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An Evaluation of the 1910 Wright Vertical Four Aircraft Engine

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Abstract

Testing of a 1910 Wright Vertical Four aircraft engine (S/N 20) was completed at the Delphi Automotive Systems Technical Center in Rochester, NY to determine typical engine performance parameters. This engine powered a Wright Model B aircraft in numerous demonstration flights from 1911 – 1912, establishing many firsts in aviation including the carriage of a 598 lb. payload. Results of the testing measured a maximum power output of 33.4 HP at 1400 RPM, which is within the range previously reported. Other parameters measured included mean effective pressures, volumetric efficiency, thermal efficiency and specific fuel consumption. Emissions data and flow measurements were also recorded that indicated the engine ran rich, most likely to keep the head components cool during operation.

Introduction

In the year 1900, the Wright Brothers began a test program of gliding flight at Kitty Hawk, North Carolina that would ultimately lead them to the first successful powered flight in 1903. This achievement was only the beginning in a series of powered flight accomplishments that lead them to record-setting notoriety and the establishment of standard design practice in the aircraft industry. One of the achievements along this journey was the development of reliable powerplants that, along with efficient propellers, provided the thrust necessary for the takeoff, climb and sustained level flight.

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The horizontal four-cylinder engine design used in the 1903, 1904 and 1905 machines proved to be an effective powerplant for the flight mission. This design initially produced 12 horsepower, but was increased to about 21 horsepower in the 1905 version[1]. In 1906, a totally new engine design was initiated by Orville while Wilbur continued to investigate improvements to the proven horizontal design[2]. The new engine was a vertical four cylinder configuration that became the standard powerplant for Wright Aircraft from 1906 – 1912. This engine had the distinction of powering their Model A and Model B aircraft in numerous demonstrations that included the well publicized European flights and the qualification flights for the U.S. Army Signal Corps. Approximately 100 of these engines were produced by the Wright Aircraft Factory.

Recently, the Discovery of Flight Foundation has acquired a 1910 Vertical Four engine, S/N 20, that saw significant service in a Model B Aircraft purchased by the Alger Brothers of the Packard Motor Car Company in Detroit, Michigan. This aircraft was equipped with floats to become one of the first "hydroaeroplanes," capable of carrying passengers safely over water. Throughout the years 1911 and 1912, pilot Frank Coffyn provided demonstration flights that included lifting a payload of 598 lbs (pilot, two passengers and floats) from Lake Michigan, taking aerial movies of New York City, and providing numerous rides for passengers. Many of these flights covered 20+ miles over water.[3]

In cooperation with Delphi Automotive Systems in Rochester, New York and the Rochester Institute of Technology, this engine has been dyno tested to obtain its performance specifications. All critical parts of the engine were x-ray inspected and limited part substitution was made to ensure a safe test program. This included new piston rings and one exhaust valve replacement with another authentic valve. The

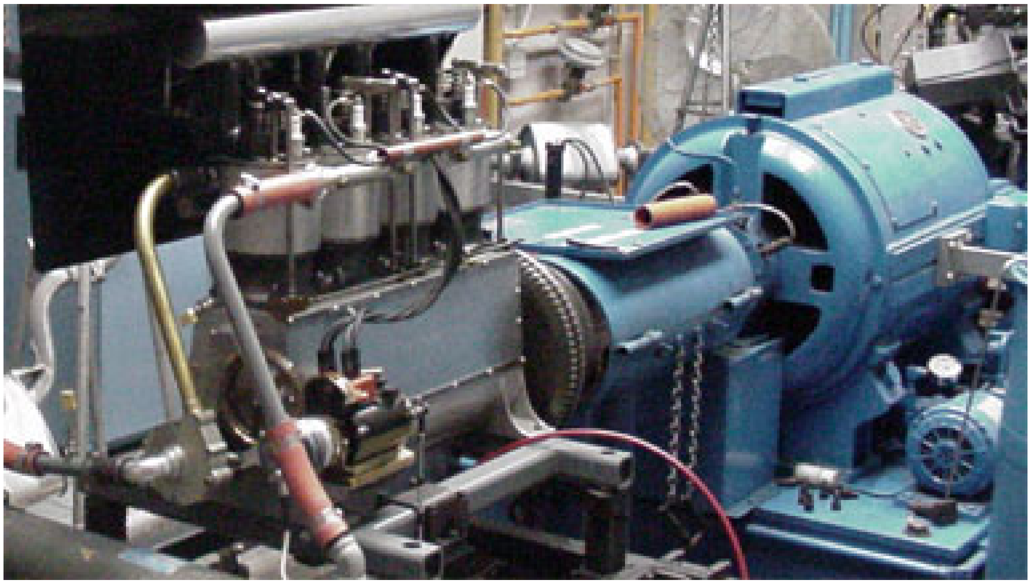


Figure 1 – Vertical Four Engine and Dynamometer Test Set-up

engine is shown in its test configuration in Figure 1.

