AC 2007-828: LABORATORY PRACTICUM IN COMBUSTION

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Laboratory Practicum in Combustion

Abstract

The textbooks on Combustion identify advanced undergraduate or graduate students as their target audience due to the high complexity of the course material. In most engineering programs, a Combustion course is a rare offering; a laboratory practicum is even less common, and a few experiments are performed. Developing a laboratory component for a Combustion course presents a challenging task where the theory quickly becomes intricate and the equipment expensive. In addition, literature about the Combustion laboratory practicum is scarce. The Grand Valley State University's School of Engineering emphasizes the importance of offering engineering courses with laboratory exercises as a tool for helping students to connect theory and practice. The purpose of this paper is to share our experiences of offering a laboratory-based Combustion course and to encourage a discussion among instructors on this topic. The following are experiments discussed in the paper:

- Calorimetry, based on a comparison of petro- and biodiesel;
- Internal-combustion engine performance, based on small- and large-engine test cells;
- Exhaust analysis, which compares engines with and without catalytic aftertreatment;
- Laminar and diffusion flames, flame speed of laminar stoichiometric flames, liftoff, blow-out, diffusion flame length, all based on a propane-fueled Bunsen burner;
- Droplet evaporation, based on a comparison of evaporative rates of petro- and biodiesel;
- Proximate analysis of coal, based on western and eastern coals.

At the end of the Combustion course, students provided their feedback on how well each experiment related to the course material. Their responses were influenced by the availability and quality of manuals, the difficulty of data reduction, and the level of participation in the experiment.

Introduction

"We use it in cooking our food, warming our homes, driving our automobiles; and industry uses it in manufacturing hundreds of articles. In fact, without combustion the world we live in would be a very cold one and life as we know it would probably not exist at all," wrote John Sellers¹ in 1927. These words will be as relevant in twenty years and beyond as they were eighty years ago. To be specific, fossil fuel combustion accounts for more than 70% of energy production in the United States and virtually all transportation. In addition, growing demands for energy, rising fuel prices, limited fuel supply and dire environmental consequences command more efficient and cleaner combustion technologies. Engineers well versed in the topic will be needed to address this societal need. However, relatively few programs offer a Combustion course at the undergraduate level; even fewer integrate a laboratory into the course.

The School of Engineering at Grand valley State University emphasizes a practical, hands-on approach to education and integrates a laboratory practicum into a large number of its courses. It has supported the offering of a Combustion Applications course with a concurrent development of a Combustion laboratory. The laboratory is housed in the Keller laboratory building in an 875 ft² room equipped with exhaust and louver systems for operating engines indoor. Finding

literature that addresses laboratory experiments appropriate for such a laboratory proved to be a challenging task. The author hopes that this paper will be followed by other accounts dedicated to experimental Combustion in the undergraduate curriculum.

The course opens with an extensive coverage of equilibrium combustion and chemical kinetics, then concentrates on the practical aspects of combustion systems such as spark-ignition and diesel engines, gas turbines, detonation and ramjets, oil and coal technologies, and even fuel cells² to contrast with combustion. The textbook by Borman and Ragland³ covers most of the topics, with supplemental materials picked from Moran and Shapiro⁴ and Turns⁵. One large liquid-fuel rocket project is assigned after the first third of the semester, which concentrates on reinforcing the equilibrium combustion in various conditions and introduces students to aerospace propulsion concepts. A smaller second project provides students with an opportunity to study incineration technologies.

Concurrently, eleven weeks of laboratory exercises are offered in the thirteen-week summer semester when the course is scheduled. Two three-hour blocks per week are allocated for the lecture and laboratory. Considering the complexity of the course material and the enrollment of sixteen students, the time is split into two lecture periods of an hour and a half with the rest of the time dedicated to the laboratory. Thus, only a half of the students is present in the laboratory at the same time, allowing the instructor closer interaction with the students.

