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Examination of Combustion Processes Using a Rankine Cycler

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Abstract

All mechanical engineering students at the University of Tennessee Chattanooga take a junior level Thermodynamics course covering topics involving power cycles and combustion processes. This course is followed by a senior level laboratory in which these topics are also examined experimentally. In 2019 a RankineCycler™ was added to the lab to enable students to investigate power generation through the use of a steam turbine. One limitation to this piece of equipment was that while the volume flow rate of fuel (propane) was measured, the air flow rate was not. This limitation prevented the examination of combustion processes using a known air to fuel ratio, which is an important parameter in exhaust calculations. The project presented in this paper covers modifications to this equipment that now allows both the measurement of the air flow rate, as well as determining the exhaust species. These modifications will greatly increase students' knowledge of the accuracy of a complete combustion assumption, as well as determine how exhaust products, such as Carbon Dioxide, can be measured.

Keywords Complete Combustion, Rankine Cycle, Gas analyzer

Introduction

All mechanical engineering students at the University of Tennessee Chattanooga are required to take two Thermodynamics classes, as well as a senior level lab class that covers both thermal/ fluid and mechanical systems. One of the thermal/fluid labs examines a steam generation power unit called the RankineCycler™, which is produced by Turbine Technologies.[1] This particular lab is used by several engineering programs throughout the country, and has been evaluated by Gerhardt et. al. quite extensively.[2-4] The focus of this lab is to provide students the opportunity to apply several of the topics covered in the Thermodynamics classes to an actual power producing system. These topics include: 1) Plotting a T-S curve for a cycle 2) Calculating the isentropic and second law efficiency of a steam turbine 3) Calculating the 1st law efficiency of a power plant.

While this system has been used effectively in our program for several years, one of the key elements missing was an evaluation of the combustion of the propane used to heat the water in the boiler. In our second level Thermodynamics class students are taught how to estimate the products produced in stoichiometric and non-stoichiometric conditions, the details of which are covered in the theory section below. One of the major assumptions made in this process is the idea of complete combustion, which assumes all Carbon in the hydrocarbon fuel, goes to Carbon Dioxide (CO2). The system, as purchased, allows for the measurement of the volume flow rate of the propane (C3H8), but the flow rate of the air is not monitored, which prevents the determination of the air to fuel ratio and thus an evaluation of the complete combustion assumption.

This study focuses on the modifications made to the current equipment that will allow us to monitor the air flow rate as well as the fuel flow rate. In addition to this a discussion will also be presented on the analyzer that was purchased to monitor the exhaust species leaving the system. Together, these two changes will greatly enhance our students understanding of the combustion process, the accuracy of the assumptions made for complete combustion, and the overall effect on the system. Furthermore, because Carbon Dioxide is one of the major exhaust components, it provides a basis for discussion as to why this is such an important topic when dealing with pollution.

Theory

Combustion is a specific type of chemical reaction that involves three components: Fuel, Oxidizer, and an ignition source.[5] The combustion process examined for this work consists of propane and air as well as an electric ignition source. Initially students are introduced to the idea of a stoichiometric combustion process, where an exact amount of air is provided to burn a given amount of fuel. Next students are introduced to fuel rich or fuel lean processes such that there are excess or deficient amounts of fuel for a given amount of air. To specify the type of process being considered it is common to list the Air to Fuel Ratio (AFR), which is defined as the ratio of the mass of air to the mass of fuel as shown in Equation 1.

$$AFR = \frac{M_{air}}{M_{fuel}} \tag{1}$$

In both the case of stoichiometric and nonstoichiometric conditions, one of the largest assumptions made in an introductory course involving combustion processes, is that all Carbon is converted to Carbon Dioxide, all of the Hydrogen is converted to water, and any excess fuel or air act as inert gasses. This is generally termed a complete combustion assumption. Below is the balanced chemical reaction for the stoichiometric amount of Propane and air (Equation 2) as well as the equation for an air to fuel ratio of 20 (Equation 3) representing a fuel lean mixture. The ratio of 20 was used as this was the initial assumption made during the lab experiment.

$$C_3H_8 + 5O_2 + 18.8N_2 \rightarrow 3CO_2 + 4H_2O + 18.8N_2 \tag{2}$$

$$C_3H_8 + 6.38O_2 + 23.99N_2 \rightarrow 3CO_2 + 4H_2O + 2.76O_2 + 18.8N_2 \tag{3}$$

It should be noted that the coefficients in these equations are in Mols and must be converted to mass by using the molecular weight of each species when calculating the AFR.

