AC 2009-1640: HANDS-ON EXPERIENCE WITH RANKINE CYCLE IN THE THERMAL SCIENCE LABORATORY COURSE

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Hands-On Experience with Rankine Cycle in the Thermal Science Laboratory Course

Abstract

Thermal Science laboratory is the third course in the sequence of four mechanical engineering laboratories offered by the Mechanical Engineering Department at North Carolina A&T State University University. The course is one credit hour, meeting once a week for two hours. The course includes selected experiments on heat transfer and thermodynamics.

In an effort to give students a combination of theoretical background and hands-on experience, a new experiment on Rankine Cycle was introduced. This paper describes the experiences the students gained in the concepts of thermodynamic cycles, mass and energy conservation and electrical power generation. During this laboratory the students actually learned how to operate a table top steam-electric power plant; collected and analyzed the output data that included heat rate calculations, cycle efficiency, turbine efficiency & energy balance studies, and related the experimental result to the theory learned in the thermodynamics course.

This experiment complemented the thermal science laboratory course and fully integrated some aspects of thermodynamics and enhanced the student's learning process. The broader educational objectives are to improve the students' understanding of thermodynamics, to help them integrate this knowledge with other subjects, and to give them a better basic understanding of the first and second law of thermodynamics. Practically speaking, it also gives them insight into the actual operation of a steam turbine electrical generation power plant, which may inspire some to eventually pursue a career in this field.

Introduction

This experiment is designed to give the students a hands-on experience with a Rankine Cycle, and to directly relate the mechanical device to the theory learned in a typical thermodynamics course. This paper describes the experiences the students gained in the areas of thermodynamics and power generation. The laboratory introduces the students to the basic principles of a real steam power plant. During this experiment the students actually learn how to operate a table top steam power plant, collect and analyze the output data and relate the result to the theory learned in the thermodynamics courses. The broader educational objectives are to improve the students' understanding of thermodynamics, to help them integrate this knowledge with other subjects, and to give them a better basic understanding of how a steam power plant works that include:

- Energy relationships and the First Law of Thermodynamics.
- Cycle analysis and the Second Law of Thermodynamics.
- Control volume analysis.
- Entropy analysis.
- Isentropic analysis and the study of turbine/nozzle efficiency.

- Heat transfer analysis and the study of boiler efficiency.
- Combustion processes.
- Vapor power system fundamentals.
- Electric power generation.
- Experimental and data acquisition technique.

Specifications of the Rankine Cycle Used in this Experiment

The steam electric power plant used in the laboratory is known commercially as the "Rankine Cycler^{TM} ", Figures 1-7, and is manufactured by Turbine Technologies, Ltd. It consists of a tube-type fossil-fueled boiler with an operating pressure of 120 psig (827 kPa) and temperature of 482° F (250° C), along with a steam turbine/generator and condenser tower mounted on a rigid mobile frame. Steam rate is adjustable through a steam admission valve which regulates turbine speed and power output. The axial flow turbine drives an alternating current generator. The 4 pole generator provides AC and DC output capabilities. Generator output is capable of delivering 15 Volts at 1 Amp to an infinitely adjustable 15 Watt load. The unit includes analog boiler pressure gauge, along with generator voltage and current meters. An on board data acquisition system provides detailed operational data from selected points in the system which can be graphed and used by students to analyze system performance. In summary the steam electric power plant used in this experiment has the following specifications:

- Consisting of a fossil-fueled boiler, steam turbine and condenser tower mounted on a rigid, mobile frame.
- Boiler of a tube-type, flame through design with access doors to view the inner workings.
- Steam rate adjustable through a steam admission valve, regulating turbine speed and power output.
- Axial flow turbine used to drive an alternating current generator.
- Generator output to be rectified allowing the output of direct current.
- Generator output capable of delivering 15 Volts at 1 Amp to infinitely adjustable 15 Watt load.
- The unit include analog boiler pressure gauge, generator voltage and generator current meters.
- The unit equipped with a USB based digital data acquisition system complete with computer and user configurable data acquisition software capable of measuring and recording analog, digital and frequency signals.
- The unit equipped with calibrated transducers and thermocouples capable of measuring boiler temperature and pressure, turbine inlet and exit temperature and pressure, turbine RPM, fuel flow rate and generator load, voltage and current.

