2006-1357: EXPERIENTIAL LEARNING IN A FLUID FLOW CLASS VIA TAKE-HOME EXPERIMENTS

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Experiential Learning in a Fluid Flow Class
via Take-Home Experiments

Abstract

This paper describes the development and assessment of a pump flow take-home experiment that was implemented in an introductory junior-level fluid mechanics course in Fall 2005. The take-home experiment, along with appropriate instructions, is assigned as homework. Students borrow the equipment from the department's equipment room, and perform the experiment either at home or in the student lounge or student shop work area. The experimental apparatus consists of a bucket, tape measure, submersible aquarium pump, tubing, measuring cup, and extension cord. Students connect the tube to the pump outlet, submerge the pump in water, and measure the volume flow rate produced at various outflow elevations. They record and plot volume flow rate as a function of outlet elevation, and compare with the manufacturer's pump performance curve (head versus volume flow rate). The homework assignment includes an online pre-test and post-test to assess the change in students' understanding of the principles of pump performance. The results of the assessment support a significant learning gain following the completion of the take-home experiment. These results and analysis of student perception data collected via an online survey embedded in the homework assignment are discussed.

Introduction

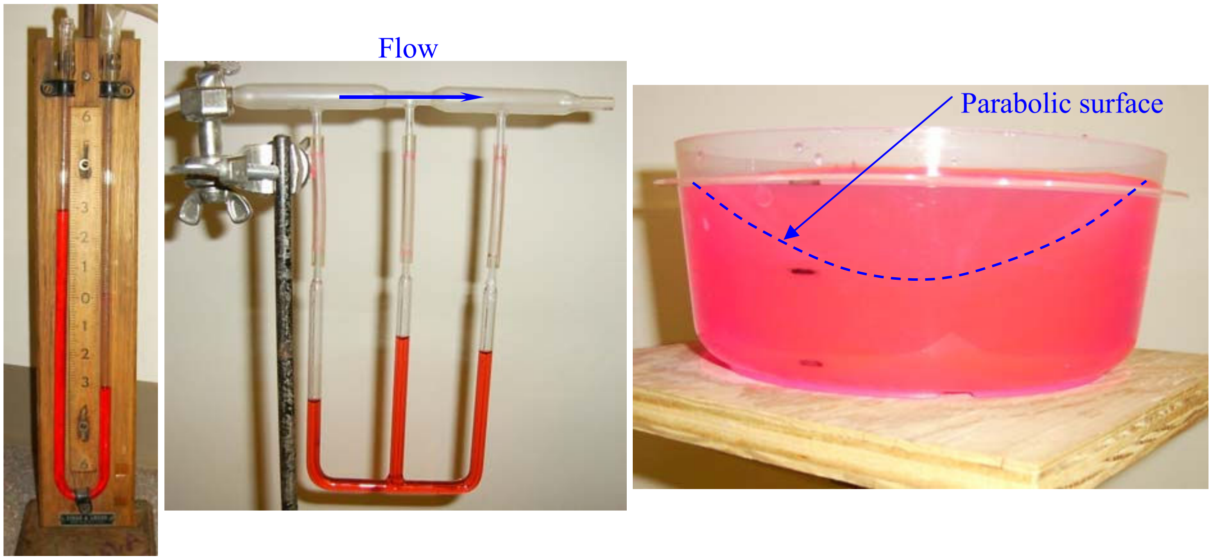
Instructors have reported various ways to introduce physical or numerical hands-on experience into traditional lecture-based courses, either in place of or as supplements to a traditional laboratory experience. Among the papers that are published in archival journals or presented at engineering education conferences, the following alternatives to traditional engineering laboratory instruction are discussed:

- take-home experiments[1, 2, 3]
- laboratories integrated with lecture[4, 5]
- distance laboratories[6, 7]
- simulated laboratories[8, 9, 10]

