CENTRIFUGAL PUMP EXPERIMENT
for Chemical Engineering Undergraduates

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Undergraduate curricula for chemical engineers of most universities include experimental studies of absorption, distillation, fluid flow, heat transfer and other topics. All these experiments seek to give undergraduates a practical sense of the basic principles they need to understand during their careers. Recently, the undergraduate chemical engineering program at the University of Missouri began to change its use of the experiments. This change came about from concerns of students who often felt that these experiments (two classes, total of six credit hours), while useful, did not give them a practical understanding of the principles and practices they would deal with in industry. Also, the dean of the college was encouraging faculty to apply "experiential learning" techniques in their classes.

Experiential learning may be defined as "a process through which a learner constructs knowledge, skill, and value from direct experience." In this paper a brief outline of the major activities of experimentally learning are presented. These activities are initiated with a "problem" that challenges the student. The problem is followed by the student "developing a plan, testing this plan against reality to discover a solution, and reflecting on the results to determine whether there are other or better solutions to the problem. The testing phase requires the learner to apply information that is often left out of the learning that occurs in a traditional education setting. Application is a critical component that identifies this theory as experiential and provides educators with a framework for designing learning activities in which students combine thinking with doing."[1]

Centrifugal pump experiments have existed in various chemical engineering laboratory curricula throughout the years.[2, 3] These experiments primarily focus on the pump's properties, including head and shaft power. LabView has also been shown to assist in student's understanding of a phenomenon when data collection is in real time.[4]

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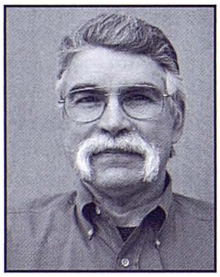

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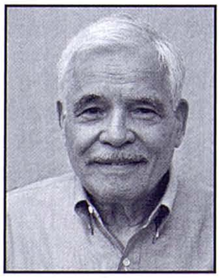

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To address this need for better learning of chemical engineering principles, several new modular experiments were added to our curriculum and some of the existing apparatus were modified. One of these new modular experiments involved the performance characteristics of a centrifugal pump. This experiment included observations of the pump performance characteristics and applications of the experimental results. One illustrated application was a typical industrial scenario: "What will be the centrifugal pump flow rate and cost of pumping power?"

This report describes the centrifugal pump experiment conducted during the spring 2010 semester; instruction used experiential learning techniques, and results indicate the experiment was a notable enhancement to the laboratory curriculum.

CENTRIFUGAL PUMP EXPERIMENT: DESIGN AND CONSTRUCTION

The centrifugal pump experiment's success was partially due to the incorporation of computer data collection and control technology.

The data collection sources were: pressure, flow, motor voltage and current, and impeller speed. The speed was determined by a pulse signal, six pulses per revolution. The current was measured with a magnetoresistive device. These source signals were direct inputs to a LabView program.

The centrifugal pump is powered by a brushless DC motor. For the control of this DC motor a simple-voltage-regulator device was utilized. This device allowed impeller speed control by the LabView program; precise to ± 1 rpm. The speed control system is possibly unique and cost-effective. The motor control operation was very reliable and user friendly based on extensive testing.

Appendix A provides a detailed description of the design, construction, and cost of the centrifugal pump system.

Using LabView data collection and control software, data were collected instantaneously from the system, which contained a water feed tank, centrifugal pump, flow meter, pressure gauge, and finally a flow-control valve, see Figure 1. The LabView software transmitted flow rate, head, impeller speed, temperature, voltage, and amperage of the system into a data file. In addition, power input to the pump was determined from the product of measured voltage and amperage. The centrifugal pump impeller speed was an independent variable and was controlled by setting the voltage in LabView. All experiments were carried out at room temperature. The centrifugal pump system used during the Spring 2010 semester is shown in Figure 2 (page 54).

OPERATING PROCEDURE

The centrifugal pump operating procedure is presented in Appendix B. The operation of the pump system generated a performance curve, head vs. flow, as a function of impeller speed (N). A brief summary of the procedure follows.

