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Designing a Low-Cost Series, Parallel, and Single Centrifugal Pumps Exercise for an Upper-Level Undergraduate Laboratory

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Design of a low-cost series, parallel, and single centrifugal pumps exercise for an upper-level undergraduate laboratory

Abstract

A four-hour long laboratory exercise has been developed for demonstrating the performance of centrifugal pumps in single, series, and parallel configurations by deploying a low-cost tabletop setup with the help of an existing water bench facility. The framework of the setup consists of two identical small-scale centrifugal pumps connected through a systematic layout featuring three ball valves to allow simple switching between the four configurations. A differential pressure transducer is connected across the inlet and the outlet of the setup to allow direct measurement of head rise of each pump configuration at different flow rates that are controlled by a throttle valve in the outlet. A Coriolis force mass flowmeter, connected to a constant head reservoir in the water bench, measures the flow rate from the reservoir through the setup. A DC power supply runs the pumps and reports the current and voltage. Without being allowed to disassemble the setups, students develop an experimental procedure to assess the performance of the pumps through measurements of the pump head and pump efficiency as a function of the flowrate. Students test hypotheses about the pump head and flowrates for the various configurations, assessing how the total pump head and total flowrate sum for series and parallel combinations of pumps. Similar assessments are made of the efficiency of the pump configurations. Evaluation surveys are taken by students and laboratory teaching assistants to examine the effectiveness of the learning outcomes of the lab exercise. A full description of the setup will be given, as well as a complete bill of materials and budget, which will be critically compared against some commercially available setups.

Introduction

It is widely acknowledged that hands-on experience through laboratory exercise is a pertinent part of the education system, particularly in the development of engineering education curriculum. Education researchers unequivocally identified the importance of incorporating laboratory exercise in engineering course curriculum design, offering valuable insights to optimize the efficacy of laboratories through several case studies [1–5]. Researchers effectively argue the case for incorporating practical components into engineering classes, emphasizing the value of problem-based or project-based learning (PBL) which aims to bridge theoretical knowledge with real-world applications [6].

Numerous literatures present some innovative designs of hands-on laboratory practice under the engineering course curriculum. Kilula et al. [7] developed experimental facilities for the upper-level engineering undergraduate students to demonstrate some engineering concepts that the students learned in their earlier semesters. The experimental pedagogy consisted of instrumentation, sensors, experimental data acquisition (DAQ), and analyzing the data through LabVIEW. Students were engaged in learning thermodynamics by conducting a thermal experiment on heat transfer using a fin, learning vibration mechanics through beam vibration experiment. Their hands-on training also included SolidWorks simulation on the two topics. Earp and Parker [8] fabricated a hands-on fluid flow trainer system that facilitates students to visualize, control, and analyze fluid flow through pipes, channels, valves, and venture. They focused on visualizing the flow path through piping where flow was controlled through different types of like ball valves, gate valves, and globe valves. Pressure gauges and manometers were used to measure the pressure losses through valves and the system. Their trainer also comes with a flowmeter to measure the flowrate which was provided by centrifugal pump. Bishop [9] focused on developing students' hand-on learning experience on material testing and then their writing skill in preparing formal engineering reports. Students performed twelve materials tests in 14 weeks utilizing a custom universal testing machine, a custom torsion testing machine, and a stress polariscope. He maintained proper institution criteria for the report writing, feedback, and students support service, for instance, making appointments with instructor in a feedback meeting. Levey [10] developed a noble hands-on learning exercise on fluid mechanics in a large-scale undergraduate classroom with 90 students. The experiment is about demonstrating the velocity profile of a falling object in viscous fluids and accessing the drag force from Stokes' law. The set-up is very simple and has been reported to be very cost-effective, offering multiple learning outcomes such as building teamwork, polishing technical skills, applying theory to practice.

Like other engineering pedagogy, an undergraduate level fluid mechanics course demands an effective PBL curriculum that involves processes of investigation and inquiry, which extends beyond a lecture-style class. A lecture-style class is undeniably the focal point in designing a mathematics rich course like fluid mechanics, but it's equally demanding practical dimensions can only be fully comprehended through the integration of a well-developed laboratory practice consistent with the lecture content. In this context, we developed a laboratory exercise for the ME 310: Fundamentals of Fluid Dynamics, which is a required course for junior undergraduate students in the Mechanical Engineering major at the University of Illinois Urbana-Champaign.

The laboratory exercise that the authors developed focuses on the operation of centrifugal pumps in three possible configurations: single, series, and parallel. To demonstrate the pump performances of these three configurations in front of around eight students in each section, the authors designed two identical table-top experimental setups on the existing water-bench facility in the fluid mechanics instructional laboratory. Each setup comprises low-cost fluidic components including two small-scale centrifugal pumps connected through three one-way ball valves layout. The valve layout is uniquely deployed to facilitate effective switching techniques between different configurations using the same pumps without necessitating their removal or rearrangement.

The objective of this experiment is to determine the characteristics of a centrifugal pump by constructing dimensional performance curves. Of fundamental interest are the pump head h_p and the efficiency η, given by $\eta = \frac{P_{out}}{P_{in}}$, where P_{in} is the power supplied to the pump by an electric motor, and P_{out} is the mechanical power imparted to the fluid by the pump [11–14]. Through laboratory activities guided by the trained teaching assistants (TAs), students find that h_p, P_{in}, P_{out} and the efficiency η all vary in interesting ways with the volumetric flow rate (discharge or pump capacity) Q, which is controlled by a throttle valve in the discharge line. Students experimentally examine how to increase the pump head, h_p, the flow rate, Q, efficiency, η, and how to achieve a fine tuning between these two performance parameters according to the application requirement through series and parallel connections.

The lab exercise was designed to provide the students with a hands-on experience to understand the fundamentals of pump performance that correlates pump pressure heads, i.e. pressure rises with pump flow rates. A simple switching technique in a table-top set-up, as described in the next section, helps the students develop knowledge of pump performance optimization by connecting two pumps in series or parallel configurations.

This lab exercise was developed out of necessity when a centrifugal pumps exercise that was purchased from an educational equipment supplier failed critically and could not be replaced in a timely manner. This paper serves as evidence of the adaptability of the instructional laboratory facility by highlighting the capacity to swiftly integrate innovative solutions into an existing course framework.

Theories of Centrifugal Pump Performance

Motor power required to run the impeller of the pumps at a specific angular speed is called the input power, P_{in} which can be found from the following electric power input expression:

$$P_{in} = VI_P \tag{1}$$

where V is the supplied voltage and I_P is the current supplied to the pump. Here the power source efficiency is assumed to be 100% (no electric loss). The output power of the pump, P_{out}, is equal to the rate of work done on the fluid:

$$P_{out} = \gamma Q h_p \tag{2}$$

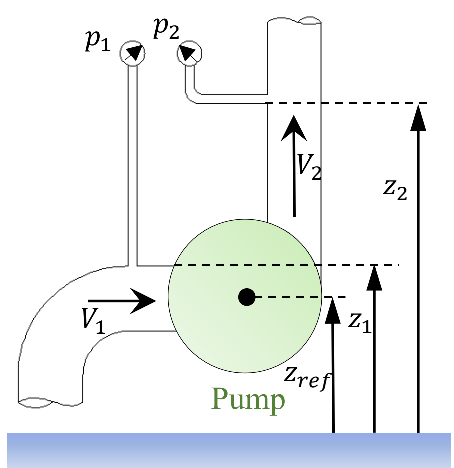


Figure 1. Pump pressure rise and velocity correlation

where γ is the specific weight of the fluid, Q is the volumetric flow rate (pump capacity), and h_p is the pump head. Applying Bernoulli's equation between point A and point B in Figure 1:

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_p = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \tag{3}$$

Since A and B are at the same reference height, this expression simplifies to

$$h_p = \frac{p_B - p_A}{\gamma} + \frac{V_2^2 - V_1^2}{2g} \tag{4}$$

where, in general, the entrance velocity V_1 and the exit velocity V_2 do not have the same value since the inlet and outlet pipe diameters are different. If the bulk flow rate Q is known, the velocities V_1 and V_2 are easily calculated from the continuity relation:

$$Q = \frac{\pi D_1^2}{4} V_1 = \frac{\pi D_2^2}{4} V_2 \tag{5}$$

The efficiency η is found to be a function of the flow rate and is therefore not just a constant for a given pump. Efficiency is an important characteristic of a pump, since, as indicated in Figure 2, the difference $P_{in} - P_{out}$ represents power that is lost.

Fundamental variables appearing in pump characteristics curves are the input power $P_{\text{in}} = T\omega$, flow rate Q, pump head h_p, output power $P_{\text{out}} = \gamma Q h_p$, and efficiency η. Usually, flow rate (or discharge) Q is chosen as the independent variable, and the other quantities are plotted as functions of Q. This curve simply plots of pump head h_p as functions of Q (sometimes called $Q - H$ curve), with efficiency η appearing as a parameter along each curve. Only one such curve is needed to characterize a given pump completely. An example of such a curve for a centrifugal pump appears in Figure 3.

