small carburetors are commercially available.
4. Spark ignition allows precise ignition timing.

Thus, the final desired engine was a 4-stroke, 4-cycle spark ignited engine with roughly 1.5 kW (2HP) that requires no fuel additives for operation. Few 4-stroke, 4-cycle engines exist in this size class, but two model aircraft engines, originally designed as for industrial applications, were found. The smaller is rated at 1.2 kW (1.6 HP) and the larger at 1.5 kW (2HP). Table 1 provides the specifications on the procured test engine and Figure 1 is a photograph of the selected engine. The engine uses a commercially available carburetor. It has two valves driven by a single cam.

Table 1[3] Test Engine Specifications

Displacement	33.5 cc	Peak Torque	2 Nm @ 5,000 RPM
Weight	2.0 Kg	RPM	1,400-9,000 RPM
Bore/Stroke	39mm X 28 mm	Fuel	87 Octane Unleaded Gasoline
Peak Power	1.49kW (2.0 HP) @7,000 RPM	Ignition	4.8 V

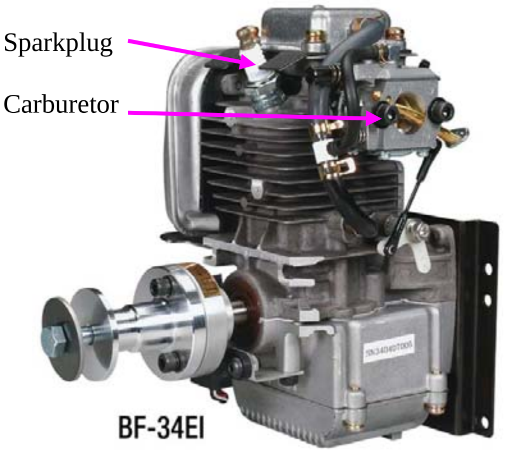

Figure 1
Research Internal Combustion Engine

TEST FACILITY

A test facility was assembled specifically for the evaluation and modification of this powerplant. A commercially available data acquisition package[6] was configured to acquire the test data. Data reduction and analysis was accomplished using a spreadsheet with macros created specifically to aid in the effort.

A waterbrake and controller were acquired to test the engine. This system is capable of testing engines from 1 kW to 37 kW (1 - 50 HP). However, it proved to be extremely difficult to test the engine because of its relatively low power output. The initial configuration was with a belt connection between the engine and the waterbrake with a 2:1 speed reduction. Belt slippage made accurate power measurements virtually impossible. Further, the downward forces on the shaft caused by belt tension resulted in the cracking of the crankcase housing at the engine coupling between the waterbrake and the engine. Still, the nature of the 4-stroke cycle where a power stroke occurs only every 720º of rotation required a number of coupling changes before a suitable coupling (Lovejoy – Jaw/Spider Type AL) was found. Figure 2 shows the test rig in the direct drive configuration. Note that the engine was started using an electric drill motor and a soft plastic fitting that applied friction to the spinner at the front of the water brake. This configuration was derived from typical setups used for starting model airplane engines.

The waterbrake system comes with its specific control and data acquisition package[7] and controller that interfaces with a personal computer. Notice the control system provides information on power output, speed (RPM), and torque. The plot screen could be used to plot various combinations of these outputs and time.

INSTRUMENTATION

Research data were acquired using the commercial software and reduced via spreadsheet macros. In addition, “operational” data from the waterbrake were also acquired.

The waterbrake operational data consisted of speed, torque, and power. In addition to manual operation, the dynamometer was capable of automatic operation where the controller would increase load at a specified rate until the engine began to lose power - the controller would then unload the engine. Information acquired in this manner provided insight into the peak power of the engine.

