AC 2007-27: THE ENERGY SYSTEMS LABORATORY AT KETTERING UNIVERSITY

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Ahmad Pourmovahed is a Professor of Mechanical Engineering at Kettering University. He received his Ph.D. in Mechanical Engineering (1985) and an M.S. in Mechanical Engineering (1979) both from the University of Wisconsin-Madison. After graduation, he worked at General Motors Research Laboratories and Lawrence Technological University. In 1990, he joined Kettering University where he teaches courses in thermal sciences, mechanics, and engineering design and serves as the Director of Energy Systems Laboratory.

The Energy Systems Laboratory at Kettering University

Abstract

Energy Systems Laboratory is a required senior level course for mechanical engineering students at Kettering University (formerly GMI). Approximately 250 students take this course every year. Thermodynamics and Fluid Mechanics serve as pre-requisites for this laboratory course while Heat Transfer is a co-requisite. This class meets six hours a week (two hours of common lecture plus four hours of laboratory experimentation). It deals with detailed application of the first and the second laws of thermodynamics; continuity, momentum, and energy equations; and principles of conduction and convection to a variety of energy systems. A design project is incorporated into this laboratory course. Currently, experiments performed in this laboratory include a *Jet Engine, Road Load Simulation, PEM Fuel Cell Performance, Centrifugal Pump, Fan Laws, Compressible Flow, Pipe Flow and Flow Meters, Lift and Drag, Heat Exchanger, and Cylinder Convection.* Among other things, the students learn how jet engines work; how aircraft wings produce lift; how a fuel cell works; how supersonic velocities are produced; how to use a dynamometer to predict the gas mileage of a car; how to match pumps and fans to piping systems and ducts and how to cool hot objects effectively. They also learn to apply the fundamental principles of thermodynamics, fluid mechanics and heat transfer in an integrated manner to a variety of energy systems. This paper describes this modern laboratory in detail, presents the course pedagogy as well as a summary of the laboratory experiments including photographs of the equipment and sample results obtained in each experiment.

Introduction

Kettering University (formerly GMI Engineering & Management Institute) is a fully cooperative institute that offers degree programs in engineering, sciences and management. All undergraduate students alternate between 11-week periods of study on campus and related work experience at one of over 700 corporations. About 55 percent of Kettering University students are enrolled in mechanical engineering.

Every mechanical engineering student at Kettering University takes a senior-level course entitled *Energy Systems Laboratory. Thermodynamics* and *Fluid Mechanics* serve as pre-requisites for this laboratory course while *Heat Transfer* is a co-requisite. This laboratory course provides students with opportunities to apply fundamental concepts learned in core energy systems courses as well as introduces students to modern measurement techniques and modern engineering tools. The course is intended to provide students with an integrated, hands-on experience since courses in the area of energy systems are often taught in isolation.

Among other things, the students learn:

- how jet engines work
- how aircraft wings produce lift
- how a fuel cell works

- how supersonic velocities are produced
- how to use a dynamometer to predict the gas mileage of a car
- how to match pumps and fans to piping systems and ducts
- how to cool hot objects effectively

The Energy Systems Laboratory also provides research opportunities. The 30-HP re-circulating wind tunnel can be used for research in aero-acoustics and the Digital Particle Image Velocimetry (DPIV) equipment is capable of generating a two-dimensional map of a flow field. A complete Air Delivery System donated by Eaton Corporation and will soon become a part of this laboratory. This system can supply air to a variety of fuel cell systems.

Course Learning Objectives

Upon completion of this course, the student will be able to:

1. apply the fundamental principles of thermodynamics, fluid mechanics, and heat transfer [ABET's A,E,K].
2. apply modern measurement techniques and experimental methods to energy systems [ABET's A,B,E].
3. apply computational techniques to energy systems [ABET's A,E,K].
4. apply team working skills [ABET's D].
5. communicate effectively [ABET's G].
6. design and conduct experiments [ABET's B,E,K].
7. analyze and interpret data [ABET's B].
8. implement experimental results in a design process[ABET's B,C].

Topics Covered

Week	*Topic*
1	Safety Guidelines, Error Analysis, Pipe Flow, Flow Meters
2	Design Project Initiation, Road Load Simulation
3	PEM Fuel Cell Performance
4	Centrifugal Pump
5	Fan Laws, Introduction to DPIV
6	Compressible Flow
7	Jet Engine
8	Design Projects
9	Lift, Drag & Aerodynamics
10	Cylinder Convection
11	Final examination and team design projects

Lecture: One session per week of 120 minutes
Lab: Two sessions per week of 120 minutes each

MECH-422 Energy Systems Laboratory
Representative Lecture/Lab Schedule

Winter 2007	LAB	Common Lecture on Wed
Week 1		
First Session	Safety Guidelines, Error Analysis	
Wednesday		*Pipe Flow, Flow Meters*
Second Session	Pipe Flow and Flow Meters, Design Project Initiation	
Week 2		
First Session	NO LAB (Martin Luther King Holiday)	
Wednesday		*Road Load Simulation*
Second Session	Road Load Simulation (Engine Lab: Room 1-220 AB)	
Week 3		
First Session	Road Load Simulation	[QUIZ #1 Pipe Flow/Flow Meters]
Wednesday		*PEM Fuel Cell Performance+ Guest Speaker*
Second Session	PEM Fuel Cell Performance	
Week 4		
First Session	Design Project	[QUIZ #2 Road Load Simulation]
Wednesday		*Centrifugal Pump and Fan Laws*
Second Session	Centrifugal Pump	
Week 5		
First Session	Fan Laws	[QUIZ #3 PEM Fuel Cell Performance]
Wednesday		***Common Midterm Exam***
Second Session	Introduction to DPIV (Room 2-224 AB)	
Week 6		
First Session	Design Project	
Wednesday		*Compressible Flow*
Second Session	Compressible Flow	
Week 7		
First Session	Compressible Flow	[QUIZ #4 Centrifugal Pump/Fan Laws]
Wednesday		*Jet Engine*
Second Session	Jet Engine (First Floor Test Cell, 1123 MC)	
Week 8		
First Session	Jet Engine	
Wednesday		*No Lecture*
Second Session	NO LAB	
Week 9		
First Session	Design Project	
Wednesday		*Lift, Drag & Aerodynamics*
Second Session	Lift, Drag & Aerodynamics	[QUIZ #5 Jet Engine]
Week 10		
First Session	Lift, Drag & Aerodynamics	
Wednesday		*Cylinder Convection*
Second Session	Cylinder Convection	
Week 11		
First Session	Final Design Project Presentations	
	Common Final Exam	

