ASEE AMERICAN SOCIETY FOR ENGINEERING EDUCATION

Paper ID #35915

Use of Capstone Engineering Design Projects to Construct a Teaching Laboratory

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Use of Capstone Engineering Design Projects to Construct a Teaching Laboratory

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"One must learn by doing the thing; for though you think you know it, you have no certainty, until you try." (Sophocles)

Abstract

This manuscript intends to show that student projects of the popular undergraduate senior-level *Capstone Engineering Design* course can be used to design and construct cost-effective teaching laboratories for other courses. The educational benefit of this undertaking has double significance. Students of the *Capstone* course design experiments and construct relevant setups, with the guidance of the instructor of the targeted course. This scheme works best if the instructor of the targeted course also serves as a project advisor in the *Capstone* course. Upon formation of a coherent laboratory for the targeted course, following a thematic approach, future students of that course will use the laboratory facility to enhance their understanding of concepts with "hands on" experiences. Over the years, a number of *Capstone* groups have been tasked with creating experiments for the laboratory of the *Internal Combustion Engines* course at Northeastern University. The resulting constructs are used to demonstrate the design of engine components and their functionality. This familiarizes the students with the hardware design and operations, and facilitates the demonstration of theories presented during the class lectures. User-friendly, educational hands-on experiments allow students to observe engine induction and exhaust processes, supercharging and turbocharging, engine valve timing, fuel injection timing, spark timing, etc. Students measure engine performance parameters and calculate engine efficiencies (mechanical, volumetric, and thermal). Finally, they study the operation of powertrain components, such as the transmission and the differential gearboxes and measure torque and rotational speed outputs. Learning goals are routinely incorporated into the final design of the new experiments and laboratory procedures. The entire laboratory follows an aesthetic theme including vibrant colors, clean lines, and hidden wiring.

1. Introduction

It has been said that curiosity leads to creativity [1, 2] and that in pedagogy project-based learning [3-5] is an excellent method for generating curiosity. In many undergraduate engineering programs the Capstone Engineering Design courses are realizing "hands-on" project based learning. In the Department of Mechanical Engineering of Northeastern University, this one and a half semester course applies engineering sciences to the design of mechanisms, such as those that transmit motion or power. Projects are faculty-proposed or, in some cases, student-proposed with the approval of faculty. Students organize in four or five-member teams and choose design projects from an available list every semester. Faculty members serve as team advisors. Projects involve open-ended problems. For each project the engineering design process is implemented, problem statements and specifications are formulated, design methodologies are developed, alternative solutions are considered and evaluated, appropriate materials are selected, systems analysis is performed and prototypes are constructed and tested. Results are collected and plotted. Reports are written and presentations are made. Realistic constraints of cost, safety, end of life disassembly, recycling, social impact, etc., are considered. The author serves as a long-time faculty advisor in this *Capstone* course. He is also the long-time instructor of the senior-level undergraduate course of *Internal Combustion Engines* (ICE). This course introduces students to concepts and theories of operation of internal combustion engines, based upon the fundamental engineering sciences of thermodynamics, fluid mechanics, heat transfer, solid mechanics and dynamics as well as materials behavior. It discusses the design and operating characteristics of conventional spark-ignition, compression-ignition and Wankel engines, both naturally-aspirated and blown. It also analyzes and discusses drivetrain components and calculates the transmission of power, torque and rotational speed through gear-ratio selections. The fact that the author is involved in both courses, has uniquely facilitated this undertaking.