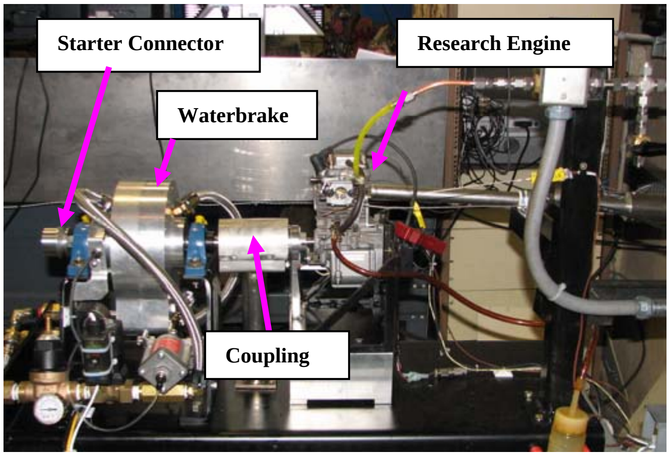

Figure 2
Waterbrake and Engine Test Setup

Research instrumentation is listed in Table 2. The instrumentation varied over the course of testing as bearing thermocouples and crankcase pressure were added. Data was acquired in 0.5 second durations at a rate of 10,000 samples/second (Nyquist criterion thus limits the maximum resolvable frequency to 5000 hz). If the maximum operational speed of the engine is ~9K RPM (150 RPS), 66 samples would be acquired per revolution. This was adequate to resolve the peak cylinder pressure. Cylinder and crankcase pressures were measured using high pressure, high temperature piezo-electric pressure transducers[8].

Table 2
Instrumentation List

Channel	Name	Channel	Name
0	1/Rev (OPR)	13	Head Metal Temperature
1		14	Rear Bearing Temperature
2	Spark	15	Inlet Air/Fuel Temperature
3		16	Front Bearing Temperature
4		17	Crankcase Temperature
5	Accelerometer	18	
6	In Cylinder Pressure (High Response)	19	Static Inlet Pressure
7	Inlet Pressure (High Response)	20	Crankcase Pressure
8	Barometer	21	Fuel Tank Level
9	Aft Carburetor Pressure	22	Speed
10		23	Crankcase Pressure (High Response)
11	In Cylinder Temperature		
12			

SIMULATIONS

The research engine was modeled with a one dimensional system simulation specifically designed to model IIC engines[2]. The initial modeling provided a straightforward 1-D representation of the engine. Shown in Figure 3 is the simulation schematic of the engine with blow-by included. The simulation used an in-house developed module for JP-8 fuel. This module used widely available information for kerosene and laminar flame speed with experimental results[9] provided by Dr. Hameed Metghalchi of Northeastern University. Information for both the model and its JP-8 module are available on request.

RESULTS

Starting

The principal goal of the test program was to determine and address the issues involved in engine operation on JP-8 fuel. This engine is designed to operate on “mogas” – 87 octane gasoline, available on the open market. Gasoline has a much lower flash point (≤230K)[10] than JP-8 (≥311 K)[4]. This significant difference in ignition temperatures leads to two important issues to be resolved. These are: 1.) Ensuring the fuel is vaporized during start and, 2.) Maintaining temperature control during operation to ensure that the engine remains within a relatively narrow temperature range.

Several methods of starting the engine were evaluated. The initial start for JP-8 combustion testing used gasoline to start the engine with a transition to JP-8 after start. This was not planned but worked well. The engine transitioned to JP-8 smoothly and ran well on JP-8.