For the experiments being conducted the volume flow rate of the fuel was determined from provided instrumentation by Turbine Technologies. An additional flow measurement was added, for the work represented here, so that the volume flow rate of air could also be measured allowing for the accurate calculation of the AFR ratio, as well as determining the accuracy of the complete combustion assumption. To convert volume flow rates to mass flow rates the density of the substances must be known. This is found using the Ideal Gas equation shown in Equation 4.

$$\rho = \frac{P}{RT} \tag{4}$$

Where P is the absolute pressure, T is the absolute temperature, and R is the specific gas constant. Using this the AFR can be determined using Equation 5.

$$AFR = \frac{V_{air} \cdot \rho_{air}}{V_{fuel} \cdot \rho_{fuel}} \tag{5}$$

The dimensionless number Lambda (L), also known as the equivalence ratio, is often used to compare an actual AFR to the stoichiometric case. As discussed above the stoichiometric AFR is the ideal ratio where all the fuel is mixed with the exact amount of air required for complete combustion.

$$L = \frac{Actual\ AFR}{Stoichiometric\ AFR} \tag{6}$$

When L > 1, as presented in Equation 3 above, the mixture is said to be lean. In this case there is more air than needed to completely burn the given amount of fuel, thus oxygen is evident on both sides of the equation. To determine the amount of each constituent in the exhaust Equation 7 will be used for each species.

$$Percentage\ of Exhaust\ Species = \frac{Moles\ of Exhaust\ Species}{Total\ Moles\ of\ All\ Exhaust\ Species} \cdot 100 \tag{7}$$

These numbers will be confirmed by directly measuring them using an exhaust gas analyzer. The results will then be compared to determine the validity of the complete combustion assumption.

Experimental Setup

The Turbine Technologies RankineCycler™ Steam Turbine Engine Lab Power System, shown in Figure 1, is used as the base for the setup. The RankineCycler uses a Propane boiler to generate steam which is fed through a single stage turbine and then to an open-air condenser. It should be noted that this system does not complete the cycle as the steam is not converted to a liquid and then fed back to the boiler through a pump. While the system comes with a monitoring system to measure the flow rate of the Propane, an equivalent system is not implemented to measure the flow rate of the air. To determine the air flow rate, changes were made as discussed below.