Topics Covered in Each Experiment

Jet Engines
Types of jet engines, thrust force, component efficiencies, energy balance, emissions

Road Load Simulation
Tractive effort, fuel economy, engine efficiency, energy balance

PEM Fuel Cell
Stack voltage, current and efficiency, polarization curves, cell reversal

Centrifugal Pump
Pump performance maps, pump efficiency, operating point

Fan Laws
Fan performance maps, fan static and total efficiencies, fan laws, operating point

Compressible Flow
Subsonic and supersonic flows, normal shock waves, choking

Pipe Flow
Pipe friction and head losses, velocity profiles, laminar and turbulent flow

Flow Meters
Flow measurement using a venturi, nozzle, orifice or laminar flow meter

Lift and Drag
Pressure distribution above and under wings, lift and drag, wing stall

Heat Exchanger
Heat transfer from a hot to a cold fluid stream, LMTD method, NTU method

Cylinder Convection
Temperature variation with angle, wake behind a cylinder, heat transfer coefficient

Refrigeration and Psychrometry
Vapor-compression refrigeration system, coefficient of performance, properties of humid air

Figure 1 shows the cover page of the textbook used in this laboratory course.

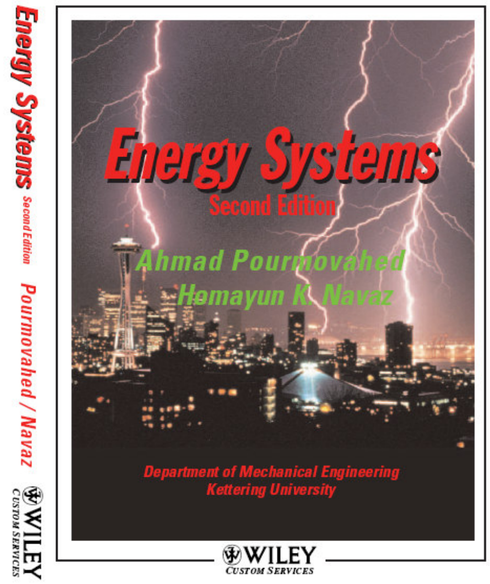

Figure 1: Cover page of the book used for *Energy Systems Laboratory*

Table of Contents for the textbook used[1]

Educational objectives, photographs of the equipment as well as representative data for the experiments currently performed in this laboratory course are shown in Figures 2-21.

Pipe Flow and Flow Meters

Educational Objectives

1. To apply the *Energy Equation* to a piping system that includes a fan.
2. To compare experimentally determined friction factors with published values.
3. To demonstrate the theory, use, and calibration of the following types of flow meters: laminar flow meter, venturi, nozzle and flat-plate orifice.