The students set the pump to a constant impeller speed value while the valve was completely open (The inlet, suction-side valve to the pump needs to be fully open before turning the pump on). Once the system reached steady-state, which takes only a minute as evident in LabView, data collection was started. The valve was slowly closed until completely closed. The completely closed valve corresponds to the pump "shut-off" head. The student was then able to change the impeller speed of the pump, and collect performance curves for as many speeds as needed. System operations or raw data were collected in Excel spreadsheets for the students to analyze, correlate, and present in their laboratory reports.

The students were also instructed to test the centrifugal pump Affinity Laws for systems with constant impeller diameter. These include:

$$Q \,\alpha\, N \tag{1}$$

$$H \,\alpha\, N^2 \tag{2}$$

$$P \,\alpha\, N^3 \tag{3}$$

where Q is flow rate, H is head, P is output power, and N is the pump's impeller rotational speed, revolutions per minute.[5] For example, the Affinity Laws were applied to calculate a standardized head for the system, as follows:

$$H_{std} = H_{max}\left(\frac{N}{N_{max}}\right)^2 \tag{4}$$

PRACTICAL APPLICATION

The students were also expected to calculate the cost to cool 1,000 computers using one pump per computer over the course of the year. To simulate the use of the centrifugal pump to provide cooling water to cool computers, it was assumed that the pumps would operate 8,000 hours of the year at constant speed.

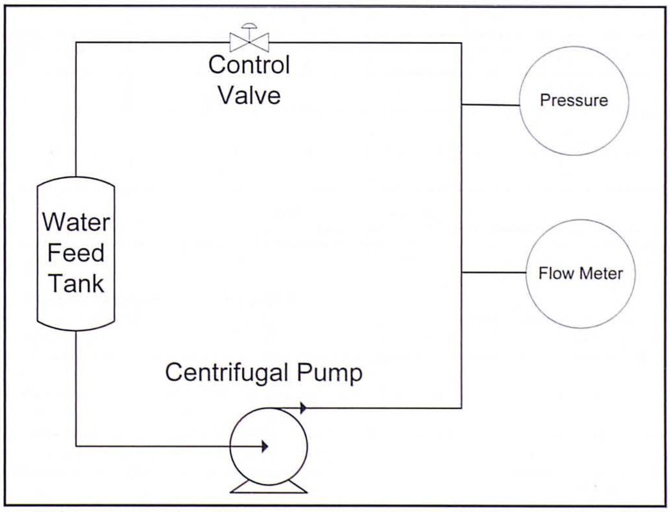

Figure 1. *Schematic of the centrifugal pump experiment.*

To do this, an arbitrary set of tabulated data for system frictional losses as a function of velocity was provided by the instructor, see Appendix C. This data set needed to be correlated by the student(s). The system curve provides quantitative values for the friction losses, as a function of flow rate through the virtual system of computers. Frictional loses were assumed to be proportional to the square of velocity.

The intersection of the curves, pump head vs. flow and system head vs. flow, determines analytically and graphically the estimated local best efficient point (BEP) for pump operation. The absolute best efficient point is where the flow and head are at the greatest efficiency.[6] The students found the local best effect point, which is the maximum efficiency for a given flow rate. This is commonly done in industry to size pumps and to specify system steady-state operating conditions. The BEP values for pressure and flow at a constant speed were then used to calculate the power input and output of the pump, and find the efficiency of the pump at its operating conditions. These values were determined by the following formulas; see Appendix D for sample calculations:

$$P_{\text{Input}}\ (\text{Watts}) = V\ (\text{Volts}) * I\ (\text{Amps}) \tag{5}$$

$$P_{\text{Output}}\ (\text{Watts}) = P_{\text{Output}}\ (\text{J/s}) = Q\ (\text{L/min}) * 1\ \text{min}/60\ \text{s} * 1\ \text{m}^3/1000\ \text{L} * P\ (\text{kPa}) \tag{6}$$

$$= Q\ (\text{m}^3/\text{s}) * (\text{N/m}^2) \tag{7}$$

$$\text{Efficiency}\ (\%) = \frac{P_{\text{Output}}}{P_{\text{Input}}} * 100 \tag{8}$$

From these calculated results, the students were also able to calculate the yearly cost of electricity, as follows:

$$\text{Cost(Annual)} = \text{Number of Pumps} * (\text{Operation Time} * P_{\text{Input}}) * \text{Cost of Electricity} \tag{9}$$

By doing this, students completed a preliminary design estimate for the cost of pumping power and system flow characteristics.