Details Specifications

Dimensions:	58 x 48 x 30 inches (148 x 122 x 77 cm)
Weight:	400 lbs (182kg)
Instrumentation:	Digital: High Speed Data Acquisition System
	20 Analog IN - 16 Digital IN/OUT - 4 Frequency/Pulse IN

Sensors
- Boiler Temperature and Pressure
- Turbine Inlet Temperature and Pressure
- Turbine Exit Temperature and Pressure
- Turbine RPM
- Fuel Flow
- System Electrical Load
- Generator Voltage Output & Current Draw

Analog: Boiler Pressure, Generator Voltage Output & Current Draw

Operating Conditions / Limitations

Boiler:	Pressure 120 psi (827 kPa), Temperature 482˚ F (250˚ C)
Generator:	15.0 Volts, 1.0 Amp (Total Load of 15.0 Watts)

Operating Requirements

Power:	120V single-phase 60Hz
Fuel:	Liquid Petroleum

Figure 1. Rankine Cycle Steam Turbine Power System

Figure 2. Steam Generation Boiler

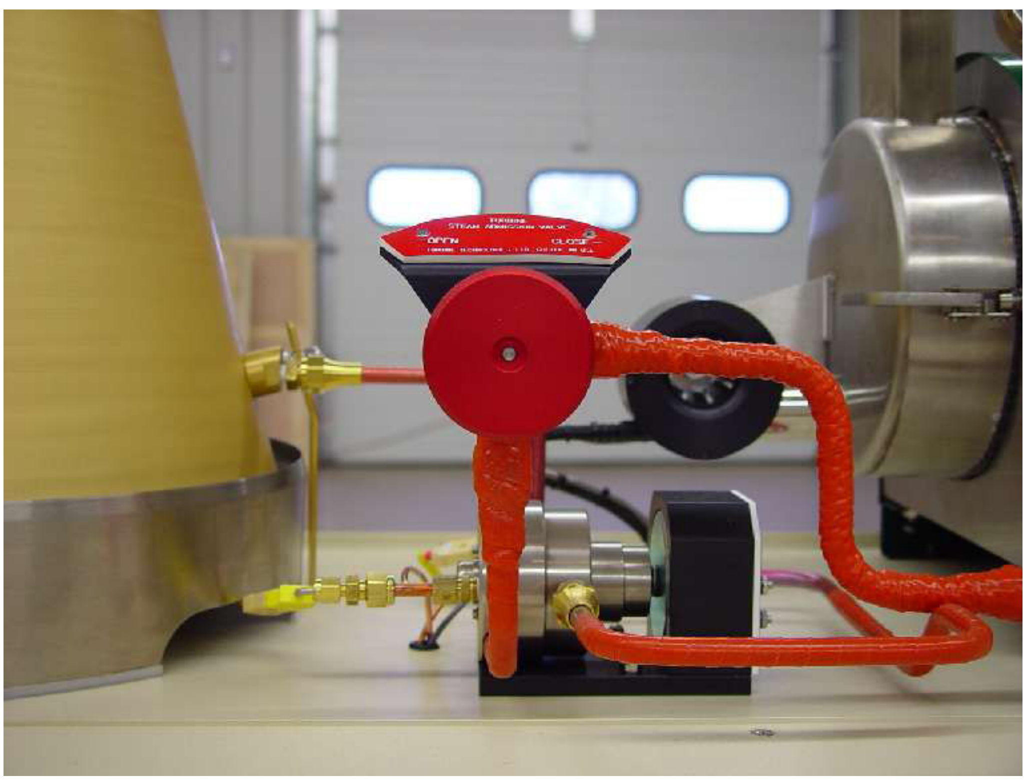

Figure 3. Steam Admission Valve

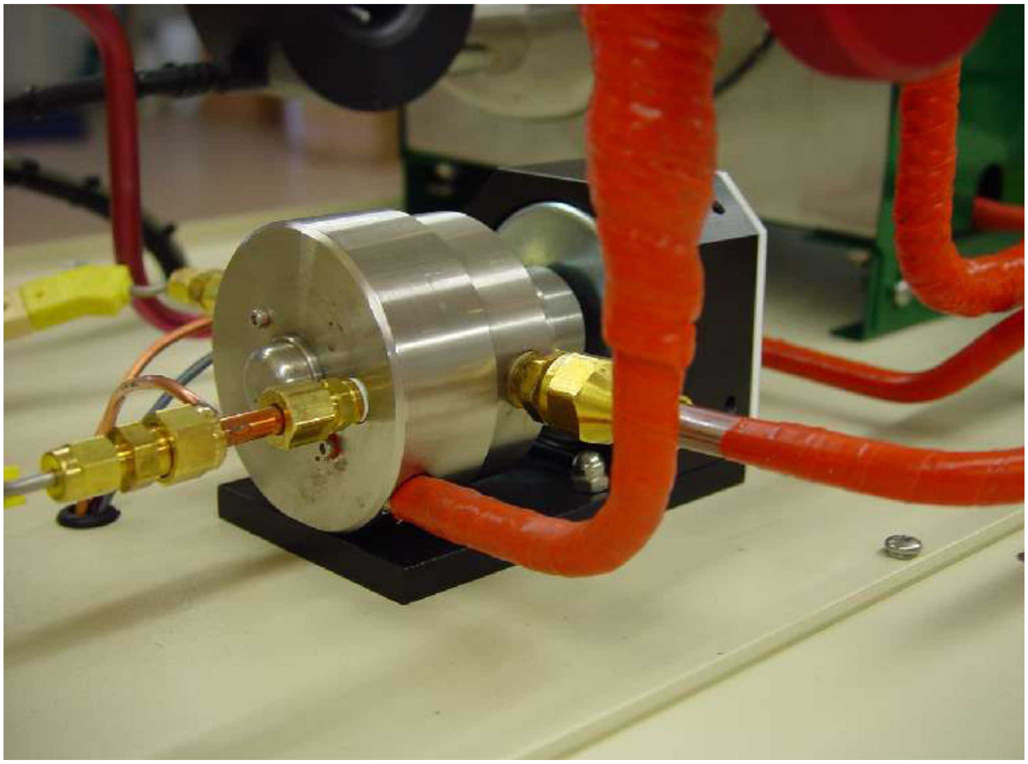

Figure 4. Steam Turbine Impulse Micro Steam Turbine driven by steam flow

Figure 5. Impulse Steam Turbine Wheel / Housing Detail View

Figure 6. Four Pole AC/DC Electrical Generator Driven by turbine to generate electricity.

Figure 7. Condenser Tower

Experimental Procedures - Cycle Analysis and Performance

Refer to the schematic diagram of the Rankine cycle, Figures 8-9. which is made up of four irreversible processes:

1 – 2 Isentropic compression in a pump
2 – 3 Constant pressure heat addition in a boiler
3 – 4 Isentropic expansion in a turbine
4 – 1 Constant pressure heat rejection in a condenser