The test results showed that the performance was in agreement with other dyno tests performed on the vertical four engine, reported to have power ratings from 28 HP to 42 HP[4].

Engine description

The vertical four engine is basically comprised of a single cast aluminum block with four independent cylinders bolted to the top face as shown in Figure 2. Similar to the horizontal engines, a suction activated (or automatic) intake valve and cam activated exhaust valve were featured on the head. Volumetric efficiency is compromised without a mechanically actuated intake valve, but weight and complexity are lessened. Unlike engines #1 and #2 (used on the 1903 – 1905 aircraft) but similar to experimental horizontal #3 engine, auxiliary ports on the bottom of the cylinders were added to allow additional exhaust gas venting at the bottom of the power stroke. These ports also served to remove heat from the uncooled heads.

A magneto spark ignition was featured on this engine as opposed to the make/break point contact ignition present in the horizontal engines. By rotating the magneto on end-support bearings, the timing could be retarded to ATDC for ease of starting. Full power operation occurred at BTDC. It should be noted that no throttle existed on this engine and power was either "full" or at the retarded ignition conditions used for starting. A compression release that held the exhaust valves open also provided on and off power control along with a fuel shut-off valve.

In horizontal engine #2, the Wrights added a fuel pump to control fuel flow better than the original gravity system which operated without the regulating benefit of a carburetor for weight savings. The vertical four engines retained the displacement fuel pump that metered fuel through a nozzle and into the intake manifold, essentially becoming one of the first successful fuel-injected engines. For this test, two injection nozzles were evaluated: one with six #57 (0.043") holes located radially around a capped-off _" copper fuel line and another with four #60 (0.040") holes. Other designs existed, indicating that there were attempts to tune the engine for better performance.

The pistons were cast iron, weighing 4.7 lbs with the piston pin and rings installed. The three-piece connecting rod consisted of two cast bronze end pieces that were threaded into a thin-walled steel tube and torqued in place. Showing the ingenuity of Charles Taylor, the "mechanician" responsible for the manufacture of the engine, the basic shape of the crankshaft was created by drilling a series of holes in a billet of steel and then knocking the free pieces out. Using offset centers, the final crankshaft shape was formed by turning it in a lathe.[5]