Five *Capstone* course teams have been involved, over the years, in designing experiments and constructing setups for the *Internal Combustion Engines* course [6-10]. This laboratory has served as a pedagogical tool for both courses. This approach for in-house laboratory development has also proven cost-effective, as turn-key commercial laboratory setups are very expensive. The primary driving force behind the different laboratory setups of the *Internal Combustion Engines* course has been to ignite the students' curiosity, so that they can develop a better understanding of the concepts presented in the lectures, and also to generate interest and to stimulate new ideas. The course "walks" the students through smaller-scale processes relevant to engines by considering how the working fluids (fuel and air) enter the engine, move inside the cylinder, react together, transform into combustion products, exit the engine, and then undergo processes designed to reduce pollutants. The first Capstone team involved in this undertaking, in 1997, developed a comprehensive sets of experiments [6]. As those experimental setups aged and the relevant technology evolved, some were refurbished and upgraded and others were replaced by new setups, constructed by four additional teams. Components for the setups were either purchased from used part outlets or were donated by various manufacturers. The primary goal of this undertaking has been to design and construct an ICE laboratory which includes engaging experiments with relevance to the course materials, see Figure 1. Each of the *Capstone* teams aimed to ensure that the designed experiments were pedagogically effective. They designed setups that can be engaging, from a student's view-point. Still, this required determining proper instrumentation and assembly of complex mechanical systems. At the same time, the setups needed simple enough to be understandable by even the most novice students of engines. The end-goal is an aesthetically pleasing, technologically relevant laboratory that can remain relevant to the targeted course material and serve the university students for many years.

Figure 1. Partial view of the Internal Combustion Engine Laboratory of the Department of Mechanical Engineering at Northeastern University.

2. Capstone Engineering Design Project Goals

To design and construct ICE lab components that allow students to obtain deeper understanding of engine operation and performance, two of the *Capstone* teams decided to demonstrate the core efficiencies of an engine. These include thermal (fuel conversion), mechanical, and volumetric efficiencies. Improving such efficiencies is paramount to enhance engine performance, reduce fuel consumption, curtail emissions and minimize the impact of operating an engine on the environment. The other three teams concentrated on engine processes related to engine operation, which are important building blocks to achieving high efficiencies, such as fuel injection, air induction, generation of electricity, fuel ignition, etc. Teams generated learning objectives, identified design requirements, conceived and built experiment apparatuses, developed data acquisition systems, generated laboratory procedures and wrote lesson plans.

In the process of designing the experiments, the Capstone teams conducted research on existing literature regarding methods of effective teaching and learning. Their findings are summarized in the following [9]. Several factors need to be considered in the development of a laboratory for engineering curriculum. Studies on education have shed light on improving teaching methods and the merits of hands-on experience in learning. In his book, *Experiential Learning: Experience as the Source of Learning and Development*, David A. Kolb states that "learning is the process whereby knowledge is created through the transformation of experience" [11]. He proposed an Experiential Learning Cycle (ELC) consisting of the following four processes: (i) active experimentation (planning and trying out what is learned); (ii) concrete experience (doing and having the experience); (iii) reflective observation (reviewing and reflecting on the experience); (iv) abstract conceptualization (concluding and learning from the experience). Abdulwahed and Nagy applied this cycle directly to learning in a laboratory setting [12]. They tested the effectiveness of the ELC by adding various elements to their educational laboratory that corresponded with each stage of the cycle, such as pre-lab lectures, pre-lab tests, post-lab tests, hands-on sessions, and virtual labs. They concluded that "designing engineering laboratory education based on well-developed pedagogical theory can lead to better learning outcomes."

Team based learning (TBL) is an educational technique widely used in engineering curricula. A significant number of studies in the literature discuss the merits of TBL. For instance, McInerney and Fink showed that student exam scores greatly improved once a team-based group project was introduced to the curriculum [13], whereas Michaelsen and Sweet implemented a TBL course and based their structure on the idea that there are four practical elements of TBL [14]: strategically-formed permanent teams, readiness assurance, application activities that promote both critical thinking and team development, and peer evaluation. That study concluded that TBL benefits students in a multitude of ways, including enhanced ability to defend their positions in an academic setting and tackling more difficult or overwhelming problems as a team. The hands-on approach has always been a popular method of educating engineers, supplementing theoretical instruction; however, as experimental education is more costly, as well as resource- and space-intensive, many schools are neglecting it. The combination of experiential education and TBL can be an optimum approach in engineering education to generate well-trained engineers.

