Development of a Slow-Speed Engine for Enhanced Understanding of Thermodynamic Concepts

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Today's engineering and technology students are often challenged to understand the fundamentals of thermodynamics and the devices that use these principles to power our society. A significant part of the problem lies in the fact that operational systems don't easily lend themselves to integration into the majority of traditional classroom environments. By developing a small, slow-speed internal combustion engine system with the assistance of the National Science Foundation, the author is attempting to provide a compact, versatile educational system that is appropriate and useful in a traditional classroom setting.

For the system to be useful there are several categories of objectives that must be applied to its design. General objectives associated with any project include the optimization of size, weight, and cost. This becomes particularly important for commercially viable systems. However, during this phase of the project, called the proof-of-concept phase, these objectives are secondary to the ultimate goal of providing a system that is both safe and realistic in its demonstration of thermodynamic principles. Here, the primary objectives center around realistic 4-stroke Otto cycle thermodynamic processes operating at a very slow speed compared to typical commercial power plants, with instrumentation that provides a comprehensive picture of the thermodynamic processes present throughout the cycle. Achievement of these objectives then assures that gas-compression processes can also be accurately represented; something equally valuable for students to examine during their exploration of thermodynamics concepts.

For this proposed system to be both realistic and effective it must involve; the safe, effective handling of a commercially available a gaseous fuel such as propane; an electric spark system involving high-voltage electricity; and an electric motor to provide and control power flow during the various strokes in the engine's mechanical and thermodynamic cycles. The most important aspect of this system, however, is the fact that it is being designed to be a compact table-top system accessible to students across a range of ages and educational levels in an open classroom-style setting, without the special equipment or facilities usually associated with experiments involving operating internal combustion engines.

To accomplish these primary objectives the system being developed, with the financial assistance of the Division of Undergraduate Education of the National Science Foundation, consists of a small engine/electric motor combination in conjunction with a comprehensive instrumentation/data collection package, all contained within a strong aluminum frame having a 30 X 18 inch footprint. The engine being used is a 5 horsepower Kohler "Command", directly coupled to a fractional horsepower AC electric motor. Instrumentation includes multiple thermocouples and pressure transducers, a shaft encoder and a bi-directional torque transducer. This is mounted to an 80/20 Inc. aluminum framing system. Electronic and data collection systems are mounted on a vertical frame section above and behind the engine/motor combination. See figure 1.