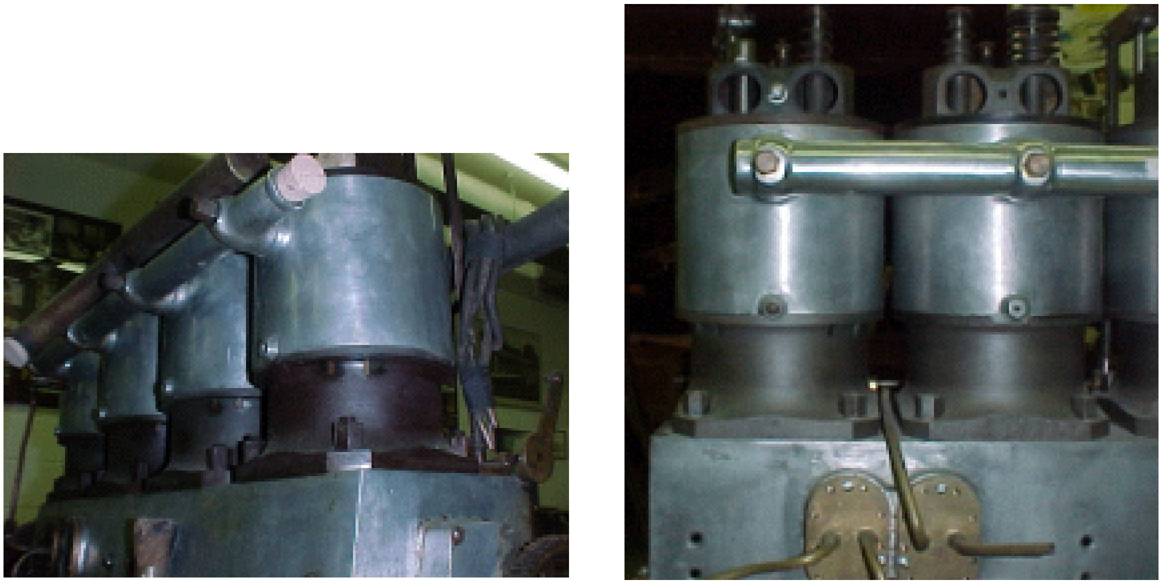


Figure 2 – Engine Details Showing Auxiliary Ports And Cooling Jackets

The crankshaft had a 2 in. throw (4 in. stroke), and coupled with the 4.375 in. bore gave a swept volume of 240 cubic inches. Measured volumes at the Discovery of Flight Foundation indicate a compression ratio of 4.7:1, which is in agreement with the engine designs of that period. It should be noted that in previous reports this engine is identified with a compression ratio of 5.15:1, which appears to be in error.

The operating speed of the engine was reported to be 1300 – 1500 RPM, turning the propellers through a 3.09 speed reduction with an 11 and 34 tooth sprocket set.

Cooling of the engine was provided by aluminum water jackets heat-shrunk onto the cylinders and a high capacity, front mounted water pump with a measured delivery rate of 13 GPM at 1400 RPM. Like much of the engine, the water pump is a Wright design with no equivalent in the fledgling automotive industry. The exhaust valves were two-piece assemblies consisting of a tool steel stem and a cast iron head. The stem was threaded onto the head and the protruding threads were peened over to add strength. Intake valves were a more modern, welded construction.

Prior to developing their own engines, an inquiry was made to existing manufacturers about acquiring a low vibration engine that met their design specifications.[6] The concern for vibration was due to the mounting on a wooden structure and the use of chain drives that would not be tolerant to a fluctuating torque. The Wright engine featured a 14” diameter flywheel with a thin 0.125” supporting web to maximize the mass at the outer radius.

Engine test parameters

Data acquisition

Testing occurred at Delphi Automotive Systems technical center in Rochester, NY on February 19 – 23. The engine was installed in an engine test cell and coupled to a DC electric dynamometer. The engine was outfitted with an exhaust header to collect the exhaust gases from the open ports and house the required thermocouples, emissions sampling, and air-fuel ratio sensors. The engine was also outfitted with combustion analysis equipment to monitor in-cylinder pressures and calculate mean effective pressure values and combustion stability. Other measurements that were taken during tests were airflow and fuel flow, engine brake torque, and standard engine temperatures and pressures.

Test Schedule

Since the engine is 91 years old, a limited test program was planned that would obtain important data while minimizing the run time. Table I shows the test points gathered during the 5 – day program.

Table I – Test Program

Run	Description	Fuel	Ignition Adv.	RPM
1	Motoring torque – compression engaged	N/A	N/A	600 - 1400
2	Motoring torque – compression released	N/A	N/A	600 - 1400
3	Max brake torque, #60 x 4 nozzle, emissions header on	80 Octane	35˚ BTDC	1200, 1300, 1400
4	Max brake torque, #57 x 6 nozzle, emissions header on	80 Octane	35˚ BTDC	1400
5	Max brake torque, #57 x 6 nozzle, emissions header on	65° *Be′*	35˚ BTDC	1200, 1300, 1400
6	Max brake torque, #57 x 6 nozzle, emissions header off	65° *Be′*	35˚ BTDC	1200, 1300, 1400
7	Idle power, #57 x 6 nozzle, emissions header off	65° *Be′*	12˚ BTDC	700

Data gathered at each point with the emissions header installed included power, torque, cylinder pressure, volumetric and thermal efficiencies, specific fuel consumption, and HC, NO_x, CO and CO_2 emissions data.

Dynamic Loads

Typical measured cylinder pressures from the indicator diagram for run # 4 are shown in Figure 3. The pressure variation between cylinders was typical and due in part to the mixture variation from cylinder-to-cylinder, slight timing variations caused by the magneto control, and variability in the intake charge.