In the course of designing effective laboratory setups for educating engineers *Capstone* teams followed recommendations outlined in a relevant ABET and the Sloan Foundation colloquium [15] including: selection of instrumentation, construction of models, design of experiments, data analysis, design, learning from failure, creativity, safety, communication, teamwork, ethics in the laboratory and sensory awareness. One of the *Capstone* teams [7] suggested the implementation of a pre-lab activity and post lab reports. They argued that a major problem with laboratory learning is that the experiments become a mindless step-by-step following of the experimental procedure. If students start to think about the lab before they get there, then they activate the dimension of thought which coincides with the concrete experience step in Kolb's Learning Cycle [11]. It can helpful if the instructor poses questions to the students in class, challenging them to think about them before going to the lab. Along with pre- and post-lab activities, the laboratories should be completed in teams. This allows for assigning experiments of a higher degree of difficulty. Though the laboratories are to be carried out in teams, each of the participants should have an active role in the experiments. Students are less likely to be engaged in lab demonstrations.

3. Experimental Setups Related to Internal Combustion Engines

Internal combustion engines (ICE) are powered by the combustion of fuel and air; the combustion gases move a piston up and down in a cylinder. The piston rotates crankshaft through a connecting rod. The crankshaft eventually rotates the wheels of a vehicle, through the drive train. The thermal efficiency of an engine is defined as the ratio of the net power produced by the engine divided by the rate of energy released from burning the fuel. The volumetric efficiency of an engine illustrates the effectiveness of the intake components of filling the piston displacement volume of the engine with air. Mechanical efficiency is defined by the ratio of the crankshaft work output to the work done on the piston by the expanding combustion gases. The difference between these work quantities is used to overcome friction and pumping losses. Advancements in air delivery, fuel delivery, ignition timing, engine management and emissions control have improved the efficiency and power output of engines over the past century, at the expense of increased complexity. Experimental setups have been designed to study these processes.

3.1. Cutaway Engine

Figure 2. Cutaway one cylinder spark ignited engine

The simplest and most basic setup is that of a cutaway of a one cylinder 4- stroke *Briggs and Stratton* engine, connected to a geared motor, see Figure 2. When the user activates the motor the piston and valves move at a slow speed. At the other end the shaft of the engine is connected to a protractor - allowing the user to stop the engine at variable rotation angles of the crankshaft and take measurements of piston position and valve position at different crank angles. This experiment is very useful as it allows the user to comprehend engine timing and develop a graph similar to those in the course textbook. Students can also observe the valve sizes and valve lifts. An engaging discussion centers around the reasons for the difference in the diameter of the intake valve (pained blue) and the exhaust valve (painted red).