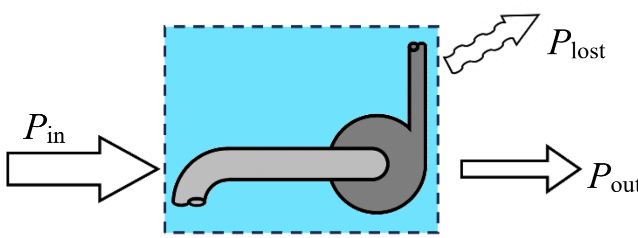


Figure 2. Schematic of input and output power.

As shown in Figure 4, pumps can be oriented in series, parallel, or a combination of these two configurations. Pumps connected in series configuration achieve a total head as the summations of the individual pump heads:

$$h_{p,series} = h_{p1} + h_{p2} + \cdots. \tag{6}$$

On the other hand, pumps connected in parallel configuration achieve a flow rate as a summation of the individual flow rates of the pumps:

$$Q_{series} = Q_1 + Q_2 + \cdots. \tag{7}$$

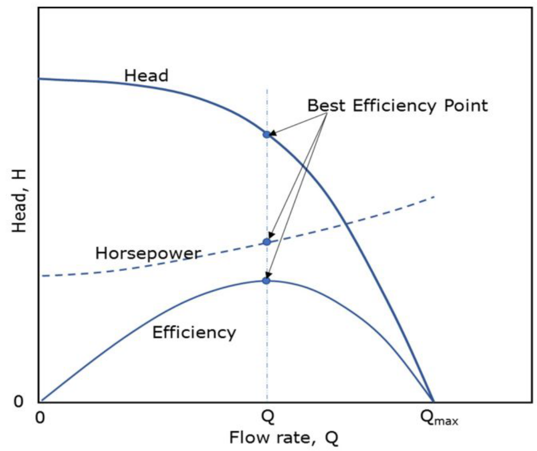


Figure. 3. Pump characteristic curve [17]

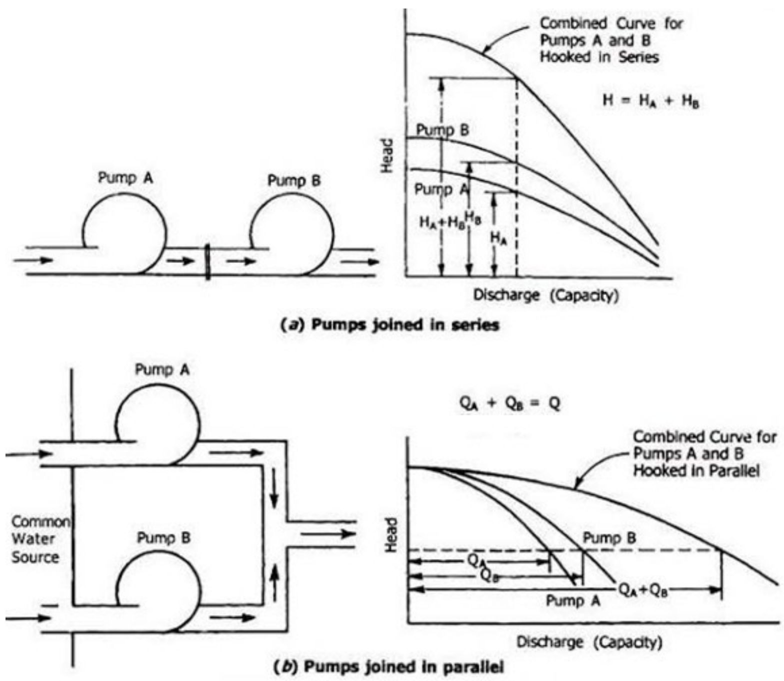


Figure 4. Characteristic curves for pumps' series and parallel connections (image modified from [18]).

Equipment and Exercise Design

The schematic of the full design layout of the table-top experiment is shown in Figure 5. What makes this initiative particularly noteworthy is its integration into an already-established water bench trainer, and the creation of in-house design. The water bench trainer, previously designed and implemented for specific educational purposes, became the canvas for incorporating this newly developed lab exercise seamlessly. The details of this water bench facility are comprehensively documented in an accompanying paper [19].

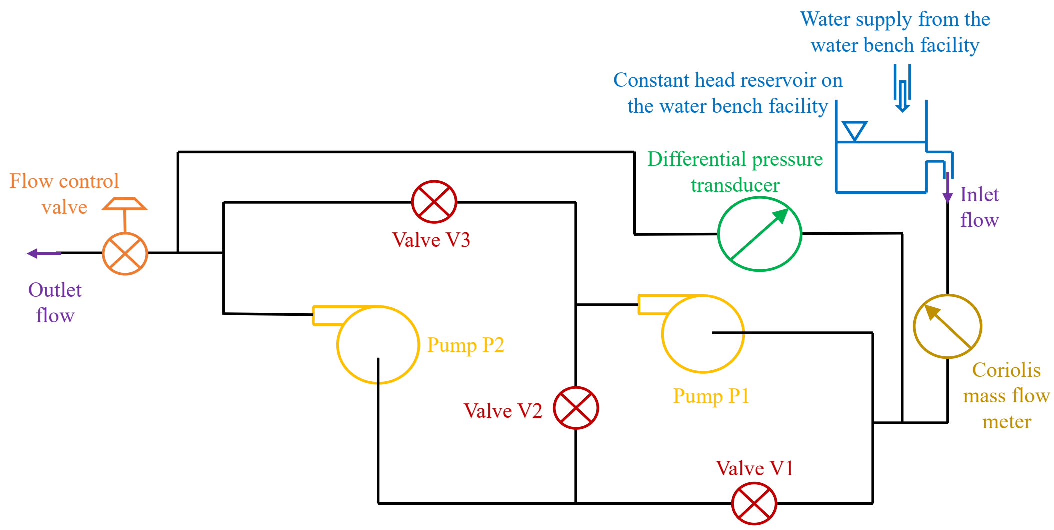
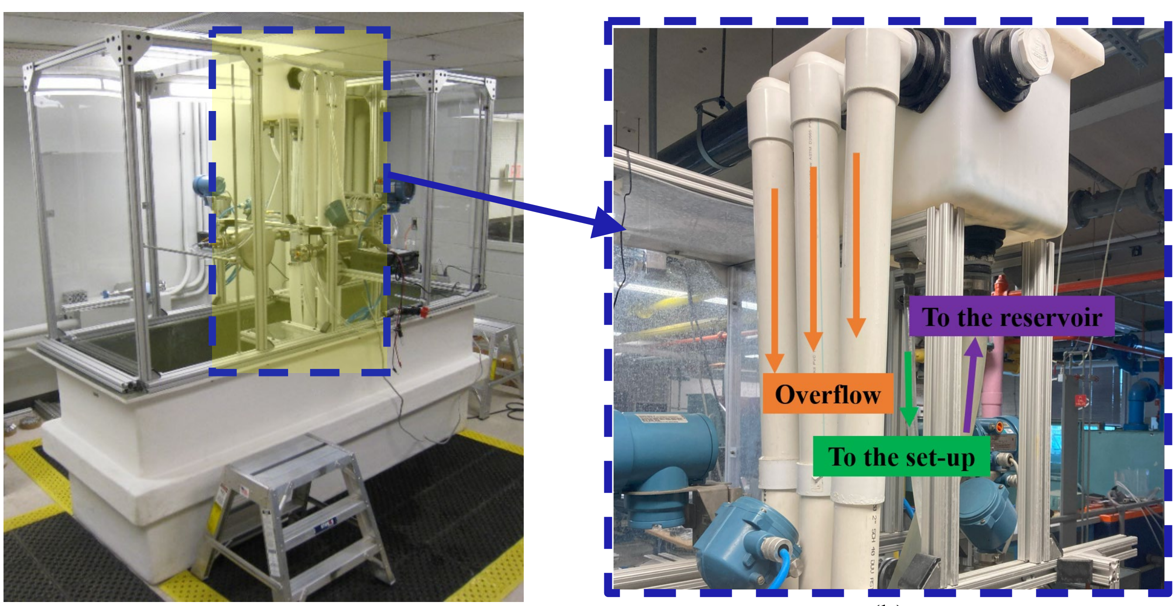


Figure 5. Schematic of the valve layout for performing three centrifugal pumps configurations: Individual (only V1 or V3 Open), Series (only V2 Open), and Parallel (only V1 and V3 Open).

