Project-based Learning: Centrifugal Pump Operations

Thomas R. Marrero

Department of Chemical Engineering

University of Missouri, Columbia, MO 65211

Abstract

The purpose of this paper is to describe a new project-based experiment on centrifugal pump performance and operation. A low-cost modular, table-top centrifugal pump system was designed and constructed for use by undergraduate chemical engineering students. The use of the pump system resulted in an increased hands-on experience. Laboratory activities included generating pump performance curves as a function of impeller speed, graphing pump characteristic curves, determining the best efficient point (BEP) of operation, and applying experimental results to a simple industrial problem. The overall result of this experiential learning activity was favorable to the students and additional advances in the lab were suggested by the students. In particular, a relatively higher number of students appreciated the practical value and hands-on learning experience. Suggestions were made to add more features, such as different size pumps.

Background

The history of experiential learning (EL) is known to have started about 5,000 years ago. This ancient mode of education has evolved. The evolution of EL is briefly summarized in Table 1.

Table 1. Historical list of philosophers who pioneered learner-centered and experiential-learning education*

Name	Date	Method
Sumerians	3500 B.C.	
Confucius (China)	5th century B.C.	schools, individual character and citizenship
Socrates (Greece)	4th century B.C.	Individual (know thyself)
Aristotle (Greece)	3rd century B.C.	logical thought processes
Bacon, Francis (England)	16th century	inductive thinking, scientific method
Locke, John (England)	17th century 1632-1704	experience based
Rousseau, Jean Jacques	18th century 1712-1778	experienced based education
Pestalozzi, Johann (Switzerland)	1746-1827	learn by doing
Thomas Jefferson (USA)	15th century	education of the people
Parker, Francis (USA)	19th century	taught teachers learner-centered method
Dewey, John	19th and 20th centuries	learn by doing

*Adopted from Henson (2003)[1]

Table 2. Summarizes current teaching approaches to experiential learning.[2]

Table 2. Teaching Approaches to Experiential Learning Descriptor	Definition
1. Active	"active learning provides opportunities for students to talk and listen, read, write, and reflect as they approach course content through problem-solving exercises, informal small groups, simulations case studies, role playing, and other activities – all of which require students to apply what they are learning" (p 17)
2. Problem-Based and Inquiry-Based	"small group, cooperative, self-directed, interdependent, self-assessed"; a dynamic approach to learning that involves exploring the world, asking questions, and rigorously testing those discoveries in the search for new understanding" (pp 33, 34)
3. Project-Based	"a teaching method that taps into students' interests because it allows them to create projects that result in meaningful learning experiences" (p 45)
4. Service-Based	"service-learning relates academic study to work in the community in ways that enhance both" (p 68)
5. Place-Based	"a holistic approach to education, conservation, and community development that uses the local community as an integrating content for learning at all ages" (p 83)

In project-based learning, there are several variations ranging from teacher-controlled to student-controlled methods; see Table 3.

Table 3. Variations of Project-Based Learning*

Type of Project	Guidelines
1. Teacher-controlled:	part of curriculum unit, test, etc all students do the same no student choice graded as part of class unit
2. Teacher-controlled:	allows student inquiry, choice of topic within curriculum students frame their own questions all students have same time frame graded as part of class unit
3. Teacher-orchestrated:	inquiry-based, looks at "big picture," curriculum based interdisciplinary and thematic students cooperative groups, teaming performance, product assessment if used as well as class grade
4. Teacher-student interaction:	inquiry-based, interdisciplinary, authentic rubric assess performances, critical thinking and problem solving cooperative groups, teaming, or whole class includes placed-based projects, community service, etc. time frame negotiable, but within semester (or unit)
5. Student-driven, authentic:	teacher-facilitated, teachers provide process curriculum is whole world state standards guide work rubrics asses learning-to-learn skills, individual development performance and products assessed, performance to real-world audience individual or group project could include place-based, community service project non-graded, time frame negotiable

*Adapted from Reference 2, pp 50-51.

In this paper, the subject centrifugal pump lab experiment is a project-based learning approach to teaching. Some educators claim that a useful set of skills can be obtained through project-based learning to better compete in the future. The set of skills includes: learning and thinking skills, technology literacy skills, and life skills.