3.2. Setups on Fuel and Air Induction, as well as on Spark Generation and Distribution

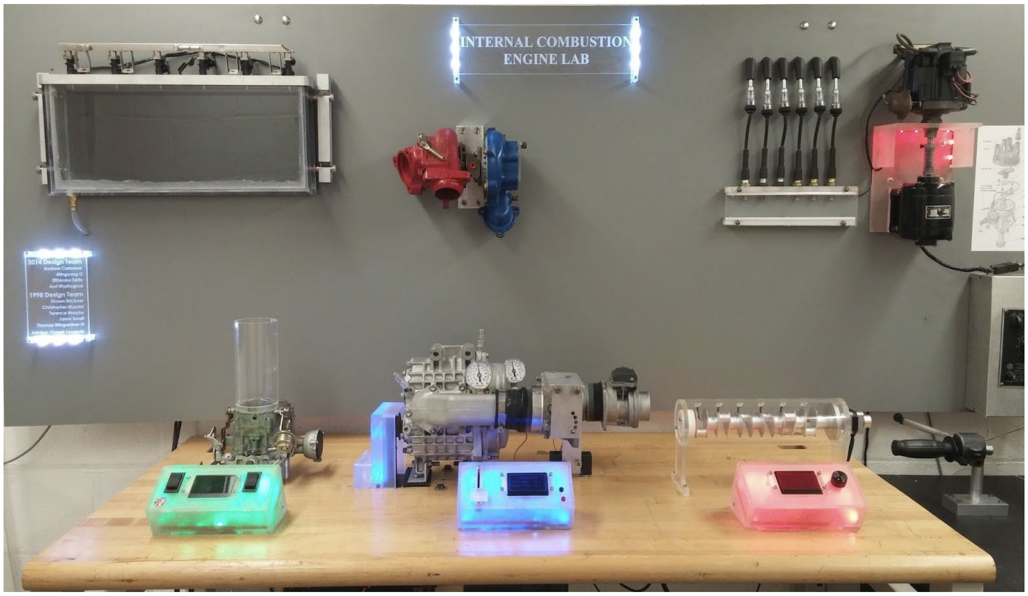

Figure 3. Air and fuel induction setups and spark generation.

For a spark ignited (gasoline) internal combustion engine to run, it needs fuel, air and a spark for ignition. Some of the *Capstone* teams chose to design setups around these three concepts: fuel injection, air induction and ignition. These sub-systems were designed to run independently of each other; however they have the ability to be integrated into one comprehensive experiment.

3.2.1 Fuel Injection

Fuel delivery has come a long way since the advent of the internal combustion engine. Originally, mechanical devices (carburetors) controlled the flow of fuel into the cylinders of gasoline engines. Carburetors utilized a venturi to draw fuel into a fast moving stream of air. Carburetors were complex, requiring regular adjustment and a choke in order to run correctly in different conditions; thus, they were eventually replaced by fuel injection systems. These devices use a fuel pump and injectors to atomize the fuel into the air stream. Eventually electronic controls were added to accurately control the amount of fuel introduced into the cylinders. As with other technologies, fuel injection has come a long way. Early injection systems used a single injector for the entire engine, i.e., SFI (single-point fuel injection). This system was replaced by MFI (multi-point fuel injection) where every cylinder was supplied fuel from a different injector, located in the intake manifold upstream of the intake valves. In the latest fuel injection technology, GDI (gasoline direct injection), the fuel is injected directly into a cylinder, akin to Diesel engines, to improve engine efficiency and reduce emissions. A carburetor setup is included in the laboratory, however it is not made into an active experiment. Students can still observe all of the components and moving parts. To the contrary, a fuel injection experiment was designed to be an active experiment. The experiment demonstrates a good physical representation of fuel spray from a fuel injector.

A fuel rail and six injectors from a BMW inline-six cylinder engine were mounted to a custom fabricated acrylic tank, see Fig. 4. Light emitting diodes (LED) provide light to view the injected fluid. The clear panel surround allows the users to safely observe the spray pattern and the state at which the fuel is being released. The students are able to interchange different types of injectors and observe different spray patterns and flow rates. An Arduino chip and a set of transistors control the firing rate and the pulse-width of the injectors. A digital flow-meter records the total amount of fluid (water is used in this experiments instead of gasoline for safety) entering the fuel rail, and subsequently leaving through the injectors, and displays the quantity on an LCD screen. An electronic control box was built to include the LCD, pump power switch, and buttons for duty cycle and engine RPM adjustment. Students can adjust the theoretical speed, then record RPM and flow rate. The injectors fire in the correct order as they would in an inline six-cylinder engine. For each revolution of the crankshaft, a total of three injectors fire. This information, as well as an accurate pulse width, is incorporated into this laboratory to make the experimental results as realistic as possible. Data is taken at increasing engine speeds until the programmed maximum RPM is reached. Students can then graph the collected data and compare to theoretical curves. Sample experimental result are also shown in Fig. 4.