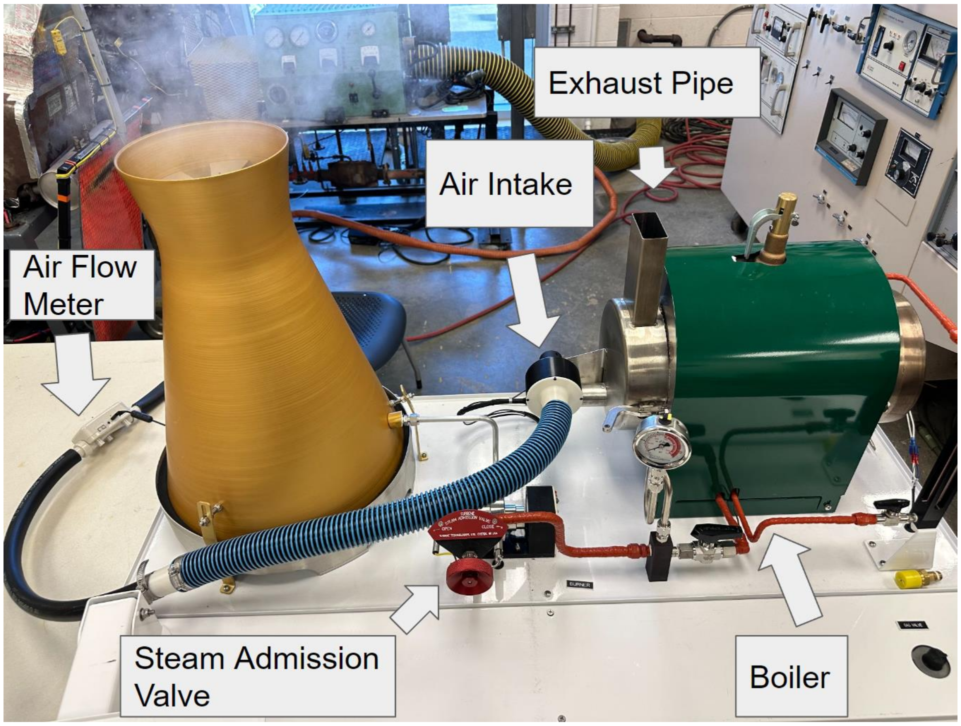

Figure 1. Rankine Cycler.

The engine's air intake was modified by adding an inlet shroud printed on an FDM printer using Amazon Basic's White PLA. This shroud was designed so that a hose could be quickly attached to the system. The other end of the hose was connected to the TSI 5310 Air Gas Mass Flow Meter. This meter is designed for continuous positive airway pressure (CPAP) machine testing and gives readings of air flow in standard liters per minute (stdL/min), absolute pressure in kPa, and temperature of the air in Celsius. A second hose was then connected to the system air of the building (Figures 2 and 3). To provide the desired flow rate a pressure regulator was put in place between the buildings air and the monitoring station, and a second valve was put in place so that the exact flow rate could be controlled from the Rankine Cycler.

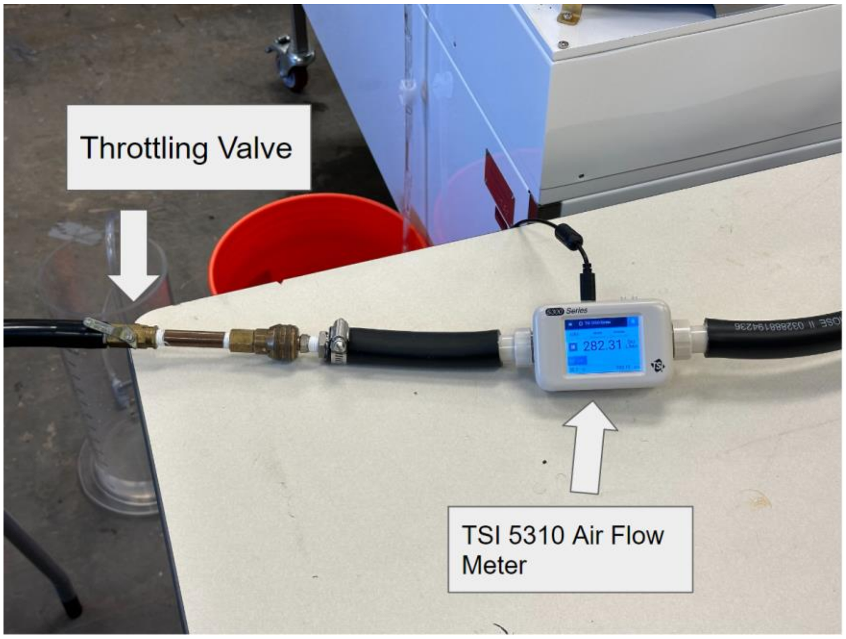

Figure 2. Air Flow meter.