Another portion of the literature that is important to this topic involves the differential experiences that students have in hands-on learning environments, including laboratories, based on their gender[11, 12]. In many cases, female students are pushed into less active roles, such as analysis of data and writing of reports, in hands-on learning environments. Therefore they fail to get experience that will assist them in developing important skills and improved understanding of the subject matter. It also seems possible that male students who are less confident in their hands-on skills, but are good at analysis and writing, also fail to get full value out of their laboratory experiences; however, evidence to support this hypothesis was not found in the literature. Perhaps an AAUW report[13] sums things up the best in recommending that we allow female students "to do the lab." The take-home experiment discussed here allows all students to conduct the experiment individually or in groups, and at their own pace.

The introductory fluid mechanics course in the Department of Mechanical and Nuclear Engineering at Penn State University is a required 3-credit junior-level course. It is normally delivered in a traditional lecture style, and covers hydrostatics, manometry, momentum analysis, energy analysis (including pumps, internal pipe flow, and losses), dimensional analysis (including lift and drag), and differential analysis (including boundary layers). The textbook by Çengel and Cimbala[14] is used. Typically 240 students/year enroll with usually four separate large sections (60-90 students) taught annually.

Fluid mechanics is a highly visual subject, and most students learn more and *retain* more when they can visualize the mathematically intense topics that are discussed in their fluid mechanics class. Therefore, it has long been the goal of our department to provide hands-on experience for our undergraduate students enrolled in our introductory fluid mechanics course. This hands-on experience comes in a variety of ways. For example, we often bring desk-top demonstrations into the classroom – U-tube manometers, converging-diverging nozzles, water containers rotating in rigid-body motion, etc., as shown in Fig. 1. While these demos allow the students to see fluid mechanics in action, they are still somewhat remote, particularly for those students sitting in the back of a large classroom. Furthermore, the students do not get to actually *touch* or *run* the experiments themselves.



(a) (b) (c)

Figure 1. Some sample class demos used in the undergraduate fluid mechanics class: (a) a U-tube manometer with higher pressure on the right column, (b) a converging-diverging nozzle with air flow from left to right demonstrating the Bernoulli principle of lower pressure at the throat, and (c) the parabolic free surface generated by water spinning in rigid-body rotation.

A more active and personal hands-on experience comes from a separate 1-credit laboratory course that is taken *after* the introductory fluid flow course. Unfortunately, only a limited number of students (typically 30 per semester) are able to take this course because it is labor intensive, and the equipment is large and expensive and cannot be easily duplicated. It would be advantageous if the lab could be incorporated into the lecture course, but this is nearly impossible logistically since we have so many students. It is also not possible to synchronize the fluids labs with the fluids lecture course since there is only one lab setup for each experiment.

Goals

The work described in this paper achieves the following goals:

1) Develop and pilot a pump flow take-home experiment for enhancing and expanding the active learning that occurs in our introductory fluid mechanics course.
2) Develop specific learning objectives for the take-home experiments using instructional design methodologies.
3) Develop and test assessment methods for these learning objectives including an investigation into the potential learning gains, students' perceptions of the take-home experiment, and gender differences.

Implementation

Of the four enhancements to traditional engineering laboratory instruction listed above, we chose to assess the educational value of take-home experiments, as discussed by Scott[2]. With this option, students take home a box, bag, or bucket of small objects with which they assemble a laboratory experiment to run in their dorm or apartment as a homework assignment. Along with each experiment comes a set of instructions, which is delivered either by paper handout or via the Internet. Take-home experiments have the following advantages:

- low cost (total cost per unit for the pump experiment is under $20) and easily duplicated
- no loss of lecture time since the take-home experiment is self-contained
- no increase in student "load" since the experiment is assigned as a homework problem, in place of one or more traditional pencil-and-paper homework problems.
- doable in less than two hours total time

Obviously, the take-home experiments need to be small enough to carry home. Therefore, these are clearly *not* intended to *replace* our current one-credit fluid mechanics laboratory. Rather, we envision them as an enhancement of our present fluid mechanics course that would not interfere with the existing laboratory course. With the take-home experiment concept, *all* the students in the course perform the take-home experiment, and thus hands-on experiential learning becomes available to *every* fluid mechanics student, rather than to only those who opt to take the follow-on fluids laboratory course.

