TFES Lab (ME EN 4650)
Spark Ignition Engine

Textbook Reference: Chapter 9 from Cengel and Boles, 5$^{\text{th}}$ ed., McGraw-Hill

Objectives

(i) measure the mechanical power (also referred to as brake power) generated by a four-stroke spark ignition engine as a function of crankshaft speed and compare to that expected in an *ideal* engine that follows the Otto cycle,

(ii) determine the thermal efficiency as a function of crankshaft speed and compare to that of an *ideal* engine,

(iii) measure the frictional/inertial losses in the engine and determine the mechanical efficiency as well as heat rejected to the surroundings, and

(iv) calculate the mean effective pressure of the engine as a function of crankshaft speed.

Background

A schematic of a four-stroke, spark ignition, internal combustion (IC) engine is shown in Figure 1, along with a description of the function of each stroke. The power generated during stroke (iii) is used to turn the crankshaft, which can then be used to drive the axle of an automobile, for example, to produce mechanical work. The performance characterization of such an engine involves specifying the amount of mechanical power (or brake power, $\dot{W}_b$) that can be produced as a function of the rotational speed (ω) of the crankshaft, as well as the thermal efficiency (η_{th}). These physical quantities cannot be measured directly. Therefore, in the laboratory, we measure surrogate quantities instead, and calculate the desired quantities of interest based on known physical (and theoretical) relationships.

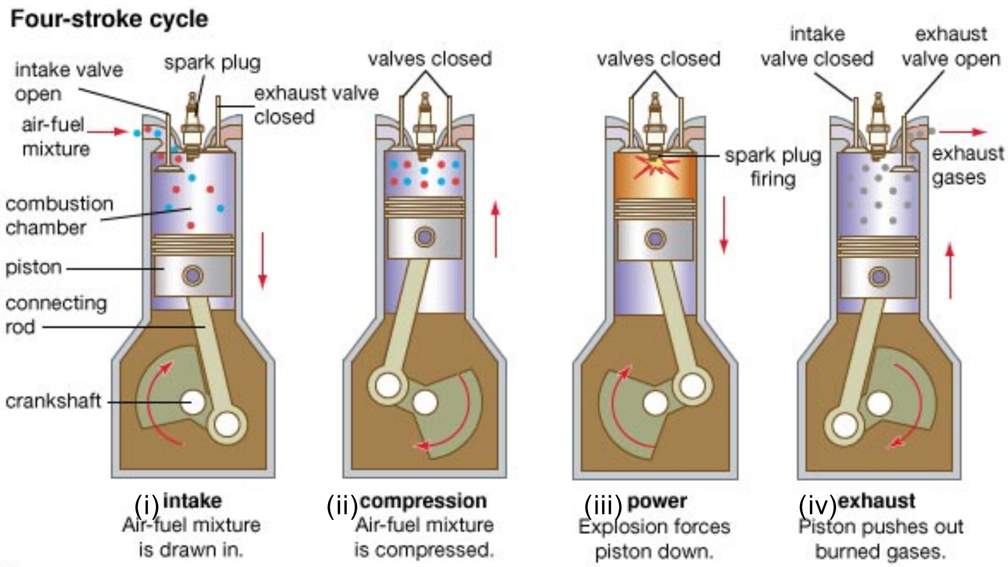
The performance of an IC engine will depend on the type of fuel used, the manner in which the fuel is ignited (spark ignition versus compression ignition), the displacement volume or swept volume of the piston, the compression ratio of the cylindrical combustion chamber, and the ignition timing (i.e., when in the cycle the spark plug fires in the cycle). Figure 2 shows important dimensions of the piston and cylindrical combustion chamber. The bore (B) is the inside diameter of the combustion chamber. The stroke (S) is the total distance the piston head can move. The displacement volume or swept volume of the piston ($\mathbb{V}_{\text{d}}$) is given by

$$\mathbb{V}_{\text{d}} = \tfrac{\pi}{4} B^2 S = \mathbb{V}_{\text{BDC}} - \mathbb{V}_{\text{TDC}}, \tag{1}$$

where the subscripts TDC and BDC refer to the “top dead center” and “bottom dead center” positions of the piston. Note, the compression ratio (r) is the ratio of the maximum to minimum cylinder volume, and is calculated as

$$r = \frac{\mathbb{V}_{\text{max}}}{\mathbb{V}_{\text{min}}} = \frac{\mathbb{V}_{\text{BDC}}}{\mathbb{V}_{\text{TDC}}}, \tag{2}$$

The bore, stroke, and compression ratio for a given engine is specified by the manufacturer.



	stroke	piston	valves	characteristic
(i)	air-fuel intake	↓	intake valve open, exhaust valve closed	low pressure, low temperature
(ii)	compression of air-fuel mixture	↑	intake and exhaust valves closed	high pressure, low temperature
(iii)	power generation due to explosion	↓	intake and exhaust valves closed	high pressure, high temperature
(iv)	expulsion of exhaust gases	↑	exhaust valve open, intake valve closed	low pressure, high temperature

Figure 1. Illustration of the cycles in a four-stroke internal combustion engine.

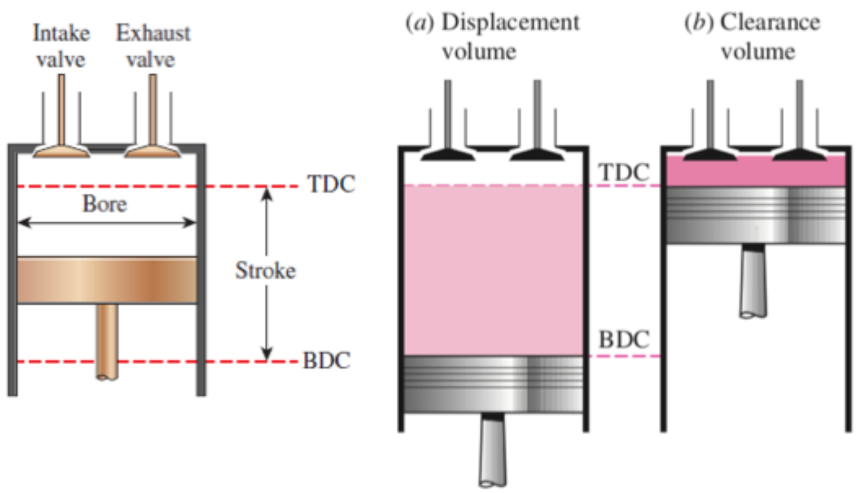


Figure 2. Piston and cylinder schematic of an internal combustion engine. The two horizontal dashed lines denote the position of the piston at its two extremes, referred to as "top dead center" (TDC) and "bottom dead center" (BDC).

Experimental Setup

A schematic of the experimental setup in the laboratory is shown in Figure 3. The main components are: the engine, the dynamometer, the air intake plenum, the fuel intake reservoir, and the exhaust pipe. The engine examined in this experiment is an air-cooled, single-cylinder, spark-ignition, four-stroke modified Briggs & Stratton model 093312–1133–B1. Important features of the engine that affect performance are listed in Table 1. The engine utilizes high octane ("premium") gasoline. The air-fuel mixture composition is controlled by a carburetor as illustrated in Appendix I. Both the ignition timing and the compression ratio are adjustable in the experimental setup. The ignition timing can be varied with a lever arm between 40° before TDC (advanced) to 10° after TDC (retarded) in 5° increments. The following compression ratios may be obtained by swapping the combustion chamber cap: 10:1, 8.5:1, 7:1, 5.5:1, and 4:1. However, the values given in Table 1 have been found to yield superior performance and are thus the ones that will be utilized in the present experiments. Note, the intake and exhaust valves on the engine are actuated by cams on a camshaft, driven by a cam gear that mates with a gear on the crankshaft as illustrated in Appendix I. Because of this, the timing of the intake and exhaust valves (i.e., when they open and close) are mechanically fixed and cannot be adjusted.