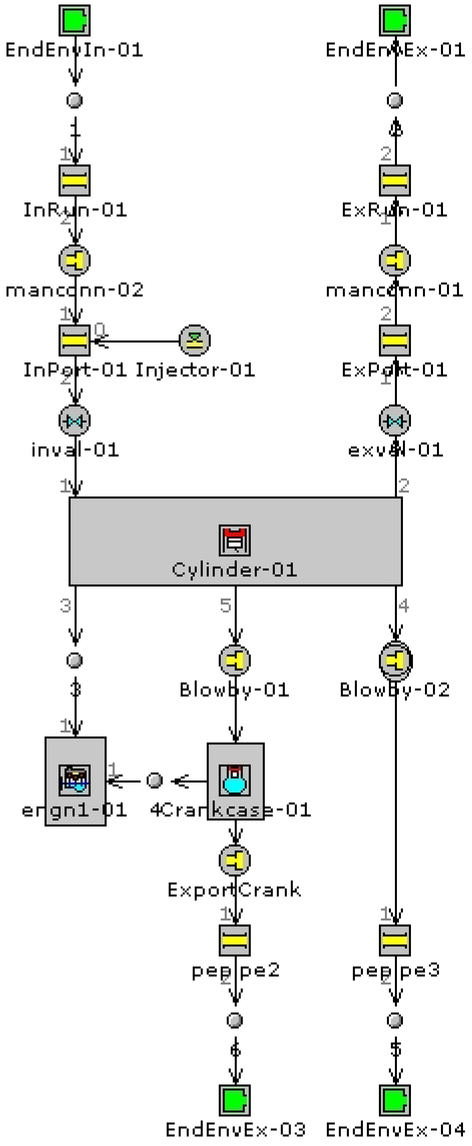

Figure 3
Representation of the Research Engine

Table 3
Attempted Start Methods

	Method	Successful Start	Comments
1	Gasoline to JP-8	Yes	Seamless Transition
2	Direct JP-8 Start	No	
3	Heat Fuel to 395K	No	Heating Inadequate – Limited by Safety – No Start
4	Hot Air/Heated Fuel	No	Heating Inadequate – Limited by Safety – No Start
5	Heated Cylinder Head – Hot Air Gun	Yes	Requires ~2 Minutes to Heat Fuel Head to 670 K
6	Copper Heater Adapter	No	Required 13 Minutes to Heat to 670 K
7	Heating Wire Around Cylinder Head	No	0.25” Heat Tape 10’ Length Would Not Heat After 20 Minutes
8	Localized Air/Fuel Heating Method	Yes	Requires ~2 Minutes, Some Backfiring

The methods attempted and respective results are presented in Table 3. Note that there were only three “successful” methods. These were method 1, the “transition method” with a start using gasoline, method 5, cylinder head heating using a hot air gun, and method 8, localized heating where the air/fuel mixture is heated immediately downstream of the carburetor. To successfully start using method 5, the cylinder temperatures were read from a thermocouple inside the piston and had to be at least 367 K (660 R).

Method 8 was selected as the preferred method for starting. The heat gun required a 120 VAC power source which would be difficult to obtain in all situations. Further, the need to force hot air over the cylinder head could require significant airframe modifications. The localized heating arrangement requires only a 12 volt automobile battery and appropriate connections as shown in Figure 4. This configuration is slightly more difficult to start, principally because the cylinder head is not heated. It normally requires approximately five additional seconds to start and the engine has, on rare occasions, backfired during start up. However, the ability to start in the field more than offsets this drawback.

Operation

Baseline testing of the engine using gasoline and baseline operation of the engine using JP-8 in the test environment revealed no pragmatic or effective difference in operation. Table 4 compares published and measured engine performance. Notice that measured performance on the dynamometer shows a lower power output than published. Figure 5 shows six “pulls” by the dynamometer on the engine. The first three pulls (Gas Run 1-3) use gasoline. The last three (JP-8 Run 1-3) use JP-8 as fuel. A pull is a fixed rate, automated increase in loading on the engine. The dynamometer increases load until it senses a specified reduction in speed (RPM) - and then unloads the engine to ensure the engine continues to operate. This figure reflects typical results from these pulls, but it should be clear from the plots, that it is difficult to assess differences. Note - the nature of the engine and the test stand made repeatable operation difficult. Figure 5 suggests that the peak power using JP-8 as a fuel is higher, perhaps by 10%. However, additional testing with gasoline would be required to verify this. The low power readings (~0.75 kW) are the result of slippage in the belt of the waterbrake system. Power output measured was substantially higher with the direct drive modifications made later in the program. Unfortunately, due to time constraints, the gasoline testing was not repeated with the direct drive configuration.