We developed and implemented a pump flow take-home experiment for our junior-level introductory fluid mechanics course in Fall 2005. The take-home experiment, along with appropriate instructions (see Appendix 1), is assigned as a homework problem. Students check out the equipment from the department's equipment room and perform the experiment either at home or in the student lounge or student shop work area. The experimental apparatus consists of a bucket, tape measure, submersible aquarium pump, tubing, measuring cup, and extension cord with on/off switch. Students connect the tube to the pump outlet, submerge the pump in water, and measure the volume flow rate produced at various outflow elevations, using a stopwatch or other timing device. They then record and plot volume flow rate as a function of outlet elevation, and compare with the manufacturer's pump performance curve (head versus volume flow rate). The homework assignment also includes an on-line pre-test and post-test, designed to assess the increase in students' understanding of the principles of pump performance. The pre-test (along with solution key) is shown in Appendix 2; the post-test is similar, but not identical, with the questions shuffled to avoid bias errors. Most students expect that at a given outflow elevation, the experimentally measured volume flow rate should reasonably match the manufacturer's pump performance curve. However, they find that the measured flow rate is in fact significantly *lower* than that of the manufacturer's data (Fig. 2). The reason for this (which many of them do not fully appreciate at the time) is due to the irreversible head losses through the tubing and connectors. In a follow-up homework assignment given one week later, the students analyze the same flow using the concepts of major (Moody chart) and minor losses through piping systems. They show that by properly accounting for the irreversible losses through the tubing and connectors, the volume flow rate can indeed be predicted quite accurately at various outlet elevations, as also shown in Fig. 2.