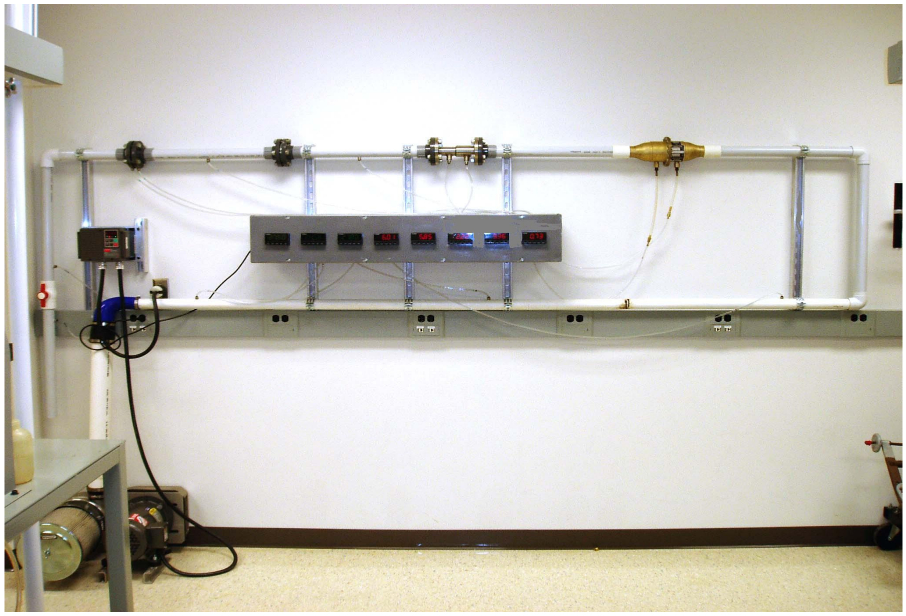

Figure 2: The combined *Pipe Flow and Flow Meters* setup

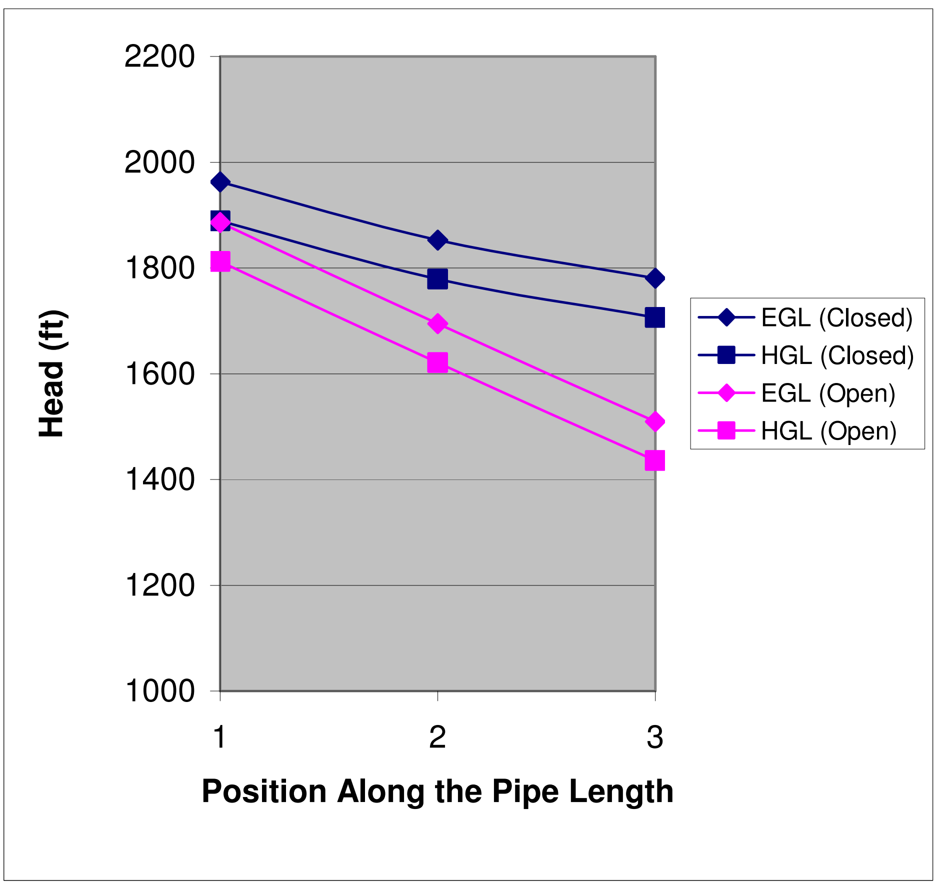

Figure 3: Energy and Hydraulic Grade Lines for the lower pipe

Steady-State Road Load Simulation and Engine Energy Balance

Educational Objectives

1. To predict, by means of a dynamometer test, the performance of a gasoline engine when installed in an automobile and operated at various speeds in third and fourth gears.
2. To determine the effect of road speed and gear ratio on fuel economy and exhaust emissions.
3. To determine the actual thermal efficiency of the engine.
4. To perform an energy balance on the engine.

Figure 4: The six-cylinder gasoline engine and the dynamometer

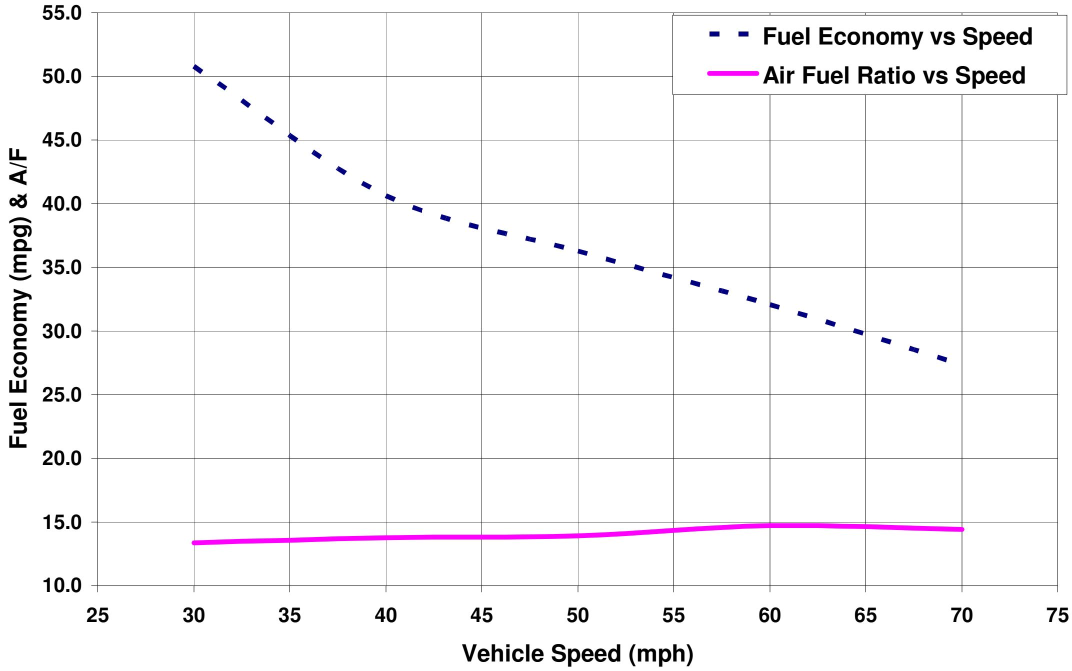

Figure 5: Fuel economy and air fuel ratio (4^{th} gear)

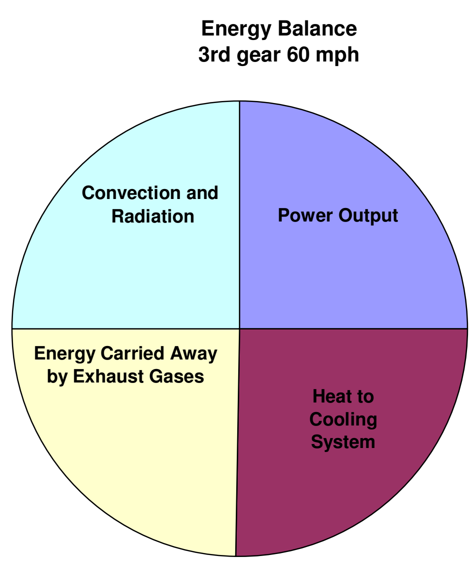

Figure 6: Engine energy balance

PEM Fuel Cell Performance

Educational Objectives

1. To familiarize the students with the principles and operation of a PEM fuel cell.
2. To compare the power output efficiency of the fuel cell with that of an IC engine.
3. To determine the effect of current density on stack voltage.
4. To determine the effect of stack temperature on the stack power output.
5. To determine the effect of hydrogen flow rate on the stack power output.
6. To determine the "second-law effectiveness" of the fuel cell.