Four laboratories are split into two-week exercises for several reasons: the complexity of the material involved, the time it takes to obtain the data, and the time it takes to become familiar with the test equipment. Indeed, one of the course's goals is introduce students to a variety of new measurement techniques appropriate at the undergraduate level. Another benefit of splitting the laboratories into two weeks is the corrective feedback for the second week. While challenging the instructor for quick turn around on grading the laboratory reports, it affords an opportunity to provide students with a quality feedback which they are able then to incorporate into the second-week work improving their overall grade and learning outcomes. Reduced data processing also allows assigning small research subprojects to be included in the reports.

Due to the explosive nature of combustion, safety is a paramount concern. In addition to the basic laboratory safety rules introduced at the beginning of the semester, each laboratory manual is supplemented with experiment-specific safety instructions.

Highly theoretical nowadays, the understanding of combustion was developed experimentally, with the first experiments most certainly staged by the cave men. Fast forwarding thousands of years, Leonardo DaVinci⁶ extensively studied the role of air in "feeding" a flame or the creation of vacuum in combustion under an enclosing vessel. He also considered a lifting machine based on pressure build-up of hot combustion gases. Faraday's lectures in "The Chemical History of a Candle,"⁷ originally published in 1861, provide an excellent source of demonstration experiments in combustion. In a few simple experiments with a candle, students can observe temperature distribution across the flame or realize that the candle vapor rather the melted wax is the fuel, that something in the air is needed for combustion, that water is one of the products of combustion, and so on.

In 1967 work, Anderson⁸ provided a thorough account of combustion literature from a chemist's point of view. He noticed the limited coverage of combustion in Chemistry texts and the lack of laboratory manuals which addressed combustion and flames beyond calorimetry experiments.

More recently, some such experiments can be found, especially aided by the modern search engines.

A recent publication by Clarke et al.⁹ expands the biodiesel calorimetry experiment by adding actual production of biodiesel, which could become a natural progression for the laboratory described in this article. Uske and Barat¹⁰ discuss their experiences with determination of flame speeds in premixed flames using digital images of the flame. Peters¹¹ describes a premixed flame experiment with the fuel and oxidizer flowrates controlled by rotameters. Temperature and velocity profiles are obtained in various axial positions of the test chamber. Combustion efficiency is monitored by an O₂ analyzer.

In addition, various commercial combustion related units (boilers, gas turbines, and engines) are available. In particular, Hampden H-FPST-1 “Flame Propagation and Study Trainer” and P.A. Hilton C551 “Flame Propagation and Stability Unit” are excellent units for flame studies. Due to premium pricing, these units are excluded from the discussion.

The Calorimetry Laboratory

The calorimetry experiment is popular in many Physics and Chemistry courses. In Combustion, it measures the higher heating value (HHV) of a fuel, which is one of the most fundamental properties of fuels. The concept of HHV is used in many combustion calculations and is a required value in the design of any combustion system. From a practical point of view, calorimetry is superior to theoretical calculations of the HHV because the exact composition of the fuel is often not known in practice. The lower heating value could also be determined if the moisture is collected from the bomb, for example with a swab.

This particular lab runs over two weeks. The first week is used to familiarize students with the equipment, procedures and calibration of the calorimeter with benzoic acid tablets. The second week is used to measure and compare the HHV values of petro- and biodiesel. The instructor’s feedback from the first week improves the quality of data reduction, errors are pointed out, and suggestions for better approaches are made. Consequently, the second week data is not overwhelming, the measuring equipment is familiar, and a part of the assignment is dedicated to research work. The objective of this lab is to compare the equivalency of the two fuels’ energy content. Generally, a 100% pure biodiesel is listed having its energy content less than that of petrodiesel. The measurements in this laboratory demonstrate much more comparable values. This biodiesel was produced by a local environmental group, Sierra Consultants, from used restaurant oil, a fact which adds further environmental perspective to the lab. Students are asked to research methods of producing biodiesel, its properties, and benefits. Another advantage of using this combination of fuels is their slow evaporation rate, which makes the time between the mass measurement of a sample and sealing of the bomb not as crucial as it would be in the case of gasoline, ethanol and other quickly evaporating fuels.

