Development of a Slow-Speed Engine
For Educational Purposes

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Introduction
This paper presents accomplishments resulting from the National Science Foundation’s support of project DUE-0231299; Educational Materials Development for Enhanced Understanding of Thermodynamics Concepts.

Thermodynamics is not an easy topic for students to learn. Likewise, inexpensive and easy-to-use equipment demonstrating its principles is not readily available for classroom use. In an attempt to improve this situation, the authors developed a slow-speed engine system suitable for classroom use that can demonstrate and measure several parameters important to an engine’s operation, and therefore the underlying thermodynamics that govern them. This system utilizes a highly modified 5hp, overhead valve, 4-stroke engine operating on propane. By operating at 30 rpm this system can continuously measure and display in real-time combustion gas and exhaust temperatures, cylinder and intake manifold pressures, crankshaft torque, and spark timing using low-cost commercial sensors and data acquisition equipment in any classroom environment, without expensive and sophisticated auxiliary equipment or facilities.

After development of the above system the authors designed lecture-style laboratory exercises for a range of high school and college student classes in order to assess its ability to improve learning of fundamental thermodynamics over current approaches to which the students had previously been exposed.

This paper discusses the most important design modifications required for proper functionality of this slow-speed engine system, the data it generated during testing, laboratory exercises that were developed to test its impact on student learning, and the results obtained from these assessments.

Design
The system began as a commercially available 5 horsepower Kohler engine with a horizontal crankshaft and overhead valves. From this starting point the final design would have; a self-contained propane-based fuel delivery system for safe, controllable, classroom operation; a ½ horsepower induction motor to insure a constant 30 rpm output speed regardless of the direction and magnitude of power flow; and real-time measurement, display, and storage of all important variables. These features were all contained within a 30” by 17” by 14” envelope weighing approximately 100 pounds, allowing the system to be safely operated in any typical classroom.

Three major modifications were required in order to operate at 30 rpm; the piston sealing system, the carburetion system, and the spark system. In each case the original system could not be modified to achieve the required performance.
The original piston sealing system, two oil control rings and one split cast iron compression ring, were replaced with an energized Buna-N seal design typically found in hydraulic cylinders, as well as a “riding o-ring” to prevent piston skirt contact with the cylinder wall. This design proved to be very effective for the application, as steady-state temperatures for the cylinder wall and piston never reached the 225 Fahrenheit limit of the material, the “energizing” feature maintained the seal regardless of internal pressure fluctuations, and its inherent lubricity against polished steel insured long-term performance during runs lasting well over an hour at times. This aspect is described in more detail in the author’s previous paper1.

For the fuel delivery system gasoline was replaced with Coleman brand bottled propane, eliminating the fuel vaporization step gasoline carburetors inherently perform as part of their metering and throttle control behavior. Then, two regulators were used to step bottle pressure down to -0.25” WC for safe, vacuum-controlled fuel delivery to two orifice plates. The outer plate contained an adjustment screw to regulate orifice size, and therefore the final fuel/air mixture. The second plate contained a series of peripheral channels, creating a venturi that introduced and blended propane into the incoming air stream. This design then provided a means to accurately control fuel/air mixture for experimental purposes, as required.

The spark ignition system differs from a typical small engine in that it supplies multiple sparks per stroke rather than the single spark from a magneto input. The system sparks continually at a rate of approximately 1 kHz when triggered by the input sensors. The spark system is described in more detail in the authors’ previous paper1. After initial testing, this spark system was altered by adding a second reflective sensor on the camshaft. The original version had only a single reflective sensor on the crankshaft. This would cause the spark circuit to activate on the both the power and intake strokes (as shown in Figures 1 and 2). The intention was that during the intake cycle the gases in the cylinder would not ignite because they were not compressed or yet fully in the cylinder. Unfortunately this was not always true, and occasional backfires did result. The authors elected to place a second reflective sensor on the camshaft so that the engine would ignite only on the power stroke. The two sensors’ inputs must be activated in order for the spark circuit to be activated. The reflective sensors output is a logic low when activated and the spark circuit is triggered by a logic high, therefore the two sensors’ inputs were connected to a NOR gate which has its output triggering the spark circuit. Initial testing showed the oil bath partially occluded the reflective strip placed on the camshaft causing the phototransistor of the sensor to switch from a high voltage of 3.5 volts to a low of 1.7 volts. The low value was insufficiently low and this was remedied by placing an analog comparator with an open collector output between the reflective sensor and the input to the NOR gate that triggers the spark circuit. This analog comparator had its inverting input set to 2.0 volts to insure a low triggering from the camshaft reflective strip.