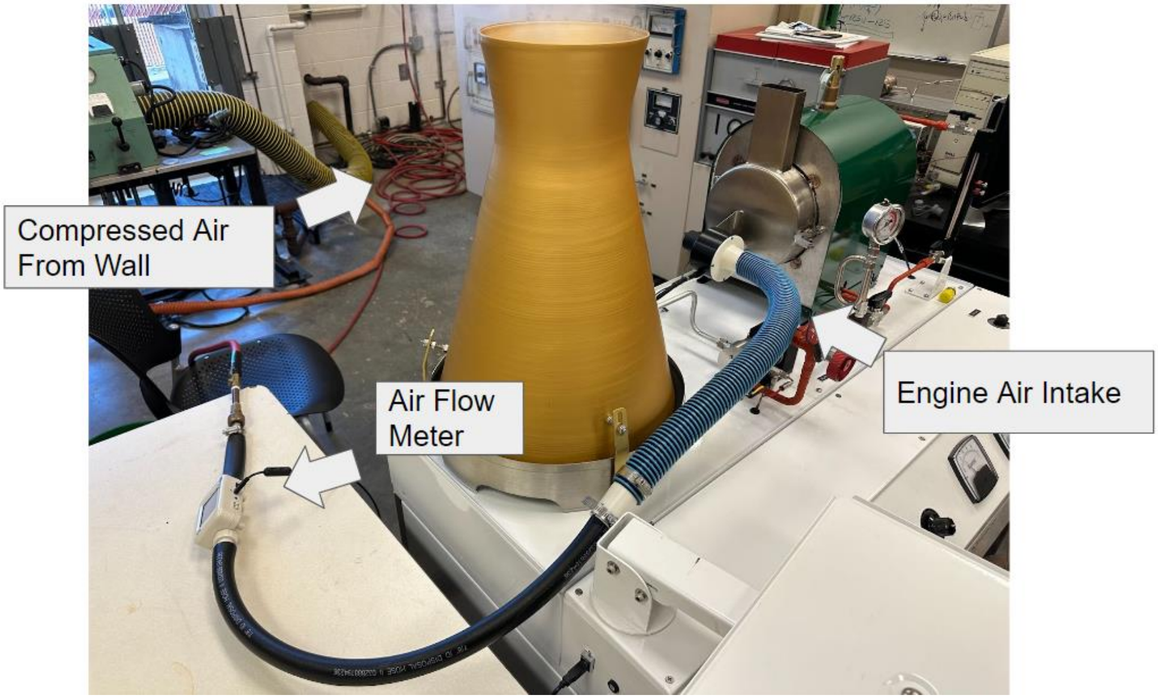

Figure 3. Connection of inlet air to the Rankine Cycler.

The exhaust products are measured using a Bridge 5 Gas Analyzer shown in Figure 4. This analyzer provides several outputs including the % of CO2, O2, and CO as well as the parts per million of unburned hydrocarbons and NoX. It also predicts the air to fuel ratio as well as the

Lambda value discussed in the theory section. It should be noted that the exhaust stream is first passed through a filter, in order to remove water from the mix, before entering the analyzer.

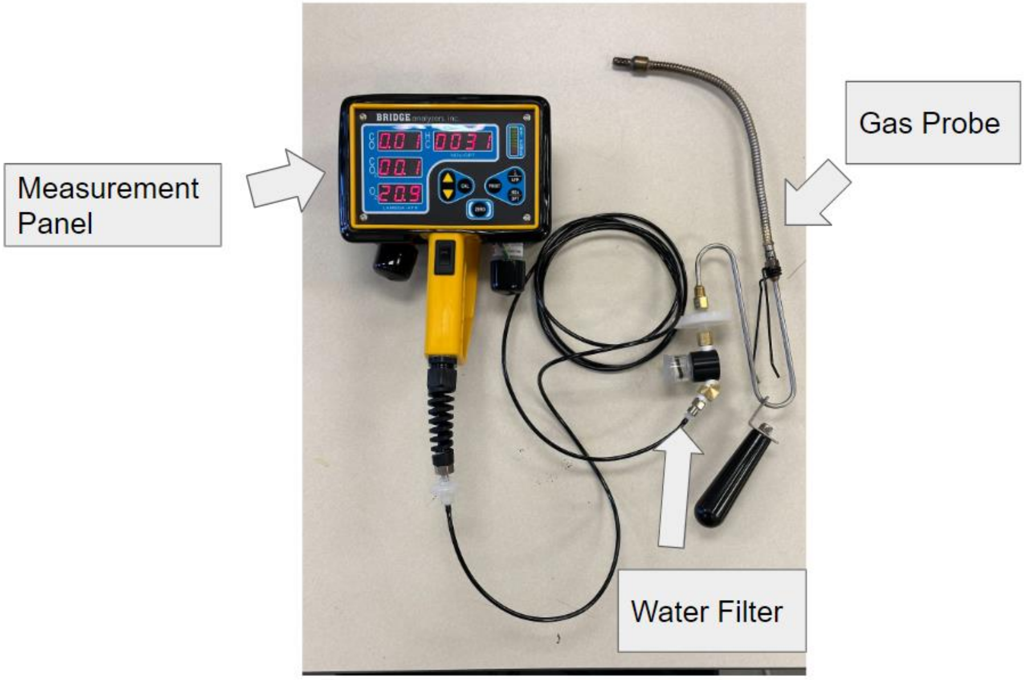

Figure 4. Bridge 5-Gas Exhaust Gas Analyzer.

