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Undergraduate Freshman Developing Advanced Research Project: Learn-by-Discovery Module to Investigate Energy Efficiency and Energy Conservation Principles

Dr. Irina Nicoleta Ciobanescu Husanu, Drexel University (Tech.)

Irina Ciobanescu Husanu, Ph. D. is Assistant Clinical Professor with Drexel University, Engineering Technology program. Her area of expertise is in thermo-fluid sciences with applications in micro-combustion, fuel cells, green fuels and plasma assisted combustion. She has prior industrial experience in aerospace engineering that encompasses both theoretical analysis and experimental investigations such as designing and testing of propulsion systems including design and development of pilot testing facility, mechanical instrumentation, and industrial applications of aircraft engines. Also, in the past 10 years she gained experience in teaching ME and ET courses in both quality control and quality assurance areas as well as in thermal-fluid, energy conversion and mechanical areas from various levels of instruction and addressed to a broad spectrum of students, from freshmen to seniors, from high school graduates to adult learners. She also has extended experience in curriculum development. Dr Husanu developed laboratory activities for Measurement and Instrumentation course as well as for quality control undergraduate and graduate courses in ET Masters program. Also, she introduced the first experiential activity for Applied Mechanics courses. She is coordinator and advisor for capstone projects for Engineering Technology.

Mr. Carlos Michael Ruiz, Drexel University (Eng. & Eng. Tech.)
Benjamin G Cohen, Drexel Department of Engineering Technology

Undergraduate Studying Engineering Technology with a dual concentration in Mechanical and Electrical fields.

Ms. Sarah Renee Andrieux

Drexel University Class of 2021, BS Mechanical Engineering

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Abstract

STEM education's importance is ever increasing with the expansion of technical fields. Learning about energy and energy efficiency is fundamental to engineering students. Theoretical concepts are better understood if students are involved in practical approach of learned concepts. Specifically, the first law of thermodynamics describes the natural and proven law that all energy is conserved and allows quantification of energy. This project describes the design and construction of an apparatus that demonstrates the First Law of Thermodynamics and subsequently energy quantification, energy conversion and energy efficiency along with learning modules to be used in an educational setting.

Introduction

STEM has been a heavily invested topic within educational curricula, from pre-K through high school and college. A persistent problem with science, technology and engineering related efforts is the ever-burdening costs of the student laboratory experiments. Also, the space associated with laboratory activities, from storage to laboratory to waste removal is constant deterrent for integration of new projects in the curricula. Therefore theory becomes more and more disconnected from its applications. It is important to have cost efficient modules available to integrate real-life applications into theoretical traditional lectures. Over the years several methods have been employed to enhance student learning and increase student exposure to competency-based education. These methods range from multimedia developments, problem-based and project based learning, collaborative learning and cooperative education. A diverse number of published papers emphasized algorithms of improving student understanding and concept retention in thermal-fluid sciences type of courses, calling attention to the important role of learning-by-discovery approach. [1], [2], [3]

Thermodynamics and fluid mechanics concepts are involved in numerous educational and career fields such as engineering, biology, chemistry, medicine, and other general sciences, which are all important and growing fields in the job industry. Therefore, learning the basics of thermodynamics and fluid mechanics is vital in the education of students. Learning about energy and energy efficiency is fundamental to engineering students as well. Theoretical concepts are better understood if students are involved in practical approach of learned concepts. [4] Specifically, the first law of thermodynamics describes the natural and proven law that all energy is conserved and allows quantification of energy. This project describes the design and construction of an apparatus that demonstrates the energy conservation principle and energy conversion and efficiency along with learning modules to be used in an educational setting. The apparatus consists of a gear water pump actuated by an air motor. Both air and water cycles are

evaluated using temperature and pressure sensors as well as the energy conversion between the air motor and gear pump. Students will be able to use various forms of energy conservation equation to evaluate the principles of energy and mass conservation and energy efficiency. The theoretical work has been performed by another Drexel University's Engineering Technology undergraduate junior student as independence study project.
We describe a freshman student's project development as well as the subsequent learning modules developed for a variety of sophomore to pre-junior courses in thermal-fluid sciences and also in courses related to teaching fundamentals of renewable energy sources [5] , [6]. The assessment of the implementation of some of the experimental activities during the first year is presented. Experiential activities will be described in such detail, so they can be replicated by any interested program or instructor, including a clear alignment of the Student Learning Objectives with measurable course assessment and evaluation tools and methods.