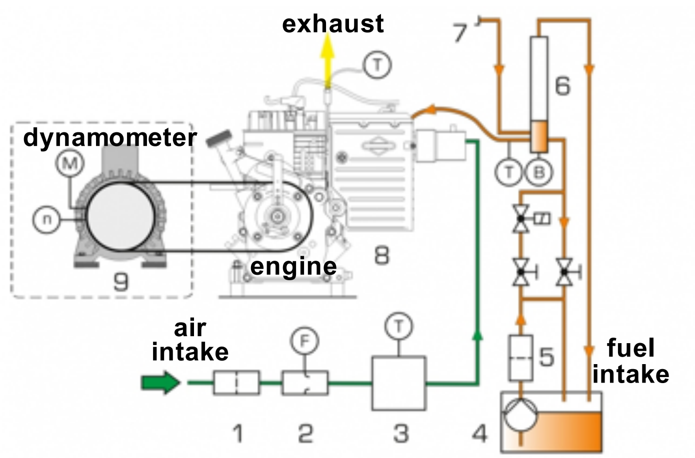


Figure 3. Schematic of the experimental setup showing the main components of the system.

Table 1. Features of the Briggs & Stratton engine used in the experiment.

Bore, B	65.1 mm
Stroke, S	44.4 mm
Displacement Volume, $\mathbb{V}_d$	0.148 L
Compression Ratio, r	7:1
Ignition Timing	20° before TDC
Fuel Type	91 octane gasoline

A photograph of the experimental setup is shown in Figure 4. The experimental setup consists of an HM 365 Dynamometer unit, the engine, and the CT 159 Teststand that houses the some of the instrumentation. The engine, teststand, and dynamometer sit on the tabletop of the workbench. Note, the crankshaft of the engine and the dynamometer motor shaft are connected using a V-belt and pulley system with a 1:1 gear ratio, so that the engine and motor rotate at the same speed.

The air intake plenum and fuel reservoir for the engine are located on the bottom shelf of the workbench. The air and fuel are routed to the engine through flexible rubber hoses (the air intake has a larger diameter hose). Filters are used on both the air and fuel supply lines to remove any particulates. The exhaust pipe extends vertically from the engine and is routed behind the workbench and outside the building through a flexible metal braided hose.

Table 2 lists the measurements acquired in the experiment along with the native units of the instruments. The air flow rate into the engine is determined using an orifice meter with a curved-shaped orifice plate. The pressure drop across the orifice plate is measured with an electronic pressure transducer and automatically corrected based on the discharge coefficient such that the value on the LCD display reads in L/min. Air flows through a filter, through the orifice plate, into an open rectangular plenum, and then through the flexible hose to the engine carburetor. The plenum is used to dampen pressure fluctuations from the combustion chamber so that the pressure readings across the orifice plate do not exhibit large fluctuations. Plenums, such as the one used in the present experiment, are not typically used

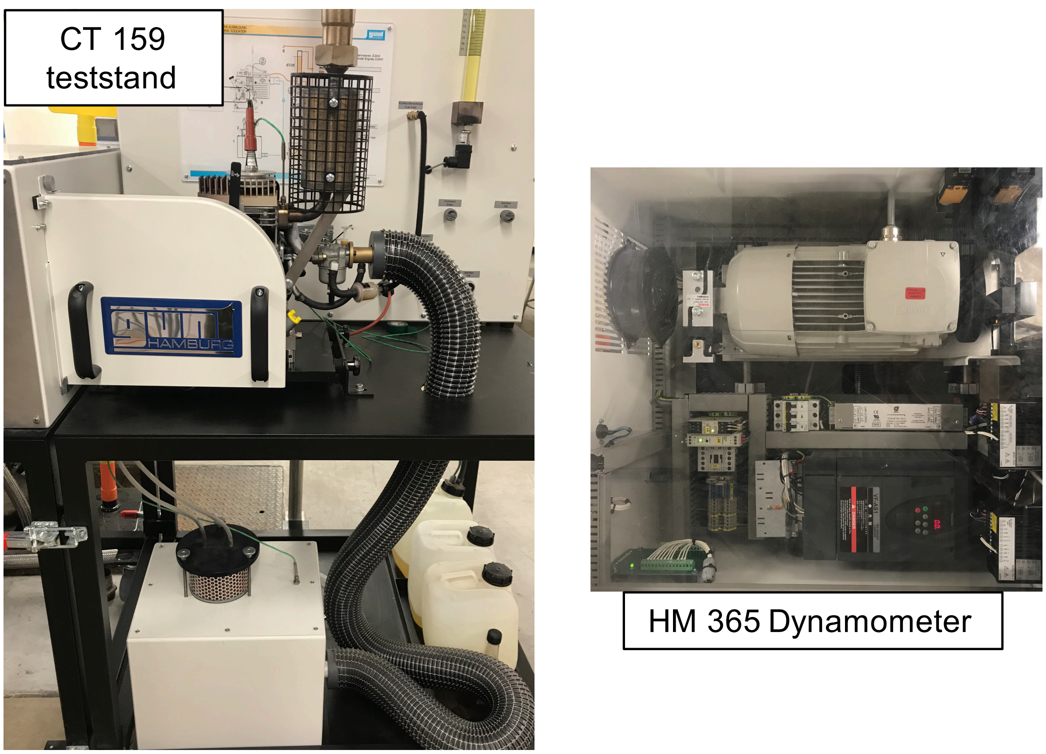


Figure 4. (left) Photograph of the CT 159 Teststand with the engine connected. (right) Top view of the inside of the HM 365 Dynamometer unit showing the electric motor and power electronics.

Table 2. List of measurements acquired in the experiment with their native units.

Quantity	Symbol	Units	Instrument
Sampling interval	Δt	sec	stopwatch
Inlet air temperature	T_{air}	°C	thermocouple
Inlet fuel temperature	T_{fuel}	°C	thermocouple
Exhaust gas temperature	T_{exhaust}	°C	thermocouple
Inlet air volume flow rate	$\dot{\mathbb{V}}_{\text{air}}$	L/min	orifice meter
Volume of fuel consumed	$\mathbb{V}_{\text{fuel}}$	cm^3	fill tube level
Rotational speed of crankshaft	ω	RPM	optical encoder
Torque of crankshaft	τ	N·m	dynamometer

on actual engines. The amount of fuel consumed is measured by observing the liquid level drop in the fill tube. Thermocouples are used to measure inlet air and fuel temperature, as well as the exhaust temperature. The tip of the thermocouple for the exhaust is positioned approximately in the center of the exhaust pipe. Because the flow exiting the combustion chamber is highly nonuniform and turbulent, the temperature measured by the exhaust gas thermocouple may not be a good indicator of the temperature averaged over the cross-section of the exhaust pipe. This may impact the accuracy of our thermal efficiency calculation. The torque on the crankshaft produced by the engine is measured using a dynamometer, which is described in more detail in Appendix II. The crankshaft rotational speed is measured using an optical reflective encoder, also described in further detail in Appendix II.

Laboratory Procedures

Figure 5 illustrates the locations of the switches, knobs, and display units on the HM 365 Dynamometer unit and CT 159 Teststand unit. The primary control variable in this experiment is the rotational speed of the engine crankshaft. This is set by turning a potentiometer knob on the front of the HM 365 Dynamometer enclosure. Measurements, as listed in Table 2, will be collected at a range of crankshaft speeds with the engine operating under normal conditions. The resistive load applied to the electric motor of the dynamometer acts like a brake on the engine crankshaft. The load required is determined automatically by the power electronics in order to maintain the engine crankshaft at the set rotational speed. In this mode, the electric motor is actually functioning as a generator. The experiment is then repeated with the engine running "dry" (i.e., with the fuel drained and the spark plug disconnected) in order to measure the mechanical losses due to friction, inertia, and cylinder compression. In this case, the electric motor is driving the engine. In case of emergency, to immediately stop both the engine and motor, the red EMERGENCY STOP button can be pushed. To reactivate the system, this button MUST be manually reset, by pulling the knob back out and rotating slightly.