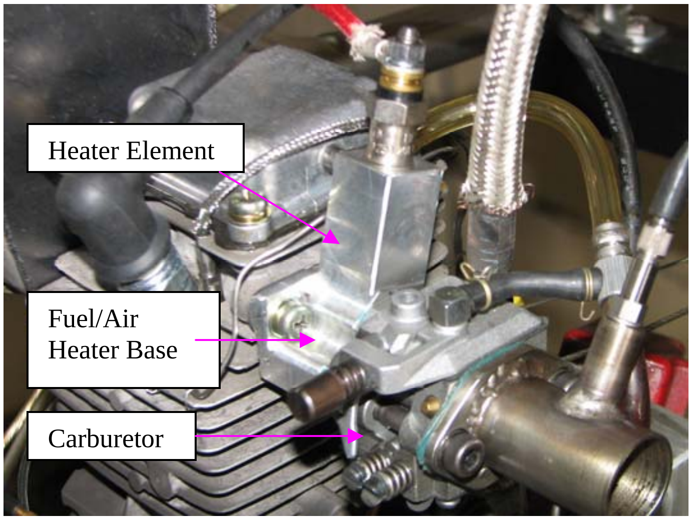

Figure 4
Inlet Modification for Heating Air/Fuel Mixture

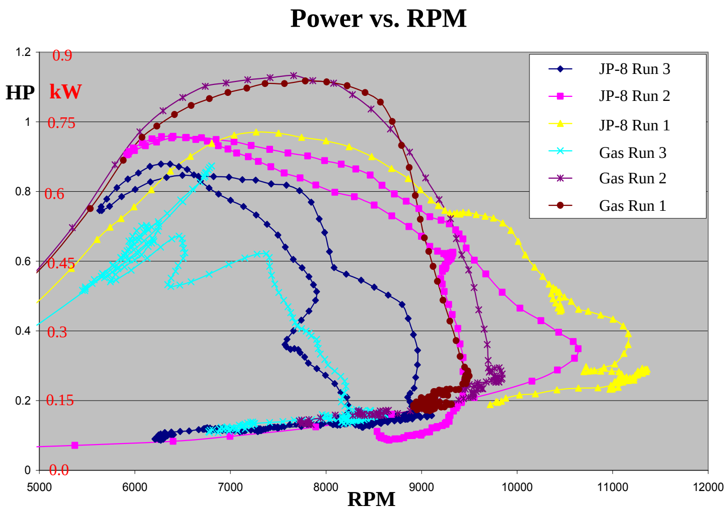

Figure 5
Typical Power vs. Speed for Gasoline and JP-8 Operation

Concerns about measured power and torque results and excessive wear of the belt during the original testing led to the decision to modify the waterbrake system to a direct drive configuration (Figure 2). This system has undergone several modifications and continues to evolve in response to the test environment. The research engine is, as previously stated, a 4 stroke, 4 cycle, aviation engine.

During the power cycle, there is a single strong power stroke every 720º of shaft rotation. This led to excessive slippage when using a belt connection to the waterbrake, resulting in inaccurate power measurements. When connected directly to the waterbrake, rapid wear and failure occurred in the coupling between the engine and the waterbrake. The current configuration, using a coupling with a rated torque at 54 Nm (475 in-lb) (@ 10500 RPM), seems to be adequate. However, it appears that the rotor in the waterbrake will need to be modified or remanufactured to handle the stresses of our anticipated endurance testing. At the attachment point of the shaft to the waterbrake, the key has become worn and loose due to the very large pulsing loads.

Representative performance results are given in Table 4. As can be seen, the measured performance is not as high as predicted performance. Fuel and oil consumption are representative of the maximum power levels.

Modifications for Improved Engine Performance

Due to oil consumption, which likely cause was blow-by through the rings, the engine could not meet the C4ISR endurance requirement of 4 hours - Note the crankcase for this engine holds 100 ml of oil. As performance is lower than published, engine modifications were initiated to reduce the consumption and improve performance.

Several modifications were made to improve engine peak power and torque. They included modifications to the carburetor to improve high power breathing, the addition of gas ports in the piston head to aid compression ring sealing, and re-ringing the piston to reduce the ring cylinder clearance. In addition, the carburetor high and low speed needles were adjusted to maximize performance. All efforts were essentially unsuccessful.

Table 4
Published and Measured Performance

Type	Power (kW) (@7000 RPM)	Torque (Nm)	Fuel Usage (L/Hr)	Oil Usage (ML/Hr)
Published	1.5	2.0 @5000RPM	-	-
Measured	~1.2	~1.8 @5500RPM	0.47	100-150

While power output was an issue, oil consumption of the standard engine prevented operation for longer than one hour. Consumption was, and remains, erratic with periods of relatively low consumption interspersed with periods of very high consumption. This was true regardless of engine power levels or whether the engine was fitted with a propeller or attached to the dynamometer. Explicitly, the oil was lost by exhausting through the cylinder and by being dumped overboard. Nonetheless, oil consumption was excessive and needed to be reduced to meet C4ISR requirement.