EXPERIMENTAL RESULTS AND DISCUSSION

Results are calculated in Appendix D and presented below.

A) Performance and System Curve

Each student or team of students was able to provide a complete performance and system curve from the experiment, as shown in Figures 3 (page 54). In this figure, the ordinate is the pump's pressure head and the abscissa is the water flow rate, with each performance curve at a constant impeller speed. In the relation of head vs. flow rate for each impeller speed, the intersection of the performance curve and system curve gives the point where each pump will operate. The intersection of these lines is also where the frictional loss for each pump design is at a minimum, and makes the point the best efficient point (BEP).

B) Best Efficient Point

From Figure 3 and Excel spreadsheets, the students determined the BEP's for the system curve provided. For the BEP values, the students were also able to go back to the raw data and retrieve the voltage and amperage values to calculate input power to the pump, and pump efficiency, as listed in Table 1. A typical set of data for the pump performance has been provided electronically and is available at <http://www.ornesen-gineering.com/Marrero_Vanderslice_Data.xls>.

TABLE 1
The Best Efficient Point (BEP) and the Efficiency for Each Centrifugal Pump Impeller Speed Value

Impeller Speed (RPM)	Flow Rate (L/min)	Pressure (kPa)	Efficiency (%)
2010	1.35	6.55	22.3
2340	1.61	7.95	25.1
2610	1.81	9.90	28.7
3330	2.36	16.7	38.8
3510	2.52	19.3	42.2

TABLE 2
The Amount of Energy and Annual Cost of the Individual Pumps at the BEP

Impeller Speed (RPM)	Efficiency (%)	Energy Input (W)	Annual Cost per pump ($)*
2010	22.3	0.66	2.72
2340	25.4	0.85	3.50
2610	28.7	1.04	4.28
3330	38.8	1.69	6.96
3510	42.2	1.92	7.91

* Annual = 8000 hours at constant speed

TABLE 3
Affinity Analysis Results for Operation of a Centrifugal Pump

N (rpm)	Q (L/min)	Q_{std}	Error %	ΔP (kPa)	ΔP_{std} (kPa)	Error %	P_{output} (W)	P_{std} (W)	Error %
2130	1.44	1.52	5.65	6.22	6.99	12.32	0.149	0.18	18.68
2633	1.82	1.88	3.34	10.04	10.68	6.33	0.305	0.33	9.88
3302	2.34	2.36	0.79	16.44	16.79	2.13	0.641	0.66	2.94
3741	2.67	2.67	0.08	21.45	21.55	0.47	0.955	0.96	0.55
4382	3.13	3.13	0	29.57	29.57	0	1.543	1.54	0

C) Application

The complete cooling problem is presented in Appendix C, and the energy requirements from Table 1 were used by the students to solve this problem. Students assumed the BEP values represent pump operating conditions (pressure and flow rate) at highest system efficiency. From this they assumed the pump system for computer cooling would operate at these conditions. The students then calculated the annual operating cost for each pump (see Table 2). Results indicated that at the lowest impeller speed, the cost was at a minimum. It may be noted that the efficiency for the pump increased with impeller speed (see Table 2, second column).

For the annual cost of 1,000 pumps at the lowest operating cost, the lowest cost is $272/yr.

D) Affinity Analysis

The students were also able to standardize the data to find the error of the system as shown in Table 3. This practice, while simple, was shown to be largely absent from the knowledge of students before the laboratory, but once the concept was explained, the simplicity and practicality of it surprised many students.