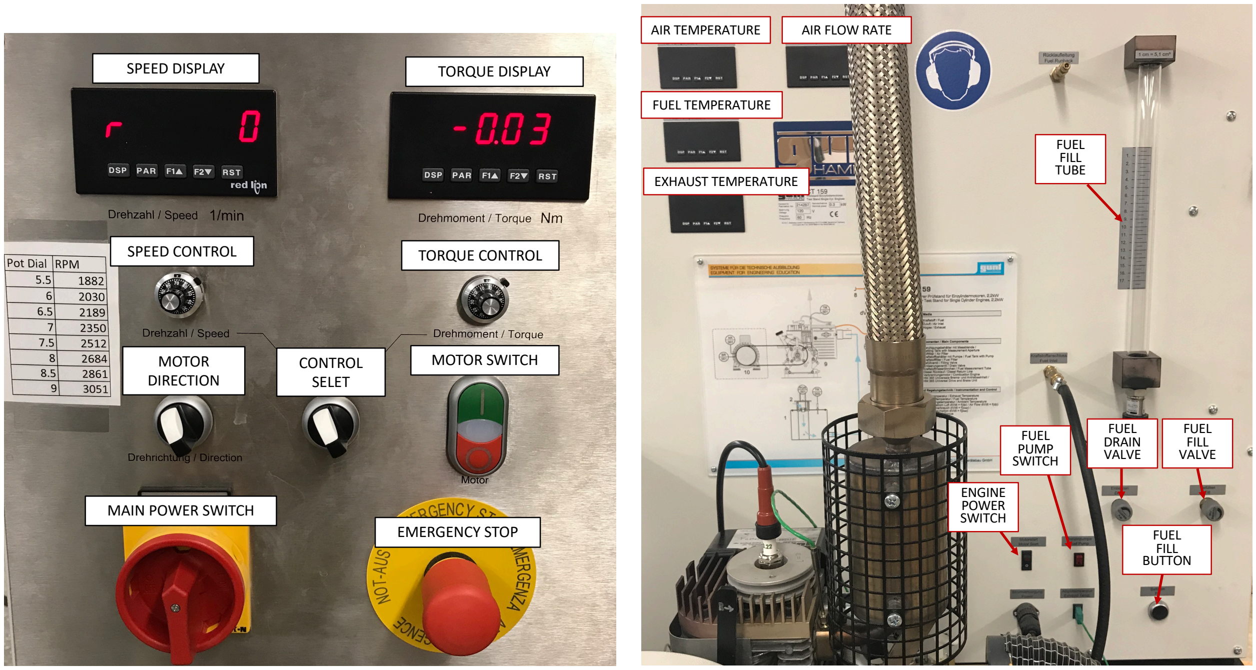
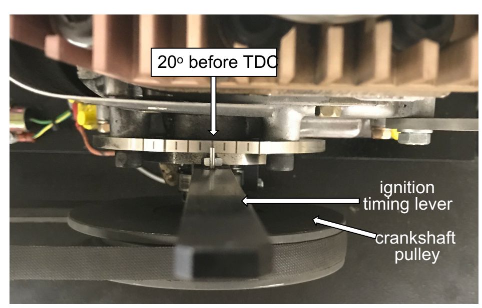


Figure 5. Control/display panels for the (left) HM 365 Dynamometer unit, and (right) CT 159 Engine Teststand.

1. Measure the atmospheric pressure P_{atm} (mm Hg) and ambient temperature T_{amb} (°C) using the barometer located on the north wall of the laboratory. Be sure to correct the atmospheric pressure for altitude. Record the readings on your data sheet.

2. Make sure the exhaust vent fan is on. The switch panel (shown to the right) is located along the west wall of the laboratory. A red light on the switch indicates the fan is running.

3. Adjust the ignition timing using the timing lever to 20° before TDC as shown in the image below. Each tick mark on the timing wheel represents 5°. The lever will click into position at each of the tick markings. The tick mark at the farthest right (when looking down from above) represents 40° *before* TDC; while, the tick mark at the farthest left represents 10° *after* TDC. The thickest tick mark denotes TDC.



4. Record the relevant physical parameters of the engine on your data sheet.

5. Set Up HM 365 Dynamometer Unit

   (a) Turn on the power to the dynamometer unit by rotating the MAIN POWER SWITCH clockwise on the front of the HM 365 unit (see Figure 5).

   (b) Make sure both the MOTOR DIRECTION and CONTROL SELECT switches are turned fully counterclockwise so that they are in the same position as indicated in Figure 5. Do NOT change these switches for the duration of the experiment.

   (c) Note, the TORQUE CONTROL knob is NOT used in this experiment.

   (d) The speed of the engine/motor is set using the SPEED CONTROL potentiometer. To begin, turn the potentiometer knob so that the dial reads 6.5.

   (e) After the HM 365 electronics have warmed up (about 5 minutes), the torque readout should be zeroed by pressing the RST button along the bottom of the TORQUE DISPLAY. If necessary, the rotational speed readout can also be zeroed by pressing the RST button along the bottom right of the SPEED DISPLAY.

6. Prime the Fuel Line

   (a) Turn on the fuel pump by toggling the FUEL PUMP SWITCH located on the CT 159 Teststand to the "on" position, as shown in Figure 5. Note, a red light will illuminate on the rocker switch when the pump power is connected.

   (b) Open the FUEL FILL VALVE by rotating the needle valve knob **counterclockwise** on the CT 159 Teststand to the fully open position. Importantly, do NOT over tighten the needle valve knobs — gently hand tighten in either direction (fully open or fully closed).

   (c) Fill the fuel measurement tube with fuel by pressing and holding the FILL TUBE BUTTON on the CT 159 Teststand until the fuel level is about 2 cm from the top of the FUEL FILL TUBE. Observe the interesting vortex flow phenomenon as the tube fills with fuel.

   (d) Close the FUEL FILL VALVE by rotating the needle valve knob **clockwise** on the CT 159 Teststand to the fully closed position.

   (e) The FUEL PUMP SWITCH can remain in the "on" position during the experiment.

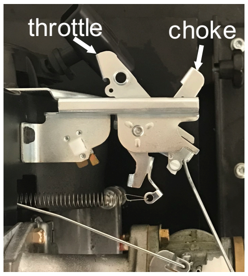
7. Zero the Air Flow Rate Display

   The display for the air flow rate may not readout zero even with no flow through the engine. To zero the display, press the RST button along the bottom right of the AIR FLOW RATE display on the CT 159 Teststand. In the event that this operation fails, the no-flow reading should be recorded on your data sheet and subtracted from all subsequent air flow rate readings in the experiment.

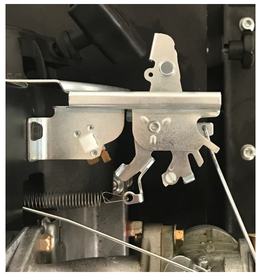
8. Cold-Start the Engine

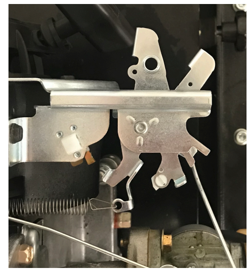
   The first time that the engine is started, it is typically necessary to utilize the **choke**. Follow the steps below.

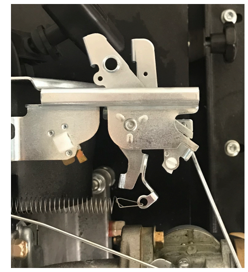
(a) Align the choke and throttle levers on the carburetor such that the choke is about 50% open, and the throttle is about 30% open. In this configuration, the levers will be nearly colinear. The images below show the choke and throttle levers in various positions. The view is from the front of the experiment, looking down.



throttle & choke fully-open


throttle 30% open & choke 50% open


throttle 30% open & choke fully-open


throttle fully-open & choke 50% open

(b) Turn on power to the engine by toggling the ENGINE POWER SWITCH located on the CT 159 Teststand to the "on" position. Note, a red light will illuminate on the rocker switch when the engine power is connected. This switch MUST be "on" in order for a spark to be generated across the spark plug.

(c) Verify that the SPEED CONTROL potentiometer on the HM 365 is set to 6.5. This corresponds to an engine speed of about 2200 rpm, which is the approximate speed of the engine running under no load when the throttle is 30% open.

(d) Engage the electric motor by pressing (and momentarily holding) the GREEN side of the MOTOR SWITCH on the HM 365 Dynamometer unit as indicated in Figure 5. Note, a white light will illuminate on the MOTOR SWITCH when the motor is engaged.

(e) A rising exhaust temperature indicates that combustion in the engine has started. If this IS the case, . . .
   - → then disengage the electric motor by pressing the RED side of the MOTOR SWITCH on the HM 365 Dynamometer unit as indicated in Figure 5;
   - → turn off the choke by rotating the choke lever to its fully clockwise position as shown in the image above; and
   - → allow the engine to warm up under no-load conditions (electric motor disengaged) for several minutes.
   - → Note, typical exhaust temperatures should be around 450°C.

(f) If the engine does NOT start on the first attempt . . .
   - → disengage the electric motor by pressing the RED side on the MOTOR SWITCH;
   - → adjust the choke lever slightly (will likely to need be closed a little more by rotating counterclockwise); and
   - → re-engage the motor again by pressing the GREEN side of the MOTOR SWITCH.
   - → Repeat this procedure several times until engine starts. Then go to step 8(e) above.
   - → If engine fails to start after several attempts, then wait a few minutes with the engine and motor off. Readjust the choke so that it is about 75% of fully open and repeat the procedures starting with step 8(d).

