DEVELOPMENT AND FIRST LAW ANALYSIS OF A TRI-GENERATION SYSTEM AS A GLOBAL SENIOR DESIGN ENGINEERING PROJECT

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Abstract. *This paper describes the development of a tri-generation system, which produces electricity, refrigeration, and heated water by recovering waste energy from an internal combustion engine. The project was developed by an international team of students from Florida State University and the Federal University of Parana as a pilot international engineering education project aiming to initiate the future mechanical engineer through his/her senior design project in the development of global engineering projects using available electronic media. A 16HP liquid cooled internal combustion engine is the heart of the system. To produce electrical power a 6 kW single phase AC generator was coupled to the engine. A conduction circuit was designed to recover heat from the exhaust to power an absorption refrigerator requiring 115 W of input energy. Finally, a spiral plate counter flow exhaust gas heat exchanger was used to transfer heat from the exhaust gas to the water contained in a 20 gallon reservoir. During testing the system recovered over 3.2 kW of the thermal energy of the exhaust. It also produced 425 W of electrical power used to power a high speed circulating fan.*

Keywords*: trigeneration, waste heat recovery, absorption refrigeration*

1. INTRODUCTION

"Energy may very well be the single most critical challenge facing humanity in this century" (Smalley, 2006). As engineers we are faced with the challenge of not only to generate energy solutions that involve alternative energy sources but to maximize existing systems efficiency.

This paper describes the development of a tri-generation system, which produces electricity, refrigeration, and heated water by recovering waste energy from an internal combustion engine. This system was designed as part of a capstone senior design project by a team of mechanical engineering students from Florida State University and the Federal University of Parana (Childress et al., 2006a; Childress et al., 2006b), to be used as a test bed to investigate the potential for trigeneration using waste heat from an internal combustion engine. Trigeneration and polygeneration are among the promising strategies for efficiency increase in power generation systems (Cardona et al., 2006; Hernández-Santoyo and Sánchez-Cifuentes, 2003; Heteu and Bolle, 2002).

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2.SYSTEM DESCRIPTION

Figure 1 illustrates the assembled system. The main system components are:

<u>Engine:</u>
A Kawasaki FD501D 16 HP liquid-cooled twin cylinder gasoline powered engine was chosen as the heart of the system.
<u>Generator:</u>
A VOLTmaster, AB60 AC generator provides 5000 Watts (41.7 Amps) of continuous electrical power at full load.

Figure 1. Trigeneration system and data acquisition

Coupler:

Directly coupling the engine shaft to the generator shaft was determined to be optimal over alternative coupling designs such as a belt driven configuration. A Lovejoy jaw type coupler was chosen because it allows for slight misalignment while still being relatively inexpensive. This type of coupler easily attaches to the engine and generator shafts by use of a set screw.

Water Heating Unit:

The two main concerns while choosing a heat exchanger were the exhaust gas pressure drop and the allowable temperature difference between the two working fluids within the heat exchanger. A spiral plate counter-flow multi-pass heat exchanger from Polar Power Inc. (model 30 exhaust heat exchanger) was selected. The model-30 heat exchanger is ideal for 10 to 30 HP engines, and the typical exhaust pressure drop is under 0.75 psi. The water outlet temperature should reach between 50˚C -100˚C depending on the number of passes through the unit. While the exhaust gas exit temperature will be approximately within 50˚C of the water exit temperature.

Refrigerator:

A Dometic RM219 absorption refrigerator was selected. Its compact size allows for 1.9 cu. ft. of cold space while only requiring 115 W of power. Applied heat to the boiler must be at a minimum operating temperature of 300°C.

Conduction Circuit:

To provide the necessary energy to power the refrigerator a copper rod was designed to conduct heat from the hot exhaust gas to the boiler of the refrigerator. The rod consists of two different cross-sectional areas. A section with 0.65 inch diameter and a length of approximately 4 inches to match the size constraint of the boiler and a section (0.75” dia.) whose length was computed to meet the 115W heat flux requirement, imposed by the refrigerator, at the desired temperature. This length was evaluated as a function of exhaust gas temperature. As a result of these calculations the length of the 0.75 inch diameter section was determined to be 4 in.

Piping:

The entire system was made of 1” nominal type L copper tubing and standard fittings. The exhaust header is 1” in diameter therefore using this size piping was the most convenient.