Multiple trials were completed during a single operation of the engine. Before taking measurements, the air inlet valve located near the system was completely opened and the pressure regulator was slowly adjusted until the maximum desirable flow rate of 300 stdL/minute was reached. After allowing the engine to run for several minutes, testing was started, and the exhaust gas analyzer was placed in the exhaust pipe as shown in Figure 5.

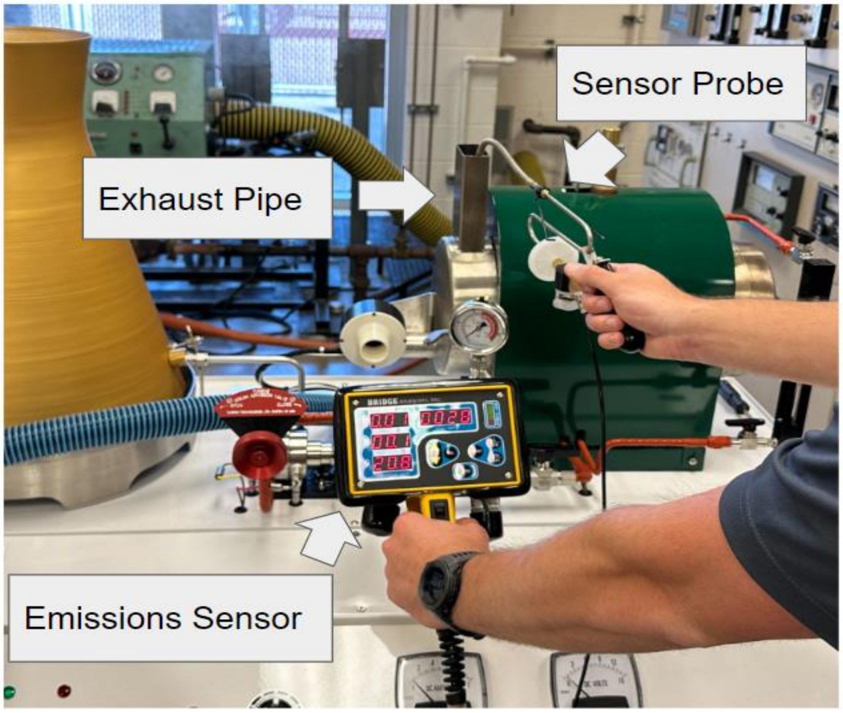

Figure 5. Demonstration of Collecting Emissions Data with the Exhaust Gas Analyzer.

The air valve at the air flow meter was incrementally closed to get the desired air to fuel ratio on the sensor. Once a desired air to fuel ratio was achieved on the exhaust analyzer, and the exhaust analyzer's data leveled off to a stable reading, the values were recorded for analysis. Air to fuel ratios near and above the stoichiometric ratio (15.67:1 for propane) were targeted for this experiment.

Results

Table 1 shows the results of the various air to fuel ratios that were tested. The initial test was conducted near the stoichiometric ratio (~15.6:1), with each subsequent test conducted at higher air to fuel ratios.

Table 1. Exhaust gas products for varying AFR's.

A/F (Measured)	A/F (Gas Analyzer)	Fuel Flow (L/min)	Air Flow (Std L/min)	L (Measured)	CO (%)	CO2 (%)	O2 (%)	HC (ppm)
19.2	17.4	5.54	174.23	1.1	0.72	11.6	2.8	551
20.6	18.6	5.60	189.22	1.2	0.16	11.3	3.9	532
22	19.7	6.02	217.69	1.2	0.05	10.6	4.8	535

23	20.3	5.62	211.9	1.3	0.04	10.3	5.3	448
25	21.6	6.03	247.00	1.4	0.04	9.8	6.2	232
28.1	24.2	5.67	261.13	1.5	0.04	8.7	8.0	284
33	28.1	5.61	304.54	1.8	0.04	7.4	9.9	339

It should be noted that the first column provides the air to fuel ratio as measured by the individual air and fuel streams. The second column provides the predicted air to fuel ratio as reported by the gas analyzer. It is evident that the gas analyzer consistently underpredicts the AFR with the difference increasing with increasing AFR (2-4.9). Also reported is the equivalence ratio (L) as provided by the gas analyzer.