The project was created by a mechanical engineering freshman student within the university's STAR (Students Tackling Advanced Research) scholars program, under the guidance and mentorship of one of the authors and faculty with Engineering Technology Department. This program is designed to attract young creative minds in their first-year to participate in faculty-mentored innovative or creative work or research during the summer after their freshman year.

The project developed involved a dual air and water system, using motor and pump as well as appropriate instrumentation to measure desired parameters in order to estimate and quantify energy and subsequently efficiency of the subsystems or components. The student developed competencies in the area of analytical modeling, CAD 3D modeling to simulate final design assembly, additive manufacturing, and system integration. Student also explored concepts from fluid mechanics and thermodynamics while performing research. The objective was to create a system capable of capturing energy transfer and conversion between two coupled fluid systems. The total cost of the system was less than \$800 to create, while sophisticated educational experimental setups normally cost upwards of \$1,500. With this assembly, educational institutions could replicate similar experimental modules that are efficient and cost effective. Learning modules provide an enhancement to student learning outcomes as students become engaged to understanding the physical system and its functionality that may not appear clearly on paper. This project was successfully completed and analyzed for data collection through thermal imaging, strobe tachometer, integrated thermocouples, flow meters, and pressure gauges within the subsystems.

Project Student Learning Outcomes

For all Mechanical Engineering majors and most if not all engineering majors, a core curriculum requirement is a course on thermodynamics to graduate. At Drexel University, mechanical engineering and engineering technology majors must fulfil this requirement during sophomore year. STAR students are recruited at the conclusion at their freshman year. Consequently, as a freshman, rising sophomore, the student will be getting a head start on the material of the course by working on and completing this research project.

During undergraduate research projects, students gain in-depth knowledge in a particular area of investigation. Student learnt basic thermodynamic relations regarding energy conversion and energy efficiency as related to integration of the theory with practical approach. Also, she gained knowledge in the introductory concepts of fluid dynamics, fluid power and mechanical design. She also was introduced to manufacturing notions and practices.

Her knowledge was assessed continuously as she worked on a daily schedule in our lab, under the supervision of her mentor and a graduate research assistant. The student built the prototype of the device in a work-in-progress phase and she developed the preliminary testing procedures. The project milestones are described below:

1. Week 1-2 Literature survey and also background research in both thermodynamics and engineering education
2. Week 3-4 Theoretical approach developed; schematic of the prototype, bill of materials and components ordered
3. Week 5 Building the prototype and developing preliminary testing procedures
4. Week 6-7 Finalizing the prototype and testing procedures; learning modules for the laboratory module
5. Week 8-9 Developing abstract, report and finishing touches for the learning modules (see deadlines for poster, abstract)
6. Week 10 Report and Poster presentation

STAR Research Project Goals

Provide an experimental set-up accompanied by the associated learning modules to be used for introductory courses in thermodynamics and fluid mechanics areas of study, by proving First Law of Thermodynamics as Energy Conservation Principle. Experimental system is to be used in an educational setting for middle school to high school students, and freshmen year college students. The following objectives are to be achieved as learning outcomes

1. Quantify energy entering in and existing of a system
2. Using Bernoulli’s equation to quantify energy
3. Using energy conservation principle to prove the First Law of Thermodynamics

Methods

1. In the apparatus, air is pushed into the system - where its temperature, flow rate, and pressure are measured.
2. The air motor will power the water gear pump. The goal is to study the energy losses and energy conversion from the air side to the shaft and to the water side.