9. Engine Performance Tests

(a) Double check that the choke lever has been rotated to its fully open position, all the way clockwise (as seen looking down from above).

(b) Set the throttle to its fully open position by rotating the throttle lever all the way counterclockwise (as seen looking down from above). The choke and throttle levers should appear as shown in the image at the top of the previous page.

(c) Observe the engine speed on the SPEED DISPLAY and set the SPEED CONTROL potentiometer on the HM 365 Dynamometer unit to the appropriate setting to roughly match the engine speed. A setting of 9.0 on the potentiometer dial should be close.

(d) Engage the electric motor load by pressing (and momentarily holding) the GREEN side of the MOTOR SWITCH on the HM 365 Dynamometer. This will now put a load on the engine.

(e) If the engine **stalls** OR if the torque values on the TORQUE DISPLAY read less than 2 N·m, then . . .

  → disengage the electric motor by pressing the RED side of the MOTOR SWITCH on the HM 365 Dynamometer unit;
  → adjust the throttle lever to 50% open; and
  → re-engage the electric motor by pressing (and momentarily holding) the GREEN side of the MOTOR SWITCH on the HM 365 Dynamometer unit.
  → Once the engine starts again with the motor engaged, then adjust the throttle to its fully open position; and proceed to the next step.

(f) Set the engine speed using the SPEED CONTROL potentiometer to approximately 3000 rpm.

(g) Let the engine reach steady-state, which should only take 30 seconds or less.

(h) Run the engine at the set speed long enough for the fuel level to drop 1.0–2.0 cm in the fill tube. Be sure to record the measurement interval with a stopwatch, as well as the starting fuel level and ending fuel level. The major tick markings along the fuel fill tube are in cm. <u>Importantly, a 1 cm drop in fuel level in the fill tube corresponds to a volume consumption of 5.1 cm^3</u>. At the end of the measurement interval, record the measurements below on your data sheet. Note, the torque and exhaust gas temperatures may fluctuate even during steady state. Therefore, do your best to visually average the readings over the measurement interval, and record the "average" readings on your data sheet.

  → Time of measurement interval (s)
  → Crankshaft speed (rpm)
  → Crankshaft torque (N·m)
  → Fuel consumption (cm^3)
  → Air flow rate (L/min)
  → Inlet air temperature (°C)
  → Inlet fuel temperature (°C)
  → Exhaust gas temperature (°C)

(i) Check the fuel level in the FUEL FILL TUBE. If the fuel level is near or below the lowest marking, then pump more fuel into the tube following the procedures of step 6.

(j) Decrease the rotational speed of the engine by an increment of about 250 rpm by rotating the SPEED CONTROL potentiometer counterclockwise while observing the SPEED DISPLAY. Repeat steps 9(d) – 9(j) until you have covered a speed range of 2000–3000 rpm, yielding a set of five different test points.

(k) Disengage the electric motor by pressing the RED side of the MOTOR SWITCH on the HM 365 Dynamometer unit.

(l) Disconnect the spark-plug power to the engine by flipping the ENGINE POWER SWITCH on the CT 159 Teststand to its "off" position (the red light on this switch should no longer be shining). This will cause the engine to cease combustion and stop the crankshaft from spinning.

10. Friction Tests ("Dry-Running" the Engine)

(a) Drain the fuel from the FUEL FILL TUBE by following these steps in order.

→ Open the FUEL DRAIN VALVE by turning the needle valve knob **counter-clockwise** to the fully open position.

→ The fuel will drain out of the FUEL FILL TUBE by the action of gravity.

→ When all of the fuel has drained from the tube, close the FUEL DRAIN VALVE by turing the needle valve knob **clockwise** to the fully closed position. Do NOT over tighten.

→ Disconnect power to the fuel pump by flipping the FUEL PUMP SWITCH to the "off" position (the red light on the switch should no longer be shining).

(b) Double check that the ENGINE POWER SWITCH is in the "off" position.

(c) Double check that the throttle lever is in its **fully open** position.

(d) Double check that the SPEED CONTROL potentiometer on the HM 365 Dynamometer unit is set to a low-speed. A value on the potentiometer dial between 5.5–6 should be sufficient.

(e) Engage the electric motor by pressing (and momentarily holding) the GREEN side of the MOTOR SWITCH on the HM 365 Dynamometer unit.

(f) Adjust the SPEED CONTROL dial on the HM 365 Dynamometer unit so that the engine speed is close to the lowest speed measured during your engine performance test. It is NOT necessary to match these values exactly.

(g) Wait for the system to reach steady-state (approximately 30 seconds or less).

(h) Record the measurements on your data sheet, similar to step 9(h).

(i) Increase the engine speed by an increment of about 250 rpm. Repeat steps 10(g) – 10(i) until you have covered a speed range of 2000–3000 rpm.

(j) Disengage the electric motor by pressing the RED side of the MOTOR SWITCH on the HM 365 Dynamometer unit.

11. Shutting Down the Experiment

    (a) Be sure the dynamometer motor has been disengaged by pushing RED side of the MOTOR SWITCH on the HM 365 Dynamometer unit. Note, the white light on this switch will be illuminated if the motor is still engaged.
    (b) Be sure all the fuel as been drained from the fill tube back into the storage containers on the lower shelf of the workbench — see instructions for step 10(a) on how to drain the fuel fill tube.
    (c) Be sure the FUEL PUMP SWITCH and ENGINE POWER SWITCH on the CT 159 Teststand are in their "off" positions, and the red lights on these switches are no longer shining.
    (d) Turn off the power to the HM 395 Dynamometer unit by rotating the MAIN POWER SWITCH counterclockwise.
    (e) Turn the exhaust vent fan off by pressing the "off" button on the wall panel — see image from step 2.

Data Analysis

The performance of an engine is typically specified according to the mechanical power (also referred to as the brake power) generated as a function of rotational speed of the engine crankshaft. From an engineering and design standpoint, it is also of interest to understand how the thermal efficiency and mechanical efficiency of the engine varies with crankshaft speed. In this lab exercise, we will compare the measured power and thermal efficiency with that of an *ideal* engine as based on the Otto cycle . The rest of this section outlines the data analysis steps required to generate the required plots.

(a) Mechanical Power

From these, the mechanical power (also referred to as brake power) is given by the rate of work done by the crankshaft when a brake is applied, and can be calculated from the following

$$\dot{W}_b = \tau\,\omega\ , \tag{3}$$

where τ and ω denote the torque about the axis of rotation of the shaft and the angular velocity of the shaft, respectively. Remember that the measured quantities will not necessarily be in the proper SI units. Therefore, it is extremely important to be mindful of your units and perform the necessary unit conversions to the SI system in your data analysis code. For example, the proper SI units on ω are rad/sec.

(b) Thermal Efficiency

The thermal efficiency of the engine is defined as the ratio of the mechanical power over the inlet power, and is calculated as

$$\eta = \frac{\dot{W}_b}{\dot{E}_{\text{in}}}, \tag{4}$$

where $\dot{E}_{\text{in}}$ denotes the rate of energy into the engine via the fuel. The amount of energy contained in the fuel is based on its Lower Heating Value (LHV), also referred to as Net Heating Value, which is a material property. A bomb calorimeter can be used to measure the LHV of a substance, as described in Appendix III. The SI units associated with LHV are typically given as MJ/kg. You can lookup the LHV for any given fuel from published engineering tables. For 91 octane gasoline, the LHV is 44.0 MJ/kg. The input energy rate is then

$$\dot{E}_{\text{in}} = \dot{m}_{\text{fuel}}\,(\text{LHV}), \tag{5}$$

where $\dot{m}_{\text{fuel}}$ represents the mass flow rate of fuel into the engine during the time interval of the experiment. The latter is, of course, given by

$$\dot{m}_{\text{fuel}} = \rho_{\text{fuel}}\,\dot{\mathbb{V}}_{\text{fuel}}, \tag{6}$$

where, ρ_{fuel} denotes the density of the fuel and $\dot{\mathbb{V}}_{\text{fuel}}$ is the volume flow rate of fuel into the engine. Note, ρ_{fuel} should be calculated based on the inlet fuel temperature and pressure (i.e., atmospheric pressure). For 91 octane gasoline, the fuel density should be close to 726 kg/m^3. The volume flow rate is simply the volume of fuel consumed divided by the time interval of the experiment, $\dot{\mathbb{V}}_{\text{fuel}} = \mathbb{V}_{\text{fuel}}/\Delta t$.