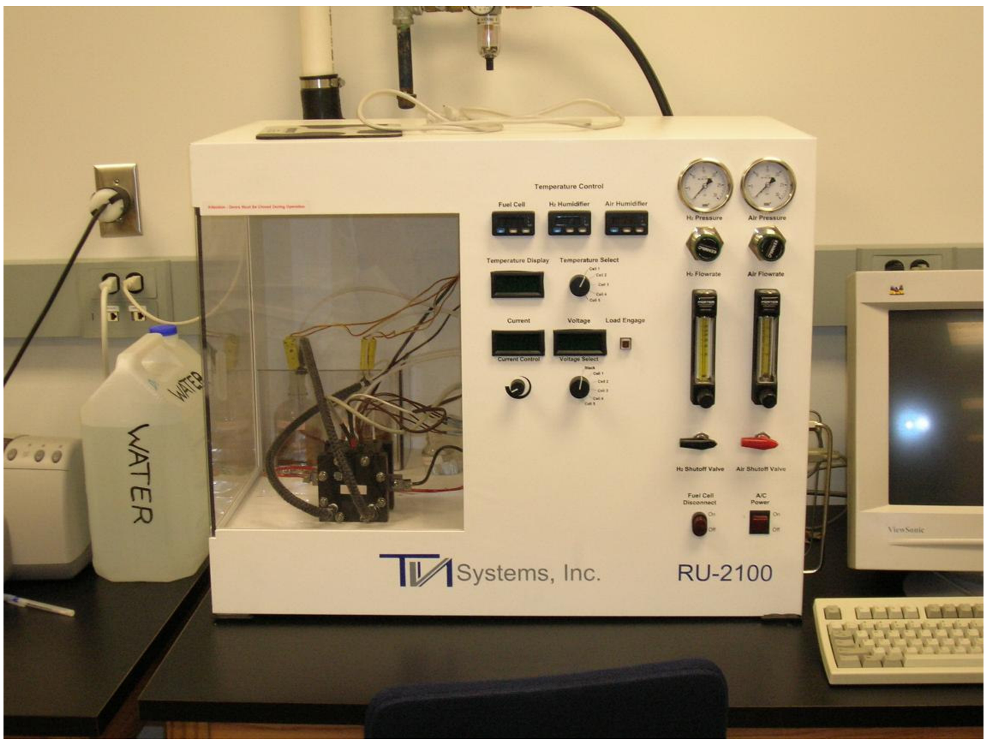

Figure 7: The three-cell PEM fuel cell system

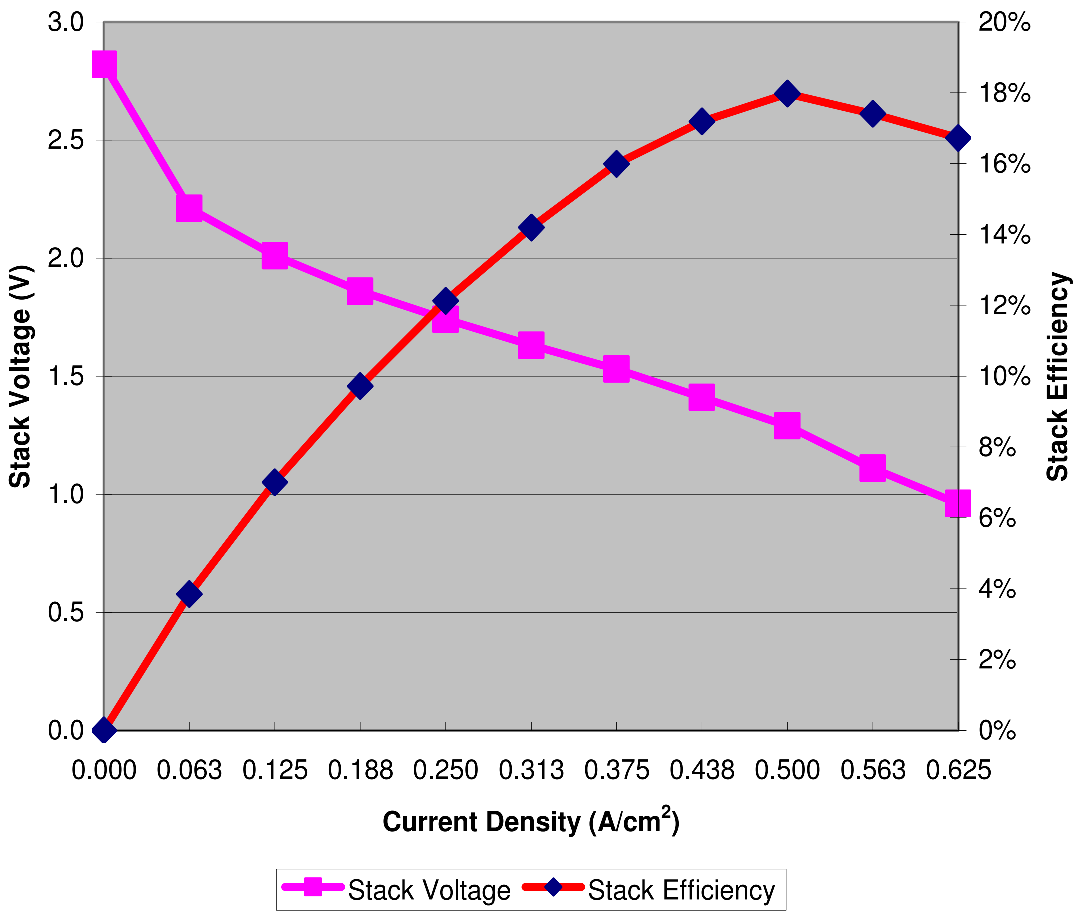

Figure 8: Stack voltage and efficiency versus current density

Performance of a Centrifugal Pump

Educational Objectives

1. To familiarize the students with the operation of a centrifugal pump.
2. To provide a thorough understanding of centrifugal pump testing and analysis on the dimensional and dimensionless bases.
3. To familiarize the students with automatic data acquisition.