Even such a relatively simple experiment provides the instructor with an excellent opportunity to reinforce the students’ work with laboratory equipment. The instrumentation used in this experiment includes:

- Parr 1341 Plain Oxygen Bomb Calorimeter and supplies,
- Oxygen gas tank and valves,
- High resolution Ohaus Scout balance (120 g / 0.001 g resolution),

- Digi-SenseThermoLogR RTD thermometer 0.01 °C resolution), equipped with RS-232 adapter for connecting to a computer.

The selection of this equipment strikes a reasonable balance between acceptable accuracy and sensible pricing.

The Small Internal Combustion Engine Test

This is a self-contained small-engine test cell (TD110-TD115), produced by TQ Education and Training Ltd., see Figs. 1 and 2. The major components are a Honda GX140 four-stroke engine ($V_d=144 \text{ cm}^3$ and max. power=5 hp at 4000rpm), a test bed with a dynamometer installed, and a controls unit. For the test-cell details, see figures below. A Digi-Sense thermometer is used to take engine surface temperature readings for the calculation of heat losses.

Figure 1. Dynamometer control unit.

In the first week of this two-week laboratory, the main goals for students are to familiarize themselves with the hardware, perform necessary calibrations on the dynamometer, and take one set of readings from all meters anywhere in the range of 2700 to 3000 RPM.

In their reports, students describe the operation of a four-stroke engine and compare it to the operation of a two-stroke engine. The collected data is used to calculate the main operating parameters of the engine, and complete the First Law analysis on the engine as an open system. The heat loss from the engine to the environment which has a convective and a radiative components is estimated as follows:

$$\dot{Q} = A \left(h(T_{surf} - T_{air}) + \varepsilon \sigma (T_{surf}^4 - T_{air}^4) \right) \quad (1)$$

where A (m^2) is the engine surface area. The convective heat transfer coefficient h , the surface emissivity ε , and the Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ are provided in the manual.

Figure 2. Engine—Dynamometer test cell.

In the second week, students obtain a full set of performance data in the range of 2200 to 4600 rpm at equally spaced intervals and at the point of maximum torque. They plot and discuss exhaust temperature, Air/Fuel ratio, specific fuel consumption, volumetric efficiency, torque, and brake power as functions of RPM.

For the brake thermal efficiency versus engine power plot, students discuss how the modern automotive engine differs from the small engine tested. Along with that work, students are asked to visit the engineering library and summarize an article in a professional magazines (SAE, ASME etc.) addressing a technology leading to a higher-efficiency engine.

In preparation for upcoming laboratories, students are asked to propose a test plan for using an exhaust gas analyzer for tuning a gasoline engine, balancing performance and fuel consumption.

The Exhaust Analysis Laboratory

In this laboratory students are introduced to measuring combustion efficiency based on the analysis of the products of combustion. The sources of pollution, mechanisms of pollution formation, and consequent reduction in combustion systems are important topics studied in the course. In addition, this laboratory allows students to become familiar with the measurement equipment and some forms of pollution data processing in automotive applications.

The laboratory utilizes the AutoLogic's 5 gas exhaust analyzer (EA), which is a portable, highly capable exhaust-gas sampling device, see Fig. 3 and Table 1 for its specifications. It measures the HC (unburnt hydrocarbons), CO, CO₂, O₂, NO_x, Air/Fuel ratio, and the equivalence ratio (in this case called Lambda).

HC, CO, C₂ are measured by an infrared spectrometer. O₂ and NO_x are measured by chemical cells, which produce an electric potential proportional to the concentration of the gas in question. Altogether, the spectrometer is a high-tech, exceptionally capable scientific tool. Instructions on how to operate the analyzer and its software are provided in the manufacturer operation manual.