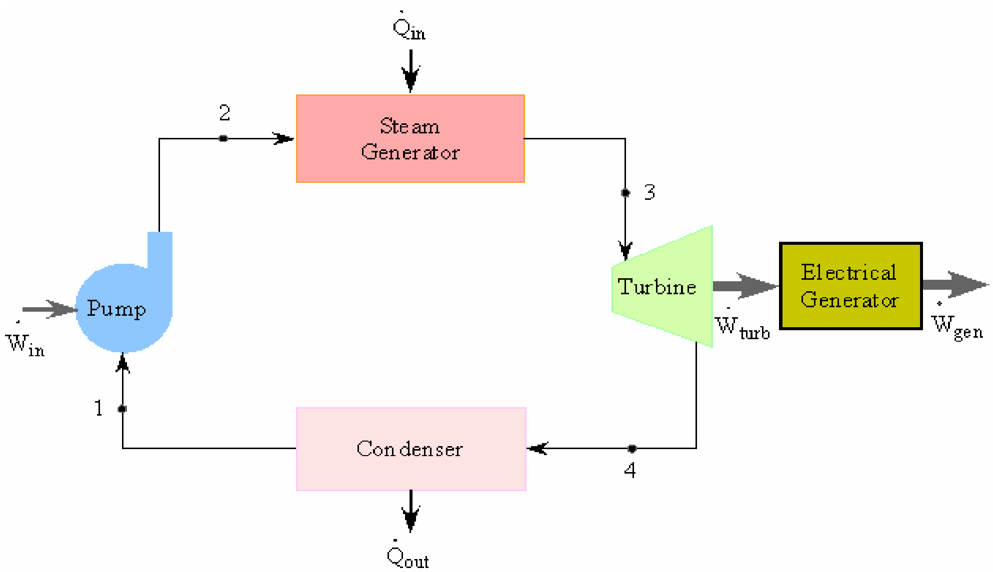

Figure 8. Components Associated with a Simple Rankine Cycle

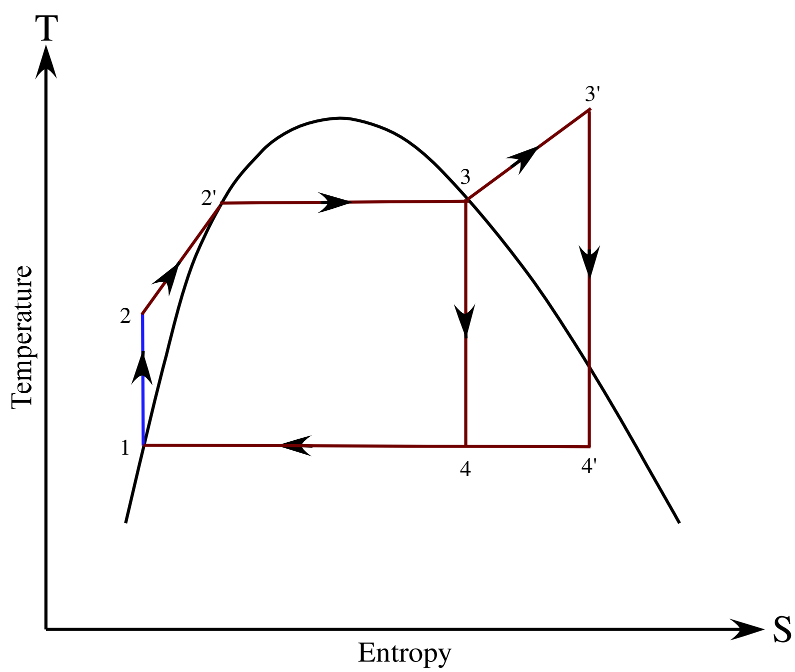

Figure 9. Simple Rankine Cycle T-s Diagram

Cycle Analysis:

The thermodynamics efficiency is defined as:

$$\eta = \frac{\textbf{useful work produced}}{\textbf{energy supplied}}$$

$$\eta_{th,Rankine} = \frac{\dot{W}_{turbine,out} - \dot{W}_{pump,\text{int}}}{\dot{Q}_{in}}$$

where,

$$\dot{W}_{turbine,out} = \dot{m}(h_3 - h_4)$$

$$\dot{W}_{pump,in} = \dot{m}(h_2 - h_1)$$

$$\dot{Q}_{in} = \dot{m}(h_3 - h_2)$$

$$\eta_{th,Rankine} = \frac{(h_3 - h_4) - (h_2 - h_1)}{\dot{h}_3 - h_2}$$

Experimental Results

Figures 10-16 shows typical output results of the steam power plants.