The water bench, shown in Figure 6(a) consists of a large fiberglass tank with inner dimensions 96 in long×32 in wide×36 in deep. The tank holds a large supply of water that is pumped upward into a constant-head reservoir. The constant head is maintained using overflow drains, as shown in Figure 6(b). At the surface of the water, the pressure is atmospheric for a gage pressure of zero. Because the height of the surface is held constant, the kinetic energy head at the surface is also zero, leaving the potential energy head as the only nonzero term in the Bernoulli equation. A drainpipe at the bottom of the reservoir provides flow to the set-up through a Coriolis force mass flow meter.



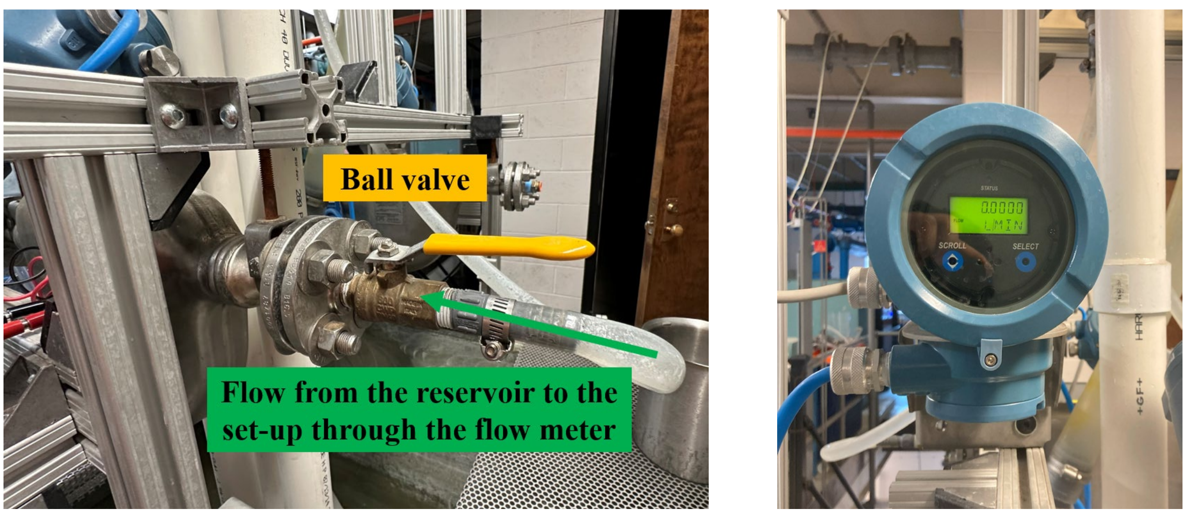
(a) (b)

Figure 6. (a) The water bench facility, (b) constant head reservoir, water is being pumped upward to the reservoir and then directed to the set-up through flexible tubing

Coriolis force mass flowmeters directly measure the mass flowrate $\dot{m}$ of a fluid travelling through a cantilever pipe. At zero flow, the pipe is actuated to vibrate at its natural frequency and the vibration is monitored electronically. The pipe has several bends in it such that fluid flowing through the bends is acted upon by the Coriolis force, which modulates the vibrational frequency of the pipe. Analysis of the modulated vibration allows highly accurate measurements of $\dot{m}$ and the fluid density ρ. The volumetric flowrate Q_{Total} can then be found simply by taking $\dot{m}/\rho$, which is also computed and reported by the meter. The flowmeter provided for this exercise has a quoted and certified measurement uncertainty of ±0.1% of the flow rate.

The connection of the flowmeter is shown in Figure 7(a). A yellow ball valve is fitted upstream of the flowmeter. It is very important to note that this yellow ball valve should be opened all the time during the experiment. If it is kept closed while running the pumps, air will be trapped in the rigid connectors in the set-up. This valve will also be used for the purpose of priming the pumps. The Coriolis force mass flowmeter will give the reading in liters/min, as shown in Figure 7(b).

The table-top set-up is shown in Figure 8. It consists of two identical pumps $P1$ and $P2$, three ball valves $V1$, $V2$, and $V3$, one differential pressure transducer that measures the difference of the pressure from outlet and inlet (thus always gives positive numbers for the current set-up), one outlet throttle valve to control the flowrate, tee and elbow connectors and fittings.



(a) (b)

Figure 7. (a) Ball valve (yellow) connected to the flow meter. This valve is used for priming and should be kept open (like the figure) throughout the experiment; (b) Flowmeter reading in liter/min

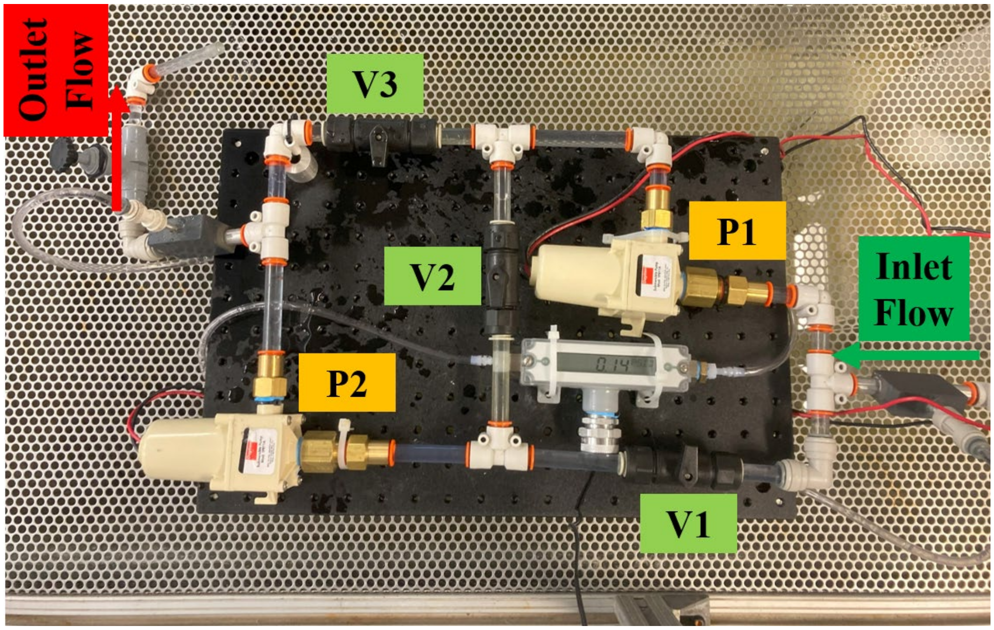


Figure 8. Layout for a universal table-top setup of series and parallel combinations using two centrifugal pumps $P1$ and $P2$.

Valves $V1$, $V2$, and $V3$, shown in Figure 9(a), are used to switch from individual to series and parallel connections. These ball valves are supposed to be used only for the binary purpose: closing and opening a connection. A needle valve is used to control the flow rate, Q, in the outlet, as shown in Figure 9(b). The differential pressure transducer in Figure 9(c) is connected to the inlet and the outlet of the set-up in such a way that it gives the difference between the outlet pressure and the inlet pressure. The rated maximum pressure difference that it can show is 50 psi. Note that at zero flow the transducer might show a small nonzero value, which is the offset bias; it should be deducted from the observed pressure reading to get the correct gage pressure difference.

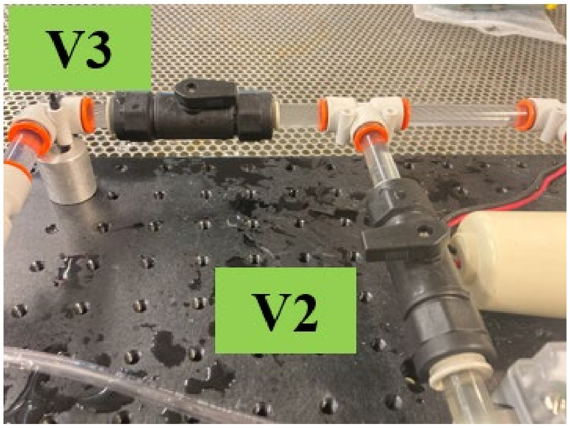
Pumps P_1 and P_2 are two centrifugal pumps used in the set-up. The two pumps are identical make and model. They are connected in a parallel electric connection to a power source (voltage source) as shown in Figure 10. Thus, the total supplied current, I, and the voltage, V relates to the individual pump input electric power as:

$$V_{P1} = V_{P2} = V \tag{8}$$

$$I_{P1} + I_{P2} = I \tag{9}$$

Here, V_{P1}, and V_{P2} are the voltages and I_{P1}, and I_{P2} are the currents for individual pumps. Assuming identical impedances of the two pumps implies equal delivery of electrical current to the pumps:

$$I_{P1} = I_{P2} = \frac{1}{2} I \tag{10}$$



(a) (b)

(c) (d)

Figure 9. (a) Ball valves in closed and open situations (V_2 is closed and V_3 is opened), (b) Outlet throttle valve to control the flow rate, Q, (c) Differential pressure transducers, (d) One of the pumps

The maximum voltage of the source is around 15 volts. The power supplies also report the total current, I, as in Figure 10(a).