(c) Mechanical Efficiency

The mechanical efficiency of the engine is defined as the ratio of the usable mechanical power over the total power (sum of the brake power plus the power required to overcome friction and inertia in the system),

$$\eta_{\text{mech}} = \frac{\dot{W}_b}{(\dot{W}_b + \dot{W}_f)}, \tag{7}$$

where $\dot{W}_f$ denotes the rate of energy lost due to friction and inertia of the moving piston. In the laboratory, the torque required to run the engine "dry", i.e., to drive the engine without combustion, is measured, and given by τ_d. Therefore, mechanical losses can be calculated as

$$\dot{W}_f = \tau_d\,\omega. \tag{8}$$

(d) Heat Loss

The heat rejected or lost to the surrounding air, $\dot{Q}$, can then be calculated from the First Law of Thermodynamics, which states that the rate of energy into the system must equal the rate of work done by the system plus the heat lost to the surroundings. Mathematically, we can write

$$\dot{E}_{\text{in}} = \dot{W}_b + \dot{W}_f + \dot{Q}. \tag{9}$$

The above equation is rearranged to yield the heat lost (also referred to as the miscellaneous loss rate),

$$\dot{Q} = \dot{E}_{\text{in}} - (\dot{W}_b + \dot{W}_f). \tag{10}$$

Note, the quantity $\dot{Q}$ as calculated from equation (10) represents a number of processes including heat rejected to the surrounding air through convection, radiation heat loss to the surroundings, combustion inefficiency, imperfect air-fuel mixing, and strain energy resulting in the expansion of the materials comprising the engine housing, amongst others.

(e) Mean Effective Pressure

The mean effective pressure, MEP, is a quantity used to characterize reciprocating engines, and essentially represents the average pressure acting on the piston during one cycle of operation (i.e., over the four strokes of the engine operation). In this manner, p_{me} provides a measure of the capacity of the engine to do work. In other words, the work done per cycle (in SI units of Joules) can be calculated as

$$W = (\mathrm{MEP})\, \mathbb{V}_{\mathrm{d}}, \tag{11}$$

where $\mathbb{V}_{\mathrm{d}}$ denotes the displacement volume of the air (i.e., $\mathbb{V}_{\mathrm{d}} = \mathbb{V}_{\mathrm{BDC}} - \mathbb{V}_{\mathrm{TDC}}$). Note, the displacement volume is specified by the manufacturer, typically in units of liters. The work done per cycle is simply the brake power multiplied by t_c, the time to complete one cycle,

$$W = \dot{W}_b\,(t_c). \tag{12}$$

The time to complete one cycle is dictated by the rotational speed of the crankshaft, ω. However, we cannot forget that, in a four-stroke engine, the crankshaft makes two revolutions per cycle. Therefore, the time to complete one cycle is

$$t_c = 2\,\pi\, n_c\, \omega^{-1}. \tag{13}$$

where n_c denotes the number of revolutions per power stroke (e.g., $n_c\!=\!2$ in a four-stroke engine), and the factor of $2\,\pi$ is needed to convert from radians to revolutions. Note, ω in equation (13) must be expressed in proper SI units of rad/sec. Substituting equation (13) for t_c and equation (3) for $\dot{W}_b$ into equation (14) gives

$$W = \dot{W}_b \left(\frac{2\,\pi\, n_c}{\omega}\right) = \tau\, 2\,\pi\, n_c. \tag{14}$$

Equating (14) and (11) and rearranging for the mean effective pressure yields

$$\mathrm{MEP} = \frac{\tau\, 2\,\pi\, n_c}{\mathbb{V}_{\mathrm{d}}}. \tag{15}$$

Theoretical Analysis (Otto Cycle)

It is instructive to compare the performance measurements of an actual IC engine to those of an *ideal* IC engine. Figure 6 illustrates the difference between the actual engine system compared to that of the ideal scenario. The following assumptions are made in the ideal system:

→ air is the working fluid, and considered to be an *ideal gas*,

→ all of the processes (in each stroke of the cycle) are internally *reversible*,

→ the combustion process is replaced by a simple heat addition process, and

→ the exhaust process is replaced by a simple heat rejection process.

In some cases, a further assumption of standard air is used, i.e., the specific heat values of air are determined assuming the system operates at standard room temperature ($T = 25°\text{C}$). In order to increase the accuracy of the ideal model, however, one can use the specific internal energy values at the state temperatures, rather than assuming a constant specific heat value.

The four strokes in an IC engine can be modeled ideally as an *Otto Cycle*. To do this, we recall the pressure-volume and temperature-entropy diagrams of an Otto cycle, as shown in Figure 7. The pressure-volume diagram of an actual IC engine is shown in Figure 8 for comparison.

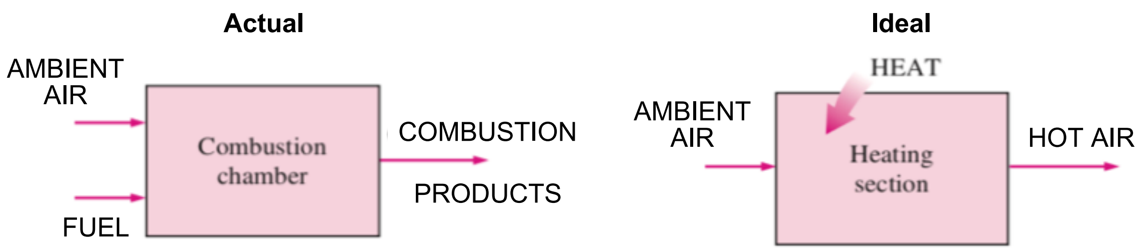
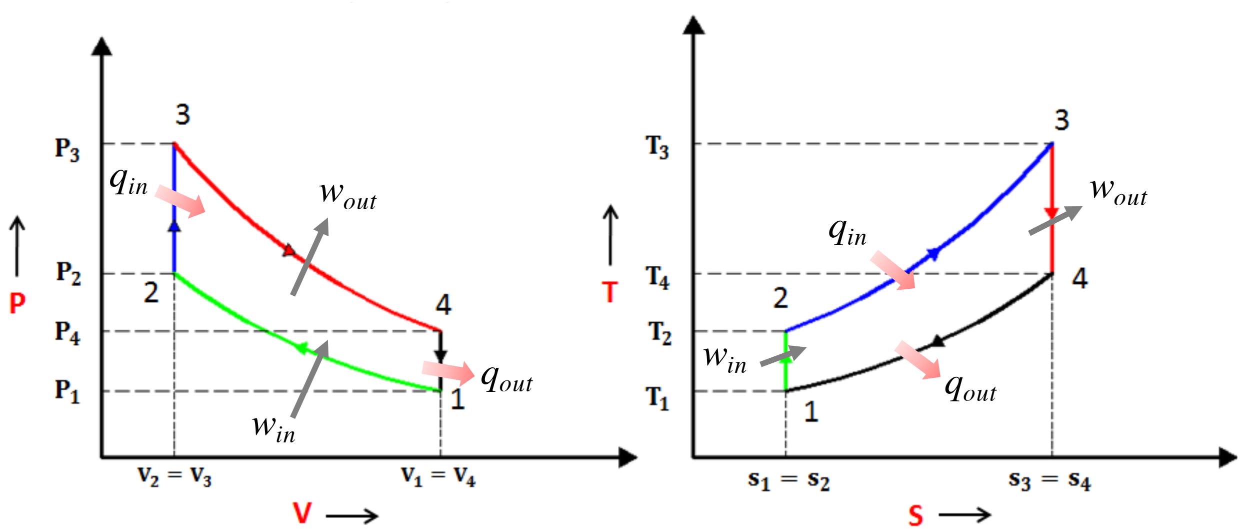


Figure 6. Comparison of the actual engine system to the ideal system.



	Stroke	Path	Process	Assumption
(i)	intake	**1–2**	isentropic compression	$s_1 = s_2$
(ii)	compression	**2–3**	constant-volume heat addition	$v_2 = v_3$
(iii)	power generation	**3–4**	isentropic expansion	$s_4 = s_3$
(iv)	exhaust	**4–1**	constant-volume heat rejection	$v_4 = v_1$

Figure 7. P-$\mathbb{V}$ and T-S diagrams of the Otto Cycle.