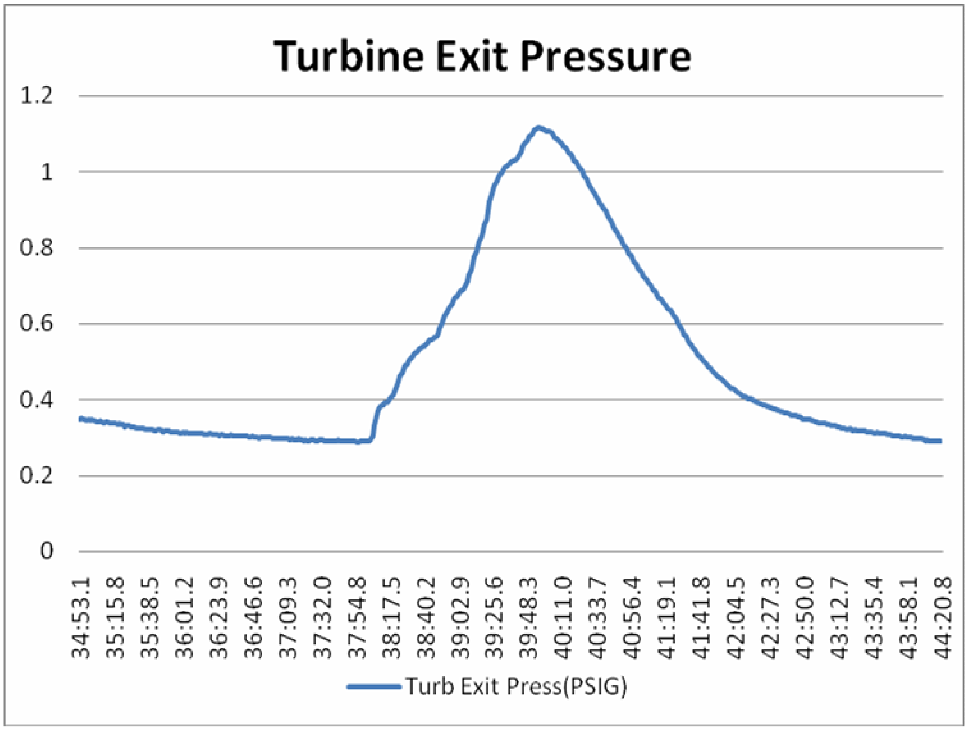

Figure 10. Turbine Exit Pressure vs. Time

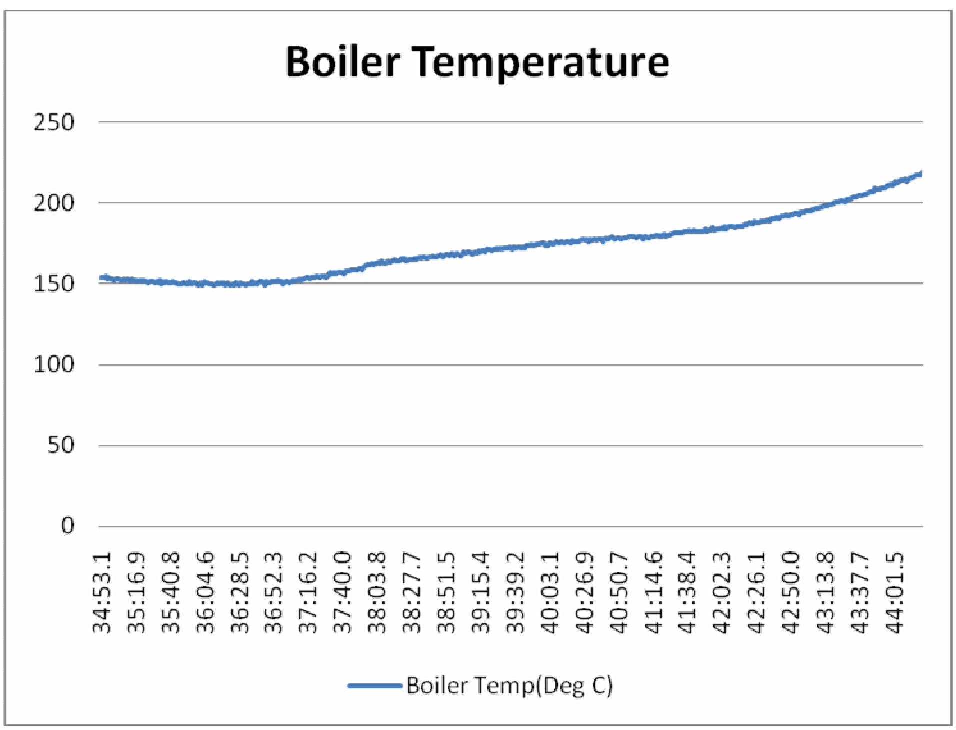

Figure 11. Boiler Exit Temperature vs. Time

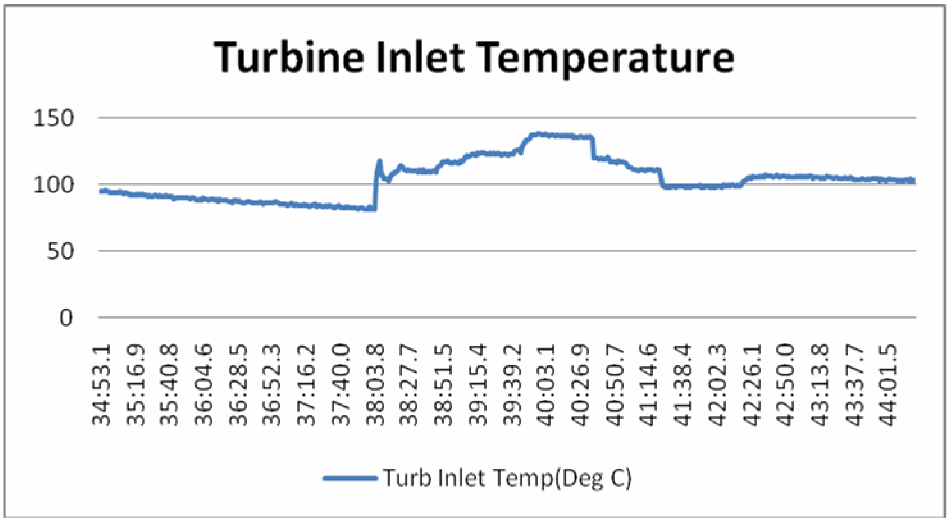

Figure 12. Turbine Inlet Temperature vs. Time

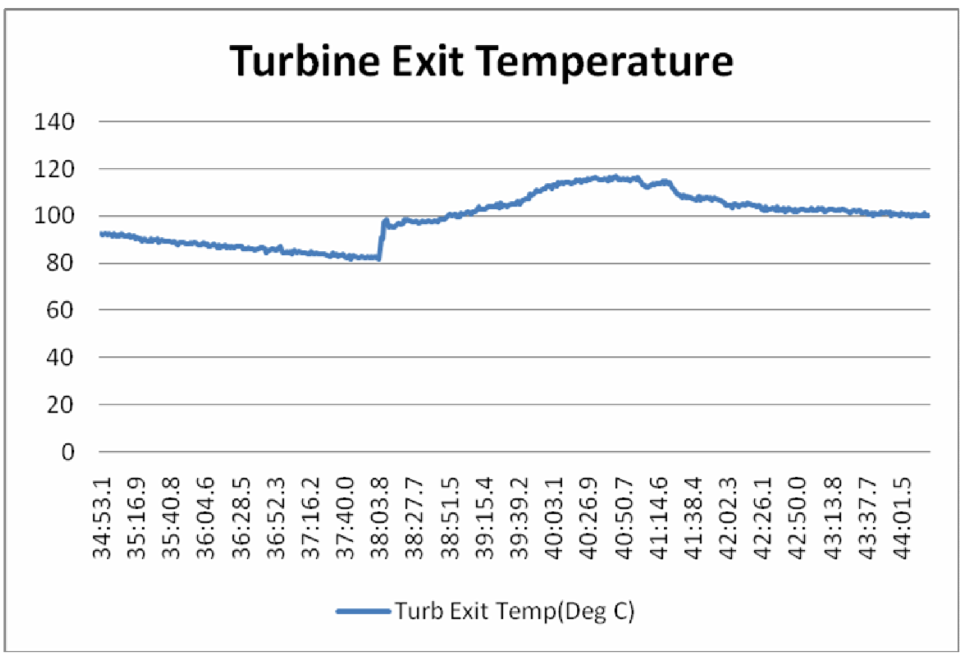