The instrumentation system for this engine system utilizes 2 pressure sensors, 2 temperature sensors, and one torque sensor. These inputs, plus a spark activation signal, are directed to a data acquisition module at a scan rate of thirty times per second, although much higher scan rates are possible. The instrumentation system was also modified by the addition of Burr-Brown instrumentation amplifiers. These amps were added to increase signal clarity to the data acquisition module. Previously the programmable amplifiers on the data acquisition module were utilized for signal conditioning, but there were not enough channels on the module in use to
suit the needs of this project. The amps are extremely easy to use and made for a simple layout on the printed circuit board due to their 8 DIP package. A PCB was made for this portion of the instrumentation system adding to its reliability. Signal quality was improved and the displays provided clear graphical displays of the thermodynamic cycle occurring within the engine.

Operation
The most important parameters for demonstrating thermodynamics to students are gas temperature, cylinder pressure, and shaft torque as a function of time (and therefore crankshaft angle). These parameters are discussed below, and shown graphically in Figure 1 over a 10 second interval in the combined form similar to what students observed during the laboratory exercise and evaluation phase of the project. Figure 2 shows a two second portion of the same data sample, where only a single compression and power stroke is shown. Ignition spark is also shown on both graphs for reference. Figure 3 shows a more-detailed analysis of the work/power concept, using an actual P-v diagram combined with an actual torque-crank angle diagram generated from the data in Figures 1 and 2.

![Figure 1 – Sample Display](image)
Gas Temperature

As would be expected, temperature changes with both volume and combustion. This leads to two types of traces as a function of time. Although not shown graphically in this paper, the first trace represents a simple compression/expansion process where pressure, and therefore temperature, changes with internal volume. Differences between an ideal trace and an actual trace could then become the subject of a laboratory exercise exploring implications of the isentropic, adiabatic assumption often made in college-level thermodynamics classes.

The primary emphasis for this project was to measure and represent the second type of trace – gas temperature during operation, as a function of time or crankshaft angle. During testing combustion temperatures generally peaked at around 600F. While adiabatic temperatures are generally expected upwards of 3500F, depending on the model used, these data show that much lower temperatures were actually measured. This results from two primary causes. First, while the thermocouple chosen for this system was the fastest stock item available from Cole Parmer, it still had a time constant of 0.1 seconds and therefore responded relatively slowly to the actual situation. Second, the ratio of masses of the thermocouple to the fuel/air mixture was on the order of unity, meaning that the thermocouple was acting as a significant heat sink for the suddenly-released thermal energy (along with the other exposed internal surfaces), and could not accurately measure the gas’ true combustion temperature. Never-the-less, the overall
temperature measured over time does a realistic job or representing this variable’s internal behavior for the purpose of instructional learning.

Cylinder Pressure
Similar to the dual-trace capability for gas temperature mentioned above, cylinder pressure can also demonstrate both compression/expansion and combustion behaviors. And again, this project’s emphasis was on the engine’s operation for the majority of its exposure to student laboratory exercises.

Combustion pressures for this arrangement were usually in the 500 psi range, although as would be expected, they varied significantly with fuel/air mixture and ignition timing. Notice also in Figure 3 that the envelope is significantly smaller (rising later, peaking lower, and falling sooner) than the ideal-case (isentropic, adiabatic) theory would predict. For more-advanced engineering classes this could also constitute another avenue of experimentation and exploration.