The engine delivers oil to the valves by using crankcase pressure to force the oil up an interior tube. An exterior vent tube from the valve cover has two Tee fittings. The tube out of Tee #1 feeds oil from the valve

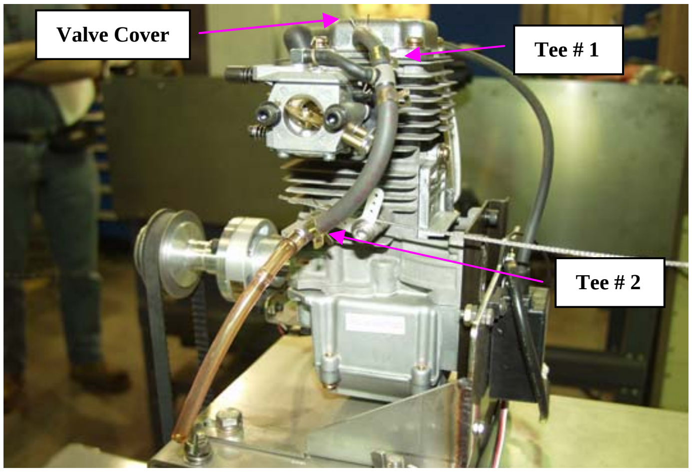

Figure 6
Original Oiling Configuration

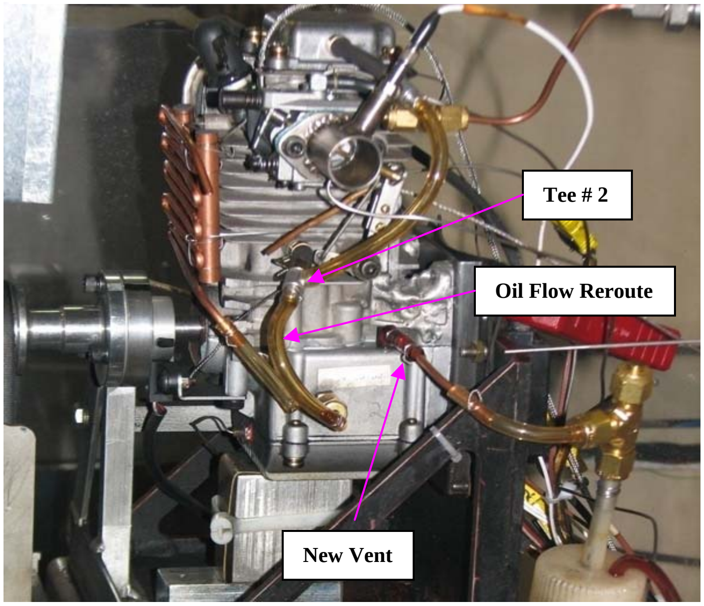

Figure 7
Modified Oiling Configuration

cover down to the crankcase while the other end operates a carburetor fuel pump. The tube that continues toward the crankcase proceeds up to Tee #2. At Tee #2 a tube out of one end dumps the oil overboard while the other continues to the crankcase. The vast majority (80%) of the oil used is vented overboard here. To reduce this oil loss, the tube from Tee #2 that led to the overboard loss was rerouted to the lower crankcase chamber and another vent was installed in the upper crankcase. This vent is located away from most of the oil splashing that might occur in the crankcase. The valves remain adequately lubricated and oil consumption has been reduced by over 80%. The 4 hour minimum operation has been met using this new system and several test runs in excess of 4 hours have been accomplished. Figures 6 and 7 show the original system and the modified oil systems respectively. Note that in Figure 2, a picture from the operator's manual, does not show a dump tube or Tee #2.

Detailed Experimental Results

Figure 8 shows the high speed pressure trace for a typically highly loaded operating point, although this is not a peak power run. This point (data point 08-8-26-003) was taken at slightly lower than peak power during one of the endurance runs that were intended to simulate cruise conditions. Power output here is approximately 0.78 kW (1.04 HP). The data for this point contains three power strokes. The peak power stroke pressure measured varied from a high of 2844 kPa (412.5 psia) to a low of 2252 kPa (326.6 psia). This variation is due to the use of a carburetor rather than fuel injection, which precisely meters fuel added.