CONCLUSION

The experimental apparatus and protocol demonstrated the performance characteristics of a centrifugal pump, verification of affinity laws, and application of pump flow rate/head data with system hydraulic characteristics to specify steady-state operating conditions, BEP. In addition, at BEP values, the annual cost of pumping for a practical application was estimated. The new centrifugal pump experimental study was "hands-on" about the practical use of pumps, and students responded to this lab experience as a more practical learning opportunity than the previous lab.

RECOMMENDATIONS

The relatively low cost and time needed to design and construct the centrifugal pump lab, plus the considerable learning by the students, implies that the lab experiment was successful and could be used at other universities, if needed.

EDUCATIONAL ASSESSMENT

Students were asked to include a brief paragraph that described their educational assessment of the centrifugal pump lab. Nineteen assessments were received. A major consensus was an appreciation of the lab's practical value. Some students mentioned the value of hands-on learning of the various principles; most students thought that the application to industrial practices was far more interesting.

In addition, many of the students thought that as essential as pumps are for the chemical process industry, they had been minimally, if at all, taught in previous classes. The students also appreciated the hands-on experience with a working pump system with real-time results (observations, calculations, and graphs). Also, students thought the knowledge of how to find the Best Efficient Point was worth learning.

Finally, in several assessments, students asked for added complexity to the lab system. Namely, to include more changes in variables, such as pump size, impeller speed at a constant control-valve setting, and determination of energy efficiency for these changes in pump design and operation.

From the Spring 2011 semester, seven assessments were collected and the predominant themes of the educational assessments are included in Table 4.

TABLE 4
Education Assessments by Students of Experiential Learning Experience- Centrifugal Pump Lab
(Spring 2010)

Favorable	Constructive
Practical value (4)	Experiment too simple (2)
Hands-on learning (3)	Add more features, such as pumps of different size, control valves, etc. (2)
Interesting industrial application (1)	
Learned new information about centrifugal Pumps (4)	Determine effects on energy consumption of any additional features (1)
Real-time experimental results (2)	
BEP determination valuable (3)	

(n) = approximate number of students who made similar comment.

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APPENDIX A. DESIGN, CONSTRUCTION, AND COST OF CENTRIFUGAL PUMP SYSTEM

Description

The pump motor is a brushless dc motor that operates between approx. 5V and 12V. The pump will shut off at voltage greater than 12V. The pump requires housing: XSPC Premium Laing DDC Clear Acrylic Top -Version 3.0. The motor's starting voltage is higher than the minimum operational voltage, and the speed of the pump varies with voltage range. Also the pump will not run in reverse.

Analog output voltage from LabView ranges from 0 to 10V. The circuit contains both Scaling trim pots and offset trim pots Offset trim pots have +/-15 V connected on either side. Scaling trim pots are in the feedback loops or on the input.

The circuit was designed to be both inexpensive and run on a single power supply.