Figure 13. Turbine Exit Temperature vs. Time

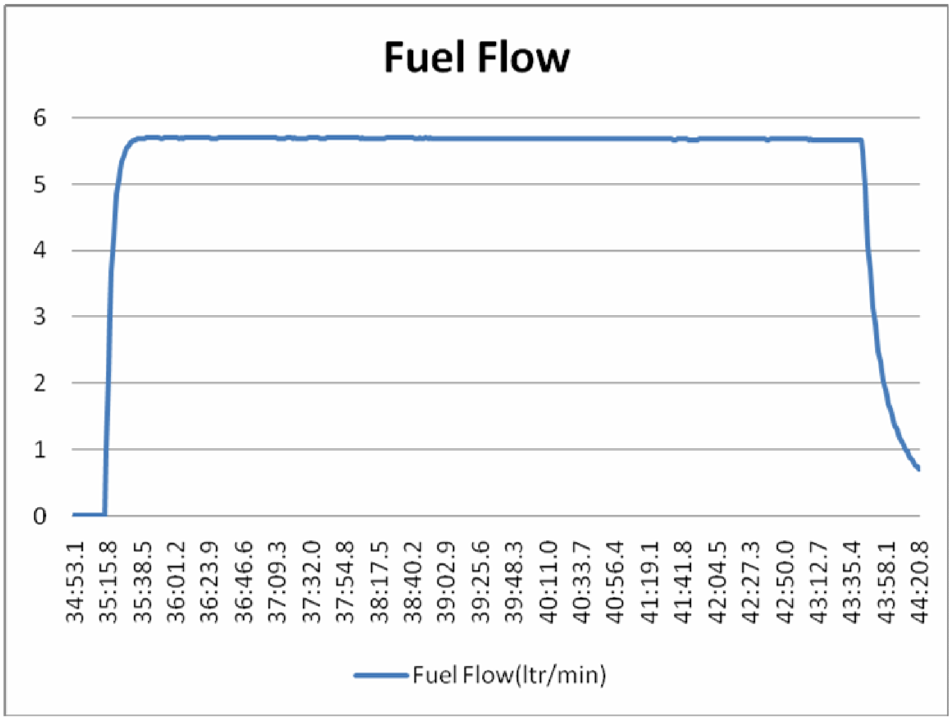

Figure 14. Fuel Flow vs. Time

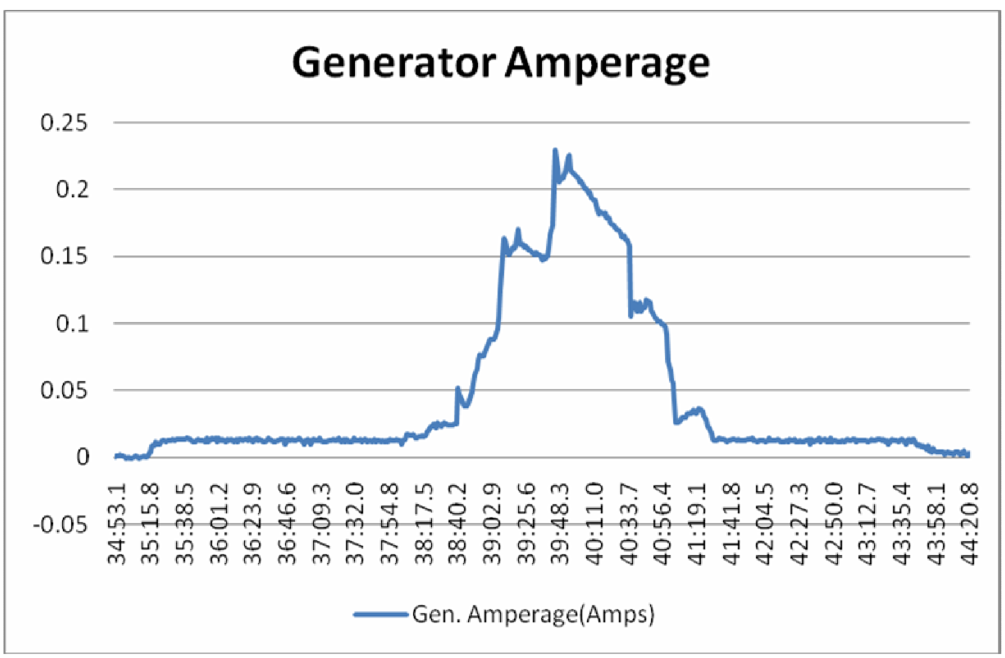

Figure 15. Generator Amperage vs. Time

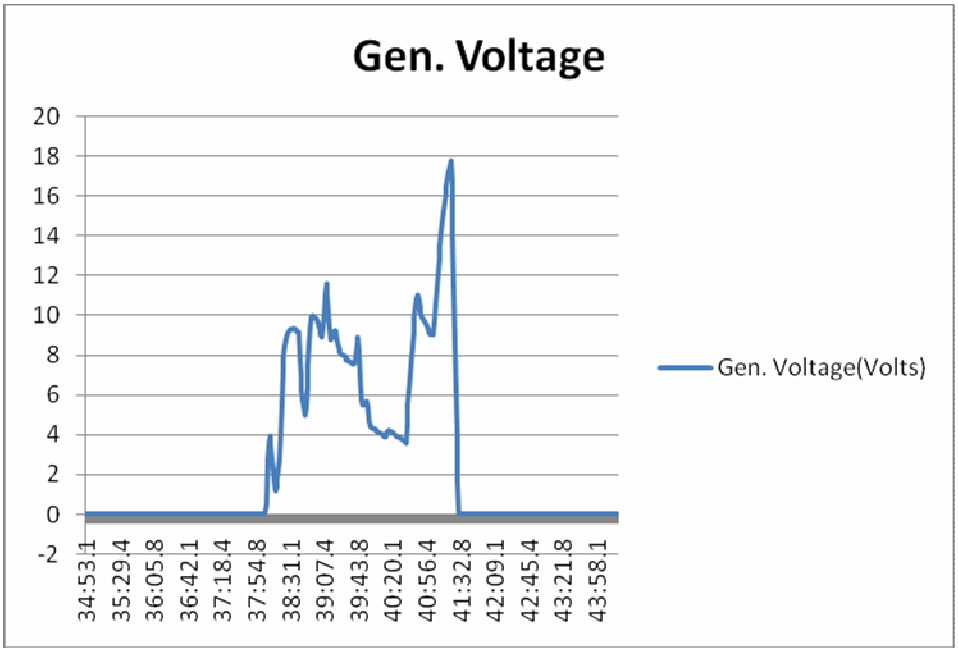

Figure 16. Generator Voltage vs. Time

Conclusions

The experiment provided the students in the thermal science laboratory course with a hands-on experience with a real steam power plant. The students were able to operate the small scale table top steam power plant and analyze the output results under various conditions and relate it to the theory learned in their thermodynamics courses.

References

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2. http://www.turbinetechnologies.com
3. "THERMODYNAMICS AN ENGINEERING APPROACH", Fifth Edition, Yunus A. Cengel & Michael A. Boles, McGraw-Hill, Inc. 2006.
4. Thermal-Fluid Science – An Integrated Approach, S.R. Turns. Cambridge,