3. Comparing the temperature, pressure, and flow of both the air and the water, the energy of each medium should hypothetically be equivalent.
4. Any loss of energy will be due to the emission of heat, caused by friction.

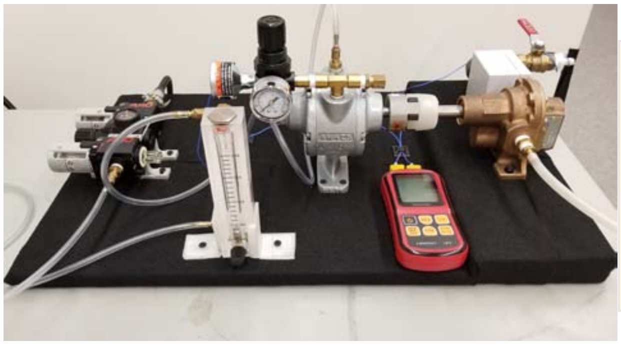

Figure 1: Complete setup of apparatus

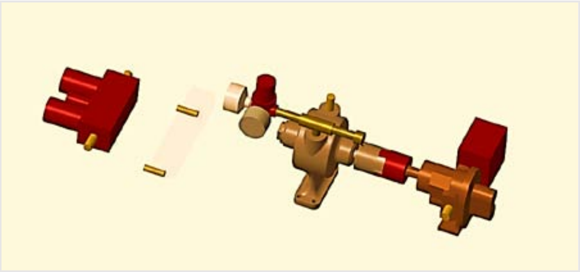

Figure 2: CREO Parametric Simulated 3D Model of the Apparatus

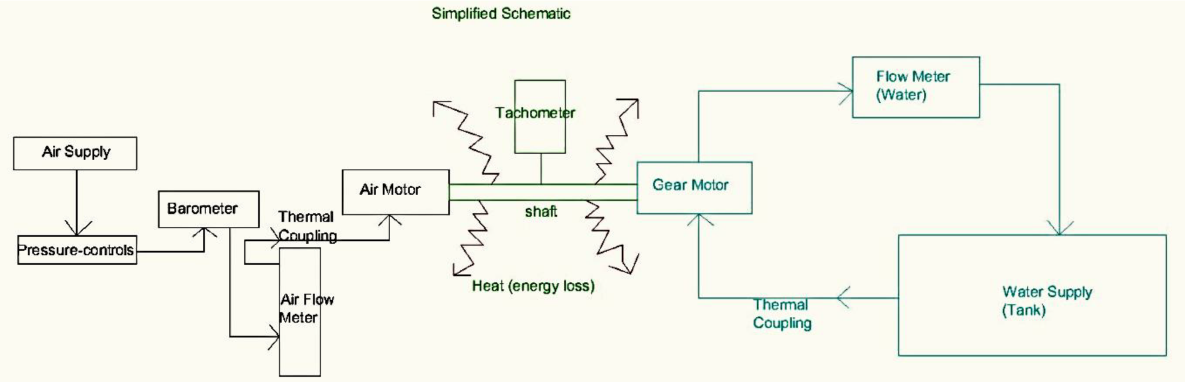

Figure 3: Schematic of the learning module

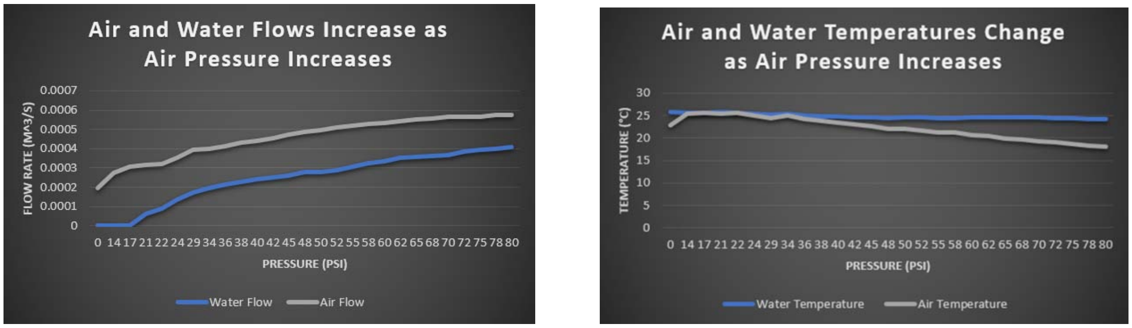

Figure 4: Air and water flow rates and temperature variations with air pressure

Using the information from the graphs above and incorporating them into the Modified Bernoulli’s Equation, the head losses from the air and water systems are calculated. As the input air pressure increases, the internal gears of the pump, motor, and shaft rotate faster, increasing friction, mechanical work, and kinetic energy, therefore causing more energy losses.

Modified Bernoulli’s Equation

$$Z_1 + \frac{p_1}{\gamma} + \frac{v_1^2}{2g} + H_p - H_m - H_L = Z_2 + \frac{p_2}{\gamma} + \frac{v_2^2}{2g}$$

Where g is the gravitational acceleration, p is the pressure and γ is the specific weight of the fluid, Z is the elevation and v is the velocity. H denotes head due to the presence of the motor, pump and losses. In order to determine the torque of the gear pump, the rpm of the pump’s shaft must be measured using a tachometer.

$N[\text{rad/s}] = \frac{2\pi}{60} N[\text{rpm}]$, where N[rpm] is the measured value from the tachometer

$$\text{Torque: } T[\text{N}\cdot\text{m}] = \frac{\text{Pump Power[W]}}{N[\text{rad/s}]}$$