Figure 3. Autologic 5-gas analyzer with Compaq's Palm Pilot for mobile measurements.

Table 1. Gas analyzer measurement ranges.

Gas	Range	Resolution
HC	0-30000 ppm	1 ppm
CO	0-15%	0.001 vol %
CO ₂	0-20%	0.01 vol %
O ₂	0-25%	0.01 vol %
NO _x	0-5000 ppm	1 ppm

Students once again operate the Honda Engine Test Cell and collect exhaust data for several regimes of the engine in a 2500-to-4500 rpm range. For each of CO, NO_x, and HC, students plot the emission index (EI), Eq. 2, and the mass specific emission (MSE), Eq. 3

$$EI_i = \frac{m_{i,emitted}}{m_{fuel}} = \frac{\dot{m}_{i,emitted}}{\dot{m}_{fuel}}, [\text{g/kg}] \quad (2)$$

$$MSE_i = \frac{\dot{m}_{i,emitted}}{\text{Brake Power}} = \frac{EI_i \dot{m}_{fuel}}{\text{Brake Power}}, [\text{g/kWhr}] \quad (3)$$

where $m_{i,emitted}$ is the mass of pollutant produced during time t , and m_{fuel} is the mass of fuel burnt for the same period of time. Based on the plots, students have to select the most optimum operation from contradicting parameters — maximum power while maintaining lower fuel consumption and lower emissions.

During the second week, students perform tests on a newer car owned by a team member to study the effects of the catalytic aftertreatment. This time the mobile configuration of the EA is employed with a Palm Pilot and special software to collect data. The collected data is later transferred to a computer and analyzed. In total, four readings are made:

1. At the idle when the engine and the catalytic converter are cold at the start up,
2. At the idle when the engine and the catalytic converter warm up,
3. The same as the last at 2500 rpm and stationary,
4. The same as the last while driving in the lowest gear.

In the report, students describe the experiment procedure and the vehicle in great detail. The EI for the 2500 rpm driving test is presented using an alternative form

$$EI_i = \left(\frac{x_i}{x_{CO} + x_{CO_2} + 6x_{unburntHC}} \right) \cdot \left(\frac{n \cdot MW_i}{MW_{fuel}} \right), [\text{g/kg}] \quad (4)$$

where x represents the molar concentrations and n is the carbon index of the fuel C_nH_m . Finally, a comparison is made between the pollution of a small engine versus an engine equipped with a catalytic converter.

The Laminar and Diffusion Flames Laboratory

Numerous industrial and appliance gas burners operate on laminar premixed or diffusion flames, or their combination. The design, proper and environmentally friendly operation, durability, and safety of the personnel and equipment depend on understanding the multifaceted combustion phenomena encountered in these flames. This lab is designed to introduce students to some of them.

Figure 4. Laminar premixed and diffusion flame apparatus.

The experiment consists of a simple Bunsen burner and a set of rotameters measuring the flow rates of the reactants to the Bunsen burner. The rotameters were appropriated from the front panel of an older gas analyzer, see Fig. 4.

The rotameters are calibrated in Standard Cubic Feet of Air per Hour, SCFH Air. The conversion to actual flow rates (cubic feet per hour, CFH) is required for pressure other than atmospheric and gases other than air:

$$CFH = SCFH_{reading} \sqrt{\frac{MW_{air} P_{actual}}{MW_{gas} P_{atm}}} \quad (5)$$

The pressure in the system is obtained from the air supply manometer.

The shop air-supply pressure reducer and the fuel source are located behind the front panel. The fuel source is a modified tube-welding propane tank. The lab natural-gas line is also available.