Insulation:

Insulation was a major concern considering the project is based upon heat recovery. Different types of insulation were chosen for different subsystems based on operating temperature. For the piping carrying the exhaust gas, mineral wool insulation was used because it can withstand temperatures up to 650 ˚C, and has a low thermal conductivity of 0.04 W/(m K). Flexible sheets, pre-molded pipe and pre-molded fittings were used for various components handling the exhaust gas. The rate of heat loss per unit length was plotted as a function of thickness to determine optimal thickness of insulation to be used. From Figure 2 below it can be seen that any thickness over 1inch does not yield significant decrease in the rate of heat loss.

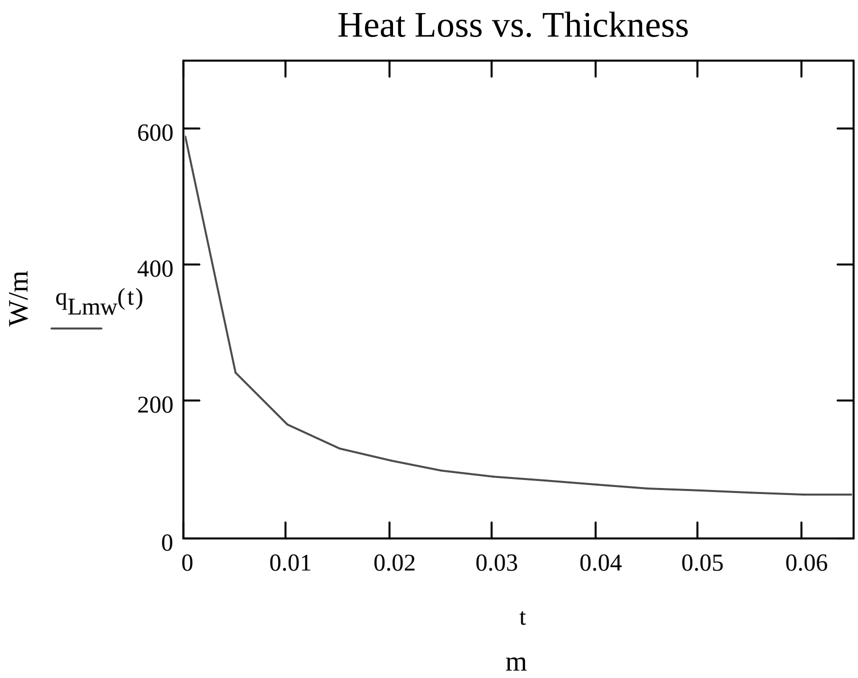

Figure 2. Graph of Heat loss vs. Insulation Thickness

One-inch thick insulation was also congruent with clearance constraints on the exhaust header. Casting tape was used to enclose the mineral wool insulation to provide extra stability and protection against the elements.

To insulate the pipes handling the water, pre-molded elastomer foam pipe and fitting insulation was used. It can handle temperatures up to 100˚C while providing excellent insulating qualities. The thermal conductivity is approximately 0.035 W/(m K). The rate of heat loss per unit length was graphed as a function of thickness to determine optimal thickness of insulation to be used. It was determined that thickness over 1" did not yield a significant decrease in the rate of heat loss in the water piping either.

Polyurethane flexible sheets were used to insulate the water reservoir. Both types of insulation are closed cell foams, which provide excellent water resistance.

Instrumentation:

Flow meters, thermocouples and pressure transducers would be the ideal devices to characterize the overall system performance. Due to budget constraints the only parameters of the system that could be measured were temperatures and the fuel consumption rate. K-type thermocouples were placed at various points within the system to measure the temperatures critical to calculating the system efficiency as well as the amount of heat recovered. K-type thermocouples were chosen because of their broad temperature range of -200˚C to 1250˚C. A digital scale and timer were used to measure the fuel consumption rate of the engine. A diagram of the thermocouple placement can be seen in Fig. 3.