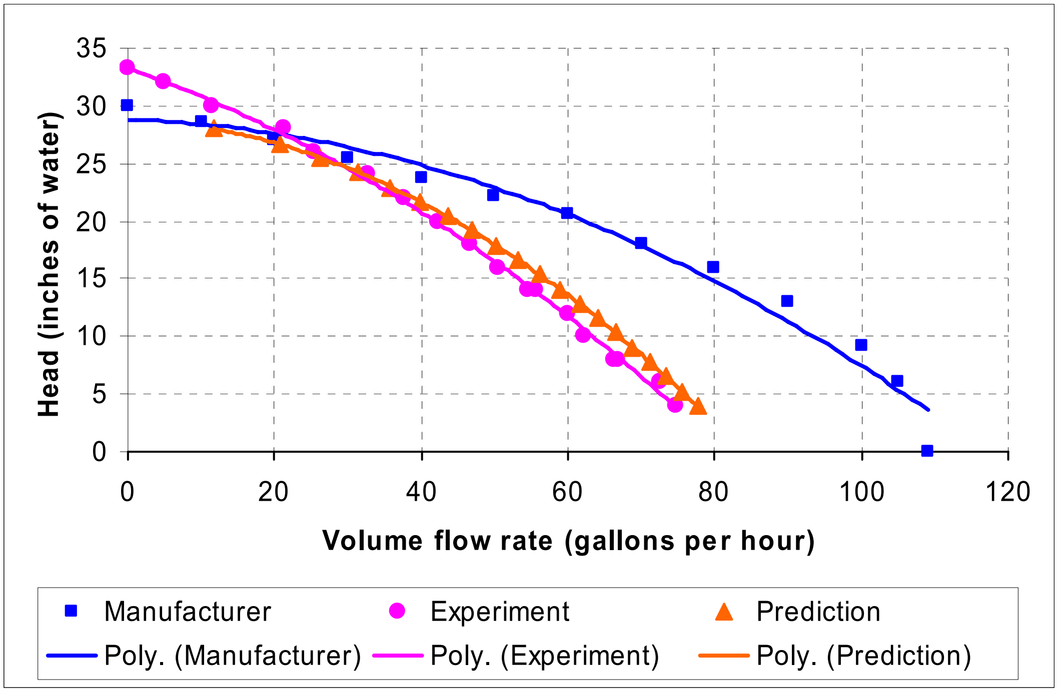


Figure 2. Sample results from the pump flow take-home experiment, along with second-order least-squares polynomial curve fits for each: manufacturer's pump performance data, experimental results, and predictions when irreversible losses through the tubing and fittings are taken into account.

Learning Objectives Reinforced by the Take-Home Experiment

The following fluid mechanics and pump performance concepts are reinforced by performing the pump flow take-home experiment:

- The volume flow rate decreases as outlet elevation increases.
- In addition to overcoming the elevation increase, the pump must also overcome irreversible frictional losses along the inside walls of the tubing and through the connectors.
- As elevation head increases, the flow rate decreases steadily until eventually the flow stops altogether – a point known as the pump's *shutoff head*.
- A pump supplies its maximum head at or near zero flow rate, and its maximum flow rate at zero head.

The last point is important from an engineering point of view when choosing a pump for a flow system application. Students learn that pump manufacturers often advertise both the maximum head *and* the maximum flow rate, but the pump cannot achieve *both* of these simultaneously.

Assessment

Students enrolled in the fall, 2005 semester were invited to participate in the assessment of the project. As mentioned above, students were asked to complete an online pre-test and post-test. These tests consist of eight true and false items and two multiple-choice items. In addition, embedded in the post-test is a short survey consisting of Likert-type scale items and open-ended questions designed to measure students' perception of the take-home experiment. The pre-test was administered to students following the course instruction on the terms and concepts relating to pump performance, but before the students completed the take-home experiment. A total of 68 students completed the pre-test. After completing the take-home experiment, students were then asked to take the post-test. Sixty-one students completed both the pre-test and the post-test. The average score for the pre-test equaled 64.92% (standard deviation = 22.11). The average score for the post-test is calculated to be 83.27% (standard deviation = 16.63). Using a paired t-test, students were found to significantly improve their scores from the pre-test to the post-test ($t = 6.394$, $df = 60$, $p < 0.001$) with an average mean difference of 18 percentage points. The percentage of students who correctly responded to each individual item is available in Appendix 3.

As mentioned above, several Likert-type and open-ended items were included in the post-test to gather students' perceptions of the take-home experiment. The survey results of students' perception of learning gains and potential difficulties related to the take-home experiment is presented in Appendix 4. Supporting the information found in the analysis of the pre-test and post-test data, approximately half of the students (52.4%) agreed or strongly agreed that the experiment increased their understanding of pump performance. For example, several students stated that their understanding increased in the following ways:

- "How height affects pumps"
- "Max pump head and max volume flow rate do not occur at the same time."
- "How the pump flow rate decreased with increased head."
- "It proved what we are learning in class with free delivery, shutoff head, and the best efficiency points."

In addition, several students noted that they were surprised by some of the data, including the inaccuracy of manufacturer's labeling, the consistency of the pump performance with the theory discussed in class, and the error associated with real-life experimentation.

Many students noted that the hands-on nature of the experiment helped their understanding. The idea of being able to physically manipulate the equipment and see first-hand "theory in action" was mentioned as an advantage for learning. As one student noted, "Working with the pumps yourself is a better way to learn than watching someone else do it." Additionally, as another student noted, "I always find that I learn better when I am performing any type of hands-on activity. I don't pay as much attention to a demonstration as I do to something I am doing myself." The majority of the respondents listed various factors when asked later on the survey what the advantages are of doing the lab as a take-home experiment. These factors included a greater understanding of the concepts because the lab was hands-on, that the lab was exciting or interesting, that the lab was a more realistic way to learn the material, and the ability to complete the lab on one's own schedule.