Students adjust the flow of air and fuel to obtain a steady inner blue conical flame and verify the stoichiometry using the flowmeters' readings. A digital picture is obtained of the flame over the Burner to determine the laminar flame speed. The flame speed is not only a technical parameter in the design of combustion systems, but also a fundamental property related to diffusion processes and chemical reaction rates. There are various methods determining the laminar flame speed, including the Schlieren method. From an educational point of view, digital photography is a modern and straightforward method to use in an undergraduate laboratory. Nowadays, most of the students possess digital cameras and many have one integrated in their cellphones, which they use to photograph the experiment.

Figure 5. Bunsen premixed flame schematic and determination of the flame speed.

The laminar premixed flame speed is determined according to Eq. 6, see Fig. 5:

$$V_L \text{ or } S_L = U_{local} \sin(\alpha) \quad (6)$$

The velocity determined with the Eq. 6 varies significantly depending on where it is determined. The tip of the flame is usually round and unstable; the location near the burner rim provides an appreciable cooling, and thus the flame speed there is slower.

In addition, the flow of the fuel/oxidizer mixture is not uniform, but fully developed with a parabolic velocity profile, see Eq. 7. It is suggested that students should determine the speed at a location that corresponds to the local velocity $U(r)$ when it is equal to the average flow speed, calculated from Eq. 8. To find this optimum location, Eq. 7 is solved,

$$\frac{U(r)}{U_{\infty}} = 2 \left(1 - \left(\frac{r}{R} \right)^2 \right) \quad (7)$$

$$Q_{mix} = U_{\infty} \pi R^2 \quad (8)$$

where U_{∞} is the average flow velocity, and Q_{mix} is the volumetric flow rate. The Reynolds number is additionally calculated to verify the laminar flow regime of gas in the burner.

Students also observe the flashback by reducing the flow through the mixed fuel/oxidizer line and taking the flow rate readings. Though there is a significant cooling effect, students are asked to comment on the magnitudes of the measured laminar flame speed and the mixed gas flow at the moment of flashback, prompting them to discuss safety and designs preventing flashback related explosions.

The diffusion flames are obtained by gradually reducing the air content in the flow through the burner. While making the adjustments, students observe the flame behavior and the yellow flame zones where the soot is formed. A few digital pictures of the diffusion flame are taken with a ruler placed behind the flame to reference the flame dimensions.

The published³ experimental laminar diffusion flame height, Eq. 9, is verified,

$$L_f = 1330 \frac{Q_{fuel} (T_{amb} / T_{fuel})}{\ln(1 + \bar{f})} \quad (9)$$

where all the variables are in SI units. The molar fuel/oxidizer ratio $\bar{f}$ is determined from the stoichiometric combustion equation for the given fuel. Once again, the Reynolds number is calculated to verify laminar flame regimes. Students are provided the polynomial expression for propane dynamic viscosity. Students are also asked to observe turbulent diffusion flames and discuss their structure.

The Droplet Evaporation Laboratory

Spray combustion has a wide-spread application in the combustion of liquid fuels. Among the applications are oil-fired furnaces and diesel engines, to name a few. Sprayed fuel breaks down into small droplets, which individually burn in the spray stream. While that individual burning is strongly affected by the surrounding droplets and availability of the oxidizer, much can be learned in studying individual droplets. Droplet size generally affects the time of combustion, which consists of two main mechanisms: evaporation of the liquid phase and diffusion combustion of the evaporated fuel some distance away from the droplet surface. Provided that a sufficient amount of the oxidizer is available, the combustion of the droplet will be controlled by evaporation. Thus, evaporation analysis becomes the first fundamental aspect of droplet burning.

The experiment was built in house with some already available equipment. A plastic tube, a hair dryer inserted in the tube, and a Panasonic VW- CL 350 video camera, all mounted on the same frame, provide the basis for this experiment, see Fig. 6. The tube also has a fine honeycomb

structure inserted to provide uniform flow in the test section. Flow temperature and speed are measured with a TA45 thermal anemometer. Pinnacle PCTV video converter and software provide the visual display and recording of the experiment on a lab computer.