(a) (b)

Figure. 10. (a) Power supply (voltage source) to both the pumps. The right-hand display shows the voltage, and the left-hand reading is the total current passing through the pumps. (b) Parallel electric connection to the voltage source. Each pair of black and red connectors comes from each pump.

Student Evaluations of the Exercise

Since this is a new exercise among other fluid mechanics laboratory exercises, feedback from the students and the TAs is sought to assess the effectiveness of the laboratory practice. Evaluation surveys using a 5-point Likert scale from "Strongly Agree" to "Strongly Disagree" were given to the students to categorize their feelings about 16 statements related to the lab exercise. The questionaries were segmented into three separate categories related to the usefulness of the lab resources, coherence with other lab exercises in the semester, and efficacy of the lab upon student learning outcomes, respectively. The students were also asked open-ended questions to comment on the positive impact of the lab and to suggest potential opportunities for improvement. The survey was given from a total of 170 registered students who participated the lab exercises during the Fall 2023 semester. The survey results were analyzed after semester grades were released. Consent to participate was requested in a preamble to the IRB-approved survey.

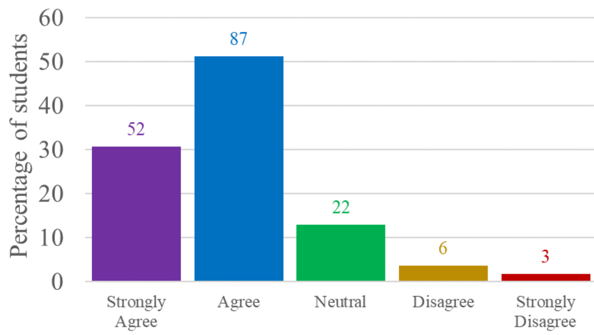
The Likert scale scores of individual questions and individual categories are presented in Figures 11–15. Answers to the open-ended questions, as well as a survey report from seven TAs are presented in the appendices.

<u>Category 1: Usefulness of Resources Provided for the Lab Exercise</u>
Statement 1: I understood the working principles of the equipment used for the centrifugal pump lab setup (operation of the pump, the pressure transducer, the flowmeter, and the valves).
Statement 2: The lab manual was a useful reference for me to understand the centrifugal pumps lab exercise.
Statement 3: The teaching assistant was helpful for understanding and performing the lab exercise.
Statement 4: The total time allocation (2 + 2 = 4 hours in the lab) was sufficient to perform the lab properly.
Statement 5: The lab setup was designed properly to accommodate all of the students in my lab section.
Statement 6: After finishing the lab exercise, I felt able to answer the questions in the lab manual.

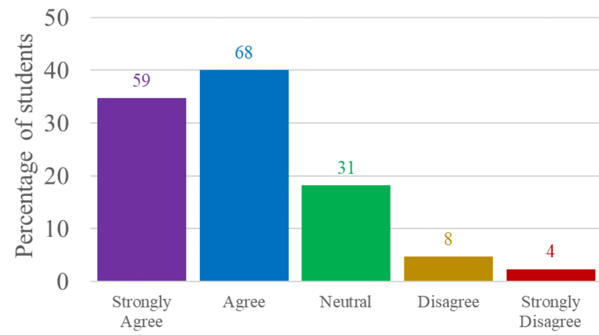
<u>Category 2: Evaluation of the Coherence of this Exercise within the Lab Course</u>
Statement 7: The centrifugal pumps lab exercise was scheduled in a reasonable place in the semester with respect to the other lab exercises.
Statement 8: Writing the previous lab reports prepared me well to write this lab report.
Statement 9: The lab report for this lab exercise was easy to prepare by the deadline.
Statement 10: Lab report grading was reasonable.

<u>Category 3: Contribution to Learning</u>
Statement 11: The lab exercise was effective for me to learn how centrifugal pumps work.
Statement 12: As a result of this lab exercise, I understand how valves and pumps work in various configurations (individual, series, and parallel).
Statement 13: I am confident about how centrifugal pumps perform in series and parallel configurations compared to a single pump.
Statement 14: I can compare the performance and efficiency of different pump configurations.

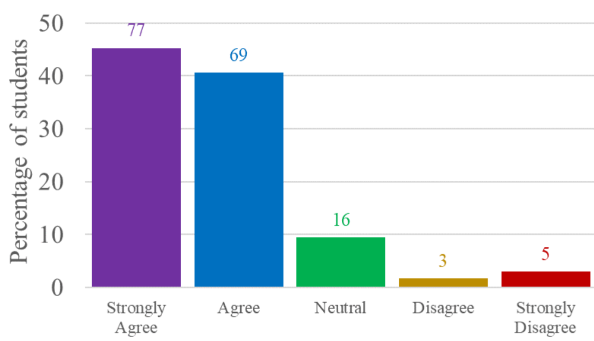
Statement 15: I now have the knowledge to specify a pump or system of multiple pumps in some engineering installation.
Statement 16: Doing this lab exercise made me excited to work with pump configurations in real-world engineering applications.



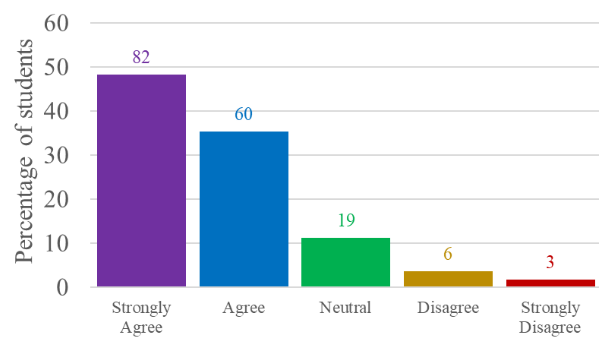
S1: I understood the working principles of the equipment used for the centrifugal pump lab setup (operation of the pump, the pressure transducer, the flowmeter, and the valves).



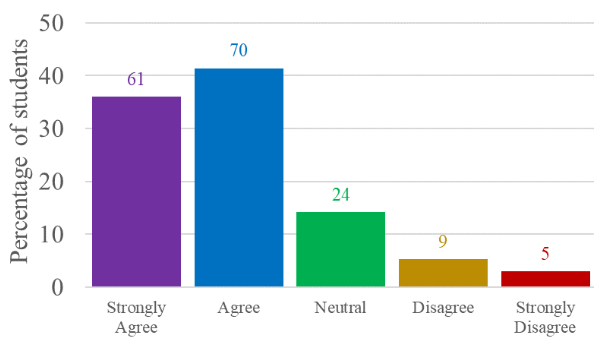
S2: The lab manual was a useful reference for me to understand the centrifugal pumps lab exercise.



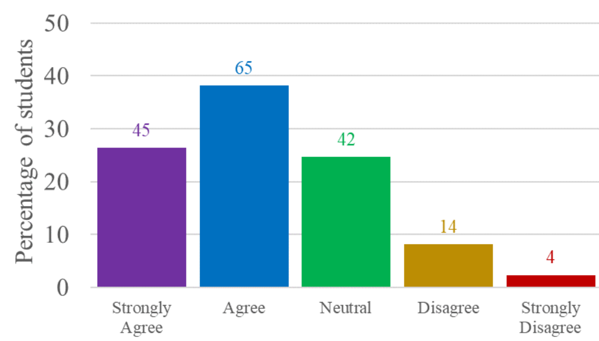
S3: The teaching assistant was helpful for understanding and performing the lab exercise.



S4: The total time allocation (2 + 2 = 4 hours in the lab) was sufficient to perform the lab properly.



S5: The lab setup was designed properly to accommodate all of the students in my lab section.

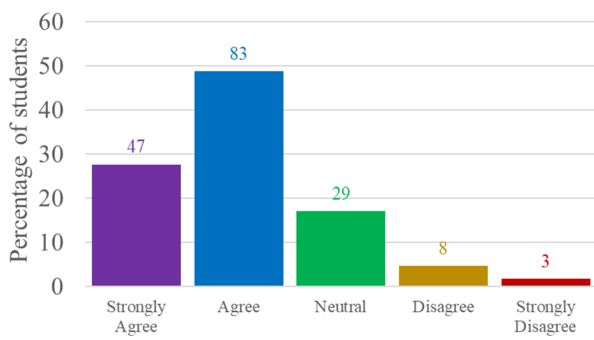


S6: After finishing the lab exercise, I felt able to answer the questions in the lab manual.

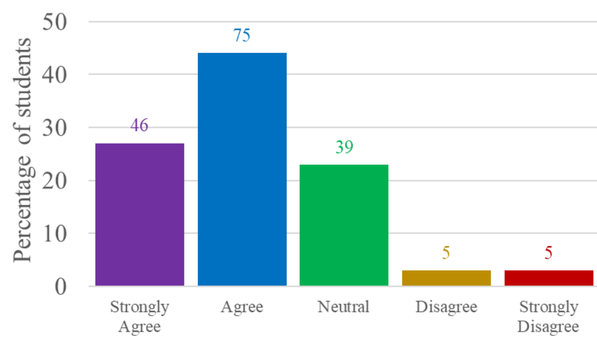
Figure 11. Survey reports of the Category 1 statements. The numeral above each bar indicates the actual count of students responded.