For this project, we assume that the torque of the air motor is equivalent to the torque of the gear pump. Therefore, we could calculate the overall efficiency of the gear pump.

$$\eta_{\text{overall}} = \frac{(\text{pressure})(\text{flowrate})}{T \times N}$$

To calculate the power of the air motor,

$\text{Power} = H_m[\text{m}] \times \gamma \times Q$, where Q is the volumetric flow rate and H_m is the head pump.

$$\text{Power [kW]} = \frac{T[\text{N}\cdot\text{m}] \times N[\text{rad/s}]}{1000}$$

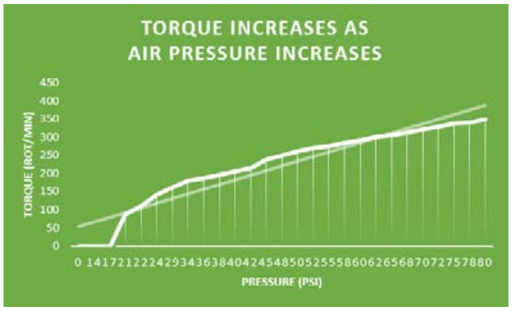

Figure 5: Experimental torque measurements as a function of air pressure

The appropriate equations are applied to the air system and water system, and the energy head losses are compared.

The torque, rotational speed, of the shaft is proportional to the input air pressure. The stronger the force of moving air inside the air pump, the faster its internal gears rotate, which in turn causes the shaft to rotate.

The system can prove energy conservation in a closed system and the conversion of energy from the air system to the water system; hence, the air motor powers the gear pump. By evaluating each side of the system with the Modified Bernoulli's Equation, we were able to calculate the head loss of each subsystem. Overall, the apparatus demonstrates that the energy of air flow is converted to the kinetic energy of the gears within the air motor, which in turn rotates the shaft. This mechanical energy is then converted to the kinetic energy of the gears within the gear pump and then to the energy of water flow. The energy head losses due to couplings, flow meters, the components of the shaft, and the gear pump, and the air motor, will be amounted for using Modified Bernoulli's Equation.