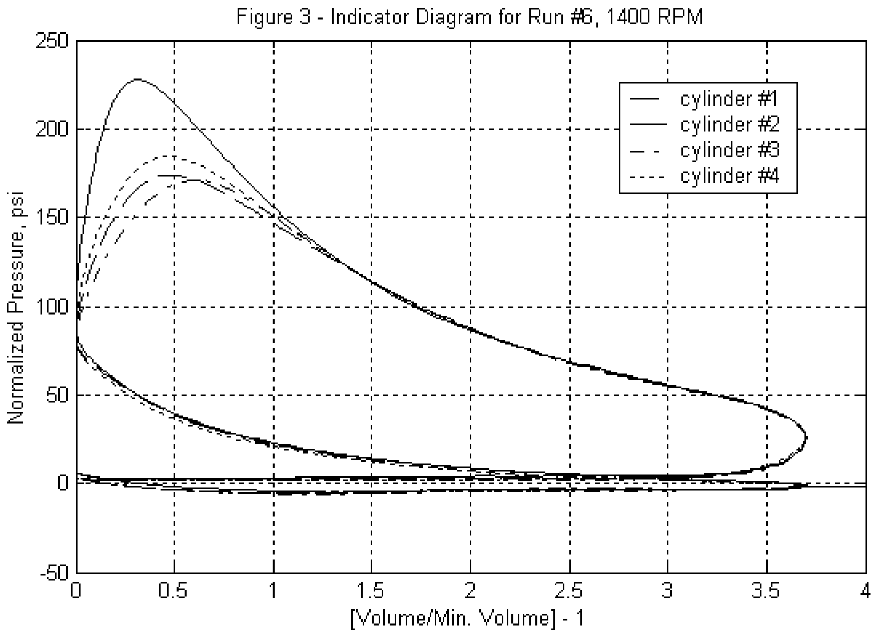
Using 232 psi as the maximum observed cylinder pressure results in a combustion force of 3,488 lbs. This force is added to the dynamic loads generated by the oscillating masses to provide the loads at the piston pin and the crank bearing, shown in Figures 4 and 5. The piston pin-end of the crank will experience a maximum force magnitude of 2925 lbs., which apparently was large enough to cause fatigue failures in the bronze cast end. As noted in Charles Wald's Flying Report, dated July 20, 1912 during a flight at 4:05 P.M., "Connecting rod broke (cylinder #2) at bronze casting below wrist-pin bearing, breaking entire piston and cam-shoes, the obstruction jamming in crank-case, tearing hole in crankcase 4" x 6" on intake side of motor and bulging out magneto side, altitude at time about 300 feet.".

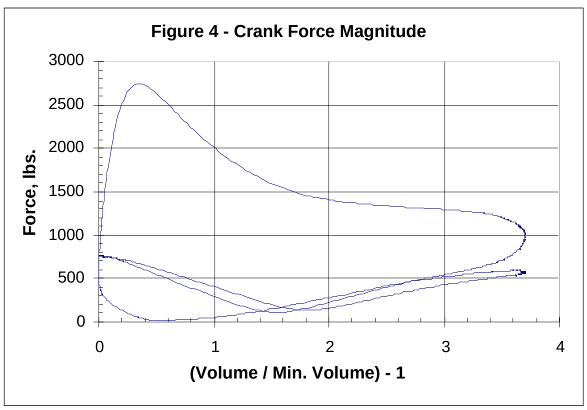
From a metallurgical analysis performed by the Xerox Corporation in Webster, NY on the bronze cast end of an original rod, the composition was detected to be:

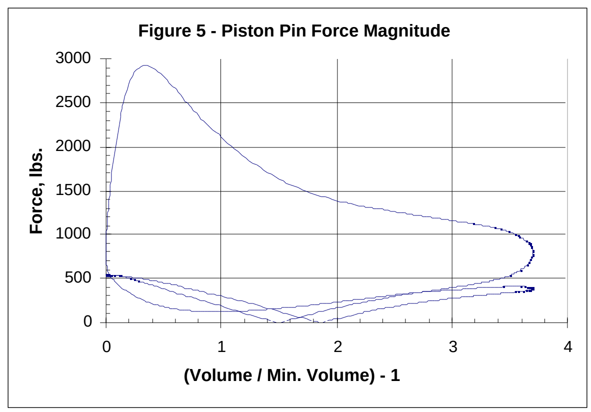
Cu – 86.5%
Sn – 8.7%
Pb – 3.4%
Other – 1.4%

In comparison with commercially available copper alloys, the Wright bronze is closely related to C83600 (leaded red brass), C92200 (Navy "M" bronze) and C93700 (High-leaded tin bronze). The minimum fatigue strengths of these alloys is 11.6 ksi. 8.5 ksi. and 12.3 ksi. respectively at 25 million cycles[7] (the number of cycles in a 300 hour engine).

A stress analysis of the connecting rod at the piston end with the 2925 lb. load applied showed a maximum stress of 4.1 ksi without stress concentration factors. Stress concentration factors certainly were present from the sharp radius at the bottom of the threaded hole in the casting as well as undesirable voids that probably existed from the casting process itself. From these results, the likelihood of a failure certainly existed in the rod although in actuality the number of failures was not large enough to warrant a redesign.