The test section is a small opening in the tube with a piece of a finely graduated ruler from which a quartz thread is suspended into the air stream of the tube, see Fig. 7. A light source and background lined with aluminum foil are recommended for the test section to improve picture quality, see Fig. 8 for the resulting quality and resolution. The camera is zoomed into the test section and provides a clear picture of the droplet. The resolution is so high that convective flow can be observed in the evaporating droplet.

Figure 6. Droplet evaporation experiment setup.

Figure 7. Test section schematic.

The first week is dedicated to becoming familiar with the equipment, practicing the test procedure, and learning how to process the video data. Two fluids tested are water and gasoline. A droplet of fluid is suspended on the string with a syringe and its evaporation is recorded onto computer.

Figure 8. Droplet of water evaporating in the test section. 1/64" grid is observed on the top.

The theory predicts that the square of the evaporating droplet's diameter reduces linearly with time as in Eq. 10, the so-called D^2 Law. A sample plot of this law is shown in Fig. 9,

$$D^2(t) = D_0^2 - K t \quad (10)$$

where D_0 is the initial diameter at time zero, and K is the evaporation constant.

Figure 9. The D^2 law for droplet evaporation.

Students obtain the droplet's diameter as the droplet evaporates, taking 4-5 snapshots over the evaporation period and recording the snapshot time. A grid to measure the droplet's size is drawn over the droplet using the ruler tick marks available in the frame. Both the vertical and horizontal diameters are determined due to the gravity-affected droplet's oval shape. The volume average diameter is obtained as follows:

$$D_i = \sqrt[3]{\frac{D_H^3 + D_V^3}{2}} \quad (11)$$

Once the plots for water and gasoline are constructed, the evaporation constants are determined. The evaporation constant for water is verified with the theory introduced in Turns⁵,

$$K = \frac{4 Nu k_g}{\rho_l C_{pg}} \ln(1 + B_q) \quad (12)$$

where

$$k_g = 0.4k_F(\bar{T}) + 0.6k_\infty(\bar{T}) \quad (13)$$

$$C_{pg} = C_{pF}(\bar{T}) \quad (14)$$

$$Nu = \begin{cases} 2, \text{ natural convection} \\ 2 + 0.56 Re^{1/2} Pr^{1/3}, \text{ forced convection} \end{cases} \quad (15)$$

$$\bar{T} = (T_{boil} + T_\infty) / 2 \quad (16)$$

$$B_q = \frac{C_{pg} (T_\infty - T_{boil})}{h_{fg}} \quad (17)$$

and where k is conductivity, C_p specific heat at constant pressure, and the subscript F stands for the fluid vapor. B_q sometimes is referred to as the Spalding or transfer number. The Pr number for air is taken as 0.7.

The conditions in Eq. 17 assume that the temperature of the environment exceeds the boiling temperature of the fluid, and an adjustment is made to match the conditions in the experiments as follows,

$$B_q = \frac{C_{pg} (T_\infty - T_{sat})}{h_{fg}} \quad (18)$$

where the corresponding saturation temperature T_{sat} is determined from the Properties of Saturated Water table, and the vapor partial pressure P_v is based on the relative humidity ϕ of air. The average temperature is adjusted accordingly.

In the second week of the laboratory, the evaporative properties of biodiesel and petrodiesel are compared in a forced-convection environment with the hair dryer set to medium speed and the highest temperature setting. In addition to the instruments employed in the previous lab, the anemometer is used to determine the speed and temperature of the flow.

The collected data is used to verify the D^2 Law and determine the evaporation constants. A reverse calculation is attempted for the Nusselt number to determine the coefficient A in Eq. 19.

$$Nu = 2 + A Re^{1/2} Pr^{1/3} \quad (19)$$

The temperature gradient in the Spaulding number is assumed to be about 5 K.