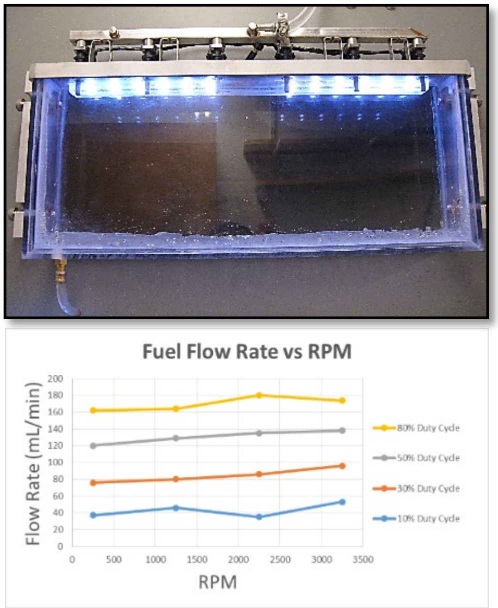

Figure 4. Fuel Injection Tank and sample results of flowrates

The *Laboratory Learning Objectives* of this experiment are given below, as an example:

- **Instrumentation**: A flow meter allows students to record real-time flowrate data.
- **Models**: Students are comparing a theoretical model (the expected linear relationship) to a real world model. There will be observed differences in the two trend lines, and the students will be asked to identify possible sources of error.
- **Data Analysis**: In producing the lab report, the students will demonstrate the ability to collect, analyze, and interpret data, and to form and support conclusions.
- **Learn from Failure**: If the students record data incorrectly, the results will be skewed.
- **Safety**: Students will observe safety requirements of the lab, which will be presented to them before and during the lab. Water is used instead of fuel.

3.2.2. Ignition of the Fuel and Air Charge

In order to ignite the air-fuel mixture in the cylinder of a gasoline engine, a source of heat is needed (in a Diesel engine the charge ignites by high compression alone). A spark plug is a small electrical device that fits into the top of the cylinder. It creates a spark from a discharge of high voltage across a gap between two conducting electrodes. This spark needs to happen at the correct moment in the engine cycle to ignite the air-fuel mixture; therefore, the timing of this spark is crucial to proper engine performance. Timing is measured in degrees before top dead center (BTDC) of the piston and is determined by the crankshaft position sensor.

A distributor is an electro-mechanical device running of the crankshaft of the engine that sends the spark to the correct cylinder at the right time. Early distributors were purely mechanical, opening and closing electronic contacts with a lobed shaft, see Fig. 5. Timing was controlled either with a centrifugal mechanism or by a vacuum. The mechanical distributor, of Fig. 5, is connected to a motor and the students can easily observe its construction, the points and the counterweights. They can also observe its operation, the spinning of the shaft and the centrifugal movement of the counterweights. Electronic distributors replaced the mechanical lobe and contacts with a magnetic pickup or *Hall* sensor. The electronic distributor setup, shown Fig. 6 is connected with a variable speed motor which allows the distributor to work at multiple speeds. The output of the distributor is connected to six spark plugs and six spark testers. When the experiment is run, the power is distributed to the spark plugs and they fire in series. Users are able to change parameters (speed of motor) and observe results (both speed and the firing order of sparks). This experiment also takes advantage of the vacuum spark advance using an electric vacuum pump to activate a pneumatic mechanism. The setup allows students to change parameters and observe the firing time. They can observe the actual sparks, and monitor their time shift with increasing engine the rotating speed of the shaft (simulating engine speed) and spark advance/retard driven with a vacuum pump (simulating the vacuum in the intake manifold of an engine).