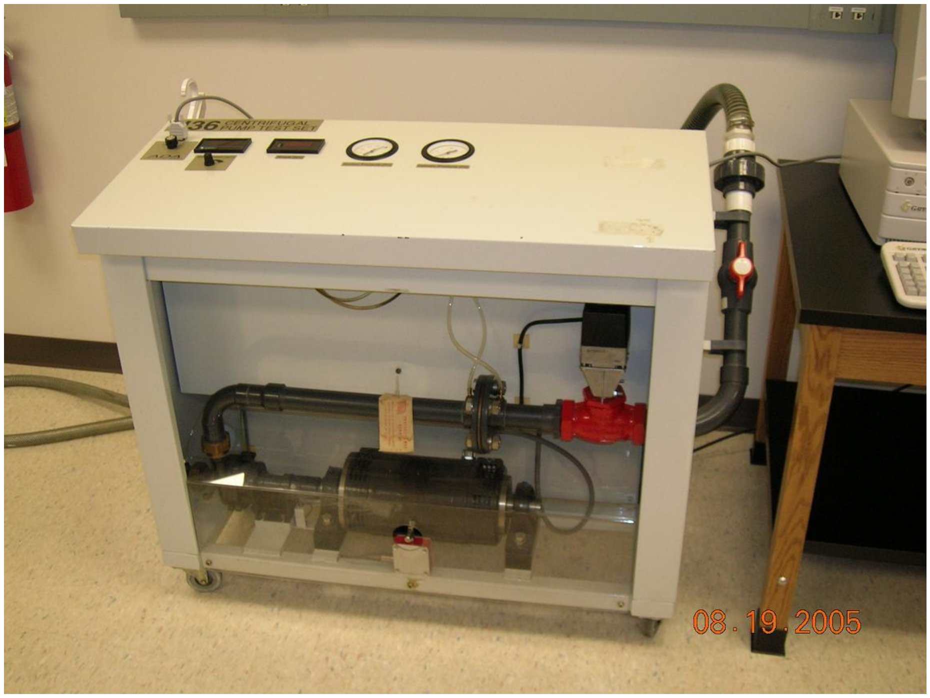

Figure 9: The *Centrifugal Pump* used to demonstrate pump performance mapping

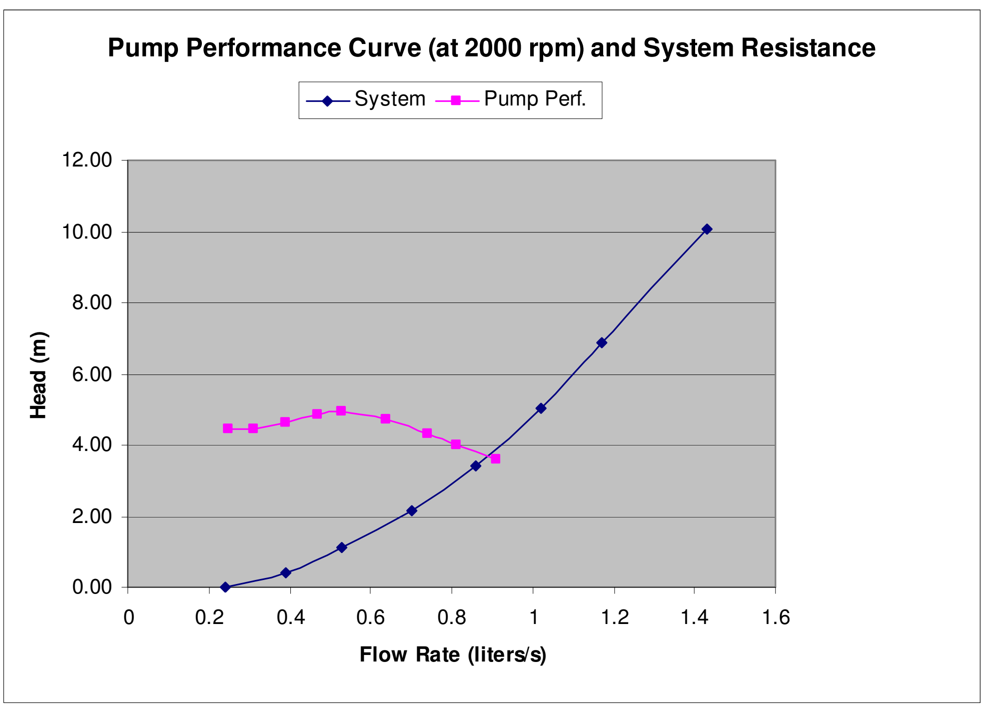

Figure 10: Pump head and system resistance versus flow rate

Fan Laws

<u>Educational Objectives</u>

1. To investigate the validity of the fan laws relating speed, volumetric flow rate, static pressure and power.
2. To determine the variation of volumetric flow rate, static pressure, power and efficiency at constant speed.