Droplet burn demonstrations are also performed. The burn time is sufficient for recording and follow-up analysis. However, the fiber string, from which the burning droplet is suspended, unfurls and requires replacement. The inclusion of droplet combustion analysis in the experiment in the future might help to demonstrate that, despite significant differences in evaporation at low temperatures, in combustion the burn constants are much closer.

The Proximate Analysis of Coal Laboratory

The proximate analysis of coal is scheduled at the end of the semester as the topics of pulverized coal combustion are covered in lecture and support the review of coal composition, properties, and techniques for clean combustion. The analysis classifies the quality of various coals by determining the moisture, volatile matter, ash, and fixed carbon content. From an educational

point of view, the proximate analysis essentially follows the natural combustion of coal particles in pulverized coal systems, aiding the learning process.

The analysis follows the ASTM D3712 standard. The pulverized coal for the tests was supplied by the local power company. First, a quartz glass crucible (by Fisher Scientific) mass is measured with the top on before any coal is added. About 2g of test coal are added, and the mass is measured again. The sample is then placed in the heat-treating furnace (available in the Materials Laboratory rather than in the Combustion Laboratory), which is heated to 105 °C.

The sample is left to sit at this temperature uncovered for approximately 15 minutes, and at the end of this time period, the crucible is removed and the mass of the sample is measured. This stage is used to determine the weight of the residual moisture in the coal.

Next, the sample was heated to 800 °C with the cover on to prevent oxidation and let sit for approximately 30 minutes. The test procedure recommends 900-950 °C; however, 800 °C is the maximum attainable with the furnace. The weight loss measured after this time period represents the weight loss of volatile matter.

Last, the cover is taken off, and the sample is heated at 750 °C, so any leftover combustibles are burnt. The weight loss experienced over the one-hour period represents the fixed carbon. The remaining residue in the crucible is ash.

In particular, samples of Eastern and Western coals were tested. An interesting lesson was learned. Tracking the samples would have been much easier if significantly dissimilar masses of samples were used for identification.

The Chevy 305 Engine Test Cell Laboratory

As part of the course, students and the instructor completed the earlier work on a large engine test cell based on a Chevy 305 5L eight-cylinder engine equipped with a D400 Pegasus-Schenk water-break dynamometer, see Fig. 10. The dynamometer was donated by the GM Corporation.

Figure 10. Chevy-305 engine test cell.

The test cell will be used in experiments similar to those of the small engine described above. Also comparative thermodynamics and exhaust studies can be conducted between the two.

The additional equipment includes:

- Fuel — Cole-Parmer C-32709-74 liquid turbine flowmeter, Brass, 50-500 ml/min,
- AirFlow — Meriam 50MC-4F laminar flow element and Dwyer Instruments 621-20 differential pressure transmitter,
- Cooling — a brass plate heat exchanger with Omega FTB4607 flowmeter and DPF701-A flow rate indicator,
- Temperature — six TJ72-CAXL-18U-6-SMP-M Type K thermocouples for the engine exhaust and cooling heat exchanger.

The cooling system uses two loops: a closed internal with glycol and an open external with water cooling via the heat exchanger. The energy transferred through the cooling system is monitored by the flowmeter and the thermocouples installed in the heat exchanger.

A LabView suite is used to collect the engine performance data from the equipment listed above as well as the dynamometer control unit (RPM and Torque).

Student Response and Discussion

Calorimetry. Most of the students found the first week lab to be a good introductory lab, some wished for more tests or expected “to blow stuff up,” probably due to the exciting name of the bomb calorimeter. The second week calorimetry lab was met with a lot of student excitement to learn about the properties of biodiesel and made students “think about the alternatives to diesel.”

Small Internal Combustion Engine Test. For some students the lab was too slow and for others just right where the “two-phases definitely helped in obtaining good data.” Students overwhelmingly welcomed the opportunity to learn the engine test procedure with a dynamometer and the operation of a four-stroke engine.