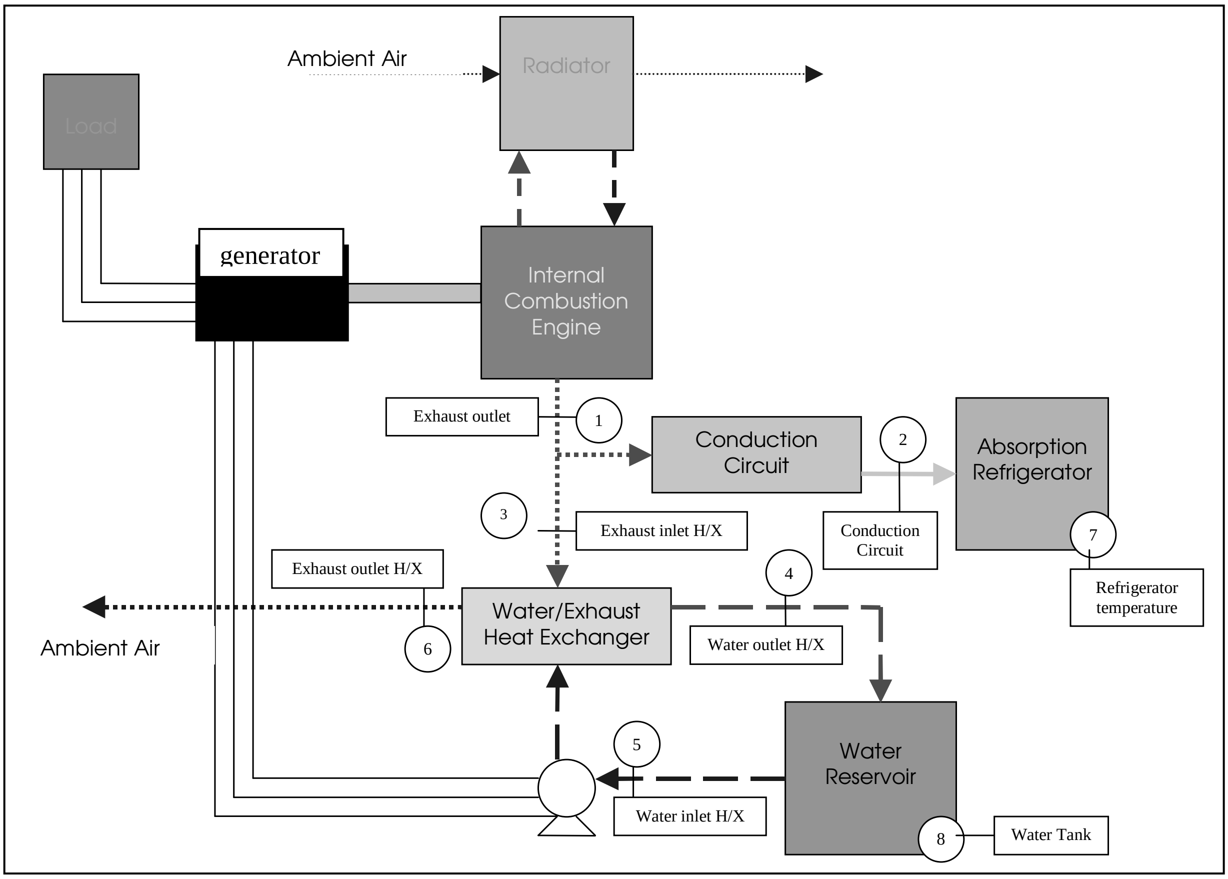

Figure 3. Complete diagram of the trigeneration system

3. TESTING AND ANALYSIS

Before testing could begin proper precautions were taken and a specific operating procedure was generated. For the purpose of testing an appropriate load was chosen that would remain constant without overheating for a significant period of time. A 20 inch high velocity circulating fan and the re-circulating pump used for the water heating unit was loaded to the generator. During the test run the voltage supplied and the current drawn under this load were measured using a multimeter. The voltage and current were 125V and 3.4A. This yields a 425W load on the generator. The fuel consumption rate was also measured over the time of the test run. Measurements were taken roughly every 15 minutes. The graph below in figure 4 shows fuel consumption vs. time.

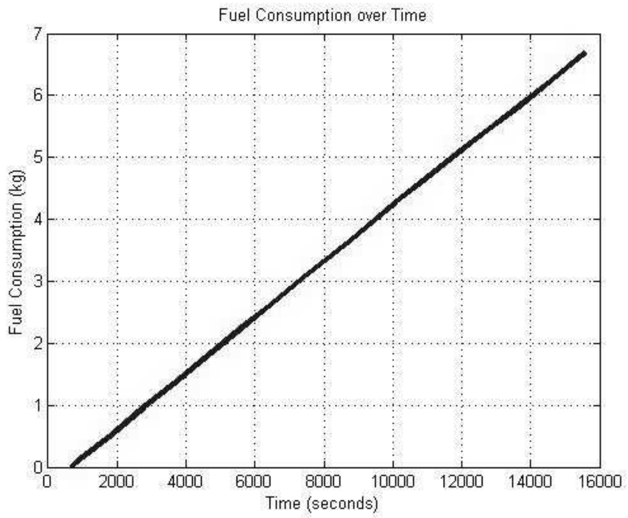

Figure 4. Fuel consumption vs. time

The engine expended approximately 6.69kg of gasoline over approximately 4 hours and 19 minutes. Comparing the trend of this graph an average fuel consumption rate of 0.0004kg/sec for the given load was calculated.