Shaft Torque
To demonstrate the most tangible aspect of thermodynamics and engine power, graphs of engine torque are also useful, especially for high school students. Figures 2 and 3 show that torque must be provided to the crankshaft during the compression stroke as work input (torque input) before it can be received from the crankshaft during the power stroke as work output (torque output). The authors found that this concept (power flow into AND out of an engine during its cycle) serves better than any other single aspect to enlighten high school students to the concepts of thermodynamics and power. Figures 2 and 3 serve as good visual aids when explaining this concept, showing a peak input torque of approximately 15 foot pounds and a peak output torque of approximately 75 foot pounds. For more advanced engineering students, a valuable exercise would be to calculate force and work as a function of crankshaft angle for both theoretical and actual pressure and torque values in order to determine total work for an actual Otto cycle engine.
Laboratory Exercises

The resulting slow-speed engine system was intended for a broad range of students, from vocational high school through engineering levels. As a result a preliminary series of increasingly involved exercises was prepared that followed this progression. More-detailed exercises specifically tailored for each category were not developed during this initial proof-of-concept phase of the project.

At the most fundamental level, appropriate for both vocational as well as pre-engineering high school classes, the concept was developed that a 4-stroke engine cycle is very different from a 4-step thermodynamic process. This involved substitution of mechanical concepts such as piston and valve movement with energy concepts such as temperature and pressure as a function of crankshaft angle (cylinder volume) and combustion (energy addition). At a slightly more advanced level, specifically for pre-engineering high school students, topics also began to encompass design and instrumentation aspects as well as a more focused exploration of energy and power. This included the formal Otto cycle and its process steps, the important variables involved, and graphical representations that could form mental images students could recall later. At the college level, engineering technology in this case, students examined differences between ideal and real compression/expansion and Otto cycles, and the parameters involved in their determination. At a higher engineering level more-detailed examinations of the variables affecting important Otto cycle parameters, as well as their application in slow-speed
environments such as this could be undertaken. However, time and class availability did not permit this final level of participation in this particular case.

Once this progression was outlined exercises were then developed and presented to students in vocational and pre-engineering high schools in the local area and in two sophomore engineering technology classes studying heat and power. In all cases the exercises presented were in demonstration form so that all students could observe and learn together. Digital projection was used for both the lessons and to observe the real-time data being collected.

For vocational high school students, including automotive and small-engine mechanics and machinists, the exercise focused on the fundamental difference between mechanical and thermodynamic approaches. A brief discussion of the mechanical modifications that were done was also included to form a bridge between their current experiences and the thermodynamic material to come. Students were shown how to examine an engine’s behavior as a 4-step energy transfer system versus the traditional 4-stroke mechanical system they were studying at the time. After this was demonstrated and discussed using graphs and the engine itself, then real-time run charts of the incoming data were presented to offer visualization for the behavior of each important parameter; temperature, pressure, and torque as a function of time. The presentation ended with mention of additional components that could be tested, such as carburetion, valve timing, and spark timing, so students could arrive back at familiar territory. A brief outline of the exercise is included below.

Why 30 rpm? – to better Visualize, Investigate, Analyze  
What systems are modified & why? – Carburetion, Piston seals, Lubrication, Spark, Block/Crank 
OK we’ve got the system, now what’s happening? - Engine cycle, Thermodynamic cycle  
Mechanical approach (4-stroke cycle) – Intake, Compression, Power, Exhaust  
Energy (thermodynamic) approach – Compression, Ignition, Expansion, Exhaust/Intake  
Diagrams (for visualizing how a thermodynamic engine works) - thermodynamic process and diagrams  
Energy & Power Flow – Compression (in), Ignition (in/convert), Expansion (out), Exhaust/Intake (out)  
What can we visualize? - Torque/Power flow, Pressure & Temperature with time  
What else could we experiment with? – Carburetion, Ignition, Valve timing, Combustion products, Heat transfer, Efficiency  
An engine → a mechanical system + an energy (thermodynamic) system

Figure 4 – Vocational High School Exercise Content

For pre-engineering high school students the laboratory exercise built on their existing knowledge of engines and the modifications needed for the slow-speed system. In this particular case the presentation also included elements of electricity and the ignition system, as well as instrumentation since it directly related to the course content being studied at the time of the presentation. Then, in addition to the thermodynamic presentation previously mentioned for the vocational high school students, the exercise further explored each individual parameter and what information it describes about energy within the system. An outline of the exercise is included below.