Table 5 shows the experimental temperatures recorded for a typical peak power point, the cruise power point discussed in this paper (also typical), and selected simulation results for the cruise power point.

Several important facts should be highlighted regarding the temperature results. First is the significant difference between the measured in-cylinder temperature and the simulation prediction. The thermocouple measuring this temperature was placed in a slightly recessed location at the top of the cylinder. It would appear likely that it did not measure the actual combustion temperatures but a reduced temperature due to the probable heat transfer to the aluminum head and its location in a stagnant region of the flow. The head temperature is measured at a boss on the front of the cylinder head while the simulation temperature is an input for the inner cylinder face. This explains the discrepancy between measurement and prediction.

Table 5
Measured and Predicted System Temperatures

Measurement	Peak Power Point (K)	Cruise Power Point (K)	GT-Power Cruise Power Point (K)
In-Cylinder Air		775	1238
Cylinder Head	700	663	647
Rear Bearing	604	600	-
Front Bearing	648	595	-
Oil Sump	596	594	-

The other important point to note is the very low temperatures measured at the front and rear bearings. These low temperatures, coupled with the measured oil temperatures in the sump, indicate that the engine is operating far from potential failure of the bearings, even under high loads.

Software Analysis

Results from the simulation of the engine were

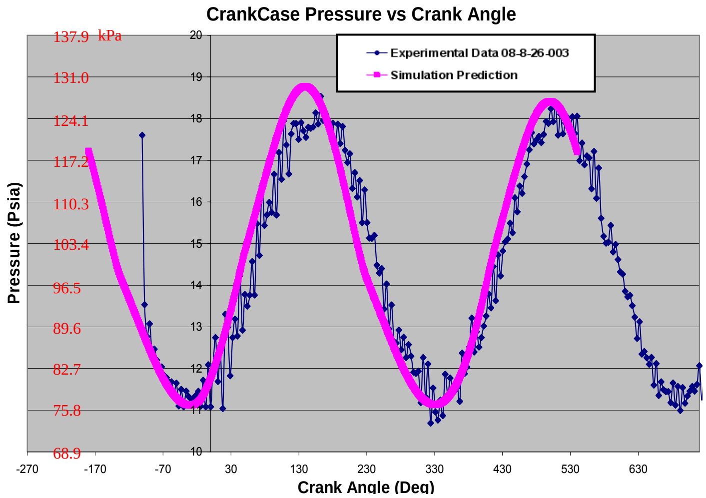

Figure 8
Measured and Predicted Crankcase Pressure

compared with experimental results. During the testing of the engine, performance was slightly higher than predicted by the simulation. The measured power output, as indicated, was approximately 0.78 kW (1.04 HP) while the predicted power output was 0.72 kW (0.97 HP). In addition, the predicted in chamber pressures were almost double those measured by the high response pressure transducer, as shown in Figure 9. To assess the possibility that blow-by through the rings to the crankcase was affecting the engine performance, the model was modified to include blow-by effects and the engine was instrumented with a high response pressure transducer in the upper crankcase. The crankcase transducer indicated little blow-by into the crankcase. Figure 8 reflects both the experimentally measured crankcase pressures and the simulation pressure, with the magnitude of the blow-by inputs modified to match the data. The sinusoidal pressure traces indicate little blow-by, which would be reflected as distortions in the sinusoidal form. The simulation indicates the blow-by to the crankcase to be of the order of $7X10^{-10}$ kg/cycle (0.025% of the total inlet flow).

The possibility of blow-by past the intake and exhaust valves was also considered. This could cause the difference between the predicted and measured peak cylinder pressures (Figure 9). However, any significant blow-by would certainly reduce the predicted power output. A parametric study indicated that a 20%+ reduction in power output would occur with only a 206.8 kPa (3 psi) reduction in peak pressure caused by blow-by.