The experiential learning approaches listed in Table 2 indicate several (5) ways to fulfill teaching objectives. Of these five approaches, the project-base approach is briefly described, here. The project-base approach has a wide spectrum for usage in classroom settings. The project could be totally teacher-directed to student-directed, see Table 3. It is up to the teacher to determine what project variation to utilize.

Of the five variations of project-based learning from Table 3, the centrifugal pump experiment would be in the first category: project-based, teacher-controlled. Namely, all students do the same thing; no student choice, and graded as part of the class unit. This variation of project-based learning is how most of the experiments of a Unit Operations Laboratory are conducted, with few exceptions.[3]

Other laboratory studies about pump performance for chemical engineering undergraduates and the value of understanding centrifugal pump performance for the optimum selection of centrifugal pumps have recently been published. [4, 5, 6]

Here, the report describes a new undergraduate centrifugal pump bench-top system that incorporates experiential learning.[7] The design, construction, operation and cost of the centrifugal pump system are described below. The system was constructed by the mechanics of the college, not a student project. Additional pump features are provided in Appendix 2, and the pump's circuit diagram is also available at http://www.ornesengineering.com/Procedure.pdf .

Centrifugal Pump Design

The pump requires housing: XSPC Premium Laing DDC Clear Acrylic Top-Version 3.0. The pump motor is a brushless DC motor that can operate between 4.8V and 12.8V. The pump will shut off at voltage greater than 12V. 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 Lab View ranges from 0 to 10V. The circuit contains both Scaling trim pots and offset trim pots. Offset trim pots have +/-15V connected on either side. Scaling trim pots are in the feedback loops or on the input. The circuit diagram is presented in Appendix 2. The circuit was designed to be both inexpensive and run on a single supply.

Appendix 2 contains a parts list and costs for the centrifugal pump lab system, except for the table top support structure.

A photograph of the centrifugal pump system used for this study is provided in Figure 1.

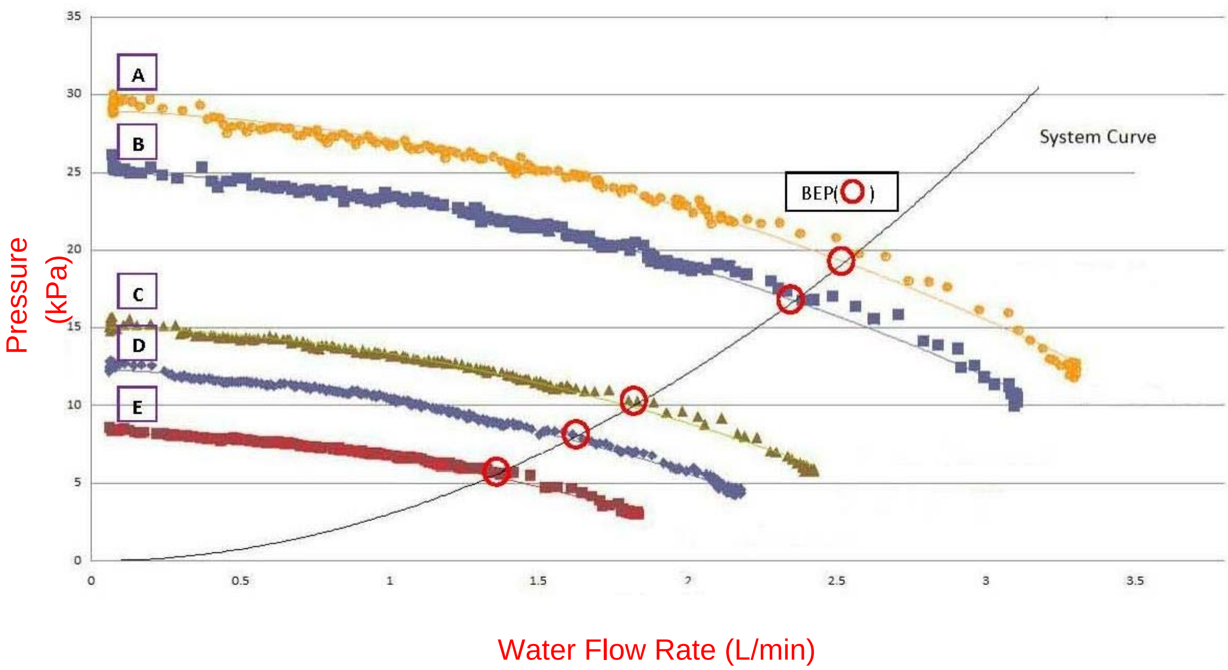
Figure 1. Photograph of the Centrifugal Pump Modular System

