Experiment #4: The Four-Stroke Combustion Engine

Introduction

Small engines are used in many applications. They are used to power motorcycles, lawnmowers, go-carts, and even small portable electric generators such as the one used in this lab. They are not very different from automobile engines at all. In fact, the only difference is the size, the way in which the engine cools itself, and the number of cylinders. An automobile engine, being larger and producing a larger amount of energy, has a water cooling system that pumps water through channels in the engine block while most small engines are air-cooled and have a fan that forces air across the finned engine block. These engines run on the four-stroke cycle, which describes how it converts the combustion energy into mechanical energy.

Figure 1: Four-Stroke Cycle (Reference 1)

In the figure above, look at the intake stroke first. It shows the piston pulling in an air-fuel mixture from outside the cylinder until it reaches the bottom dead center position (BDC). It then travels back up the cylinder to compress the air-fuel mixture on the
compression stroke until it reaches the top dead center position (TDC). At this point, the spark plug ignites the mixture, sending the piston back down to BDC as the combusting gases expand on the power stroke. Finally, the piston travels back up to TDC while it forces the combustion products out of the cylinder and the cycle continues.

Figure 2 is a schematic drawing showing the basic parts of a four-stroke engine. It shows how the piston converts the linear up and down motion to rotational motion in the crankshaft. The crankshaft spins the transmission in a vehicle or in our case, it spins the shaft of the generator to produce electric energy. The generator is similar to an electric motor that is driven in reverse to covert mechanical energy into electrical energy instead of the other way around.

**Objective**

To show that in this energy transferring system, as in all systems, the energy is conserved. The efficiency of the system will also be determined and compared to the amount of pollutant emissions in the exhaust. Engine performance will be evaluated as a function of load and air-fuel ratio.
Theoretical Considerations

Part 1: Conservation of Energy

Conservation of energy means that the energy into the system is equal to the energy out.

In the case of the combustion engine, the energy in is the fuel power into the engine and the energy out is the mechanical power out and the heat transferred out.

The energy balance equation is as follows.

\[ \dot{Q}_{in} + \dot{W}_{in} + \sum n_r (\tilde{h}_f^o + \tilde{h} - \tilde{h}_r^o) + \sum n_p (\tilde{h}_f^o + \tilde{h} - \tilde{h}_p^o) = \dot{Q}_{out} + \dot{W}_{out} + \sum n_p (\tilde{h}_f^o + \tilde{h} - \tilde{h}_p^o) \]

Where \( n(r) \) and \( n(p) \) are the molar flow rates of the combustion reactants and products respectively. The \( h \)'s are the molar enthalpy of formation at the standard conditions, the molar enthalpy at the present condition, and the molar enthalpy at the standard conditions respectively. A standard condition refers to 25 degrees C and 1 atm.
The work and heat transfer into the system is equal to zero so the equation reduces to:

$$\sum n_r (h_f^0 + h - h^0)_r = Q_{out} + W_{out} + \sum n_p (h_f^0 + h - h^0)_p$$

The **unbalanced stoichiometric** equation for this combustion reaction is as follows.

$$CH_4 + (O_2 + 3.76 N_2) \rightarrow CO_2 + H_2O + 3.76 N_2$$

The engine is actually burning natural gas, which is a combination of methane, propane, and a small amount of nitrogen. For this portion of the lab assume that the gas is pure methane. The work output of the engine can be directly obtained from the generator load, which is a set of large resistors that consume the electrical energy produced. The resistors are set up in four pairs of two. Each pair consumes about 1000 W of electricity. The actual work output can be calculated by using the handheld Wattmeter and multiplying it by the number of resistor pairs in the circuit. The heat transfer out of the engine is a very complex heat transfer problem. Most of the heat is transferring out through the exhaust. The remaining heat is transferred from the finned engine block to the open air with the help of the cooling fan. But the engine is mostly made out of steel and cast iron which has a very high thermal conductivity so heat travels in every direction from the combustion chamber. It is not a bad assumption though to say that the heat transfers from the engine block uniformly from the finned surface alone. The next complication comes from the engine block geometry. By a quick examination, it can be seen that the fins are not exactly symmetrical and that the engine block is not exactly square or circular in cross-section. To simplify the calculations, the fin lengths have been
averaged together and the cross-section of the engine block is assumed to be circular.

This simplification can be visualized in the figure below.

![Figure 4: Fin Approximation (Right side from Reference 4.)](image)

The total heat transfer can now be calculated using the equation below.

\[
Q_{out}^* = hA_i \left[ 1 - \frac{NA_f}{A_i} (1 - \eta_f) \right] (T_b - T_\infty)
\]

Where \(A_f = 2\pi (r_{2c}^2 - r_1^2)\) \(A_i = NA_f + 2\pi r_1 (H - Nt)\) \(L_c = L + \frac{1}{2}t\) \(r_{2c} = r_2 + \frac{1}{2}t\)

\(N\) is the number of fins.

Next, determine \(L_c^{3/2} \left( \frac{h}{k_{Al} L_c t} \right)^{1/2}\) where \(k_{Al}\) is the thermal conductivity of the fin material (aluminum), and \(h\) is the convection heat transfer coefficient. Use figure 3.19 of your text (Incropera and Dewitt, 4th Ed., Figure 3.19) to determine the fin efficiency, \(\eta(f)\).