The temperature of the refrigerator was observed over the course of the test run to identify the time it takes to reach a minimum steady state temperature. The graph below, in Fig. 5, shows the relationship between the conduction circuit temperature and the refrigerated space temperature for the entire time period of the test run.

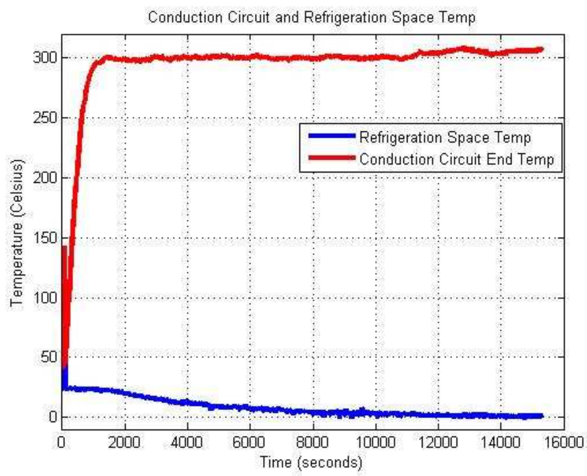

Figure 5. LabVIEW data collected from conduction circuit and refrigerator temperatures

The initial and final temperatures of inside the refrigerator were 23.87°C and 3.2°C. The conduction circuit data was plotted on the same graph to compare the rise in conduction temperature to the fall of the refrigerated space temperature. The temperature inside the refrigerator did not significantly decrease until the conduction circuit temperature reached approximately 294°C at a time of roughly 23 minutes. The temperature inside the refrigerator steadily decreased until it reached a steady state temperature of roughly 3°C at time 2 hours and 56 minutes. The temperatures of the conduction circuit and inside the refrigerator then maintained these constant values for the duration of the test run.

The inlet and outlet temperature of the water reservoir, which was filled to a capacity of approximately 18 gallons, was monitored and the temperature profile was plotted vs. time. This relationship can be seen in figure 6 below.

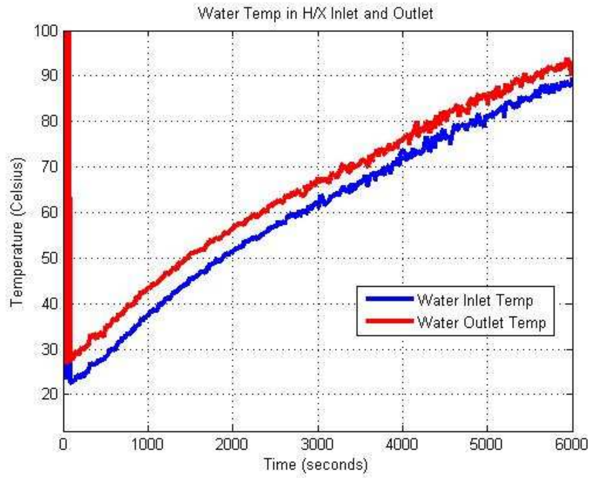

Figure 6. LabVIEW data collected from water inlet/outlet temperatures

From the graph it can be seen that the initial and final temperatures of the water were approximately 23.0°C and 95.0°C respectively. Higher water temperatures could be achieved, the temperature of 95.0°C was taken as the maximum during the test run for safety reasons. The time it took to reach this maximum final temperature was 1 hour and 43 minutes. This time period is significantly shorter than the time it took the refrigerator to reach its minimum steady state temperature, therefore the water tank was partially drained and refilled multiple times so that operation of the system could continue without damage to the water-heating unit. The difference between the inlet and outlet temperatures shows that the water gained an average of 1.6°C after each pass through the heat exchanger based on the flow rate of 7.5gpm through the heat exchanger.