Students learned skills from the lab experiment as follows:

1) How to determine the best efficient point (BEP) of pump operation and what it means,
2) How to correlate and use (practically) experimental data.
3) How to prepare a technical report that is scientific in structure, brief, yet clear, and emphasizes results.

The products produced by the students that are the basis of assessment are:

1) Laboratory report
2) Quantitative values of BEP (see Figure 2)
3) Affinity analysis related to pump (with constant impeller diameter) performance
4) Graphs of pump performance curves, pressure versus flow rate
5) Pump efficiency (see Table 4 and Appendix 1)
6) Safety practices in laboratory (for example, wear safety goggles)
7) A surrogate practical application (see Table 5 and Appendix 1)



Equations: Pump Performance Curves:

A (3540 rpm), Eq. 1. $y = -1.3262x^2 + 0.5228x + 29$,

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

C (2610 rpm), Eq. 3. $y = -1.4025x^2 - 0.282x + 15.002$,

D (2340 rpm), Eq. 4. $y = -1.3596x^2 - 0.6461x + 12.331$,

E (2010 rpm), Eq. 5. $y = -1.5414x^2 - 0.069x + 8.152$,

System Curve: Eq. 6. $y = 3.0156x^2 + 9\times10^{-14}x - 5\times10^{-13}$

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

Figure 2. Best Efficient Point (BEP) of centrifugal pump system

Table 4. 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 5. 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	0.26
2340	25.4	0.85	0.34
2610	28.7	1.04	0.42
3330	38.8	1.69	0.68
3510	42.2	1.92	0.77

Note: The assumed cost of power is 5¢/kWh and annual operating time is 8000 hours.

The above figures and tables complete the presentation of products and skills obtained from this project-based learning experience.

The students' assessments of the centrifugal pump experiment are summarized in Table 6.

Table 6. Student assessment results for centrifugal pump experiment.

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)	Determine effects on energy consumption of any additional features (1)
Learned new information about centrifugal pumps (4)	
Real-time experimental results (2)	
BEP determination valuable (3)	

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

The basis of Table 6 is written responses by the students, as part of their lab reports[7]. The students were asked to include a brief paragraph that described their educational assessment of the centrifugal pump lab. A total of 19 assessments were received. A major consensus was an appreciation for the lab's practical value. Some students mentioned the value of "hands-on" learning of the various principles; most students thought that the application problem to industrial practices was far more interesting.

In addition, many of the students thought that for as essential as pumps are to chemical process industry, they had been minimally, if at all, taught about pumps 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 BEP 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 instructor's perspective, the centrifugal pump lab was a big improvement in lab equipment, subject content, and student performance. However, based on his experience as an undergraduate at Brooklyn Polytechnic Institute and in industry, (was employed for a few years like a mechanical engineer in design and start-up of nuclear power plant secondary systems, or hydraulics) the pump experiment could use a larger pump, different types of pumps, and somehow bring about better preparation by the students prior to starting the experiment.

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. A new centrifugal pump experimental study was "hands-on" about the practical use of pumps, and students responded to this project-based experience as a more practical learning opportunity than previous labs. The relatively low cost and short 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.

Bibliography

1. Henson, K. T. "Foundation for Learning-Centered Education: A Knowledge Base," Education (Chula Vista, CA), vol. 124 (1), Fall 2003, pp 5-16.

2. Wurdinger, S.D. and J. A. Carlson, "Teaching for Experiential Learning: Five Approaches that Work," Rowman & Littlefield, New York, 2010.

3. Joye, D. D., A. Hoffman, J. Christie, M. Brown, and J. Niemczyk, "Project-Based Learning in Education: Through an Undergraduate Lab Exercise," *Chem. Eng. Ed*. **45**(1) 53-2011.