Figure 11: The *Centrifugal Fan* used to demonstrate "*Fan Laws*" and fan performance mapping

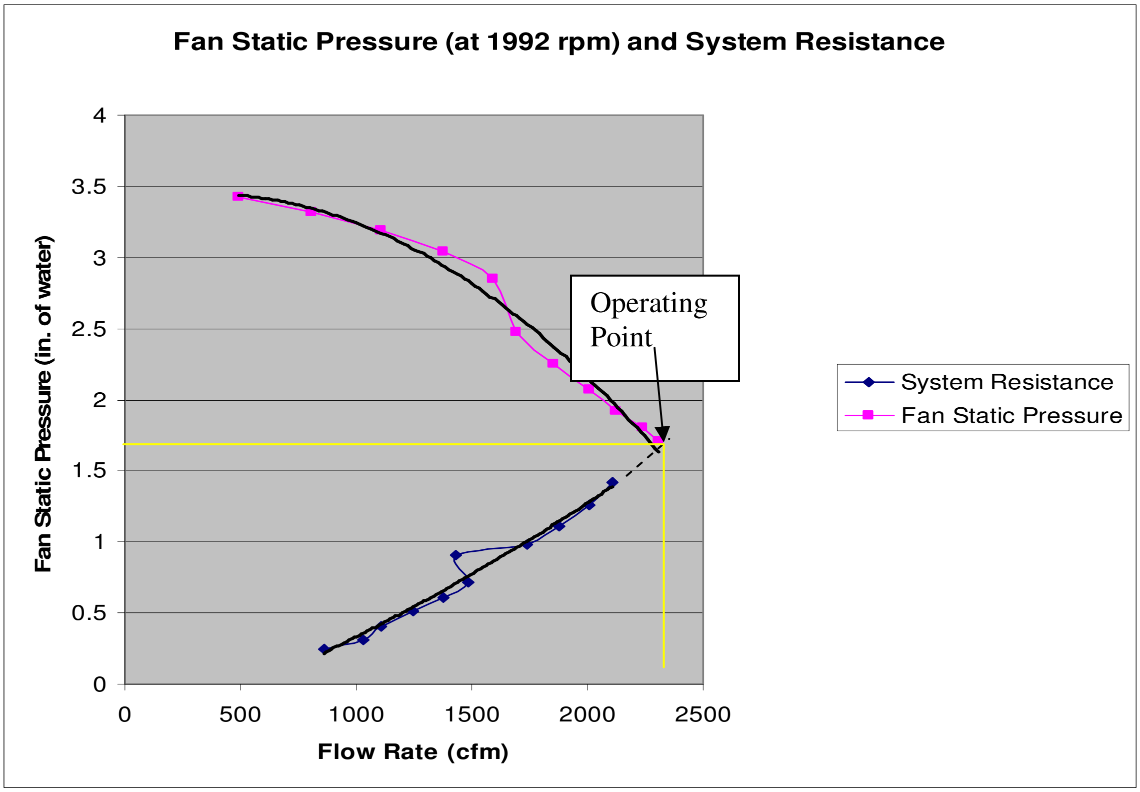

Figure 12: Fan static pressure and system resistance versus flow rate

Compressible Flow in a Converging-Diverging Nozzle

<u>Educational Objectives</u>

1. To determine the effect of inlet and exit pressures on the static pressure distribution in a converging-diverging nozzle.
2. To determine the effect of exit pressure on the location of a normal shockwave and the pressure rise across the same.
3. To determine the effect of the inlet/exit pressures on the mass flow rate through the nozzle under choked and unchoked conditions.
4. To determine the effect of boundary layer formation inside the nozzle on the mass flow rate.

Figure 13: The *Compressible Flow* apparatus

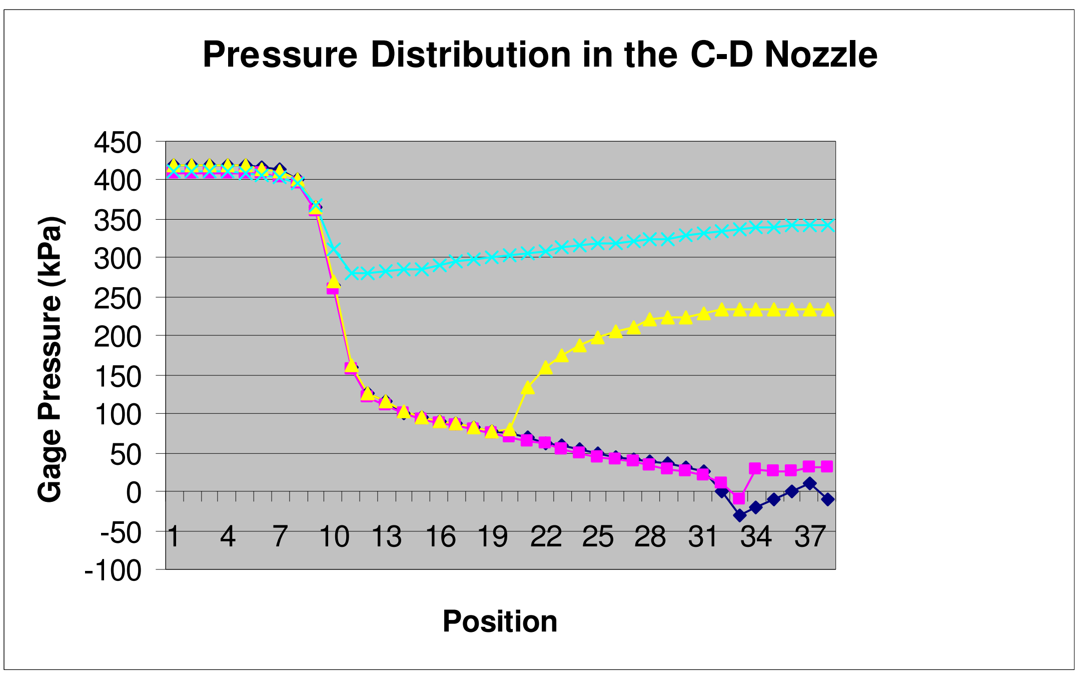

Figure 14: Pressure distribution along the axis of the C-D nozzle

The Jet Engine

<u>Educational Objectives</u>

1. To familiarize the students with the operation of a turbojet engine, the theory behind the thermodynamic processes involved, and the linear momentum equation.
2. To determine theoretical values of engine thrust and the actual efficiencies of the compressor, the combustion chamber and the turbine.
3. To determine the effect of engine speed on the thrust force, thrust-specific fuel consumption, and air-fuel ratio.
4. To perform an energy balance on the jet engine.