Figure 11 shows the Likert distributions for the first six statements (S1–S6), which comprise Category 1. It is evident that the students generally found the resources to be useful, from understanding the working principles of each flow component, to the lab manual, TA, and time provided to do the work. In each distribution, a strong majority exceeding 60% of the students were in either agreement or strong agreement with the positive statements about the resources. For every statement in Category 1, fewer than 11% combined to disagree or strongly disagree.

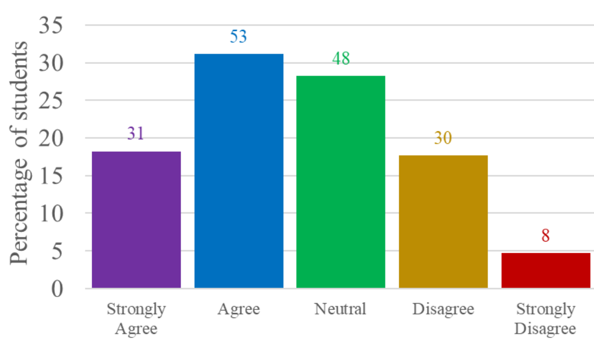
Figure 12 shows the Likert distributions for statements S7–S10, which comprise Category 2. The Likert distributions for the Category 2 items reveal similar trends in the feelings of the students about how the lab fit into the broader curriculum of the course. Compared with Category 1, the distributions also indicate general Agreement among the students, but with the distributions shifted nearer to Neutral. Majorities of students Agree or Strongly Agree with the statements with one exception: For Statement 9, a plurality of 49% Agree or Strongly Agree, while 28% remained Neutral about the lab report being "easy to prepare by the deadline."



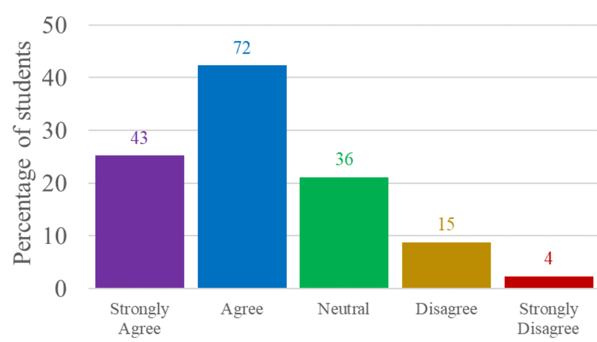
S7: The centrifugal pumps lab exercise was scheduled in a reasonable place in the semester with respect to the other lab exercises.



S8: Writing the previous lab reports prepared me well to write this lab report.



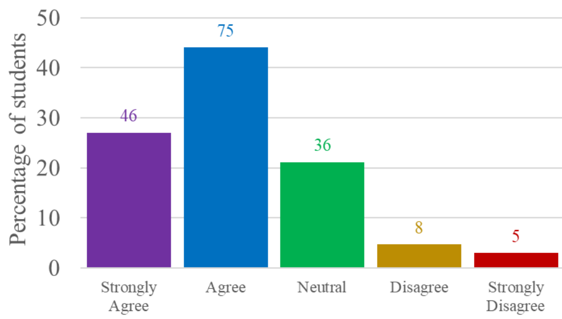
S9: The lab report for this lab exercise was easy to prepare by the deadline.



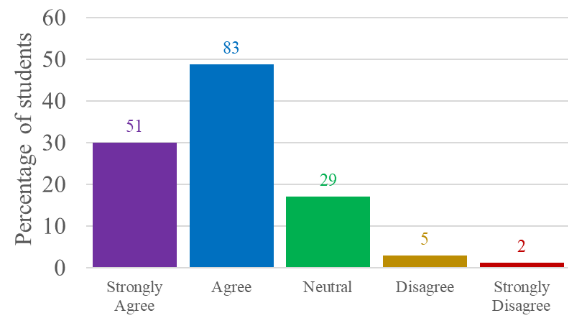
S10: Lab report grading was reasonable.

Figure 12. Survey report of Category 2 statements. The number value above each bar indicates the actual count of students responded.

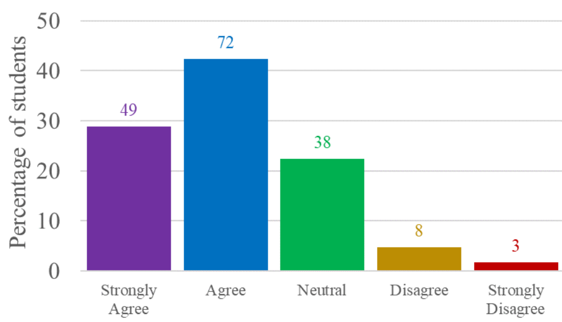
Figure 13 shows the Likert distributions for statements S11–S16, which comprise Category 3. The Likert distributions for the statements about learning self-efficacy are again strongly positive, with at least 55% indicating that they Agree or Strongly Agree with all statements. The most disagreement occurs for S16 about the lab exercise making the students excited to work with pumps, for which a sum of 16.5% of respondents Disagree or Strongly Disagree. In none of the other statements do even 10% of respondents disagree. The students in large proportions found the exercise to benefit their knowledge and understanding of the operation of pumps.



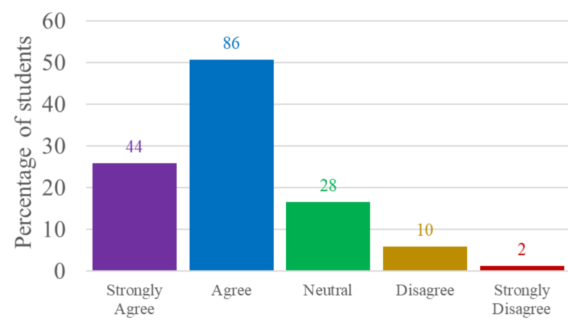
S11: The lab exercise was effective for me to learn how centrifugal pumps work.



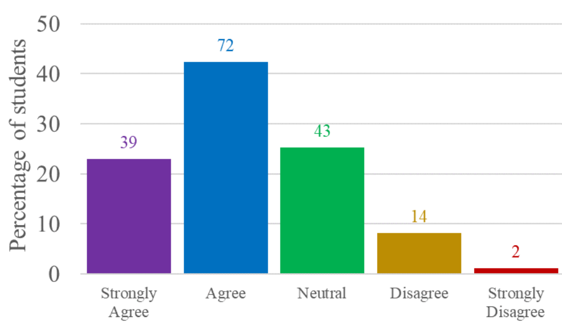
S12: As a result of this lab exercise, I understand how valves and pumps work in various configurations (individual, series, and parallel).



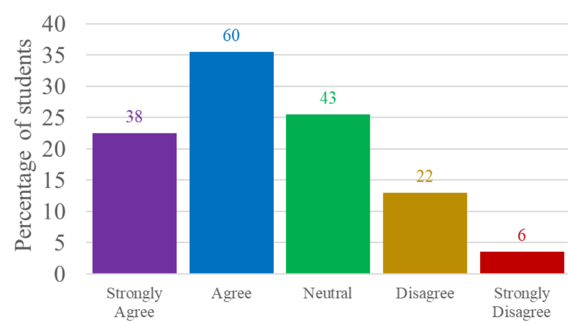
S13: I am confident about how centrifugal pumps perform in series and parallel configurations compared to a single pump.



S14: I can compare the performance and efficiency of different pump configurations.



S15: I now have the knowledge to specify a pump or system of multiple pumps in some engineering installation.



S16: Doing this lab exercise made me excited to work with pump configurations in real-world engineering applications.

Figure 13. Survey report of Category 3 statements. The number value above each bar indicates the actual count of students responded.

Project Expenses

Table 1 shows the costs associated with development of this laboratory exercise, which came to approximately $2,500 for two identical setups. All costs for parts and labor were paid by the home department of the co-authors without the assistance of an external funding agency. Student labor was provided as part of a summer TA appointment. No additional faculty salary was provided in support of this project.