4. Davies, W. A., R. G. Prince, and R. J. Aird, "An Engineering Applications Laboratory for Chemical Engineering Students," *Chem. Eng. Ed*., **25** (1) 16 (1991).

5. Jones, W. E., "Basic Chemical Engineering Experiments," *Chem. Eng. Ed*., **27**(1) 52 (1993).

6. Kelly, J. H., "Understand the Fundamentals of Centrifugal Pump," *Chem. Eng. Prog*., **106**(10) 22 (2010).

7. Vanderslice, N., R. Oberto, and T. R. Marrero, "Centrifugal Pump Experiment for Chemical Engineering Undergraduates," to be published, *Chem. Eng. Ed*., Vol. **46**(1), Winter, 2012.

Biographical Information

Thomas R. Marrero received all his degrees in chemical engineering; B.S. from the Polytechnic Institute of Brooklyn, M.S. from Villanova University, and Ph.D. from the University of Maryland-College Park. He is a professor of Chemical Engineering at the University of Missouri-Columbia, Fellow of the American Institute of Chemical Engineers, and a registered Professional Engineer in Missouri. He recently taught the Chemical Engineering Laboratory course and developing interactive learning techniques in environmental lecture courses. Tom has 15 years industrial experience in design engineering and research.

Appendix 1. Simple Application for Centrifugal Pump System: Computer Cooling

Determination of Pump Operating Conditions

A. Data

1,000 computers must be cooled and CHE3243 lab data have been obtained. These data are the bases for calculating the BEP; the intersection of the pump characteristic curve and the system curve.

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

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

Calculate the pump (each) flow rate, head, BHP, efficiency, and speed (rpm) for the BEP that requires the least annual cost for electrical power.

Assume commercial rate is 5 cents / kWh and pump operations are 8000 hr/ yr.

B. Calculation of Pump Efficiency

Input data from Figure 2 and Table 4: Impellor Speed = 2010 RPM
Flow Rate = 1.35 L/min = $2.25^{x}10^{-5}$ m^3/s

And from operating data file http://www.ornesengineering.com/Marrero_Vanderslice_Data.xls

Voltage = 6.5V
Amperage = 0.11015A

A) Input Power $P_{Input} = V * I$

where V is pump voltage and I is pump amperage

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

$P_{Input} = 0.66\ W$

B) Output Power

$P_{Output} = Q * p$

where Q is flow and p is the head

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

$= 0.147W$

C) Efficiency

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

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

These results are presented in Table 5 for impeller speeds from 2010 to 3510 rpm.

C. Determination of System Curve and Best Efficient Point (BEP)

The determination of the system, a virtual set of computers cooled by water supplied by centrifugal pumps, cure was done based on knowledge of the pump performance curve characteristics from prior experiments and the assumption that the elevation head for the system was zero. Data for system water flow rates versus pressure drop were selected based on two criteria: 1) the pressure drop varied as the velocity squared, water density and pipe diameter were assumed constant; and 2) the values of the flow rates and pressure differences would intersect the pump performance curves at impeller velocities from 2000 to 3600 rpm. The system data were provided to the students in U.S. Engineering Units and these values were converted to SI units by students. The data provided are presented in Table A-1.

Table A-1
System Data for Flow Rate versus Pressure Drop

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

*Note: at zero pump flow rate the pressure drop was taken to be 0 psi.

A brief summary of the laboratory procedure is as follows.

The students set the pump to a constant impeller speed value while the valve was completely open (The inlet, suction-side value to the pump needs to be fully open before turning the pump on). Once the system reached stead-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.

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, se Figure 1. The LabView software transmitted flow rate, head, impeller speed, 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.

Each student or team of students was able to provide a complete performance and system curve from the experiment, as 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).

Best Efficient Point

From Figure 2 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 4. A typical data set for the pump performance has been provided electron-ically and is available at http://www.ornesengineering.com/Marrero_Vanderslice_Data.xls .