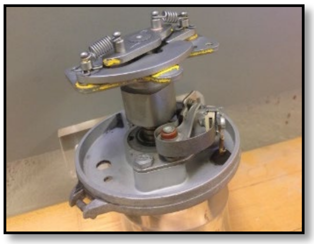

Figure 5. Mechanical Distributor

Figure 6. Electronic Distributor

3.2.3. Air Induction

Air delivery systems can be classified in one of two categories: naturally-aspirated or forced induction. In a naturally-aspirated engine, the downward movement of the piston creates a vacuum and draws air through the intake manifold at atmospheric pressure. Since fuel and air can only burn stoichiometrically at a certain ratio, the amount of air, and therefore available power, is limited. Engines with forced induction use either a turbocharger or supercharger to increase the amount of air entering the cylinder. This induced pressure above atmospheric is called “boost”. The presence of additional air means that more fuel can be injected into the cylinder, which results to more power output without the need to increase cylinder displacement.

<u>Supercharger Experiment:</u> This experiment involves a compressor driven by a motor through a belt. The motor speed can be controlled by the user, and the mass flow rate of the air passing through supercharger can be measured as a function of engine RPM. The setup, shown in Figure

7, has an air-flow sensor and two pressure transducers. An analog pressure gauge is placed at the outlet. Each temperatures are measured using J-type thermocouples. The data is collected by an Arduino microcontroller and outputted to an LCD screen. Students are required to use an anemometer to manually calibrate the voltage into a mass air flow. The students set the speed using a potentiometer knob and a stroboscope; the air flow rate and pressure is then measured and a new speed is selected. To measure the inlet pressure, the students are using a vacuum pressure gauge attached to the inlet tube. Thus, the students are able to use instruments to measure physical phenomena, collect and analyze data. This experiment allows the students to change parameters. The students use the collected results to calculate the mechanical efficiency of a supercharger. This experiment assists the students in developing a good understanding of how superchargers work and in determining at what conditions they are most effective. The largest strength of this experiment is that the student can use their own senses to understand the system. When the speed of the motor is changed, different sounds can be heard. Such sounds include the vibration of the machine and the airflow out of the tub. By holding their hand in front of the output tube the students can also get a physical sensation of the delivered volume of air.

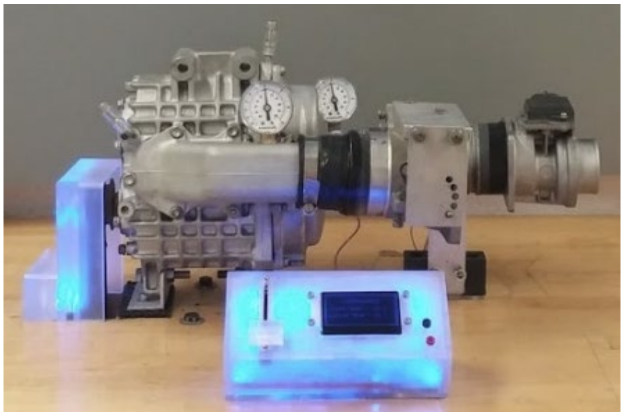

Figure 7. Supercharger Experimental Setup

Turbocharger demonstration: The turbocharger portion of the forced induction section of the laboratory is mostly a display, shown in Figure 8. It would take a very large amount of compressed air to run the turbocharger at a speed that would create measurable boost pressure. Hence, this experiment is run only at low speeds, by ducting compressed air from the supercharger into the turbine. The students can observe the centrifugal compressor of the turbocharger spin and measure its RPM with a stroboscope.