Fuel

Two types of fuel were used in the testing: modern 80 octane aviation fuel and a vintage blend rated at $65^\circ\ Be'$, or 65 "test." The $65^\circ\ Be'$ refers to a specific gravity specification based on the Baume′ scale:

$$^\circ Be = 140/\gamma - 130 \qquad (1)$$

Where γ is the specific gravity of the fluid.

As the Baume′ number increases, the specific gravity (or molecular weight) decreases corresponding to an increasingly volatile hydrocarbon blend. Gasoline in the early 1900's was produced by batch distilling crude oil in a cheesebox or shell still[8] and had a Baume′ rating of. $55^\circ - 75^\circ\ Be'$

ExxonMobil Research and Engineering has provided a fuel blend for testing that closely resembles the original fuel. The octane rating of the Wright fuel was not available in 1910 since detonation research was not undertaken until 1919, however the rating for this fuel was. $(R+M)/\ 2 = 58.4$ ExxonMobil Research and Engineering has provided a fuel blend for testing that closely resembles the original fuel. The octane rating of the Wright fuel was not available in 1910 since detonation research was not undertaken until 1919, however the rating for this fuel was .

Performance Evaluation

The testing was limited to a maximum speed of 1400 RPM due to concerns about the engine dynamic loads. Initially, a series of spark advance settings were to be mapped, but time constraints and concerns about engine wear limited the testing to the full advance setting of BTDC. Maximum brake torque (MBT) occurred at the BTDC setting for speeds from 1200 RPM to 1400 RPM, and if available, even more advance would have been desirable. This is due to the low compression ratio of the engine resulting in a slowly propagating flamefront, which in turn requires a larger spark advance to complete the combustion.

Horsepower, Torque and Mean Effective Pressures

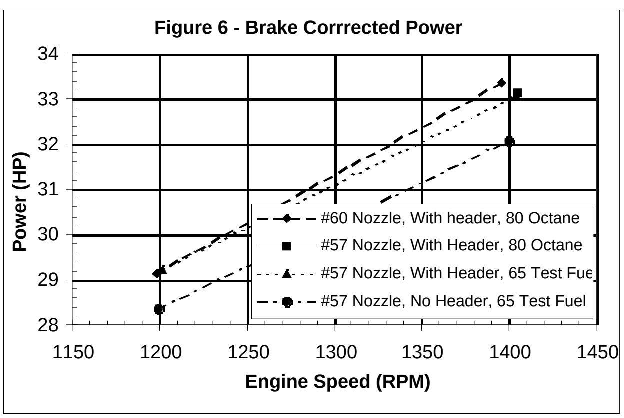
Figures 6 and 7 show the brake corrected horsepower and torque for the 1200 RPM and 1400 RPM test cases at full advance. The exhaust emissions header was removed at the end of the testing period so that power could be measured in the engine's actual operating state. Exhaust gas was restricted from impinging on the intake header during the instrumented testing which resulted in a cooler charge entering the engine. It is believed that this is the reason for the higher power values with the header installed. Peak power in the original operating condition (no header and 65 test fuel) was 32.1 HP, and 33.4 HP was recorded with the header installed using 80 octane fuel.

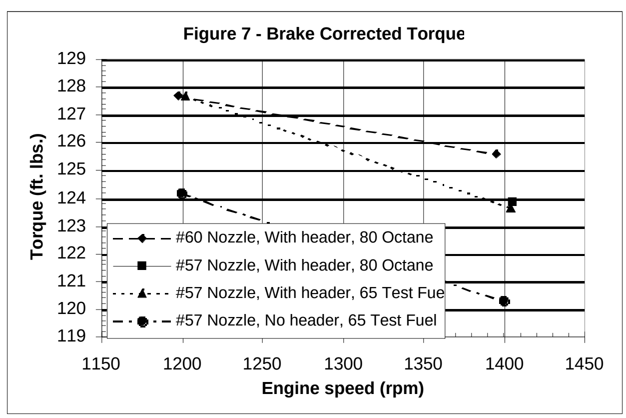
There is no appreciable difference in power between the vintage fuel and the modern aviation fuel at the full advance setting. It was observed however that at highly retarded spark settings, flames were visible exiting the exhaust ports when the vintage fuel was used. No flames were observed with the aviation fuel.