Table 1. Labor and material expenses to develop the laboratory exercise

Item Description	Vendor	Part of System	Unit Price	Qty	Total Price
Aluminum Breadboard 12"×18"×0/5"	Thorlabs	Base for setup	$214.65	2	$429.30
Push-to-connect needle valves	McMaster-Carr	Flowrate control	$37.84	2	$75.68
Push-to-connect ball valves for 1/2-in tubing	McMaster-Carr	Series/parallel pump control	$30.63	6	$183.78
Clear PVC tubing, 1/2-in. OD, 6-ft long	McMaster-Carr	Tubing for pipes	$17.32	1	$17.32
Push-to-connect adapter for 3/8 NPT pipe	McMaster-Carr	Push-to-connect adapters for pumps	$8	8	$64.00
PVC bar stock, 3/4-in×2-in×24-in	McMaster-Carr	Transfer blocks for pressure measurement	$23.16	1	$23.16
1/4-in OD Aluminum tubing, 0.035" wall thickness, 3-ft long	McMaster-Carr	Transfer blocks for pressure measurement	$9.20	1	$9.20
1/2-in OD Aluminum tubing, 0.065" wall thickness, 3-ft long	McMaster-Carr	Transfer blocks for pressure measurement	$16.18	1	$16.18
Machinist labor costs	Institution	Transfer blocks for pressure measurement	$59/hr	2	$118.00
18VDC AC Adapter	McMaster-Carr	Pressure transmitter	$29.96	2	$59.92
Wet-wet differential pressure transmitter	Dwyer	Pressure transmitter	$445	2	$890.00
LCD Display for pressure transmitter	Dwyer	Pressure transmitter	$169	2	$338.00
12 VDC Marine Pump	Zoro	Pumps	$39.66	4	$158.64
Miscellaneous items	--	Fittings, zip-ties, etc.	$100	--	$100
				Total cost:	$2,483.18

Discussion & Conclusions

Students broadly found this lab equipment to be useful for learning about the use of centrifugal pumps and how their performance can be predicted in series and parallel configurations. The experiment fit coherently into the lab curriculum. Because of the nature of this course and lab exercise, whereby students must develop an understanding of the equipment in order to perform the experiments, this exercise may be useful for direct evaluation of ABET Criteria 3: Student Outcomes 6 regarding "an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions." With careful planning and administration of this exercise, other outcomes could also be evaluated, such as Outcomes 1, 3, 5, and 7 [20]. Additionally, the system described in this paper has the benefits of being easily maintained at low cost. For example, to replace any single system in one of the two setups would cost at most $644 (that is, the pressure transmitter assembly costs a sum of $29.96 + $445 + $169; see the line items in blue in Table 1). For comparison, the authors have had experiences where sending working educational laboratory equipment to its manufacturer merely to be recalibrated cost multiple thousands of dollars with a lead time on the order of multiple weeks.

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References

[1] D. Pusca, R. J. Bowers, and D. O. Northwood. "Hands-on experiences in engineering classes: the need, the implementation and the results." *World Trans. on Engng. and Technol. Educ* 15, no. 1: 12-18, 2017.

[2] A. Hofstein, and V. N. Lunetta. "The laboratory in science education: Foundations for the twenty-first century." *Science education* 88, no. 1: 28-54, 2004

[3] D. A. Bergin, "Influences on classroom interest." *Educational Psychologist* 34, no. 2: 87-98, 1999.

[4] N. Holstermann, D. Grube, and S. Bögeholz. "Hands-on activities and their influence on students' interest." *Research in science education* 40: 743-757, 2010.

[5] L. E. Carlson, and J. F. Sullivan. "Hands-on engineering: learning by doing in the integrated teaching and learning program." *International Journal of Engineering Education* 15, no. 1: 20-31, 1999.

[6] A. Johri, and B. M. Olds, eds. *Cambridge handbook of engineering education research* in Cambridge University Press, 2014.

[7] D. Kilula, S. Haran, and L. R. Neal. "Achieving Student Outcomes through Hands-on Design of Experiments." In 2023 *ASEE Annual Conference & Exposition*. 2023.

[8] B. C. Earp and K. R. Parker. "Hands-On Fluid Flow Trainer to Support Experimental Learning." In *2023 ASEE Annual Conference & Exposition*. 2023.

[9] J. Bishop, "Designing the Laboratory Experience from the Ground Up: Custom Laboratory Equipment and Writing-Intensive Pedagogy." In *2023 ASEE Annual Conference & Exposition*. 2023.

[10] F. C. Levey. "Work-in-Progress: Hands-on group activities for large Fluid Mechanics classes in a traditional lecture hall setting." In *2023 ASEE Annual Conference & Exposition*. 2023.
[11] B. R. Munson, D. F. Young, and T. H. E. Okiishi. *Fundamentals of Fluid Mechanics*, 4th ed. New York: Wiley. 2004.
[12] R. L. Street, G. Z. Watters, and J. K. Vennard. *Elementary Fluid Mechanics*, 7th ed. New York: Wiley. 1996.
[13] F. M. White. *Fluid Mechanics*, 5th ed. New York: McGraw-Hill. 2003.
[14] M. C. Potter, and D. C. Wiggert. *Mechanics of fluids*, 3rd ed. CL Engineering. 2001.
[15] Y. Wu. "Cultivating technical writing skills through a scaffold peer review-approach of lab reports in a junior-level laboratory course." In *2023 ASEE Annual Conference & Exposition*, 2023.
[16] A. Paul, M. J. I. Moran, R. Hussein, and D. May. "Exploring diversity, equity, and inclusion in remote laboratories." In *2023 ASEE Annual Conference & Exposition*. 2023.
[17] https://eng.libretexts.org/
[18] www.rgaalmer.top
[19] B. E. Johnson. "A modular water bench and fountain design project for an undergraduate fluid dynamics laboratory." To be published in 2024 *ASEE Annual Conference & Exposition*. 2024.
[20] https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2024-2025/

Appendix A

Students Answers on 3 Open-ended Questions

Question 1: What aspects of this lab were most useful or valuable?

1. Learning how pumps work
2. Overall the procedure was pretty logical
3. Understanding the differences in pump configurations
4. The hands on experience of working with centrifugal pumps.
5. Learning about how the pumps worked
6. Seeing an actual application of series vs parallel, instead of just on a breadboard.
7. Seeing the parallel and series configurations, getting to take measurements
8. One of the aspects of this lab that was most useful is the way the series and parallel configurations result in a different way the flow rate reacts.
9. I did not get a solid understanding of the concepts from this lab.
10. Understanding the losses in each of the fittings and being able to calculate the distance for the projectile fountain.
11. Understanding how the efficiencies of a pump work and how they change with regard to different configurations.
12. N/A
13. Isolate specific variables to see how each aspect affect efficiency
14. Learning the idea of adding pumps in parallel vs in series
15. Learning about how the pumps themselves worked
16. Help me to have a deeper understanding for knowledge
17. Hands on experiments
18. Pumps in series and parallel
19. I think the most useful one is that it teaches us how to write an report in appropriate format.
20. Visualizing the series and parallel flows
21. I can have deeper understanding for the knowledge
22. in-lab experiment
23. Hands on activity
24. writing technical reports
25. Seeing the flow behave in a way that's similar to electricity
26. I would say it was cool to use pumps and see how different configurations effected pressure and flow rate.
27. Comparing the pump configurations to electrical circuits
28. being able to work with peers and having opportunity to ask for clarification
29. The idea that pumps can somewhat be treated like circuits
30. The hands on aspect, being able to physically see how the different arrangements was helpful for my understanding
31. Lab report
32. The TA will help me understand the manual
33. Getting hands on experience.
34. The experimental procedure of the lab and the manual were essential in understanding the fundamental concepts we need to apply and gave us directionality.
35. Helped me understand and be able to apply information to real world
36. Learning how efficiency is affected by the orientation of the pumps.
37. the lab was pretty easy to do and I liked that i could compare it to things I learned in other classes like ECE205
38. I enjoyed the turbulent flow lab and it helped in understanding wakes, laminar flow, and turbulent flow
39. The analysis of the data was useful in the understanding
40. I think this lab helps me understand what I learned from the class more clearly.
41. The use of the pumps has the potential to provide a significant level of understanding and appears to be quite applicable to real world mechanical engineering problems.
42. it was kind of interesting
43. Group work
44. Practicality.
45. The physical interaction with the pump setup was the area where I learned best about the different configurations.
46. All aspects were very helpful
47. N/A
48. The hands on experience and that facts that we all did the work and not just watched someone donit