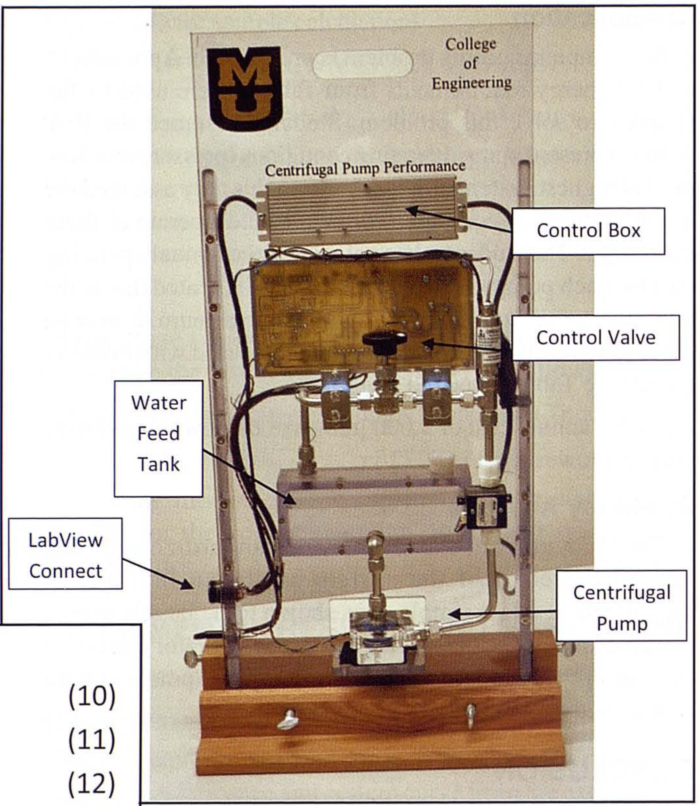


Figure 2 (above). *Photograph of the centrifugal pump experiment.*

Pump Performance Curves:

A (3540 rpm) $y = -1.3262x^2 + 0.5228x + 29$ (10)

B (3330 rpm) $y = -1.3516x^2 - 0.3309x + 25.01$ (11)

C (2610 rpm) $y = -1.4025x^2 - 0.282x + 15.002$ (12)

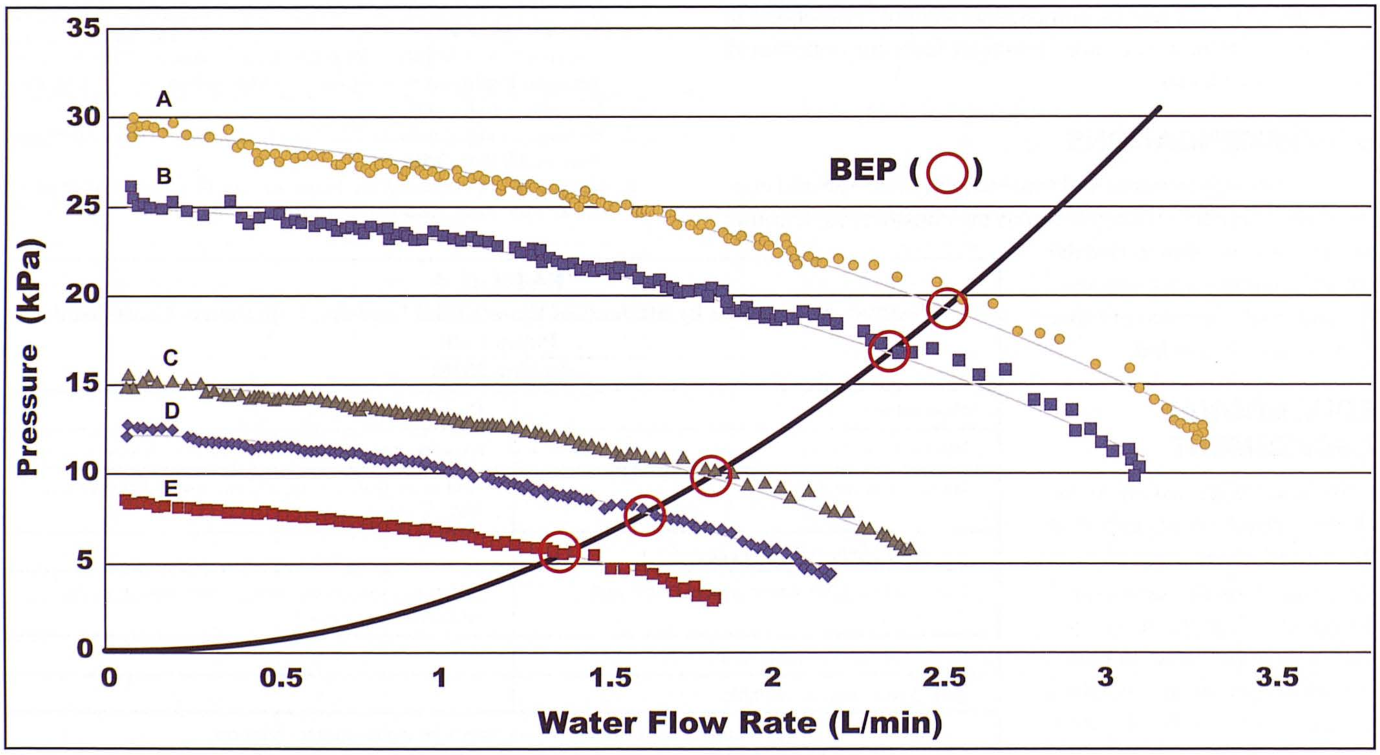
D (2340 rpm) $y = -1.3596x^2 - 0.6461x + 12.331$ (13)