Possible reasons why some students did not feel the take-home experiment enhanced their learning include reasons such as the intuitive nature of the lab and the perceived sufficiency of the in-class lecture. Few students felt that the experiment increased their confidence in their laboratory skills (26.3%). The students who stated that the experiment did not increase their confidence noted that the experiment was relatively simple. Others noted that they already felt confident in the lab setting. Many students (50.8%) felt that they would rather have an in-class demonstration than a take-home experiment. Reasons listed that students would rather have an in-class demonstration mostly reflected a negativity towards having to do additional work outside of the classroom.

Most of the students felt that the lab did not pose any difficulties with the equipment or with working as a team. An overwhelming majority of the students (90.2%) agreed that the instructions were easy to follow for the lab. Approximately 77% felt that they did not have difficulties in using the equipment. A total of 85% felt that their team worked well together. The open-ended comments corroborated these results. The only potential problems listed in the open-ended statements included splashing water or flooding, difficulty finding times for group members to meet, difficulty measuring using the equipment provided, lack of congruence between observations and manufacturer's charts, lack of necessary materials (i.e., stopwatch, larger bucket, and problems with air bubbles).

Learning gains regarding the take-home experiment were also investigated in terms of gender differences. Of the students who took the pre-test, a total of 56 were male and 12 were female. For the post-test, a total of 49 students were male and 12 were female. The means for the pre-test were quite similar between males (63.9%) and females (62.5%). The means for the post-test appeared to have a larger difference (males = 81.2% and females = 87.2%). However, an independent t-test failed to detect any significant differences in the scores on the post-test for males versus females ($t = -1.433$, $p = 0.258$). Due to the small number of females in the classroom, the statistical power afforded to the test may not be adequate to detect a significant difference. Additional data collected in future semesters may allow a greater opportunity to explore the gender differences on the take-home experiment.

Discussion and Conclusions

A pump flow take-home experiment was designed, implemented, and tested in our introductory fluid flow lecture class. As part of a homework assignment, students sign out some equipment, perform some simple experiments, and analyze their results. Assessment shows that the students increased their knowledge of several fundamental concepts about pump performance. A follow-on homework assignment during the following week clarified some of the fluid mechanics concepts that were misunderstood by many of the students.

We consider this a successful first attempt, and plan to develop several more take-home experiments in our fluid flow course and in other courses. Through this process we have established methods for expanding and enhancing the experiential learning components related to laboratory instruction that we can scale up to encompass our entire curriculum.

We hope to repeat this experiment in the future, but we plan to randomly choose half of the students to perform the take-home experiment, and the other half to do a traditional homework problem that deals with the same pump performance curves – perhaps with simulated pump head versus volume flow rate data. That way, we can assess whether students who perform the take-home experiment increase their understanding more than students who do a traditional homework problem in place of the take-home experiment. In other words, we can assess whether or not the *hands-on aspect* of the take-home experiment is the aspect that leads to the increase in understanding.

Appendix 1. Pump take-home experiment instructions

List of Equipment:

- bucket
- tape measure
- aquarium pump, model UP-110
- 4-ft section of tubing, ½-inch inner diameter
- measuring cup
- extension cord with on/off switch
- some kind of timer (stopwatch, wristwatch, cell phone timer, etc.) *Note*: If you do not have a timer, you can sign one out from the Instrument Room separately.

Educational Objective: To more fully understand and appreciate the pump performance curve, i.e., pump head as a function of pump capacity (volume flow rate through the pump).