49. Know how to apply the knowledge
50. Writing the reports helped me best understand as it allowed me to analyze the data we took from the lab
51. Physically seeing how the different pump configurations worked.
52. the chance to test out all the tubing
53. The reports were most useful because that is when I fully understood everything in the lab.
54. Practice the procedure
55. Office hours and group members
56. The demonstration of efficiency with the pump configurations
57. Being hands on, building the different configurations, and seeing how the flow behavior changes.
58. Learning to work with push to connect fittings
59. Probably how data should be recorded and manipulated on spreadsheet
60. Learning how water flows in series and parallel.
61. I enjoyed the building part
62. The introduction performed by TA.
63. Analyzing different configurations of centrifugal pumps setup.
64. The lab design part
65. Practical application of concepts
66. We saw how pumps worked practically
67. All
68. Pump design
69. Hard to say though
70. design the circuit by ourselves
71. Comparing efficiencies and learning excel graphs
72. I worked in an HVAC internship over the summer, so seeing the real world applications of pumps at a smaller scale was very enjoyable.
73. I learned about how to operate centrifugal pumps and got a general idea of what the efficiency curve should look like.
74. I feel the lab manual and giving real life examples was the most useful and valuable.
75. The use of real equipment was enriching and insightful.
76. learning the physical components lkke impeller
77. Learn about pumps
78. Nice to learn about the pump
79. Hands-on experiment
80. To apply the principles into practice
81. learn how to use the equipments
82. The ability to use the equipment hands on and take data in real time.
83. I learned how to build a system with a water pump.
84. Seeing how the different layouts of pumps affected the entire system and using the data to back up the reasoning.
85. I really enjoyed being able to immediately see how the different pump configurations affected the flow rate and pressure on the spot.
86. First time really working with these pumps so was able to learn how they work
87. The putting pipes in different configurations seems to have the most understanding.
88. The hands on nature of the labs, especially the final project and the equipment offered
89. I knew the performance and efficiency of different pump configuration.
90. Being able to change flow rates and visually see the difference in flow rate out. In other words the hands on work.
91. Learning how to calculate the effects of the pumps being in each configuration was extremely valuable
92. Probably the experience of working with the valve and water pump system, which I had never had any experience with before.
93. Getting to actually demo and set up the configurations ourselves helped me cement my learning. I also appreciated the TA drawing out and explaining configurations before we built them.
94. I think the entire lab and understanding how the pump works with different pipes was most useful
95. Testing the different configurations and quantifying the variables (power, pressure drop, flow rate) that a small pump might be able to handle.
96. Seeing how pumps could be set up similar to circuits
97. Writing report
98. No
99. TA and manual
100. Cool to see efficiency and performance changes physically.
101. Learning the difference between how pumps in parallel and series act.

102. Being able to visually see how the flow changed.
103. Comparing both configurations to see how the difference changes to get a better understanding.
104. Gain knowledge from manual.
105. The ability to visualize theoretical concepts and troubleshoot real life problems.
106. It helps me to preview and review the related equations, like Bonoulli equation.
107. Being able to make our own contributions to the system and understand them.
108. The structure of the data that was being taken. It was helpful for understanding.
109. The hands on experience with pumps
110. Drawing comparisons between series and parallel
111. The hands on portions and the plumbing balancing in excel
112. teaching
113. Understanding the concepts behind the pumps
114. lam manual
115. Use real experiments to understand the knowledge better is pretty good.
116. The teamwork aspect.
117. This lab was very easy for me to understand because of a circuit analysis class that I have previously taken. The pipe system was setup similarly to that I have seen before and it allowed me to understand series and parallel
118. The pump lab was interesting
119. The hands on experience and design challenge was valuable to my future as an engineer because it showed me a glimpse of what I could potentially do in the future
120. Using the pumps and seeing the water flow
121. Learning about pump configurations and pumping curves.
122. Getting to know the different format of report
123. Working in the lab and working on the post lab allowed me to better understand these concepts
124. The activity of constructing and testing hypotheses.
125. Hands on figuring out of how the different pump configurations behaved was useful.
126. Tinkering with the pumps.Question 2: What aspects of this lab were most useful or valuable?

Question 2: What are some unexpected technical challenges (if any) that you faced while performing the lab exercise, and how did you overcome them?

1. air bubbles in pump
2. Mainly doing the calculations and finishing up the lab reports
3. n/a
4. Pumps not working and pressure not reading
5. Making sure the pumps were primed properly
6. I don't recall any specific issues.
7. our data was definitely inaccurate so it was hard to fully understand the material when preparing the report
8. An unexpected technical challenge was that we didn’t account for testing different tube diameters for a flow rate. We overcame this by doing what we can and worked without that data.
9. My results did not fit the expected curve.
10. The calculations were somewhat difficult when calculating the losses and how that effected our flow rate.
11. We did not have enough trial runs but overcame this by using our best judgements.
12. N/A
13. NA
14. Some confusions for the operation. I just ask TA for help
15. I don’t remember
16. I think the challenges mainly comes from the report. Initially we will find the report hard to finish.
17. Figuring out which of the pumps contributes most to the flowrates
18. No
19. The manometer doesn't work properly.
20. Some problems only occur when the experiment has been done, so we have nothing to do but write about our failure in the report
21. Nothing really
22. The data did not point to an obvious trend which made it frustrating in the lab report because I could not say with great confidence of the trends described in the lab manual.
23. Can't remember any challenges with the lab exercises
24. don’t remember but i’m sure we asked for assistance from TA

25. N/a
26. I don’t remember having any
27. Nothing
28. The data is hard to plot, but we work together to overcome
29. We mostly got help from the TA if we were having difficulties.
30. Some technical challenges included varying data and skewed analysis which we overcame by taking more data into account and thereby creating an effective analysis.
31. This was a pretty straightforward lab. No challenges
32. None - I think after asking the TA about what needs to be measured and how to do it properly, the rest of the lab made sense.
33. the joints tended to leak a lot so we had to hold them together and plug the leaking parts with our fingers
34. no comment
35. It was difficult to use the pressure sensor and get accurate readings
36. Sometimes I just don’t know how to do the experiments. I overcome this by asking teammates and professor for help.
37. The pump reader was broken for part of it but this was not really an obstacle as there is a manometer as well.
38. na
39. Excessive lab reports
40. The technical challenge I faced is that it's hard to measure the angle of the tubes, we use the spirit level in the cellphone to overcome it.
41. The tubes used in the lab limited the flow rate of the parallel configuration which limited the data we could collect. Additionally, we were supposed to see the point where the pumps reached a maximum efficiency and started decreasing, but never reached high enough flow rates.
42. The in lab exercise had no challenges, it was very straightforward
43. Na
44. N/A
45. None
46. The lab reports are way too long
47. No
48. Leaky elbow connectors and old tubing. We overcame this by choosing the best tubing and connectors and minimizing the amount of parts used.
49. None
50. the tubing and fittings are sometimes inaccurate and have small issues
51. None
52. Sometimes we had unknown error
53. Data does not meet the expectation, analyze the uncertainty aspects
54. None
55. I was not present for the lab with my group as I was sick
56. Some of the connectors were a little stubborn to remove. Things also got a little wet.
57. Pumps were too weak. One had a broken fitting and would jettison the pipe attached to it every so often.
58. Not much difficulty
59. Leakage from pipes. The sometimes had to be held together to minimize this.
60. None
61. As I am not a native speaker of English, it challenges me to write report.
62. Data collection accuracy.
63. no
64. NA
65. It was hard to work excel
66. None
67. Connection wasn’t so tight
68. No
69. None
70. The lab did not produce any proper data, and we had to confer with the TA to receive instruction to produce any results.
71. There were a lot of errors with getting the data which then gave us bad results. We overcame it by understanding what and where it went wrong.
72. We were not able to measure the entire performance curve
73. The results were not as complete as expected, so we inferred and explained why on our report as well as made suggestions to prevent this in future sections.
74. pump would die or leak

75. flow rate not high enough — nothing we could do
76. The connectors are weak to be combined
77. The pump was too strong so the data in excel did not reflect the lab manual
78. No
79. By asking peers.
80. no
81. None
82. It is hard to calculate the flow rate for the supporting fountain, and we use the same layouts for both fountains.
83. None that I recall.
84. There was not really any technical challenges with this lab.
85. No major challenge
86. None really
87. I think no
88. The leaking of water. This was fixed by just squeezing the pipes closer together and swapping some tubes.
89. N/A
90. We did not face any unexpected technical challenges.
91. I don't remember any besides pipe leaking.
92. Running out of time but we just delegated our work better
93. We had no major challenges in this lab
94. The leafiness was unexpected, but we determined that as long as the leakiness was included everywhere it was fine
95. Something will go wrong when conducting the experiments.
96. Joints leak
97. The series pump did not have a higher flow rate as expected
98. read the pressure
99. The parallel pump setup did not perform remotely as well as expected which was a bit confusing and never properly explained.
100. The pressure and flow rates for pumps in series weren't giving the intended results. We overcame this by writing in the lab report that there was an error with the set up which is why it resulted in incorrect flow rates/pressures.
101. There was some confusion about whether our results were correct. From what I remember we discussed it further with the TA and came to somewhat of a conclusion
102. The results from the lab did not align with the theoretical results which could be due to apparatus error.
103. The set up has some bug that do not perform theoretically.
104. We got the opposite results than were expected. The TA was unable to explain why, and we never found out why this was happening for every section. This made it difficult to have confidence that our data was worth analyzing.
105. Leaks of water and the lacks of specific-length tubes. We push the tubes and elbows to stop leaks and cut the tubes to get.
106. The parallel pump system wasn't giving us the expected graphical output. We believe there was something wrong with the set up.
107. One of the pipe configurations (parallel) did not work during the lab. We accounted for that error by explaining it during the report.
108. The pumps in parallel did not function as predicted on the manual as the flow rate of each individual pump did not add up to the new flow rate
109. The pumps in parallel did not actually work (the flow rates did not add). My guess as to why is because the inflow was maxed out, it just maxed at a relatively small value. I am guessing this because our fountain drew the max flow rate and I believe it was a somewhat similar value.
110. Wish I had the freedom to come and test out plumbing design prior to lab presentation to catch my mistakes. Still uncertain if my proposed error is correct or not.
111. no
112. N/A
113. none
114. Sometimes lab report takes a lot of time to finish.
115. Maybe is the data accuracy didn't live up to our expectation. We changed the experimental method to overcome it.
116. There were no technical issues
117. Lab 4 videos were low quality and created issues
118. The pump system not working one week
119. I don't remember any
120. The range of flow rates we tested did not capture the maximum efficiency point. We should be told what range of flow rates to cover so our data captures it. Our analysis was weaker because we didn't have this important point.
121. Some complex steps in the procedure. Understand them by TA's explanation