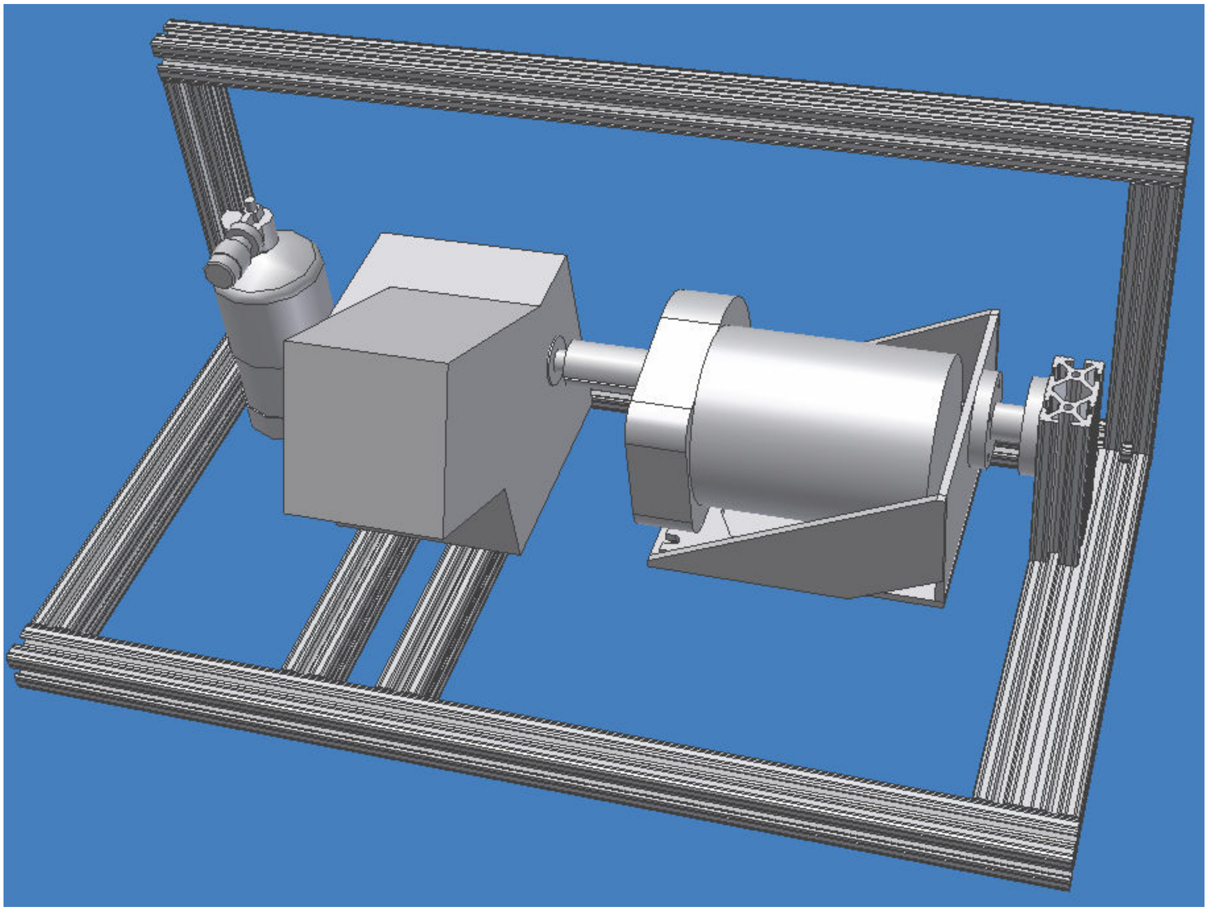

Figure 1. The Physical Arrangement

Results thus far have been encouraging. The engine has been operated for extended periods of time with all instrumentation operating as anticipated.

The Starting Point

The engine system that was chosen began its life as a 5 horsepower, horizontal shaft, air-cooled 4-stroke Kohler Command. It had a splash-style lubrication system, venture-style gasoline carburetor, magneto ignition, internal inertial governor, flywheel-type cooling fan and shroud, and an “easy-start” compression release system to prevent compression at speeds below approximately 300 rpm. In developing a system that could work at the target speed of 30 rpm, virtually all of these subsystems required substantial modification or removal.

Initial work included the removal of several unnecessary components and subsystems; among them were the flywheel and cooling shrouds, the governor, the patented Kohler “easy-start” system, and numerous ancillary mounting locations cast into the block as part of its original commercial design. Also included in the initial barrage of modifications were machining operations to the crankshaft to facilitate attachment of the drive motor and instrumentation, and a large opening in the top of the block to allow visibility and run-time access to its internal workings. Once the bare system was ready work could begin on the fundamental engine systems critical to its operation; lubrication, cylinder sealing, carburetion, and ignition.

Lubrication

The original splash-style lubrication system obviously would not splash at 30 rpm. With the enhanced visibility of its inner working facilitated by the opening mentioned above, it was discovered that the normal wetting of parts immersed in a partially filled sump could provide adequate lubrication to all internal parts except the piston. This occurred as the oil initially wetted the camshaft gear teeth, then migrated to the other components as the teeth meshed with the crankshaft gear. Rolling action of the camshaft and crankshaft effectively distributed the oil to all bearings within the block, including the camshaft and crankshaft/connecting rod journal bearings. Addition of a very small positive displacement pump that provided a periodic lubricant stream to the top sidewall of the piston insured that all necessary piston surfaces could also be adequately lubricated at all times.

Cylinder Sealing

The original piston rings served two purposes; containment of combustion (or compression) gases, and removal of excess oil coming from the splash system. The original compression rings consisted of two gapped metallic rings designed to expand and close as operating temperatures were achieved, thus sealing the cylinder/piston gap against combustion gas leakage. An oil control ring set consisting of thin scraper rings on either side of a corrugated separator, was also placed below the second compression ring to remove excess oil splashing into the cylinder from below. For this application, however, these piston rings proved to be completely inadequate. Temperatures were too low to accommodate designed-for ring expansion, and the rings would never “wear in” to insure an optimum seal between sliding metal parts. The solution was to modify the ring grooves and install completely different styles of seals.

For the compression sealing requirement an “energized” type of elastomeric sealing ring was chosen. This design provided a positive pressure against the cylinder wall at all times and had good performance up to a rated temperature of at 225 degrees Fahrenheit. Several hours of testing showed that this design could seal effectively, tolerate a wide range of lubrication levels, and withstand the temperatures of combustion experienced at 30 rpm.

For lubrication control another style of piston ring was chosen. With the addition of a deliberate lubrication stream to the piston/cylinder region of the engine there was a need for lubrication control to the piston seals since, unlike a normal engine, excess lubrication would not “burn off” or blow out of the combustion chamber. The solution here was a wiper-style seal typically found in hydraulic applications, with the sealing lip facing towards the crankshaft. This arrangement allowed only residual lubricant to remain on the cylinder wall, thus lubricating the compression seal without allowing excess lubricant to enter and remain above the piston to possibly affect instrumentation.