Procedure:

1. Fill the bucket about half-full with water.
2. Make sure that the tubing is attached securely to the outlet of the pump.
3. Make sure that the valve on the pump is fully open, i.e., pointing *horizontally*.
4. Submerse the pump in the water, with its suction feet attached to the bottom of the bucket. *Caution*: At no time should the power cord plug be submerged. For safety, it is best to conduct the experiment using a ground-fault circuit – we don't want any of you to get electrocuted!
5. Set up the tape measure so as to measure the vertical distance from the water surface. One person can hold the tape up, but it is more convenient to attach the tape measure to a shelf or bookcase or wall, securing it with a weight or with tape. The goal is to be able to conveniently monitor the height of the tube above the water surface.
6. With the open end of the tube pointing *into the bucket*, turn on the pump.
7. Move the open end of the tube to a height of 4 inches above the water surface. Using the timer and measuring cup, measure the volume flow rate of water. *Note*: It is wise to take at least two or three readings at each elevation. *Be careful not to kink the tubing* (notice the smooth bends in the tubing on the photograph to the right).
8. Move the open end of the tube up two more inches and measure the volume flow rate. Repeat for every two inches until the pump can no longer overcome the elevation difference (the flow rate decreases to zero). At this point, record the elevation – this is the **shutoff head**. *Caution*: Do not let the pump operate for more than a few seconds at the shutoff head, or it may burn out.

9. Turn off the pump and unplug it. Remove the pump, dump the water, and restore everything back to its original condition so that the equipment is ready for the next group.

Presentation of Results:

1. Using Excel, generate a plot of tube outlet height (inches) vs. volume flow rate (gallons per hour), making the necessary conversions. On your figure, label the shutoff head and extrapolate to approximate the maximum flow rate.
2. On the same figure, plot the manufacturer's pump performance curve, as shown below:

UP-110 Aquarium Pump Performance Data

Volume flow rate (gallons per hour)	Head (inches)
0	30
10	28.6
20	27
30	25.5
40	23.8
50	22.2
60	20.6
70	18
80	15.9
90	13
100	9.25
105	6.09
109	0

3. Compare your results to the pump manufacturer's performance curve. Which is higher? Explain why.
4. Pump manufacturers always advertise their pumps according to maximum head *and* maximum flow rate. Explain why this can be misleading – i.e., can a user expect to pump the maximum flow rate at the maximum head? Why or why not?

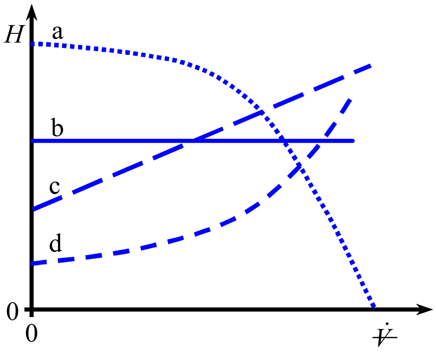
Appendix 2. Pre-test to go along with the pump flow take-home experiment

True/False Questions:

1. The volume flow rate at a pump's ***free delivery*** is greater than the volume flow rate at its ***best efficiency point***.
2. At a pump's ***shutoff head***, the ***pump efficiency*** is zero.
3. At a pump's ***best efficiency point***, its ***net head*** is at or near its maximum value.
4. At a pump's ***free delivery***, the ***pump efficiency*** is zero.
5. At a pump's ***shutoff head***, the ***volume flow rate*** is zero.
6. At a pump's ***free delivery***, the ***net head*** is zero.
7. At a pump's ***free delivery***, the ***net head*** is at or near its maximum value.
8. At a pump's ***shutoff head***, the ***net head*** is at or near its maximum value.

Multiple Choice Questions:

9. Which curve (a, b, c, or d) on the plot below is most typical of a ***pump performance curve***, which plots net pump head H versus volume flow rate $\dot{V}$?
10. Which curve (a, b, c, or d) on the plot above is most typical of the ***system*** or ***required curve*** for a pump operating in a piping system?