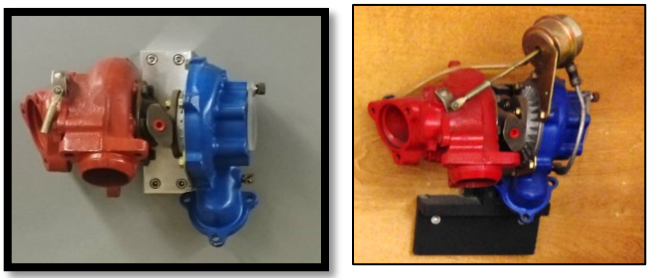

Figure 8. Turbocharger and vacuum control device

3.3. Engine Efficiencies

3.3.1. Thermal Efficiency

To obtain thermal efficiency and visually observe combustion inside the engine, a transparent cylinder engine is used, connected to a dynamometer. This setup is manufactured by *Megatech* Corporation. An old manual version of this engine setup was available at the University. It included a dynamometer to both start the engine and absorb the power when the engine runs. The experiment aims to explain to the students the various relationships between power, torque and RPM of and engine – and how these relate to throttle position, and fuel and air flow rates. The dynamometer gives outputs of current, voltage, RPM, and various pressures in different parts of engine. A *Capstone* team instrumented the engine with sensors to measure fuel flow rate, air fuel rate, speed of the engine, torque output, and emissions, see Fig. 9. The gas analyzer extracts data on the percent composition of the exhaust gases including O_2, CO_2, and CO components. By varying the electric load of the dynamometer, students are able to determine the type of combustion (rich, lean or stoichiometric) and the air/fuel ratio. The objective of this laboratory is to determine the thermal and combustion efficiencies of the *Megatech* engine.

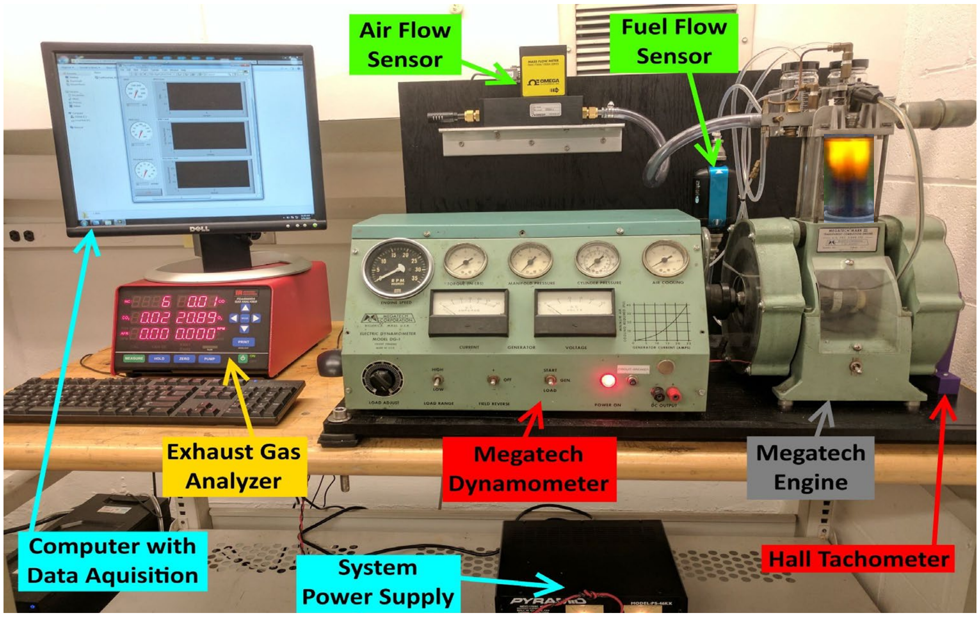

Figure 9. Fully-instrumented *Megatech* transparent single-cylinder spark-ignited engine