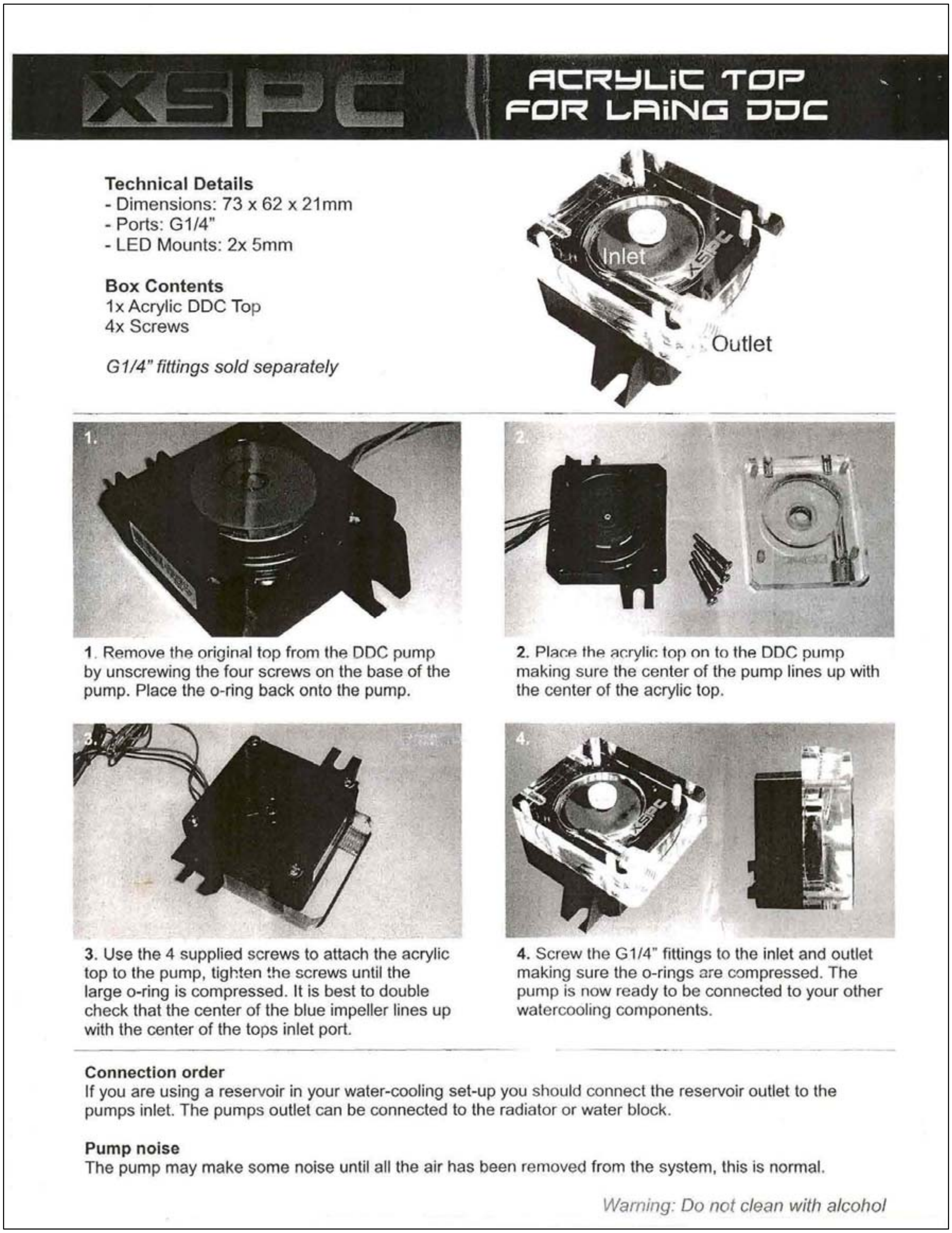
These data needed to be correlated by the student(s). The system curve provides quantitative values for the friction losses, as a function of flow rate through the virtual system of computers. Frictional loses were assumed to be proportional to the square of velocity.

The intersection of the curves, pump pressure vs. flow and system pressure vs. flow, estimated local best efficient point (BEP) for pump operation. The absolute best efficient point is where the flow and pressure 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.

Experimental data were reduced by Excel and equations solved by Solver.

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 equations by Solver in Excel gives:
x= 1.35 L/min y = 6.55 kPa
which corresponds to values listed in Table 4.