Exhaust Analysis. One student summarized well most of the responses for this lab by stating “I really enjoyed this lab because the actual emissions of internal combustion engines were measured and concluded on.” Certainly adding student vehicles to the testing sparked their interest. However, many wished for more coverage in the lecture of engine emission theory and data reduction.

Laminar and Diffusion Flames. Students experienced some confusion with this lab, especially in the part of calculating flow rates and using the flame formulas. Due to the safety concerns, some of the demonstrations were facilitated by the instructor, and students wished they could play with the flames more independently. That could be accomplished as the experiment develops further. The majority of students found the lab to reinforce “the different aspects of each of the flames learned in class.” One comment particularly relates to the summer time offering of the course, “I liked learning about the flashback and think about it every time I turn off my gas grill and it flashes back.”

Droplet Evaporation. Student comments ranged from “this was a good lab that used some unique equipment that was interesting” to the “lab seemed to be quite limited as far as data collection and analysis.” Following student suggestions, one week of the laboratory could be eliminated by performing data analysis on already collected samples. Some students did not like

waiting for the biodiesel to evaporate, so other experimental activities could be implemented to occupy students while collecting data.

Chevy 305 Engine Test Cell. Although a full set of data was not obtained for the large engine, students really liked calibrating the equipment in the test cell and asked to do even more calibration. Perhaps because it was a real engine and not a candy-wrapped set-up, students had a more excited response than the instructor anticipated for such a limited version. Further development will be needed to efficiently integrate the small and large engine test cells in future offerings of the course.

Student comments for the Coal Proximate Analysis laboratory were not collected.

Conclusions

The new undergraduate Combustion laboratory has been developed to support the practicum in the Combustion Applications course at Grand Valley State University. It incorporates a number of experiments, which support student learning and research of combustion phenomena. In addition, students are introduced to various instrumentation, multiple experimental techniques and data processing methods encountered in modern engineering. Student feedback is incorporated into the future laboratory development.

The author hopes that the discussion of the Combustion lecture and laboratory curriculum will (spark and) continue.

References

1. Sellers, J., 1927, "Combustion Demonstrations," *J. Chem. Ed.*, V4, pp 914-919.
2. Blekhman D., and Mohammadzadeh, A., 2006 "Do Fuel Cell Topics Belong in a Combustion Course?" Proc. 2006 ASEE Annual Conference & Exposition, Chicago, Illinois, June 20-23.
3. Borman, G., and Ragland, K., 1998, *Combustion Engineering*, McGraw Hill
4. Moran M., and Shapiro, H., 2004, *Fundamentals of Engineering Thermodynamics*, Wiley, New York.
5. Turns S., 2000, *An Introduction to Combustion: Concepts and Applications*, McGraw Hill.
6. Reti, L., 1952 "Leonardo Da Vinci's Experiments on Combustion," *J. Chem. Ed.*, V29, pp 590-596.
7. Faraday, M, 1988, *Faraday's Chemical History of a Candle*, Chicago Review Press.
8. Anderson R, 1967, "Combustion and Flame," *J. Chem. Ed.*, V44, pp 248-260.
9. Uske, J., and Barat, R., 2003 "Estimation of Laminar Burning Velocities by Direct Digital Photography," Proc. 2003 ASEE Annual Conference & Exposition, Nashville, Tennessee, June 22-25.
10. Clarke, N., Casey, J., Brown, E., Oneya, E., and Donaghy, K., 2006, "Determination of the Heat of Combustion of Biodiesel Using Bomb Calorimetry: A Multidisciplinary Undergraduate Chemistry Experiment," *J. Chem. Ed.*, V83, pp 257-259.
11. Peters, J., 1985, "A Combustion Laboratory for Undergraduates," *J. Eng. Ed.*, V75, pp 654-655.