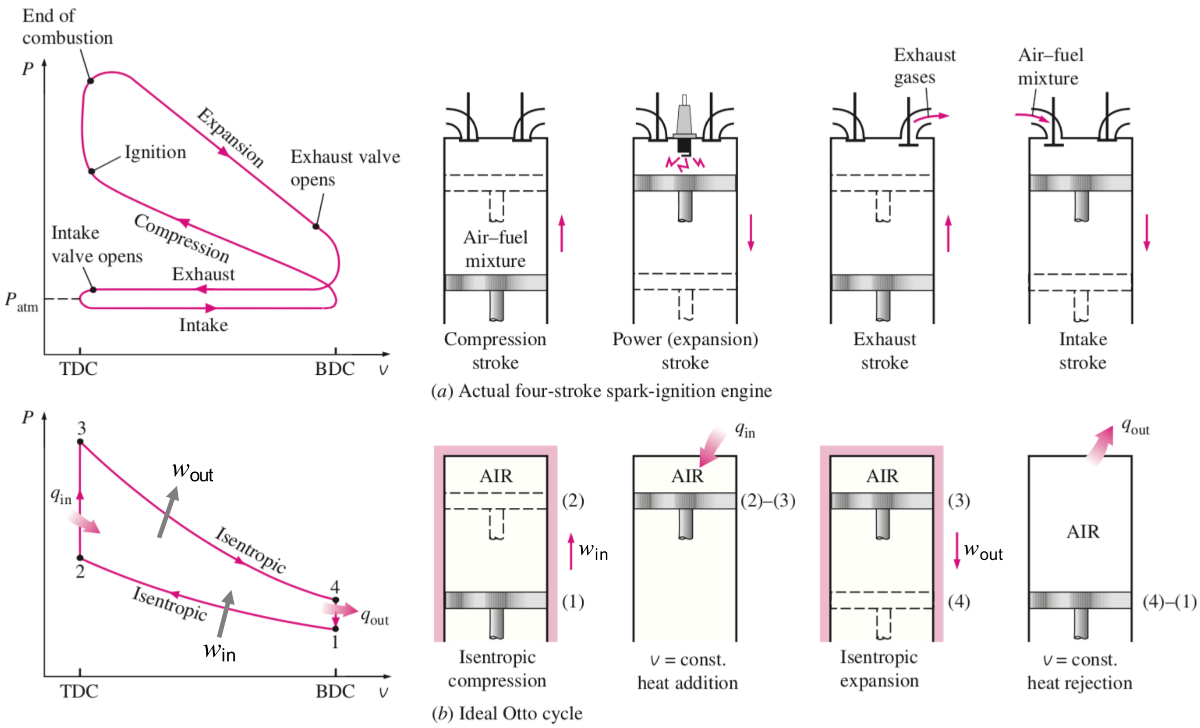


Figure 8. P-$\mathbb{V}$ diagrams for the actual IC engine (top) compared to that of the Otto cycle (bottom).

(a) Ideal Thermal Efficiency

Thermodynamic analysis of the Otto cycle, assuming a constant specific heat ratio, reveals that the thermal efficiency is

$$\eta_{\text{Otto}} = 1 - \frac{1}{r^{k-1}}, \tag{16}$$

where r is the compression ratio and k $(= C_p/C_v)$ is the ratio of the specific heats. In the air-standard analysis, $k = 1.4$ based on the room temperature values of C_p and C_v. Of course, this assumption is not quite correct, because (1) the exhaust includes gases other than air, like CO and NO_x, and (2) the temperature during the power stroke is much higher than the exhaust temperature. The value η_{Otto} from equation (16) can be compared to that measured from equation (4) to determine how close the actual engine efficiency is to the ideal case.

We can see from (16) that the thermal efficiency of the engine increases as the compression ratio r increases. Unfortunately, there is a practical limitation to this effect. If the compression ratio is too high, then the air-fuel mixture inside the combustion chamber will tend to undergo autoignition (also referred to as "knocking"). The autoignition temperature of a substance is the lowest temperature at which it spontaneously ignites (without the need of a spark). The autoignition temperature decreases as the pressure increases. Autoignition is a problem because it upsets the timing of the engine, typically creating combustion too soon in the stroke that leads to loss of power as well as potentially engine damage.

(b) Ideal Work

For the ideal system (no losses), the First Law of Thermodynamics states that the net rate of work done by the system ($\dot{W}_{\text{net}}$) is equal to the difference between the rates of heat transfered into and out of the system,

$$\dot{W}_{\text{net}} = \dot{W}_{\text{out}} - \dot{W}_{\text{in}} = \dot{Q}_{\text{in}} - \dot{Q}_{\text{out}} \,. \tag{17}$$

The work rate done *on* the system ($\dot{W}_{\text{in}} = \dot{W}_{1-2}$) is required in order to raise the pressure of the air during the compression stroke between states 1–2. While the work rate done *by* the system ($\dot{W}_{\text{out}} = \dot{W}_{3-4}$) is obtained during the power stroke between states 3–4. Note, the net usable mechanical work ($\dot{W}_{\text{net}}$) is the one analogous to the measured brake power in the actual engine. We assume that all of the heat available in the combustion of the fuel is transfered to the system between states 2–3 of the Otto cycle. Thus,

$$\dot{Q}_{\text{in}} = \dot{E}_{\text{in}}, \tag{18}$$

where the right hand side of the above equation is given by the expression in equation (5). This means we only need to calculate the the ideal rate of heat rejected from the system, $\dot{Q}_{\text{out}}$ The steps required to do this are outlined below.

i. Heat Transfer Rates ($\dot{Q}_{\text{in}}$ and $\dot{Q}_{\text{out}}$)

For an ideal system, heat transfer is given by the difference in internal energy (u) between the two thermodynamic states before and after the heat addition/rejection. Furthermore, for an ideal gas in a constant-volume process (as is the case in the Otto cycle), the difference in internal energy between two states is equal to the difference in temperature at those two states, assuming the specific heat does not change appreciably with temperature. For the Otto cycle then, we can write

$$\dot{Q}_{\text{in}} = \dot{m}_{\text{air}}(u_3 - u_2) = \dot{m}_{\text{air}}\, C_v\, (T_3 - T_2) \tag{19}$$

$$\dot{Q}_{\text{out}} = \dot{m}_{\text{air}}(u_4 - u_1) = \dot{m}_{\text{air}}\, C_v\, (T_4 - T_1), \tag{20}$$

where C_v is the specific heat at constant volume and $\dot{m}_{\text{air}}$ is the mass flow rate of air into the engine cylinder. In the air-standard model, $C_v = 1005$ J/kg· K, which represents its value at room temperature conditions. Since $\dot{Q}_{\text{in}}$ is known from the material properties of the fuel, we only need to calculate $\dot{Q}_{\text{out}}$ in order to determine the ideal work rate as given in equation (17). Note, temperatures T_1 and T_4 correspond to the measured inlet air temperature and exhaust gas temperature, respectively.

ii. Mass Flow Rate of Air ($\dot{m}_{\text{air}}$)

The *volume* flow rate of air into the engine cylinder, $\dot{\mathbb{V}}_{\text{air}}$, was measured during the experiment. In order to calculate the *mass* flow rate, we use the relation

$$\dot{m}_{\text{air}} = \rho_{1_{\text{air}}}\, \dot{\mathbb{V}}_{\text{air}}, \tag{21}$$

where $\rho_{1_{\text{air}}}$ denotes the density of the air at state 1 (i.e., the inlet). The air density at the inlet is calculated using the ideal gas law based on the measured inlet temperature (T_1) and pressure (P_1). Note, the inlet pressure is assumed to be the same as the measured barometric pressure in the lab.