Solutions

1. *True*: The maximum volume flow rate occurs when the net head is zero, and this "free delivery" flow rate is typically much higher than that at the best efficiency point (BEP).
2. *True*: By definition, there is no flow rate at the shutoff head. Thus the pump is not doing any useful work, and the efficiency must be zero.
3. *False*: Actually, the net head is typically greatest near the shutoff head, at zero volume flow rate, not near the BEP.
4. *True*: By definition, there is no head at the pump's free delivery. Thus, the pump is working against no "resistance", and is therefore not doing any useful work, and the efficiency must be zero.
5. *True*: By definition, the shutoff head is the head that "shuts off" the flow rate; thus the volume flow rate is zero at the shutoff head of the pump.
6. *True*: By definition, the free delivery is the volume flow rate at which the net head of the pump is zero. In other words, there is no load on the pump so it is "free" to deliver its maximum flow rate.
7. *False*: By definition, the free delivery is the volume flow rate at which the net head of the pump is zero. In other words, there is no load on the pump so it is "free" to deliver its maximum flow rate.
8. *True*: By definition, the shutoff head is the head that "shuts off" the flow rate; thus the volume flow rate is zero at the shutoff head of the pump. This head is typically at or near the maximum possible head of the pump.
9. *a*: A typical pump performance curve starts out at the maximum value of net head at zero volume flow rate, and then slowly drops off to zero net head at the maximum flow rate, also called the free delivery.
10. *d*: A typical pump system curve, or required curve starts at some net head equal to the elevation difference at zero flow rate, and then increases nonlinearly with volume flow rate. The intersection of curves a and d is the operating point of the pump and piping system.

Appendix 3. Mean score difference between pre-and post-test

Items	Pre-test (pt1)	Post-test (pt2)	Difference (Pt2-Pt1)
1. The volume flow rate at a pump's *free delivery* is greater than the volume flow rate at its *best efficiency point*.	54%	54%	0%
2. At a pump's *shutoff head*, the *pump efficiency* is zero.	85%	89%	4%
3. At a pump's *best efficiency point*, its *net head* is at or near its maximum value.	56%	85 %	29%
4. At a pump's *free delivery*, the *pump efficiency* is zero.	38%	92%	54%
5. At a pump's *shutoff head*, the *volume flow rate* is zero.	89%	93%	4%
6. At a pump's *free delivery*, the *net head* is zero.	59%	87%	28%
7. At a pump's *free delivery*, the *net head* is at or near its maximum value.	79%	95%	16%
8. At a pump's *shutoff head*, the *net head* is at or near its maximum value	69%	84%	15%
9. Which curve (a, b, c, or d) on the plot above is most typical of a *pump performance* curve, which plots net pump head H versus volume flow rate $\dot{V}$?	70%	87%	17%
10. Which curve (a, b, c, or d) on the plot above is most typical of the *system* or *required curve* for a pump operating in a piping system?	51%	68%	17%

Appendix 4. Mean score for students' perception of learning gains and potential difficulties (n=61)

	Strongly disagree	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**	**Mean (SD)**
11. The take-home experiment increased my understanding of pump performance.	6.6%	14.8%	26.2%	47.5%	4.9%	3.30 (1.01)
12. The take-home experiment increased my confidence in my laboratory skills.	11.5%	18%	42.6%	23%	3.3%	2.88 (1.01) *n=60
13. I prefer taking the experiment home rather than having a demonstration by the professor in class.	18%	32.8%	26.2%	16.4%	4.9%	2.57 (1.13) *n=60
14. I learn more by taking the experiment home rather than having a demonstration in class.	13.1%	27.9%	26.2%	24.6%	6.6%	2.83 (1.15) *n=60
16. Working at my own pace on the take-home experiment is beneficial to my learning.	6.6%	8.2%	32.8%	45.9%	4.9%	3.35 (.95) *n=60
17. The instructions for the lab were easy to follow.	3.3%	0	6.6%	62.3%	27.9%	4.11 (.80)
18. My team and I had difficulties using the equipment in the take-home experiment.	23%	54.1%	14.8%	6.6%	0%	2.05 (.81) *n=60
19. My team and I worked well together in completing the take-home experiment.	3.3%	0	11.5%	54.1%	31.1%	4.10 (.85)

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