E (2010 rpm) $y = -1.5414x^2 - 0.069x + 8.152$ (14)

System Curve: $y = 3.0156x^2 + 9\times10^{-14}x - 5\times10^{-13}$ (15)

where y = head (kPa) and x = water flow rate (L/min)

Figures 3 (left and below). *Best Efficient Point (BEP) at intersections of system curve and centrifugal pump performance curve(s) as function of impeller speed (rpm).*



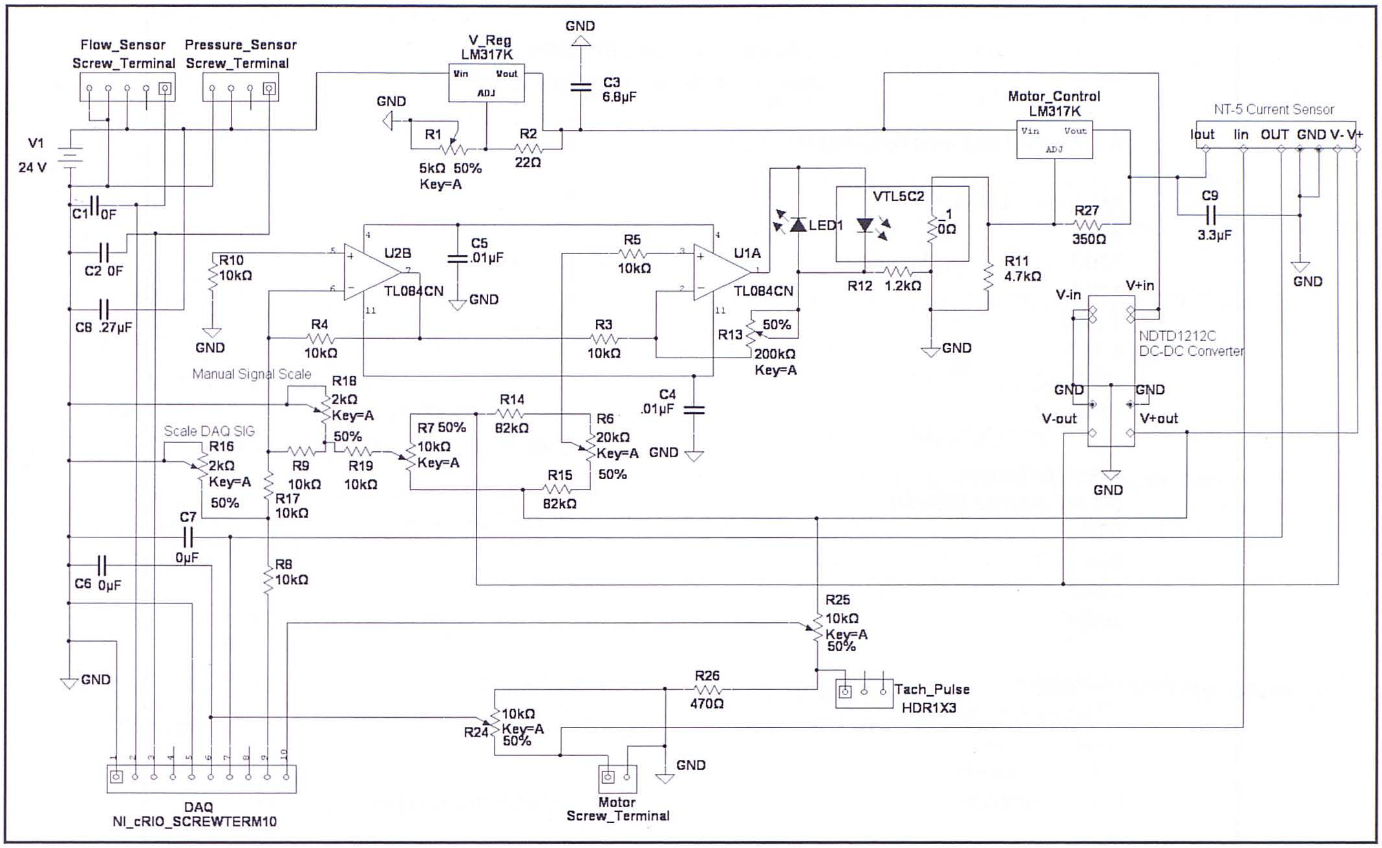


***Figure A-1**. Diagram of centrifugal pump system control and interface circuit.*

The dc-dc converter is used to supply bipolar power to the op-amp IC in order for it to operate from OV. The 0-10V from labview transformed to 1.2-12V for the motor. A 2-stage opamp scheme includes:

- *1st for scaling, mixing signals (manual and data acquisition (DAQ)) and preliminary offset,*
- *2nd for LED in Resistive-optical-isolator (more offset and scaling plus some linearization)*

The offset can be used to approximate the OV DAQ output with the minimum voltage of the control regulator (1.2-1.7 V). The voltages going into motor starts at 6.8V and stops at 4.8V.

The scale factor of LabView voltage is not an issue due to the measuring of the voltage and current of the motor in Labview.

The tachometer has a voltage divider pull-up arrangement to match the counter input voltage to the DAQ.

Vreg1 (LM317K) is adjusted to a fixed value of 15V and is used as a pre-regulator. Vreg2 is used in adjustable mode implemented using the Resistive-optical-isolator. Non:-galvanic current sensor (NT-5) does not affect the operation of the circuit from which the current is being measured. It also provides no stray current paths. Capacitors on schematic with a value of OF are place holders for optional capacitors that were not used on the reference design.

Schematic