Appendix 2. **Pump System Design, Costs and Operating Procedure, including Pre-Lab Test**



XSPC

ACRYLIC TOP FOR LAING DDC

Technical Details
- Dimensions: 73 x 62 x 21mm
- Ports: G1/4"
- LED Mounts: 2x 5mm

Box Contents
1x Acrylic DDC Top
4x Screws

G1/4" fittings sold separately

Inlet

Outlet

1. Remove the original top from the DDC pump by unscrewing the four screws on the base of the pump. Place the o-ring back onto the pump.

2. Place the acrylic top on to the DDC pump making sure the center of the pump lines up with the center of the acrylic top.

3. Use the 4 supplied screws to attach the acrylic top to the pump, tighten the screws until the large o-ring is compressed. It is best to double check that the center of the blue impeller lines up with the center of the tops inlet port.

4. Screw the G1/4" fittings to the inlet and outlet making sure the o-rings are compressed. The pump is now ready to be connected to your other watercooling components.

Connection order
If you are using a reservoir in your water-cooling set-up you should connect the reservoir outlet to the pumps inlet. The pumps outlet can be connected to the radiator or water block.

Pump noise
The pump may make some noise until all the air has been removed from the system, this is normal.

Warning: Do not clean with alcohol

Figure A. Photograph of centrifugal pump

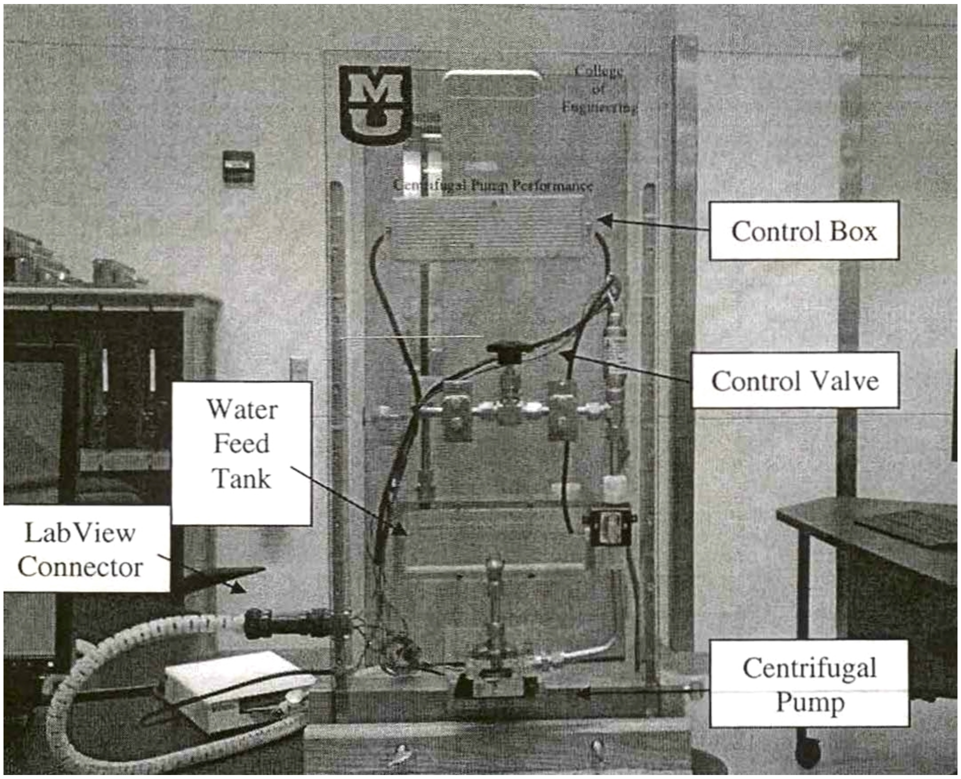


Figure B. Photograph of centrifugal pump system in laboratory

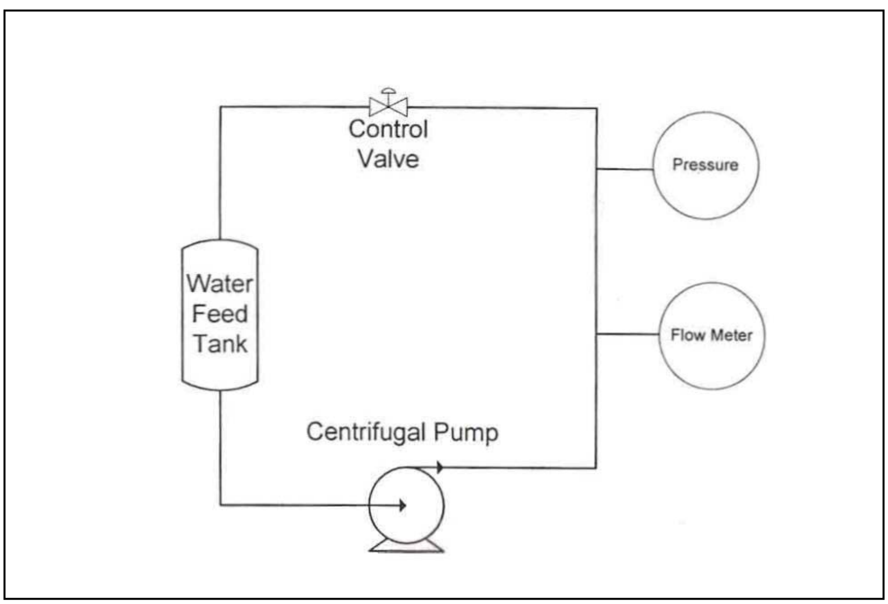


Figure C. Schematic of centrifugal pump system

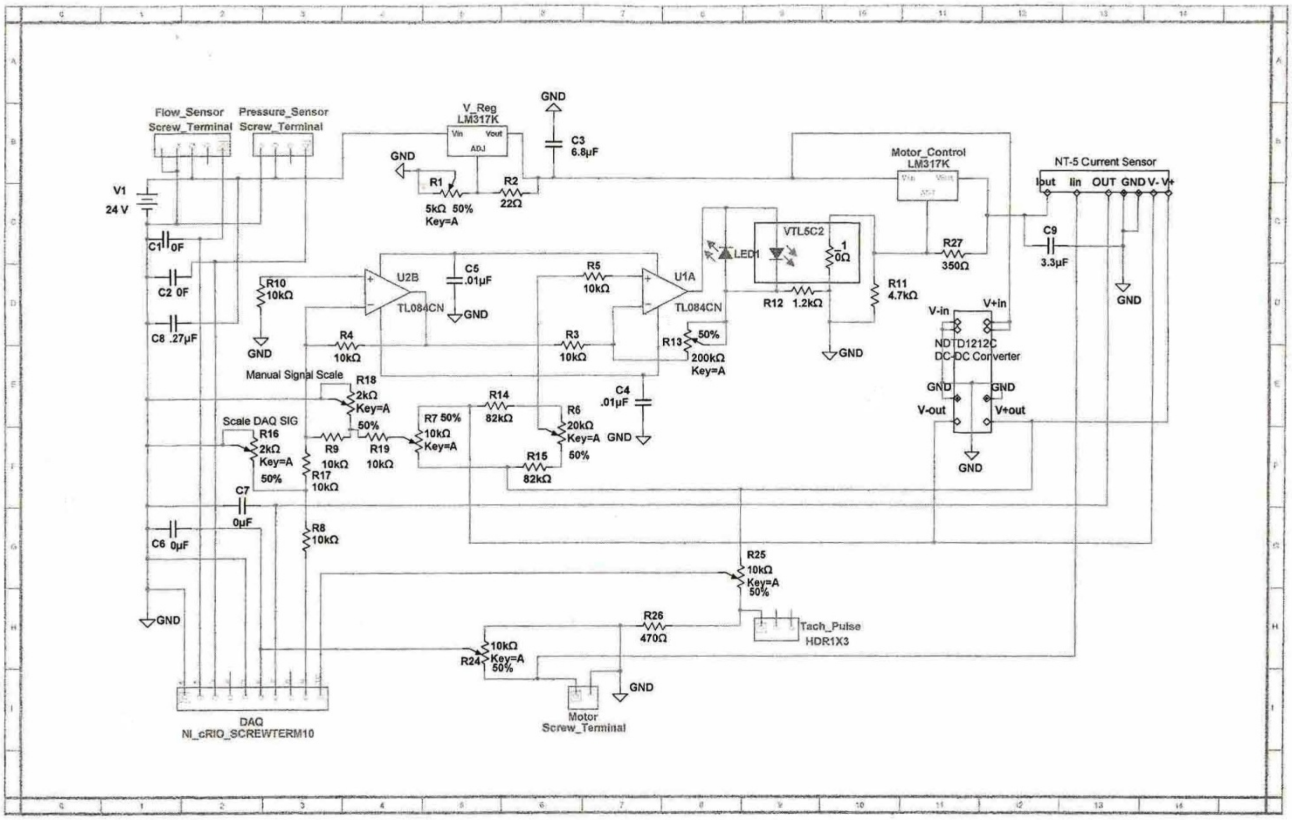


Figure D. Schematic of centrifugal pump control and interface circuit system