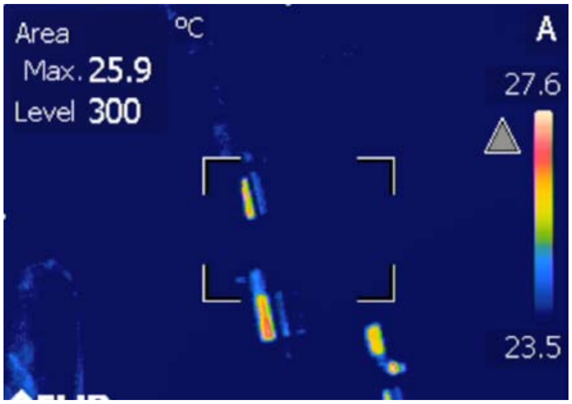

Figure 6: Thermal image of heat loss from shaft

A thermal camera is used in addition to thermocouples to illustrate the heat emissions. As future work, the student will explore improving the system's efficiency with stronger couples, reducing leakage. Also accessibility of the learning module for a larger range of age groups or those with disabilities will be investigates. Students also might be able to assess and address slippage within shaft to demonstrate that we should not assume equivalent torques (Torque of air motor ≠ Torque of gear pump).

Learning Modules - Activities

Two learning modules have been developed to be used for initial courses in Thermodynamics and Fluid Mechanics areas. Students will explore possibility to assess energy balance for each system as well as power transmission in real-like situation, by measuring temperature and air and water pressure changes, and how one parameter may influence another parameter of each system (air and water). Students will explore mechanical limitations of such a systems as well as thermodynamic implications of these limitations. Thermal imaging may be used in conjunction with direct parametric measurement to assess error, uncertainty and estimation of a value assigned to a measurement.

A theoretical model of this device was developed earlier by another student as independent study research. A comparison between mathematical modeling and experimental data will enable students to explore deviation of theoretical models from the physical system as also how well an assumption may describe a real system behavior.

Conclusions

The SLOs related to the course implementation of the learning modules are related to the two main areas: (1) introductory notions for thermodynamics and fluid mechanics and (2) energy conversion and energy efficiency, from estimation to direct quantification. Therefore ABET criteria and b will guide our SLO assessment as main criteria [7]. Also, criterion c will be important to assess, due to experimental nature of the activities developed. The system will be used also to illustrate energy conversion and energy efficiency notions for courses related to “energy and manufacturing”, trying to address the competency gap in this area. Students can explore various aspects of “energy” and related them back to manufacturing systems, methods and techniques such as cooling and heating phenomena in manufacturing processes, energy embedded in a product and so on [8] [9]. The initial learning modules are addressing the instructional needs of the students in Thermodynamics I course for next AY. It will complement the theoretical course modules related to study of control volumes for liquids and gases, will use as comparison base for studying properties of water and air as “pure substances”.

The device was presented at two main events for middle and high school students and received particular attention from STEM inclined students. Students became very easily interested in energy conversion facts and notions and the module facilitated their understanding in this area within minutes. They were curious about varying air and water flowrates as well as air pressure and their interdependence.

The STAR student developed a research project involving building an educational learning module. The main learning outcomes were related directly to the ABET [10] criteria a and b, as she demonstrated abilities in the areas of mathematics, science and engineering . Also the student demonstrated comprehensive skills related to criteria c and d, specifically designing a system and its components for “a broadly defined engineering problem”. She also conducted tests and measurements; she analyzed and interpreted experimental data and she applied her results to results to improve the developed module. She gained new knowledge in the area of mechanical design, being able to created linkages between the components based on manufacturer’s specifications. She used CAD techniques to model the system and component subsystems, and additive manufacturing techniques to generate the necessary parts for the device. The student’s final work was presented as a posted and physical prototype at two main events, being awarded 2nd Place - Engineering at 19th Annual Philadelphia Louis Stokes AMP Research Symposium and Mentoring Conference.

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