For the geometry of the engine block, use the following values:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H)</td>
<td>13.34 cm</td>
</tr>
<tr>
<td>(r_1)</td>
<td>7.00 cm</td>
</tr>
<tr>
<td>(r_2)</td>
<td>9.53 cm</td>
</tr>
<tr>
<td>(t)</td>
<td>0.25 cm</td>
</tr>
<tr>
<td>(N)</td>
<td>11 fins</td>
</tr>
</tbody>
</table>
The convection heat transfer coefficient \( (h) \) can be calculated by measuring the air
velocity, calculating the Reynolds Number, and using the Nusselt number relation below.

\[
Nu = \frac{hD}{k_{\text{air}}} = 0.0529 \Re_{\text{max}}^{0.704}
\]  
(Note: The expression at the left is for air, with Pr = 0.72)

Where \( \Re_{\text{max}} = \frac{\rho_{\text{air}} u_{\text{max}} D}{\mu_{\text{air}}} \) and \( u_{\text{max}} = \left[ \frac{(s + t) S_T}{(s + t) \Delta + s(D_f - D)} \right] u_\infty \)

The equations above were derived for use with flows passing finned tubes and can be
depicted in the figure below.

![Figure 5: Flow Passed Finned Tubes. (Reference 5)](image)

The equation above relating \( u(\text{max}) \) and \( u(\infty) \) is for cases when there is
more than one finned tube present. In the case of the engine block, it is
being approximated as one finned
tube. This causes the \( \Delta \) and S(T) terms to go to infinity. Therefore,
the equation reduces to \( u(\text{max}) = u(\infty) \).

The variables that are not already listed above are as follows:

\[ D = 2*r_1 \quad D(f) = 2*r_2 \quad \Re = \text{Reynolds Number} \quad \Nu = \text{Nusselt Number} \]

\[ \rho = \text{air density} \quad \mu = \text{kinematic viscosity of air} \]
**Part 2: Emissions and Efficiency**

The efficiency for this system can be calculated with the following equation:

$$\eta_{overall} = \frac{\dot{W}_{out}}{HHV \cdot m_{fuel}}$$

Where HHV is the higher heating value of the fuel. There are many different components in the exhaust of an engine. They are mainly carbon dioxide and water but also includes carbon monoxide, oxygen, hydrocarbons (unburned fuel), and small amounts of NOx and SOx. Since the amounts of SOx and NOx are minute, they will be ignored for this experiment. When the air-fuel mixture entering the combustion chamber is lean (high air, low fuel) there is an excess amount of oxygen in the exhaust. When the engine is running rich (low air, high fuel), CO and hydrocarbons are present in the exhaust. CO and hydrocarbons are bad for the environment and are deadly if inhaled. Running an engine at optimum efficiency is a struggle between increasing the fuel and therefore the power and keeping the harmful emissions low. The efficiency of the engine will increase with increasing fuel until all of the available oxygen is used up, and then it will decrease with increasing fuel. The actual amount of hydrocarbons will not be measured but note that when CO is present, so are the hydrocarbons.
Example:

Assuming an air-fuel ratio of, say 15, the combustion equation is (note that there are 3.76 parts of N₂ for 1 part of O₂ in air):

\[ CH_4 + 3.15O_2 + 3.76 \times 3.15N_2 \rightarrow xCO_2 + yH_2O + 11.84N_2 + zO_2 + aCO + bH_2 \]

where \( x, y, z, a, \) and \( b \) are unknowns. \( a \) and \( b \) may be obtained using the values from the \( O_2 \) and CO sensors. The remaining quantities may be calculated by noting that:

\[ x + y/2 + z + a/2 = 3.15 \] (balancing \( O_2 \))

\[ x + a = 1 \] (balancing C)

\[ y + b = 2 \] (balancing H)

Procedure

1. With the engine warmed up, turn on the first resistor pair and wait for steady state.
   The velocity of the cooling air can be measured with the handheld anemometer at this point. Also record the ambient room temperature.

2. Take mass flow readings of the fuel and the air, temperature readings of the engine block base and the exhaust, and a power reading with the handheld Wattmeter.

3. Turn on the second resistor pair and repeat step 2 after waiting for steady state.
   Repeat with three resistor pairs and then four.

4. With two resistors loading the engine and the intake valve all the way open, take readings of the \( O_2 \) and CO content in the exhaust, a mass flow reading of the fuel, and a power reading. (this is the lean setting)

5. Repeat step 4 at the rich setting. Set the engine rich by slowly adjusting the intake valve until the oxygen display reads zero.

6. The optimum air-fuel ratio lies somewhere between these two points. Adjust the intake valve to some point between the lean and rich settings and repeat step 4.
Analysis

1. Calculate all of the quantities in the energy balance equation for all four trials.

2. Construct a chart of trial number vs. power and include a line for input power and one for output power. Does the energy appear to be conserved? Are there any increasing or decreasing discrepancies as the power demand is increased?

3. Calculate the efficiency of the system at the optimum, lean, and rich settings of the air-fuel ratio. Construct a plot showing the efficiency of the system vs. air-fuel ratio. Which setting yields the most efficient system?

4. Construct a chart showing O2 and CO content in the exhaust vs. air-fuel ratio. From the chart, determine the optimum air/fuel ratio.

5. Explain the sources of error in this experiment.

References