Figure A-1 presents a diagram of the centrifugal pump system control and interface circuit. A color version of the schematic can be found at <http://www.ornesengineering.com/schematic2.pdf>. The colored circuit schematic facilitates the design and verification of the system circuitry with the use of Multisim 11.0 in the Labview suite.

Parts Lists and Costs

A tabulation of the centrifugal pump lab costs and parts list is provided in Figure A-2 (page 56).

Total Cost of Parts: $893.75

APPENDIX B. CENTRIFUGAL PUMP LAB, OPERATING PROCEDURE

The procedure is available to students on Blackboard and readers at <http://www.ornesengineering.com/Procedure.pdf>.

APPENDIX C. SIMPLE APPLICATION FOR CENTRIFUGAL PUMP SYSTEM: COMPUTER COOLING

Determination of Pump Operating Conditions:

Data: One thousand computers must be cooled and CHE3243 lab data have been obtained. These data are the

Parts list for Centrifugal Pump
(Not including mounting structure)

A. Control and interface circuit			
Resistors: (1/4 Watt)			
22Ω			
350Ω			
470Ω			
1.2KΩ			
4.7KΩ			
10KΩ x 8			
82KΩ x 2		$ .05 ea.	$.75
Potentiometers: (all are Bourne 3296W)			
5KΩ			
10KΩ x 3			
20KΩ			
200KΩ	(all 3296W's)	$4.00 ea	$24.00
Capacitors:			
.01μF x 2 ceramic			
.27μF ceramic			
3.3 μF Tantalum			
6.8 μF Tantalum		(Total all Capacitors)	$2.00
Solid State Parts:			
TL084CN x 2			
LM317K x 2		$5.00 ea.	$10.00
Misc. Parts:			
NDTD1212C			$11.00
NT-5 Current Sensor			$30.00
VTL5C2 optical isolator			$ 6.00
Mean Well 24V Switching Power Supply (CLG-100-24)			$80.00
LED (optional)			
3pin molex connector (for tachometer connector)			
B. Pump and transducers			
Swiftech MCP355 centrifugal pump			$90.00
XSPC housing accessory for Pipe fittings			$90.00
Omega Flowsensor FLR1000			$255.00
Omegadyne PX-209-030-10V		$195.00	
C. Miscellaneous:			
Valve, Fittings and tubing		$100.00	