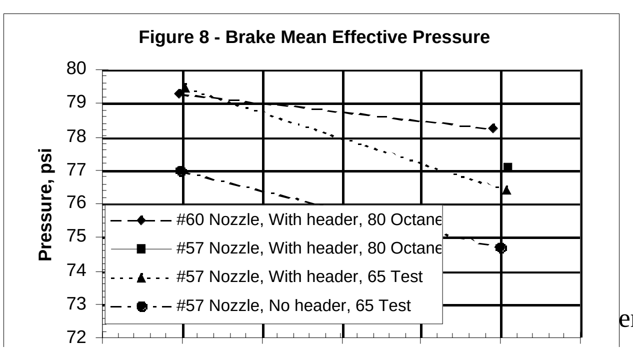
The brake mean effective pressure is shown in Figure 8 for the same four test cases. The indicated, pumping and friction mean effective pressures are also shown in Figures 9, 10 and 11.

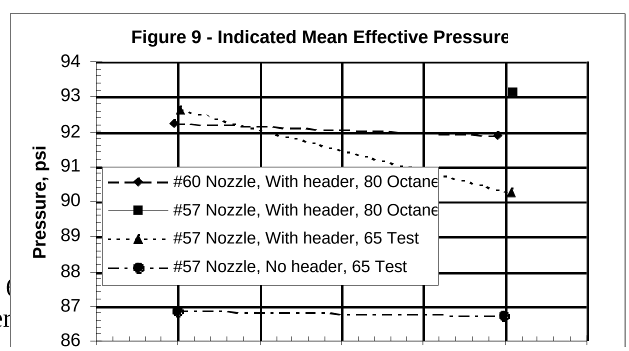
From these plots, the following conclusions can be drawn:

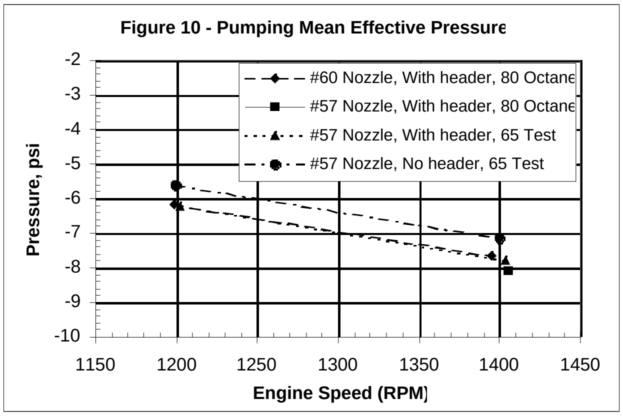
1. Pumping and friction losses are typical for pre-WWII engines.[9] Pumping losses range from 7.7% to 9.5% of output power at 1200 and 1400 RPM respectively, and friction losses (which includes the accessories such as the water pump) range from 5.6% to 6.5%.
2. The brake mean effective pressure (BMEP) is typical of pre-WWII engines, with values in the mid-70's. This was quite an improvement over the first flight engine that had a BMEP of approximately 40 psi.

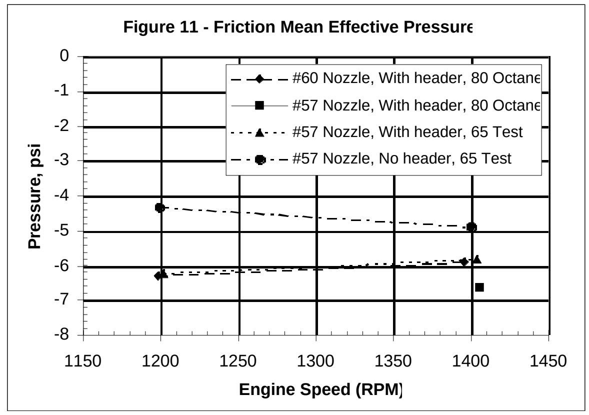












Volumetric Efficiencies

The volumetric efficiency is the ratio of air volume intake to the displacement volume of the engine at atmospheric pressure conditions. It was calculated in two ways: directly by measuring airflow into the engine and indirectly by using the fuel flow calculations and the air/fuel ratio to extract airflow information. In the direct method, the auxiliary port intake air was not considered and hence resulted in a low value of almost uniformly 58% for all test cases. Using the indirect method gave a value of about 75% for all test cases, much higher and more accurate with the added intake from the auxiliary ports considered.

These values are low compared to contemporary engines, but are expected due to the restricting effect of the automatic intake valves, the reduced effective compression ratio caused by the auxiliary ports, and blow-by past the piston rings. The auxiliary ports allow some charge venting during the first 12% of the compression cycle, resulting in an effective compression ratio of less than 4.7:1. Although a smaller effect, leak-down measurements showed significant blow-by that increased after all testing was completed. Cylinder #3 had the lowest measured leak-down with 18 psi / 75 psi at the beginning of the test, and only 9 psi / 75 psi at the end of the test.