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 E. Parts, lists, and costs of centrifugal pump system

Centrifugal Pump

A. Start-Up 1. Obtain the Centrifugal Pump Performance module, a wooden stand, and a power supply. 2. Take the measurement of the various fittings in the system. 3. Set up the module at a computer station and attach the data acquisition cable and plug in the external power cord. 4. From the Blackboard website, open the CentrifugalPump.vi Lab View file. 5. Click the white arrow button and name your file	Safety: Be careful in handling the apparatus. -You will use this for creating a diagram of the system. -The file name should include the name of the experiment and the name of all group members.
B. Centrifugal Pump Study 1. Ensure that the valve is fully opened. 2. Click the "Write to File" on the program's control panel. 3. Note the initial flow rate and pressure values. 4. Very slowly, turn the valve clockwise until it is closed. 5. Note the final values of flow rate and pressure. 6. Stop data collection by hitting "STOP" on the program control panel. 7. Repeat steps 1-6 twice for that power setting. 8. Repeat steps 1-7 for 4 different pump powers	-You should have three separate data files for analysis. -There should be 5 total sets of data comprised of 3 runs each.
C. Shut Down 1. Close Lab View. 2. Unplug the power supplies to the module and the data acquisition cable. 3. Put away the module board, stand and power supply.	

Figure F. Centrifugal pump laboratory operating procedure

ChE 3243 Centrifugal Pump Pre-Lab 1/18/11

Name:

Date:

Lab Period:

Group Members:

Key Words

Pump Efficiency

Characteristics curve