A brand new (high speed) engine converted to a slow-speed engine  
The custom systems needed – carburetion, piston sealing, ignition, etc  
Ignition System design – sensing, coils, voltages, timing  
Sensors & Data Acquisition – reflective sensor, thermocouple, strain gage, torque sensor  
A 4-stroke engine cycle – mechanical approach, 4 piston strokes  
The problem is we can’t examine energy or power  
A thermodynamic cycle – based on energy flow & change, 4 process steps make a cycle  
Diagrams (for visualization) - Thermodynamic cycle, Pressure-volume (P-v), Pressure-time (P-t)  
Parameters we can visualize with this 30 rpm engine – Temperature, Pressure, Torque, Ignition
What does our instrumentation show us? –
How pressure behaves
How temperature behaves
How torque behaves

Engineering analysis we could do - pressures, temperatures, torque, energy & power, efficiency, energy conversion

Figure 5 – Pre-engineering High School Exercise Content

For engineering technology students the laboratory exercise explored the differences between ideal and real processes, first using a simple compression/expansion cycle, then exploring the Otto cycle. Each section used the slow-speed engine to demonstrate the non-ideal case and its degree of deviation from the ideal case they had been studying in their textbook. An outline of the exercise is included below.

1. Ideal versus Real Compression/Expansion Cycle
   A. Compression = …, Expansion = …, Ideal Gas Law → …
   B. Isentropic Compression/Expansion = no losses, can return to its original state
   C. Potential sources of loss that make the process “non-ideal”
   D. Testing to see “how isentropic a situation really is” - Ideal case, Actual case, Difference, Reasons & Tests

2. A Real Otto Cycle
   A. Pressure behavior:
      - The ideal P-V cycle diagram
      - Unfolding the trace with & without combustion
      - Accounting for intake suction
      - Use of Mean Effective Pressure
   B. Temperature behavior:
      - Actual combustion rise ≈ 600°F
      - Shape of the curve & why
   C. Torque behavior:
      - Profile of a full-speed engine
      - Profile of a slow-speed engine
   D. Efficiency:
      - Ideal case based on compression ratio
      - Ideal case based on actual temperatures
      - Actual case based on the basic definition: (why?)
   E. Additional areas of investigation and likely outcomes:
      - Fuel/air ratio – lean & rich limits
      - Ignition timing – advance, retard, duration
      - Total cycle power – as a function of crankshaft angle

Figure 6 – Engineering Technology Exercise Content

Learning Assessment
In order to determine the slow-speed engine system’s value as an instructional tool, two separate aspects were assessed after each laboratory exercise was conducted. The first aspect dealt directly with the information students learned as a result of the exercise. This was determined using multiple choice survey questions given both before and after the lab exercise. Questions looked for increased knowledge of specific topics, with results shown as percentage improvement between the “before” and “after” surveys. Figure 7 presents these surveys and their results in a condensed form showing all groups tested. From this information vocational high school students appeared to benefit the least, while engineering technology students appeared to benefit the most. Also note that the pre-engineering students were given additional questions relating to sensors and amplifiers. This aspect was not used for comparative purposes beyond this group. The authors strongly believe engineering students would also show strong benefits, if they had been exposed to the system.
The second aspect that was evaluated dealt with students’ perceptions of the slow-speed engine’s value and suitability to their situation, i.e. was the system better than other alternatives at their disposal. Students were asked to compare the slow-speed engine to any other system they had used; (donated engines and vehicles in an adjacent shop for the vocational high school students, no equipment in the case of the pre-engineering high school students, or a full size engine dynamometer lab on another part of campus for the engineering technology college students).

Figure 9 presents these results in condensed form, using the standard 5-point Likert scale. While results were generally positive, pre-engineering students showed the strongest preference for this system, probably since they had no other experimental equipment available. Anecdotally, they also showed the most interest before, during, and after the exercise was presented.
Figure 9 – System Attractiveness Survey (combined form)

Summary
This proof-of-concept project appeared to be very successful. The system appeared to produce realistic information, exceeded all initial expectations and proposal deliverables, and was personally and professionally rewarding for both authors. The authors wish to thank the National Science Foundation’s for its support. Additional papers that explore technical engineering aspects are planned.

Bibliography


Biography
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