Carburetion

The original carburetion system consisted of a venturi-style liquid (gasoline) feed and atomization mechanism, combined with a butterfly-style throttle for speed and/or load control. For this design, however, safety concerns regarding the use of gasoline in a classroom, combined with the original objective of constant 30 rpm operation made a new fuel delivery and control system necessary. Propane was chosen as the necessary fuel based on its relative safety compared to gasoline and its near-ubiquitous presence in laboratory settings. If a "house supply" was unavailable, the system was also designed with the option to carry its own self-contained propane supply similar to modern propane camping lanterns. To insure a controllable fuel/air mixture is delivered for every intake stroke, the author has developed two options; normal aspiration, and fuel injection. The first option is the simplest and consists of a pair of calibrated orifice plates that operate on the cyclic vacuum created during the engine's intake stroke. The outer plate contains the air orifice and an adjustment screw to fine-tune its pressure differential. The inner plate contains the fuel orifice. Using the outer plate adjustment screw the fuel/air mixture can be fine-tuned so that a consistent and repeatable range of mixture ratios is obtained, from beyond the rich limit to beyond the lean limit. This mixture adjustability allows interested students to experiment with yet another variable important to the operation of an internal combustion engine. The second option, fuel injection, provides a metered fuel charge to an unregulated air flow during every intake stroke. It can also provide a controllable mixture ratio but is more mechanically complicated.

Ignition System

The original spark ignition system consisted of a common magneto-style coil in close proximity to a moving magnet attached to the flywheel. For a design where the flywheel is absent and the engine it rotating at only 30 rpm, this system is obviously inadequate. Instead, a proprietary system was devised that relies on an optical sensor to detect a properly positioned target attached to the camshaft. This sensor triggers a circuit to deliver a high frequency 12 volt current to a standard automotive ignition coil that, in turn, delivers the required voltage to the spark plug. Additional information on the design of this system is presented in another paper to be published in the 2004 Proceedings of the American Society of Engineering Educators national conference. This ignition system delivers a high quality spark pulse for a predetermined period of time during every ignition sequence required, thus insuring combustion will occur if the fuel/air mixture is anywhere within its combustible range.

The Drive Motor

The electric drive motor system first chosen was a 90 volt DC gearmotor having a range from 6 to 62 rpm, controlled by a "Leeson Speedmaster" motor control using voltage to control speed. This arrangement was used to test for overall functionality of the entire system. Results showed that while a speed of 10 rpm was functional and all systems worked as planned, conceptual visibility of each stroke of the engine was not as clear as it was at 30 rpm. This initial testing also showed that this type of motor/controller did not have effective braking capacity during the power stroke. For these reasons it was subsequently replaced with a fractional horsepower 110 VAC gearmotor operating at 1800 rpm with an output speed of 30 rpm. Being an induction motor, it automatically compensated for variations in load in order to maintain its rated speed. During the intake, compression, and exhaust strokes negative net mechanical power was required by and delivered to the engine with little strain. Conversely, during the power stroke there was a high positive net mechanical power delivered by the engine. The induction motor proved to be very capable of maintaining the required speed under this fluctuating condition.

Instrumentation and Data Acquisition System

Instrumentation for this system consisted of three thermocouples, placed in the intake manifold, directly into the combustion chamber, and in the exhaust manifold; two pressure transducers, placed in the intake manifold and directly into the combustion chamber; a shaft encoder placed on the crankshaft opposite the gearmotor; and a torque sensor placed in-line with the crankshaft/gearmotor. Together, this package of instruments allows an experimenter to observe and measure the important aspects of an engine's behavior during all portions of its thermodynamic cycle. In the event fuel was not provided, the engine can be used as a simple compression/expansion chamber to demonstrate fundamental thermodynamic aspects of gases as a function of volumetric change. Data collection is accomplished using a DAQ card in conjunction with a desktop or laptop computer. Both LabView and WinView have been used for graphical representation.

Testing to date has shown valid instrumentation responses in both cases (combustion and simple compression). A more detailed discussion of the design and performance of the instrumentation and data acquisition system can be found in paper to be published in the 2004 Proceedings of the American Society of Engineering Educators national conference.

Initial Performance Results

Operation was initially verified at a speed of 10 rpm. Although all performance parameters were realistic, the author increased the system speed to 30 rpm to improve visualization of the 4-stroke cyclic nature of the engine. This new speed was judged to provide less experienced students with a better conceptual understanding for the dynamics of each stroke in the cycle, especially during the intake stroke where valve and piston movement coordinates with carburetion functions to deliver the correct fuel/air mixture in appropriate quantities. At this speed each stroke takes 2.0 seconds and results in 15 power strokes each minute.

The instrumentation/data collection sub-system has proven to be capable of measuring internal cylinder conditions (temperature and pressure), as well as inlet/outlet gas conditions and power-stroke reaction torque, all in real time as a function of time. Display of these parameters as a function of crankshaft angle is also under development.

Next Steps

There have been many technical challenges to overcome in the successful development of this system. As these have been addressed, attention is turning towards development and testing of training modules suitable for a range of students, from high school to undergraduate college students. This is planned for late-spring through fall. Results of these efforts will be reported in the appropriate venues as they become available.

BIOGRAPHY

TIM COOLEY is an Assistant Professor in the Mechanical Engineering Technology department of the Purdue University, School of Technology.