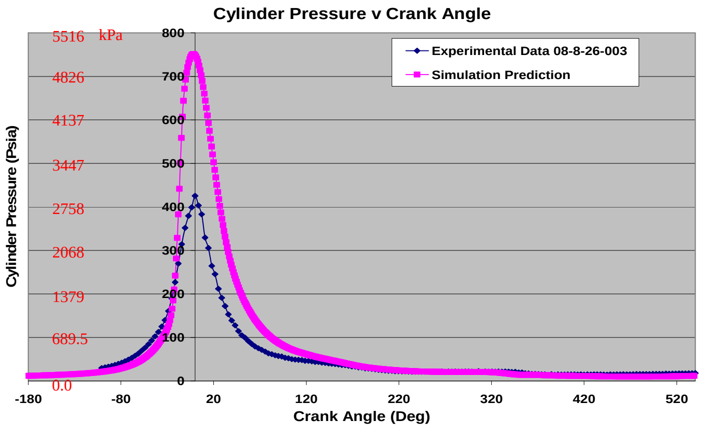

Figure 9
Measured and Predicted Cylinder Pressure

In summary, the predicted and measured shapes of the crankcase pressure and also the cylinder curves pressure are clearly similar. However, Figure 9 shows a substantially higher predicted cylinder pressure than was ctually measured. Predicted and measured output power was close. However, the intake pressure measurements, desired for the calculation of airflows, were not accurately measured. This was likely the result of vibration in the engine, coupled with the very small pressure variations. For example, average measurement of acceleration was over 18 Gs with peak accelerations of over 100 Gs. The GT-Power simulation predicted a maximum ΔP over the 720º to be 5.9 kPa (0.085 psi), with measured pressures randomly varying over 69 kPa (1 psi).

Temperature differences between the model and measured data were also significant. These are compared in Table 5. This is the result of the simulation required inputs for cylinder wall temperatures and have not yet been updated.

Flight Testing

An integral part of the research program included a flight demonstration. This demonstration helped uncover issues that may occur in engine/airframe integration or may occur as a result of the unique environment of operation as opposed to the test cell environment. Flight testing occurred at a flying field at the US Army's Aberdeen Proving Ground in Aberdeen, MD.

The aircraft chosen is a typical hobby model aircraft, the PLZ35 "Wilga", pictured in Figure 10. This airframe was selected because of its Short Take-off and Landing (STOL) design which allows short field takeoffs.

As part of the flight test program, a flight data recorder was installed. Data measurements acquired by the flight data recorder are shown in Table 6.

Table 6
Flight Data Recorder Measurements

Aileron Position
Elevator Position
Rudder Position
Throttle Position
Altitude
RPM
Airspeed
Battery Health Measurements
Cylinder Head Temperature

Figure 10
Wilga Aircraft

The flight test program consisted of an initial flight using gasoline, followed by ground runs of the engine using JP-8. Note – the engine installed does not have the updated oil system.
Preliminary flight testing has resulted in a power loss shortly after takeoff. To ensure that the problem was not the result of excessive cooling of the engine block, the airframe has been modified to enclose the engine. The modification includes cowl flaps to allow more precise control of the engine operating temperature. In addition, an external fuel pump was added to ensure the engine did not suffer from fuel starvation during flight. Flight testing is scheduled to resume in November.

SUMMARY AND CONCLUSIONS

This research project was initiated to identify and find solutions to difficulties in the use of JP-8 fuel in a very small reciprocating engine. The program consisted of three major parts: 1.) engine simulation, 2.) engine operation and testing and 3.) flight demonstration. The following conclusions concerning operation of a very small reciprocation engine with JP-8 as a fuel were made:

1. The engine cannot be started with JP-8 as a fuel without modifying the start procedures. The method of starting most appropriate for this engine/airframe was a glow plug heater between the carburetor and the intake manifold.
2. While the engine runs well with JP-8, engine operation appears to be much more sensitive to engine cylinder temperature when JP-8 is in use. This temperature sensitivity requires airframe modifications to ensure the engine is kept in a specific temperature range between 366 K (660 R) and 478 K (860 R).
3. Power output from the engine remains approximately the same, perhaps slightly higher, with the new fuel.

Though the observations presented were specific to our experience, these tendencies can be inferred to be applicable at large.

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