For fun (not required), we can compare the measured mass flow rate of air into the engine cylinder with that estimated based on the known geometry of the cylinder, as described below. The mass flow rate is simply given by the mass of air (m_{air}) drawn into the cylinder during the intake stroke divided by the time to complete one cycle (t_c),

$$\dot{m}_{\text{air}} = \frac{m_{\text{air}}}{t_c}, \tag{22}$$

where t_c is obtained from the measured rotational speed of the crankshaft as given by equation (13). The mass of air in the cylinder is given by

$$m_{\text{air}} = \rho_{1_{\text{air}}} \, \mathbb{V}_{\text{BDC}}, \tag{23}$$

where $\rho_{1_{\text{air}}}$ denotes the density of the air at state 1 (i.e., the inlet), and $\mathbb{V}_{\text{BDC}}$ is the total volume of the cylinder. The air density at the inlet is calculated using the ideal gas law based on the measured inlet temperature (T_1) and pressure (P_1). Using the definition of the compression ratio, r, in equation (2) and the definition of the volumetric displacement, $\mathbb{V}_{\text{d}} = \mathbb{V}_{\text{BDC}} - \mathbb{V}_{\text{TDC}}$, we can write

$$m_{\text{air}} = \rho_{1_{\text{air}}} \, \mathbb{V}_{\text{d}} \left(\tfrac{r}{r-1}\right). \tag{24}$$

Finally, the mass flow rate of air into (and out of) the system can be written by substituting equation (24) above back into equation (22),

$$\dot{m}_{\text{air}} = \rho_{1_{\text{air}}} \, \mathbb{V}_{\text{d}} \left(\tfrac{r}{r-1}\right) \, (2\,\pi\, n_c)^{-1}\, \omega. \tag{25}$$

Figures

A meaningful and comprehensive figure caption must accompany all figures. The figure caption must include the following label: Figure 1X. where X denotes the letter a – e according to the order listed below. For this lab, use the figure captions in the Word template that has been provided for you (check under "Resources" in the CANVAS assignment).

1a. Plot the measured crankshaft torque (versus crankshaft engine speed (ω). Plot torque on the y-axis in units of N·m and speed on the x-axis in units of RPM. Use a black open circles for the data points. Do NOT connect the circles with a line.

1b. On a single figure, plot the measured brake power ($\dot{W}_b$) and the lost mechanical power ($\dot{W}_f$) versus crankshaft engine speed, compared to the net work ($\dot{W}_{\text{net}}$) of an *ideal* engine operating under the same conditions. Plot power on the y-axis in units of kW and speed on the x-axis in units of RPM. Use the following linestyles: ○ $\dot{W}_b$; □ $\dot{W}_f$; — $\dot{W}_{\text{net}}$. Do NOT connect the data markers with a line. Include a legend.

1c. On a single figure, plot the measured thermal efficiency (η_{th}) versus crankshaft engine speed, compared to that of an ideal engine (η_{Otto}) operating under the same conditions. Plot efficiency on the y-axis in terms of a percent, and speed on the x-axis in units of RPM. Use the following linestyles: ○ η_{th}; — η_{Otto}. Do NOT connect the data markers with a line. Include a legend.

1d. On a single figure, plot the work rate terms in the energy balance (9) versus crankshaft engine speed for the data only. Plot the work rate terms on the y-axis in units of kW, and the speed on x-axis in units of RPM. Use the following linestyles: ○ $\dot{E}_{\text{in}}$; ◇ $\dot{W}_b$; □ $\dot{Q}$; × $\dot{W}_f$. Do NOT connect the markers with a line. Include a legend.

1e. Plot the mean effective pressure (MEP) versus crankshaft engine speed. Plot pressure on the y-axis in units of kPa and speed on the x-axis in units of RPM. Use black open circles (○) for the data. Do NOT connect the circles with a line. Linearly interpolate your data to estimate the value of MEP at 2600 RPM; plot that single data point using a black plus sign (+).

Short-Answer Questions

2a. State the value of the following energy ratios (in terms of a percentage) averaged over the entire range of engine speeds examined: $\dot{W}_b/\dot{E}_{\text{in}}$, $\dot{W}_f/\dot{E}_{\text{in}}$, and $\dot{Q}/\dot{E}_{\text{in}}$. Discuss how the frictional/inertial loss compares to the miscellaneous heat lost to the surroundings, and how this affects the overall thermal efficiency of the engine. [2–4 sentences]

2b. Write one sentence for each of the items below related to engine efficiency. [3 sentences total]

→ State the average mechanical efficiency of the engine (averaged over the range of crankshaft speeds measured), and compare this value with the typical mechanical efficiency of an *electric motor* having an equivalent power rating (1–2 hp).

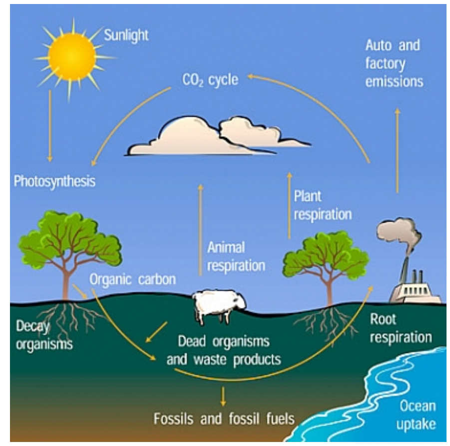
→ Write a statement that compares the calculated thermal efficiency with that of an ideal Otto cycle, by quantifying the discrepancy (ϵ) with a percentage, as follows

$$\epsilon = \frac{\eta_{\text{Otto}} - \eta_{\text{th}}}{\eta_{\text{Otto}}} \cdot 100 \; . \tag{26}$$

→ State three things that were neglected in the ideal model of the Otto cycle that might contribute to such a discrepancy.

2c. Based on your calculations for the mean effective pressure (MEP), estimate the average force acting on the piston head during the cycle when the engine is operating at 2600 RPM. State your answer in units of both N and lbs. Include this calculation in your Matlab code and have the code display the result to the screen. [1 sentence]

2d. Carbon dioxide (CO_2), a greenhouse gas, is released into the environment from the exhaust of spark ignition engines. A diagram of the carbon lifecycle is shown at the right, illustrating how auto emissions tend to alter the natural balance by creating excessive carbon dioxide in the atmosphere. Spend some time to research (using the internet, textbooks, or other sources) solutions for reducing CO_2 gas emissions from combustion engines. For example, some technologies can help increase engine efficiency, thereby reducing CO_2 emissions. State one operation or hardware modification that could be implemented to improve the efficiency of a spark ignition engine, such as turbo-charging, inner cooling, split-fire spark plugs, variable valve timing, etc. Explain how this modification works to improve engine efficiency and describe some of the challenges associated with implementing this modification in practice. Include your references. [4–6 sentences]



Appendix I — IC Engine Operation

The engine used in the present experiment utilizes a camshaft driven by a set of gears connected to the crankshaft as illustrated in Figure 9. A cam, in the shape of a lobe, sets the timing for when the valves open and close during the cycle. Note, since the crankshaft rotates twice per cycle, but the valves only open/close once per cycle, the cam gears must be in a 2:1 gear ratio so that the camshaft rotates at half the speed of the crankshaft.

The air-fuel mixture is set by the carburetor as illustrated in Figure 10. The throat of the carburetor is narrower than the inlet/outlet, creating a venturi effect when the air flows. The pressure drop due to the venturi draws fuel from the fuel bowl into the throat where it is atomized into tiny droplets. The geometry of the carburetor along with the position of the throttle butterfly valve determines the amount of fuel that is mixed with the air.

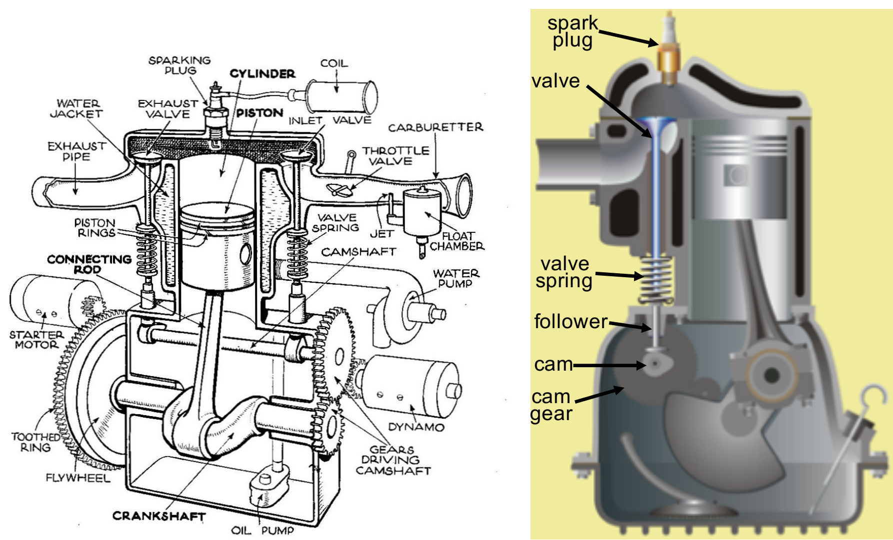


Figure 9. (left) Section view of a small IC engine similar to the one used in the present experiment. (right) Close-up view of the valve actuation mechanism.