Lastly, the exhaust gas initial and final temperatures of the inlet (at the header) and outlet were monitored. A graph showing these values vs. the time of the test run can be seen in figure 7 below. The exhaust gas inlet temperature initially jumps to a temperature of 693°C while the exit temperature stays relatively constant at 50°C. The slight drop of the exit temperature correlates to the time periods where the water tank was partially drained and refilled.

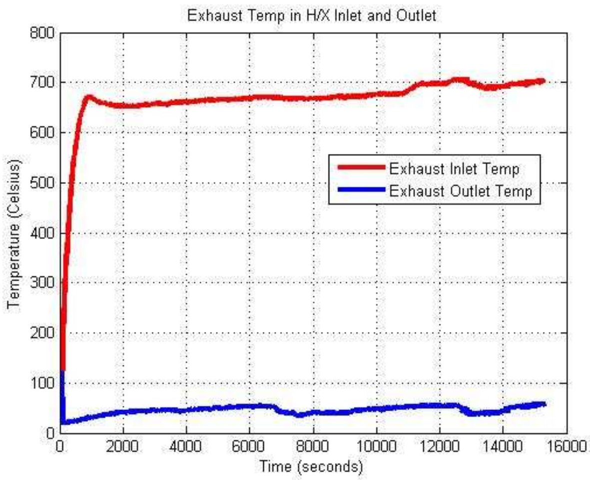

Figure 7. LabVIEW data collected from exhaust inlet and outlet temperatures

With the temperature profiles the total amount of heat recovered from the exhaust gas was calculated. The first parameter calculated was the total amount of input energy. This was determined by multiplying the lower heating value (LHV) of gasoline with the mass flow rate of the fuel. Given the LHV of 41760kJ/kg (Chejne, 2000) and the mass flow rate of 0.0004kg/sec the input energy was found to be 16.7kW. The water-heating unit recovered 3.31kW of heat from the exhaust gas. When including losses this value decreases to 3.03kW. The heat recovered by the refrigerator was estimated from the heat transferred to the boiler from the conduction circuit. From the end temperatures of the conduction rod and its known geometry, it was determined that 142.7W of energy was transferred from the conduction circuit to the boiler. The refrigerator was rated at 115W and the rod was designed to transfer this amount. When losses to atmosphere by convection were included the total heat recovered by the conduction circuit was reduced to 128.0W.

In order to calculate the power rating of the engine at the given load the torque of the engine shaft needed to be measured. This proved to be an unattainable parameter at the time of testing. Assuming a typical efficiency for an engine of this size (25%) and the calculated value for input energy, the power rating was estimated to be 4.62kW. Next, the heat recovered by the water-heating unit needed to be calculated. With the initial and final temperatures known along with a mass of 68.14kg in the tank the heat gained by the water was determined.

4. CONCLUSIONS

The goal of this project was to develop a tri-generation system for the simultaneous production of electricity, hot water and refrigeration. A prototype was designed using an internal combustion engine as the power source. Electricity was then produced by coupling an AC generator directly to the engine shaft. A direct drive coupler was used to allow for complete transfer of shaft work to the generator. Hot water was created by transferring heat from the exhaust gas to the water through a spiral plate heat exchanger. The advantage of this particular heat exchanger was the low exhaust gas pressure drop (less than 1psi). The refrigerated space was produced by utilizing an absorption type refrigerator that was also powered by recovering heat from the exhaust gas. This was accomplished by using a conduction circuit. Using conduction was advantageous over other designs because of its simplicity and manufacturability. The system was made portable by mounting all subsystems onto a wheeled two-tier stainless steel frame. Subsystems were made modular by utilizing threaded union fittings within the piping system. This entire system was designed, built and tested within a budget of US$3500 dollars. The system was developed by a group of Mechanical Engineering students as part of the Capstone Senior Design course.

Fuel consumption was also measured during testing to determine the amount of input energy required by the engine under the test load of 425W. It was found to be 0.0004kg/sec. The conduction circuit reached the required temperature of about 300°C and transferred approximately 128.0W to the refrigerator boiler. This correlated to an internal refrigerator temperature of approximately 3.2°C in 3 hours. Eighteen gallons of water were brought to a final temperature of 95.0°C from an initial temperature of 23.0°C in 1 hour and 43 minutes. With this temperature rise, 3.03kW was recovered from the exhaust gas over the given time period. The total amount of heat recovered by the system was 3.2kW.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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7. RESPONSIBILITY NOTICE