Figure 15: The SR-30 *Turbojet Engine*

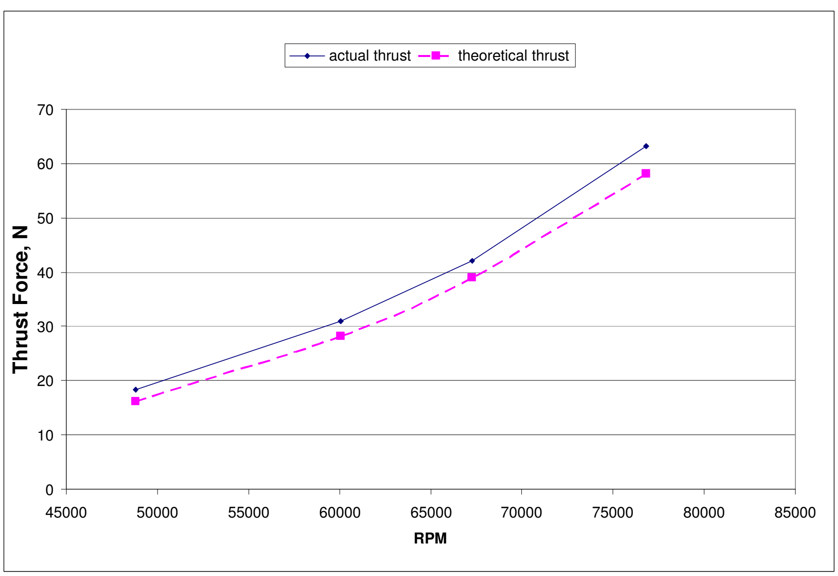

Figure 16: Measured and theoretical jet engine thrust force versus rotational speed

Lift, Drag and Introduction to Aerodynamics

<u>Educational Objectives</u>

1. To understand airfoil pressure distributions and how they relate to lift and drag.
2. To understand lift and drag characteristics of airfoils.
3. To understand the effects of camber, angle of attack, and stall on airfoil lift.
4. To understand the effect of approach flow velocity on lift and drag forces and on the coefficients of lift and drag.

Figure 17: The 30-horsepower *re-circulating Wind Tunnel*

Figure 18: Automatic data acquisition system for the *re-circulating Wind Tunnel*

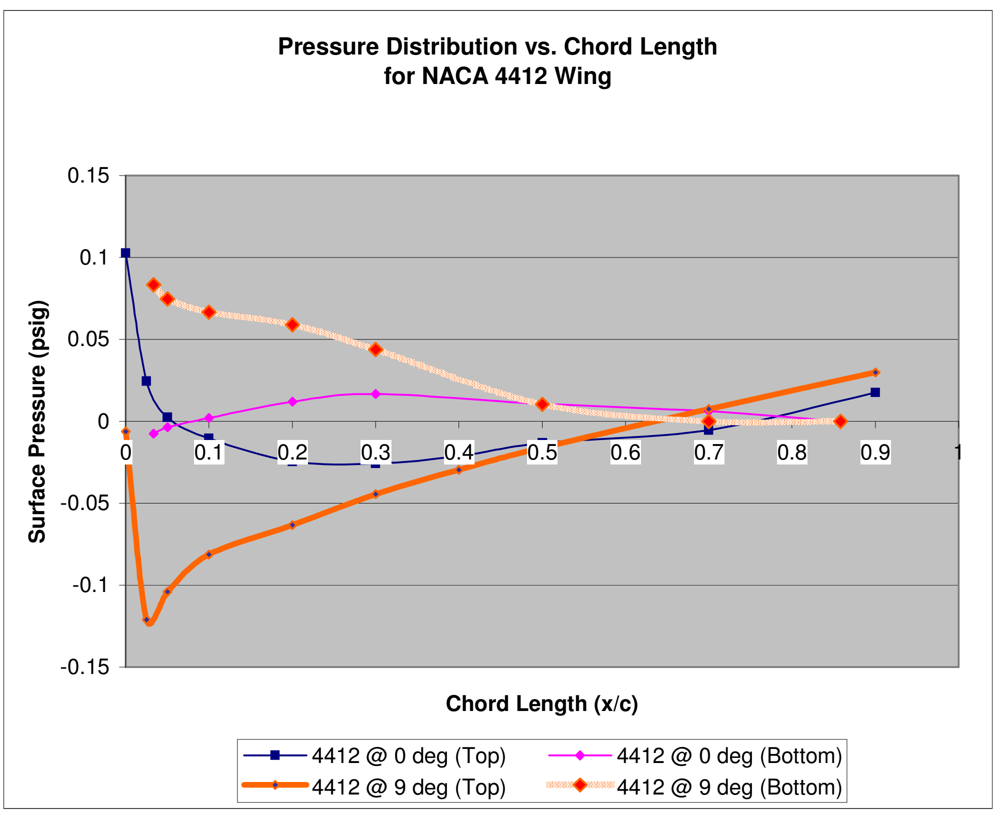

Figure 19: Surface pressure variation on a cambered wing

Cylinder Convection

Educational Objectives

1. To determine the change in surface temperature around the circumference of a heated cylinder in cross-flow.
2. To compare the experimentally measured convection coefficients with published values.