It should be noted that since there are no mechanical connections to the intake valves, significant variability in the charge intake can occur from cylinder-to-cylinder which will affect volumetric efficiency. A motoring test at 1400 RPM showed cylinder #4 having 18% less dynamic compression than cylinder #2. This is probably attributed to variations in the intake valve spring tension and "stiction" between the valve and guide.

Thermal Efficiencies

The indicated thermal efficiency (ITE) is defined as the ratio of indicated work to the available work from the fuel, or:

$$\eta_i = \frac{W_{indicated}}{m\ Q_{HV\ fuel}} \quad (2)$$

Figure 12 shows values ranging from 17 – 19.5% depending on the test run. These are certainly low by contemporary standards where 50 – 60% is common, but are typical of a low-compression engine running on the rich side of stoichiometric. Average air/fuel (AF) ratios of 10.7 for the #57 nozzle and 11.1 for the #60 nozzle were considerably richer than the ideal value of 14.97 for the 65 test fuel.

As previously mentioned, the fuel delivery system consisted of a displacement-type pump that delivered fuel either through four #60 holes or six #57 holes. Because of the regulated fuel supply, the nozzle type minimally affected the average AF ratio but individual cylinder AF ratios did show more uniformity with the #57 x 6 nozzle. Individual cylinder AF ratios were generally observed to be richer at the front of the engine than at the rear of the engine, with the 1200 RPM test case, 80 octane fuel, #60 x 4 nozzle having the largest difference. In this case, cylinder #1 AF ratio = 10.0 and cylinder #4 AF ratio = 13.8. It is this favorable AF ratio towards the back of the engine that boosted the combustion pressure of cylinder #4 in Figure 3 to second highest despite having a relatively low dynamic compression.

The brake thermal efficiency (BTE) is shown in Figure 13 and the mechanical thermal efficiency (MTE) is shown in Figure 14. The mechanical thermal efficiency, representing BTE / ITE shows a fairly