Initial observations of the products show that near stoichiometric conditions the amount of CO is much higher as the AFR increased. Also, the percentage of CO2 decreases with increasing AFR. Finally, as expected, the amount of O2 increases with increasing amount of air, while fewer Hydrocarbons (HC) are observed as there is a better chance of combustion occurring with the increased oxygen content.

Table 2 provides the calculated values for CO2 and O2 for the same AFR assuming complete combustion.

Table 2. Calculated Combustion Products assuming complete combustion.

A/F (Measured)	Fuel Flow (L/min)	Air Flow (Std L/min)	L (Calculated)	CO2 (%) Calculated	O2 (%) Calculated
19.2	5.54	174.23	1.2	11.1	4.1
20.6	5.60	189.22	1.3	10.2	5.4
22	6.02	217.69	1.4	9.6	6.4
23	5.62	211.9	1.5	9.1	7.1
25	6.03	247.00	1.6	8.4	8.3
28.1	5.67	261.13	1.8	7.4	9.7
33	5.61	304.54	2.1	6.2	11.5

Table 3 provides the comparison between the values measured by the gas analyzer and those calculated assuming complete combustion.

Table 3. Comparisons of measured (GA) and predicted (PR) CO2, O2, and L.

A/F (Measured)	CO2 (%) (GA)	CO2(%) (PR)	CO2 Diff.	O2 (%) (GA)	O2(%) (PR)	O2 Diff.	L (GA)	L (PR)	L Diff.
19.2	11.6	11.1	0.05	2.8	4.1	-1.3	1.1	1.2	-0.1
20.6	11.3	10.2	1.1	3.9	5.4	-1.5	1.2	1.3	-0.1
22	10.6	9.6	1.0	4.8	6.4	-1.6	1.2	1.4	-0.2
23	10.3	9.1	1.2	5.3	7.1	-1.8	1.3	1.5	-0.2
25	9.8	8.4	1.4	6.2	8.3	-2.1	1.4	1.6	-0.2
28.1	8.7	7.4	1.3	8.0	9.7	-1.7	1.5	1.8	-0.3
33	7.4	6.2	1.2	9.9	11.5	-1.6	1.8	2.1	-0.3

The data shows that the complete combustion assumption for CO2 slightly underpredicts the actual measured value by an average difference of 1.04. While this shows good agreement, the fact that the predicted values are lower is unexpected. For complete combustion it is assumed that all carbon is converted to CO2, therefore it was expected that the predicted value would be above the actual value. The data shows that some of the carbon in the measured values either remains as unburned fuel, or is converted to CO, again making the case that this value should be lower. One possible reason for this is the uncertainty in calculating the mass flow rate of the Propane when converting from volume flow rate. It was assumed that the pressure and temperature at the point of measurement were standard atmospheric values, because it was not possible to put instrumentation in this area without opening the combustion chamber. This uncertainty would then be built into the density calculations and finally into the mass flow rate, thus slightly changing the measured AFR.

For O2 good agreement was found between measured and predicted values with an average difference of 1.66. In the case of O2 the prediction was slightly greater than the measured values. Lastly, the equivalence ratio showed good agreement with a slight increase in predicted values at higher AFR's.

Conclusion and Recommendations

The modifications made to the Rankine cycler have greatly enhanced the opportunity for students to examine how accurate one of the fundamental assumptions made (i.e. complete combustion) is when conducting a first level analysis. Excellent agreement was found for both the percentages of CO2 and O2 based on measured and calculated values, although the CO2 was slightly underpredicted. Future work will examine all of the uncertainties associated with this system including both the air and fuel flow rates as well as the exhaust gas uncertainties. This system has been incorporated into the current lab, and its effectiveness will be evaluated at the end of the semester.

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