Figure A-2. *Parts List and Cost for Centrifugal Pump Lab.*

basis for calculating the BEP (Best Efficient Point); the intersection of the pump characteristic curve and the system curve.

The 1,000 computers release 15,000,000 Btu/hr. The system friction losses are as follows:

Calculate the Pump (each) Flow Rate, Head, BHP, Efficiency, and Speed (RPM) for the BEP that requires the least annual cost for electrical power. The data for this task is included in Table C-1.

Assume commercial rate is 5 cents/kWh.

Assume pump operations are 8000 hr/year.

APPENDIX D. SAMPLE CALCULATIONS

Input data are from Figure 3 and Table 1. Values for annual energy used to calculate power cost are based on a July 2010 power cost for Columbia, MO.

Input Data

$V = 6.5$ V Impeller Speed = 2010 RPM

$I = 0.11015$ A Flow Rate = 1.35 L/min = 0.0000225 m^3/s

A) Input Power

$$P_{Input} = V * I$$

Where V is pump voltage and I is pump amperage

$$P_{Input} = 6.5\text{ V} * 0.1015\text{ A} = 0.66\text{ W}$$

B) Output Power

$$P_{Output} = Q * P$$

Where Q is flow and P is the pressure

$$P_{Output} = 0.0000225\text{ m}^3/\text{s} * 6.55\text{ kPa} * 1000\text{ Pa/kPa} = 0.147\text{ W}$$

C) Efficiency

$$\text{Efficiency} = \frac{P_{Output}}{P_{Input}} * 100\%$$

$$\text{Efficiency} = \frac{0.147\text{ W}}{0.66\text{W}} * 100\% = 22.3\%$$

D) Determination of Local BEP

Pump Impeller speed = 2010 RPM

Pump Performance curve for selected speed:

$y=-1.5414x^2 + 0.069x + 8.152$

System Curve:

$y=3.0156x^2 + 9.0x10^{-14}x + 5x10^{-13}$

Solving the system of equation by Solver in Excel gives:

x=1.35 L/min y= 6.55 kPa

which corresponds to Table 1.

E) Annual Cost

Electrical cost was assumed at $0.0515/kWh.

Total Cost (Annual) = Number of Pumps * Operation Time * Cost of Power *P_{Input}

Total Cost (Annual) = 1000 pumps * 8000 hour

$$* \frac{\$0.0515}{\text{kWh}} * 0.66\text{ W} * \frac{\text{kW}}{1000\text{W}} = \$272/\text{yr}$$

Affinity Law Calculations

For the affinity law calculations input data is taken from Table 3.

Input Data

$P_{max} = 29.57$ kPa

$N = 2130$ RPM $N_{max} = 4382$ RPM

F) Standardization of Value by Affinity Laws for Constant Impeller Diameter

$$P_{std} = P_{max}\left(\frac{N}{N_{max}}\right)^2$$

where P_{max} is the maximum experimental pressure and N is the maximum impeller speed.

$$P_{std} = 29.57\text{ kPa}\left(\frac{2130}{4382}\right)^2 = 6.99\text{ kPa}$$

G) Percent Error

$$\text{Error }\% = \frac{Pstd - P\exp}{P\exp} * 100\%$$

$$\text{Error }\% = \frac{6.99\text{kPa} - 6.22\text{kPa}}{6.22\text{kPa}} * 100\% = 12.32\%$$ ❑

TABLE C-1

System Data for Flow Rate vs. Pressure Drop

Water Flow Rate, lb/hr	Total Pressure Drop, psi
200	1.0
400	4.0
800	16.0