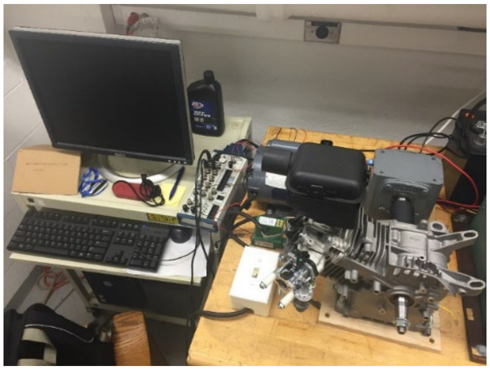

Figure 10. Setup to measure mechanical efficiency

3.3.2. *Mechanical Efficiency of the Engine*

The goal of the mechanical efficiency experiment was to measure the amount of friction caused by individual components within an internal combustion engine. Losses due to pumping of air in and out of the engine are also included. This experiment is dry run, meaning the engine is cycled through the use of an electric motor connected to the crankshaft. By maintaining a constant engine speed and measuring the power drawn by motor while removing key components (piston, camshaft, and valves), a difference in electrical load can be recorded and used to calculate the difference in mechanical efficiency. The setup used a 4.5 hp engine donated by *Briggs & Stratton* for use in the ICE Laboratory, see Fig. 10. It was connected to an AC motor, which rotates at a speed of 1750 rpm and has 0.25 horsepower output which provides 9 in-lb. of torque. The chosen 950 series Briggs & Stratton engine requires 50 in-lb. of torque to turn through the compression stroke, hence a gearbox with a 40:1 ratio was used to increase the torque output of the motor and lower the speed. As the engine is brought to a halt and components are removed one by one, the students can see that the power required to turn the engine decreases. This is due to less friction in the engine, which reduces the amount of torque required to spin it. LabVIEW was used to display the power drawn by the AC motor. Students use this data to calculate the mechanical efficiency at each step of the experiment.

3.3.3. Volumetric Efficiency of the Engine

The volumetric efficiency of an engine is a measure of the amount of air that enters in the cylinder during intake relative to the maximum amount of air that could enter the cylinder,based on its displacement volume. Ideally, if the entire displacement volume of the cylinder could be filled with air, it would be able to burn more fuel. However, the flow of air into a cylinder is limited by the geometry of the intake manifold and valves. In this lab the volumetric efficiency for a single-cylinder Briggs & Stratton Engine is measured, see Figure 11.

Figure 11. Setup to measure volumetric efficiency

A number of additional experimental setups have been developed, such as an alternator experiment as well as experiments with the powertrain gearboxes of the transmission and the differential, however their presentation herein is not possible due to the page limits.

4. Summary

Experiments were designed and physical setups were built to construct a laboratory for the undergraduate senior-level course of *Internal Combustion Engines* (ICE). The laboratory was assembled in a dedicated space. The design of the experiments were executed by students taking the one-semester *Capstone Mechanical Design* undergraduate senior-level course. The author is the instructor of the former course and a co-instructor of the latter course and served as the advisor of these *Capstome* teams. Some of the Capstone team members had already taken ICE. The major strength of this approach is that the participants reflected on what makes a laboratory interesting and enticing from a student perspective. They also learned a lot by “doing the thing”. A constructivist learning approach was used, as the *Capstone* teams had to figure out how to design experiment to clearly demonstrate concepts. Both Capstone teams and the ICE students benefitted from hands-on experiences in this laboratory. They all learned how to select instrumentation, how to collect data, conduct error analysis, perform calculations, interpret results and analyze them, how to compare experimental results with idealized model predictions, how to reflect on these comparisons, how to critique them and to look for uncertainties, and how to learn from failure. Their feedback in student evaluations was enthusiastic. With this method students do not simply learned, but they also learned how to learn [16].

5. Acknowledgement

The author acknowledges the excellent work of the following students who participated in the Capstone Mechanical Engineering Design course and designed, constructed and tested the experimental setups: S. Brickner, C. Mazzini, T. Murphy, J. Small and T. Wingardner, A. Carbonar, M. Li, E. Tsirlis, A. Wyshogrod, D. Balogh, C. Emanuel, E. Paskalis, A. Sherman, C. Cashen, H. Li, S. McGinn, V. Swan, Z. Zhang, G. Blaney, I. Corey, Z. Jagla, and G. Tomic. Financial support for building this laboratory was provided by the university.

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