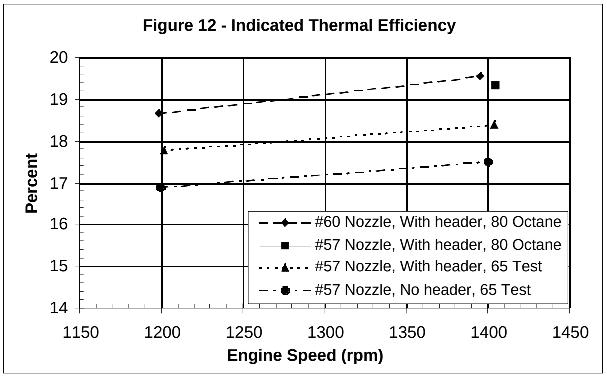


Figure 12 - Indicated Thermal Efficiency

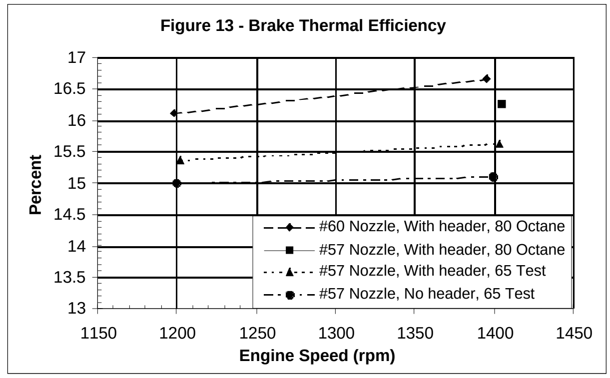


Figure 13 - Brake Thermal Efficiency

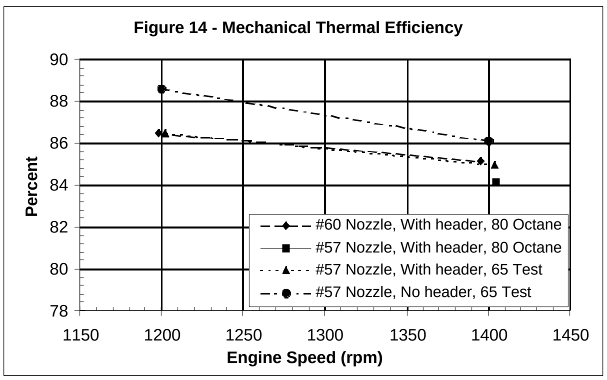


Figure 14 - Mechanical Thermal Efficiency

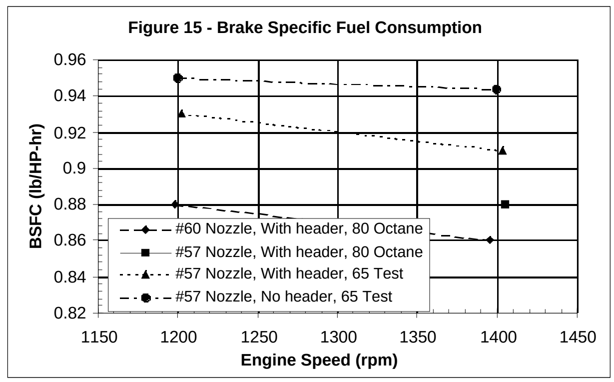


Figure 15 - Brake Specific Fuel Consumption

efficient transfer of energy from the cylinders to the crankshaft.

Specifc Fuel Consumption

Brake specific fuel consumption was again high due to the rich mixture, shown in Figure 15. These values are approximately double of what modern engines are capable of performing at.

Combustion Stability and Emissions

Combustion stability measured as the coefficient of variation (COV) of IMEP exceeded today's limits of less than 3.0. The average for one test on the 65 test fuel was 6.8. Many factors contributed to this condition, most notably variations in the intake charge, the air-fuel distribution and the combustion process.

Total hydrocarbon emissions for the engine averaged 716 PPM for the 65 test fuel. While not a world-class by today's standards, this number is within the range of modern day engines. Reasons for this number to be on the high side can be contributed the poor combustion stability and a large combustion chamber area design.

Nitrogen oxides had very low numbers for the same tests above and averaged only 71 PPM. Such numbers for nitrogen oxides are unheard-of for modern engines. Nitrogen oxides emissions are a direct effect of combustion gas temperatures. Inherently this engine has lower combustion temperature due to low compression ratio, retarded or limited spark and a rich air-fuel ratio.

Carbon Monoxide and carbon dioxide were 9.6% and 6.2% respectively during this test. Both of these numbers are not representative of a today's value, but are in-line with the rich air-fuel ratio condition at which the engine was running. Carbon monoxide is typically much lower at 0.5% to 0.8%.

Evaluation of Results

In a letter dated April 12, 1911, Orville stated that "We look upon reliability in running as of much more importance than lightness of weight in aeroplane motors."[10] The rich AF ratio, suction activated valves, auxiliary ports and low operating speed of this engine all contributed to enhanced reliability by lowering the cylinder head temperatures. Problems associated with high head temperatures included valve failures and detonation, which were common in engines of this period. By intentionally detuning the engine, a significant gain in longevity was achieved.

Variations of the AF ratio *between* cylinders as well as the variation in dynamic compression values resulted a wide range of cylinder combustion pressures. The direct cause of the AF variation from cylinder-to-cylinder is not known, but it may be a flow phenomenon in the intake header which existed despite the symmetry just past the point of fuel injection.

Combustion pressure variability and an unbalanced crankshaft contributed to vibration levels that peaked at 4.88 g RMS in the vertical direction at the flywheel end of the block, measured at 1400 RPM. These results may be different than in-situ measurements due to the mass effects of the dynamometer driveshaft.

Similar to the previous Wright engines, there was no throttling mechanism to allow partial power operation. The wide range of magneto retard and advance did provide a crude means of power control (via a foot pedal), but this feature was mainly used for starting the engine. The high drag coefficient of the Wright aircraft warranted full power operation through all phases of flight, and only on short final would the power be reduced or cut altogether with the compression release and/or fuel shutoff valve.

The significant novel features of this engine include the suction-activated intake valves, the fuel injection system and the auxiliary exhaust ports. These design features represented a compromise in performance for increased reliability which, even today, is still the primary driver in aircraft engine design.

Conclusions

The Wright Vertical Four engine was an effective powerplant for the mature aircraft designs of the Wrights. With a relatively low BMEP and a rich AF ratio, the engine was intentionally "detuned" to prevent overheating and subsequent failure.

Maximum recorded power was 32.1 HP at 1400 RPM in the original configuration, a value close to previously reported power measurements. Maximum brake torque was achieved at the full advance setting of BTDC, a relatively large advance due to the low compression ratio of 4.7:1.

Variability in combustion pressures from cylinder-to-cylinder was high and due to many factors, such as a varying AF ratio, variability in the automatic valve operation, piston ring blow-by and combustion process variability. Considering the 91 year age of this engine, the performance was quite good and in-line with other pre-WWII spark ignition engines.

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