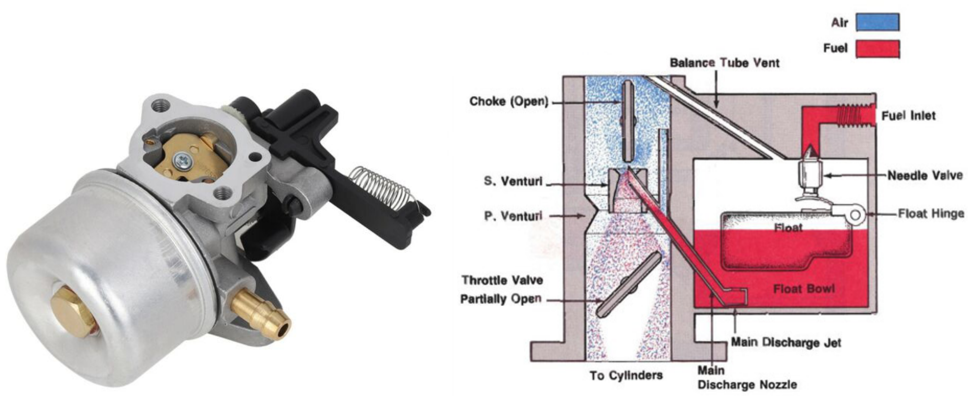


Figure 10. (left) Photograph of a typical float-style carburetor. (right) Schematic of the principle of operation of a float-style carburetor with a butterfly valve throttle.

Appendix II — Dynamometer

The HM 365 Dynamometer unit used in the present experiment measures torque based on the principle of operation of a gimbal motor mount as shown in Figure 11. When torque is generated on the motor shaft, the motor housing will rotate with the same torque unless it is fixed to a stationary structure. In this type of system, the motor is mounted to a gimbal that allows one degree of freedom (i.e., angular rotation about the axis of the motor shaft). A lever arm attached to the gimbal is constrained by a connecting rod that pushes on a strain-gage load cell. By measuring the force applied to the strain gage and knowing the length of the lever arm, the torque acting on the motor shaft can be accurately calculated.

The engine speed is measured using an optical reflective encoder as illustrated in Figure 12. The code wheel is a white/black pattern painted on the face of the pulley attached to the electric motor of the HM 365 Dynamometer unit. A light source shines on the code wheel and measures the reflection by the white pattern using a photodetector that outputs a corresponding digital TTL signal. The speed of the wheel is determined by counting how much time it takes between the rising and falling edges of the TTL signal. Since the motor and engine are connected by a 1:1 belt and pulley system, the engine speed is equal to the motor speed.

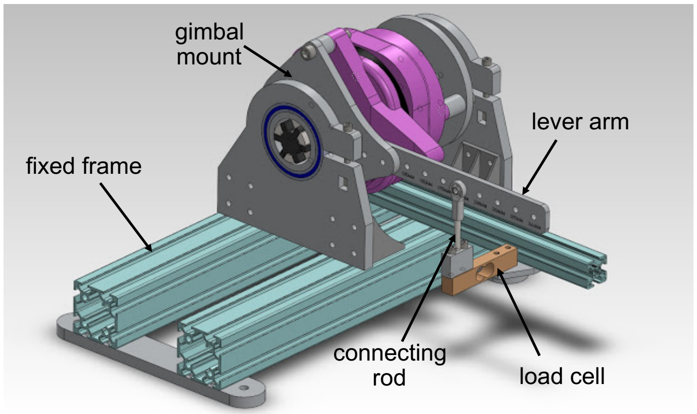


Figure 11. Illustration of how to measure the torque of a gimbaled motor using a lever arm and load cell.

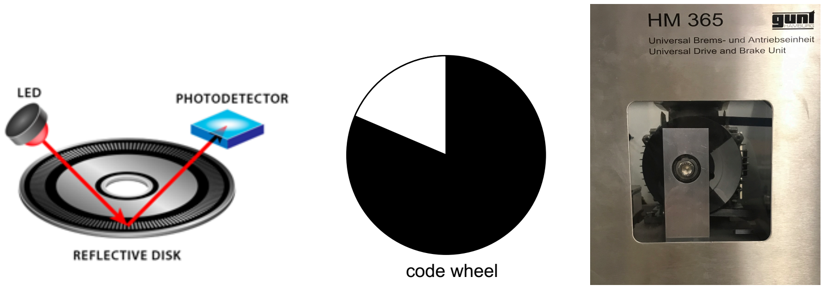


Figure 12. (left) Principle of operation of an optical reflective encoder. (middle) Code wheel pattern painted on the pulley attached to the HM 365 electric motor in the present experiment. (right) Actual photo of the code wheel as viewed from the front of the HM 365 Dynamometer unit.

Appendix III — Bomb Calorimeter

The heating value of a fuel, such as that used in an IC engine, can be determined empirically using a bomb calorimeter device, as shown in Figure 13. In this device, a combustible substance is placed inside a steel container, referred to as the "bomb". The steel bomb is submerged in an insulated water bath. The water inside the bath is stirred to ensure a homogeneous water temperature. The water bath temperature is measured with a thermometer or thermocouple. The substance inside the "bomb" is ignited via an ignition coil. Finally, the increase in water temperature is measured during combustion.

The Higher Heating Value (HHV), also referred to as the Gross Heating Value, of the combustible substance is calculated by applying the First Law of Thermodynamics to the closed system. The units of HHV are energy per unit mass (typically MJ/kg). The Lower Heating Value (LHV), also referred to as the Net Heating Value, is obtained by subtracting the latent heat of vaporization of water from the calculated HHV. This is done, because part of the chemical energy stored in the fuel is used to produce water vapor from the water in the fuel during combustion, and thus cannot be used to produce mechanical work.

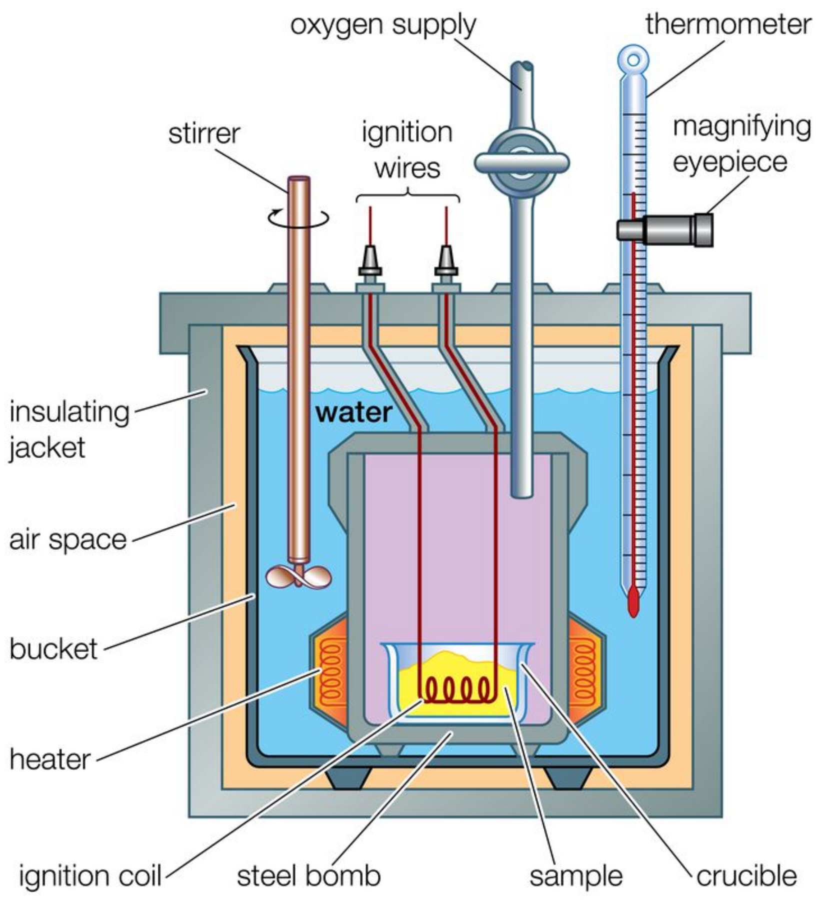


Figure 13. Schematic of a bomb calorimeter used to measure the Higher Heating Value (HHV) of a combustible substance.