Best Efficient Point (BEP)

Affinity Laws

Answer questions and turn in to T.A.s before you start the lab.

1. Describe a **centrifugal pump**?

2. Explain how a **pump characteristic curve** and the pump **system curve** are used to calculate the **best efficient point**.

3. Draw a flow diagram of the experiment (Include: flow path, valves, controls, and other important features).

For help answering questions:
-C.J. Geankoplis, **Transport Processes and Separation Process Principles**, Prentice Hall (2003). 147-148.
-Understanding the Fundamentals of Centrifugal Pumps.

Figure G. Pre-laboratory preparation test for student teams

ChE 3243 Centrifugal Pump Pre-Lab 1/18/11

Use Table 1 for questions 4-8 and show all work.

Table 1. Sample data for water in centrifugal pump.

Time (s)	Flow (L/min)	Head (kPa)	Pump Voltage (V)	Amps	RPM	Deg C
1	1.87	2.519	6.078	.119	2040	27.3

4. Calculate the input power of the pump.

5. Calculate the output power of the pump.

6. Calculate pump efficiency.

7. Assuming a cost of $0.05/KWhr for electricity, calculate the cost ($) of running the pump for 24 hours a day for one year (365 days).

8. Using the **affinity laws**, calculate the Head if the RPMs are increased to 4000.

*Note: After conducting the centrifugal pump experiment, verify the affinity law relationship(s) based on your experimental data in your final report. Explain reasons for error.

For help answering questions:
-C.J. Geankoplis, **Transport Processes and Separation Process Principles**, Prentice Hall (2003). 147-148.
-Understanding the Fundamentals of Centrifugal Pumps.

Figure G. Pre-laboratory preparation test for student teams, continued