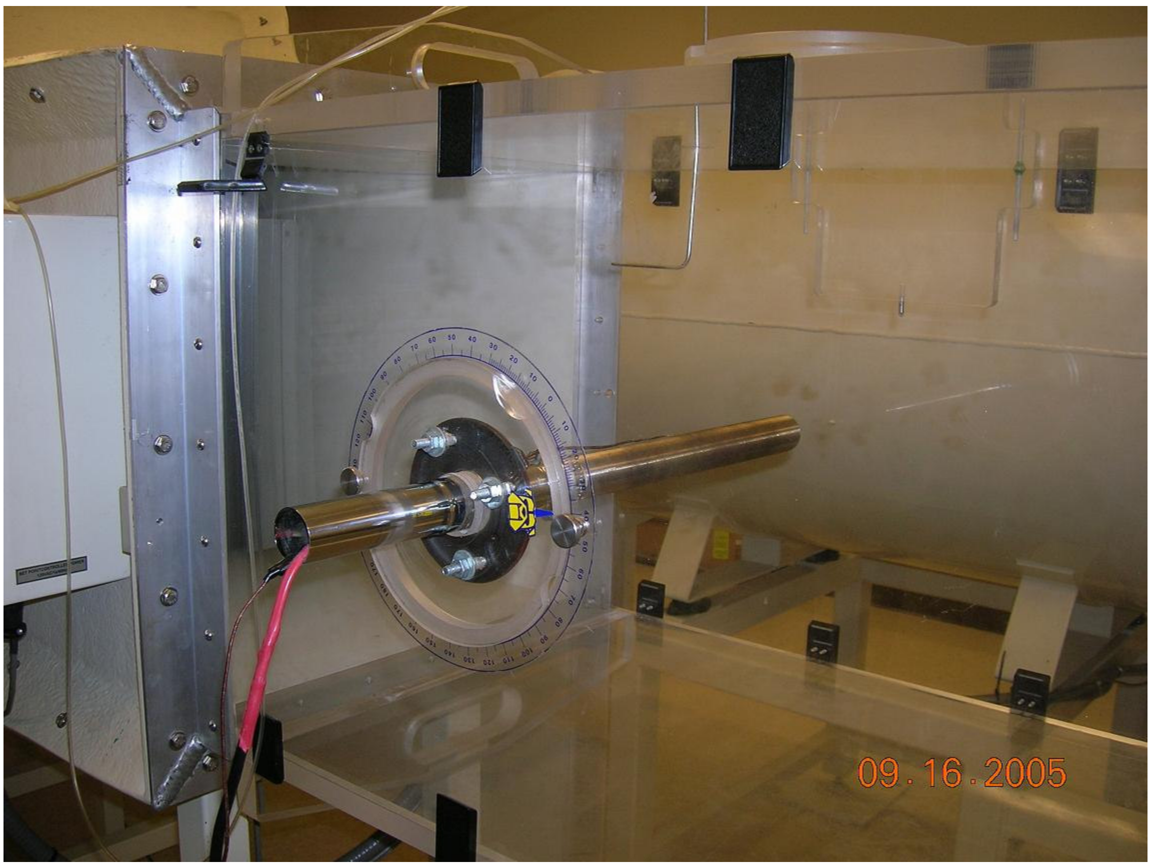

Figure 20: Heated cylinder in cross-flow

Nusselt number vs. Reynolds number

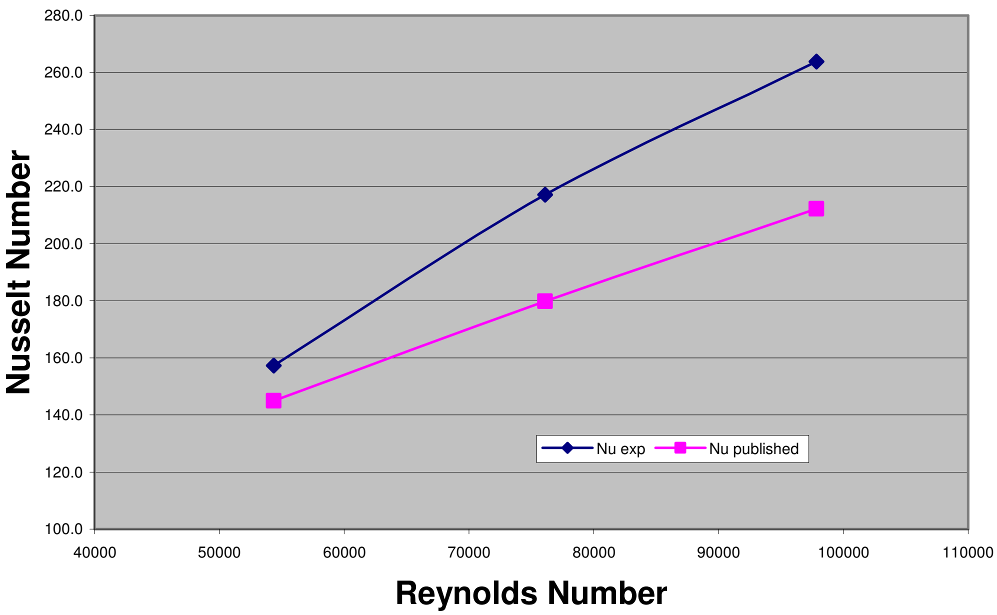

Figure 21: Experimental and actual Nusselt number vs. Reynolds number

Discussion

In addition to the experiments shown above, a design project is included in this laboratory course. Student teams propose their own project in the general area of *Energy Conversion*. Although building a device is not required, most teams design, build and demonstrate their project during the last day of class. These projects are funded through proceeds from the sale of the laboratory textbook[1]. Some completed projects become permanent displays in the laboratory.

Future plans include the addition of a *Fuel Cell Air Management System* and a *Thermal Shock Chamber*. They will be used for experiments involving flow and humidity control and transient conduction, respectively.

Conclusions

Energy Systems Laboratory is an integral part of the mechanical engineering *core* at Kettering University. This modern laboratory educates the students in the area of energy conversion, thermodynamics, fluid flow and heat transfer. It is continuously updated and improved to integrate well with Kettering University's world class mechanical engineering curricula. It provides an opportunity to about 250 mechanical engineering students per year to become familiar with the analysis of numerous energy systems by applying the principles of thermodynamics, fluid mechanics and heat transfer in an integrated manner.

Bibliography

1. Pourmovahed, A. and Navaz, H.K., *Energy Systems,* 2e, John Wiley & Sons, ISBN 0-471-74421-2, 2005.