122. There were times the lab equipment wasn't working so we called in tech support
123. The manometer was broken, as well as the digital pressure reader. Also, the lab's electricity cut out once. We had to collect data from other groups, but this should not have been an issue.
124. There was leakage in some of the joints, which we had to reconnect or brace to make them effective connections.
125. Finding laminar flow.

Question 3: How do you feel this lab could be improved?

1. Not sure to be honest
2. n/a, solid lab as is
3. Fix the lab manual. I had to write two reports for this lab because of misinformation.
4. Clear instructions on how much data to collect
5. The lab manual wasn't clear as to the style of lab report that was required. It stated that it was time be a full report when it was actually an engineering letter.
6. more precise measurements or better instruction to help understand the material before beginning the lab
7. This lab doesn't need to be improved.
8. It came at a point in the semester in which we had not yet built a solid understanding of these concepts.
9. Nothing. It was set up well.
10. I think learning the material at the same time as the lecture could help improve this lab.
11. The TAs could grade past reports before this lab so that we have an idea on how well we write a report, and for the reports that had been graded could provide more (if any) comments so we understand what it is we are doing right or wrong. Also the TA could use part of lab time to discuss what part of the material from class we are testing that day (which happened rarely if ever)
12. It would be great if we're allowed to work ahead if we finish the lab early
13. The TA did not explain anything about background or the lab. He expects us to learn everything from the lab Manual that was not even posted until the lab was done.
14. The lab report is overly difficult for no reason
15. Lower down the homework
16. Talk about pumps in class before lab
17. aybe we can add some reaction part.
18. allowing students to work at their own pace and not prevent them from finishing the lab in one week.
19. More setups not just one.
20. Give more time to finish the assignment
21. No
22. More time should be provided
23. Allocate more time to write the report
24. Not much comes to mind.
25. I feel the set up could be better to get good results to see trends. There were some leaks in the connectors. Also maybe a quick part of the lab about friction factor which could explain some of the data not being great which could be a good precursor to the fountain design lab.
26. There isn't as much lab activity covering how the pumps work, just how the pump configurations affect the flow.
27. N/a
28. I don't know
29. Lower workload
30. Maybe reduce some content in the post lab question
31. No suggestions.
32. This lab could be improved by increasing the lab hours so that we can get more data.
33. I don't think there's anything to be improved upon.
34. N/A - I think the lab was structured well and made sense to me.
35. I like the engineering letter format of reports, I think that that format is a good solo report and the full reports are best for group reports. Other than that I think this lab was good, went pretty smoothly for us
36. Videos could help improve learning experience for prelabs/manuals. I tend to have a hard time understanding concepts when reading, but concepts become clearer through videos as it helps with visualization.
37. There wasn't much material on how the pumps actually operate and rather the lab focused more on just the performance metrics
38. I think the equipment of the lab is bad. Maybe you can improve the equipment.

39. Although I think the lab could be beneficial I do not feel like I took away a lot of information from it. I think it works well as a teacher of concepts but the report needs to better teach students and allow them to retain the information, or the data collection needs to be modified slightly.
40. na
41. Better grading
42. Giving more useful report examples and explanations will be better.
43. Change the hardware to allow for higher flow rates so the drop in efficiency can be seen in the data.
44. The report format should have been more specific because I used the same format as a normal report (24pt line spacing) and didn't have enough space in two pages to write all the content I needed to and I lost points because of this.
45. Na
46. None
47. Provide a grading rubric for the lab reports
48. Have more lab ta office hours and TAs that actually help in office hours
49. Less workload
50. I think the lab was good as is.
51. better tubing and fittings
52. None
53. Good enough
54. None
55. I heard something about potential leaky connections. Maybe get newer fittings?
56. For a 10 person lab, the "workspace" was a bit small and couldn't really fit everyone.
57. Better hardware, or possibly adapt the lab to the pumps we have
58. Add an AC or fan, it can get kinda hot sometimes
59. N/A
60. I can't think of anything
61. The score should focus more on lab, instead if language
62. Improve data collection and digitization.
63. nothing
64. The lab manual was very ambiguous on the requirements
65. Perhaps more explanation of software and student expectations. I ended up with a 99 but I was really confused.
66. It is good bow
67. All fine
68. Improve the accuracy of the reading of voltage
69. Change it
70. The experimental setup needs to be altered to produce data-driven results; then the lab would be more useful.
71. It was confusing that the data many groups collected revealed a straight line, rather than a curve, making it difficult to gain a conclusion for the maximum efficiency of the pump in each configuration.
72. I would account for area and other variables instead of ignoring them.
73. I do not know the exact equipment that would need to be replaced but something needs to be replaced in order to actually observe the entire behavior curve
74. The lab could be improved by adjusting the setup to be able to observe performance characteristics at higher flow rates. This is because it appeared that flow rates were not high enough to see the complete performance.
75. better setup, make it so everyone can participate
76. higher flow rate maximum
77. Renew some components
78. Put in a section in the lab manual explaining that the graphs won't match
79. Good enough
80. I think it's good.
81. make it more clear about the principle of the experiment
82. More in depth background of pump working principles in lab manual
83. None.
84. None
85. Possibly adding a nozzle or adding more different configurations.
86. I can't think of anything
87. It was pretty good I think the only suggestion I would contribute is to make the rubrics more specific about what equations or key ideas we are expected to discuss in our reports; also to make the rubrics more thorough in what's requested
88. Give a prelab to get familiar with it
89. Make prelab videos or walk throughs on how to interpret received data.

90. N/A
91. Perhaps a reminder to keep checking the current and voltage, as my group occasionally forgot about that.
92. Just ensuring equipment works properly, which goes for all labs.
93. More time
94. It needs better alignment with the lecture material. Obviously that's not entirely practical but I think that instead of changing the lab schedule we should do a lesson in class to prepare us for each beforehand, simply for the sake of exposure to the material. For example, before doing lab 2 it would be nice to know what laminar and turbulent flow are and why free jets look like they do. Lab 3 should come after the conservation of energy lectures, and lab 5 following the culmination of chapter 8. If this is impossible, it would be nice to perhaps accelerate the relevant lessons to introduce students to the material prior to learning about it in a lab manual
95. Just warn the students more about the length of the report
96. No need to improve, I think it is good.
97. No
98. Improve the lab manual, lots of requirements and expectations of the report are ambiguous. Clearer directions in the future would streamline the completion of lab reports.
99. It was fine.
100. Make the manual more understandable
101. Maybe more pump configurations
102. Make sure equipment is properly set up.
103. I think it's good as is.
104. Ensure the configuration complements theory more closely by testing it out beforehand.
105. Show students correct data to compare.
106. Ensure that the configuration works as expected by troubleshooting the setup and analyzing collected data from this. Also, providing a rubric for deliverables in the paper would make grading more fair, as otherwise we are unsure what to provide and what to omit.
107. Interesting
108. Better equipment
109. Fixing issue with pumps in parallel to make sure their flow rate add up.
110. The lab manual might need some work because most of it was odd background on pumps and it felt like there wasn't a lot of info directly about the lab
111. More access to lab outside lab hours
112. no
113. It was good as is.
114. none
115. Honestly not sure, it wasn't too hard but I think the lab material needs to be a bit more related to course material
116. It is great!
117. Everything goes well.
118. Maybe a more complicated setup to give a more difficult challenge
119. Lab 4 could be better
120. A little bit more time to just come into the lab and test
121. I don't know
122. The workload of the report should be less
123. there were 5 people on my lab group and only 2 were really able to work on the project hands on the rest were just watching
124. The reports for this lab have incredibly vague requirements. A couple were misleading, and included requirements that weren't actually necessary. Some things are directly contradictory. The lab manuals and rubrics need to be more accurate and consistent.
125. Better connections used in lab, updated lab manual.
126. NA

Appendix B

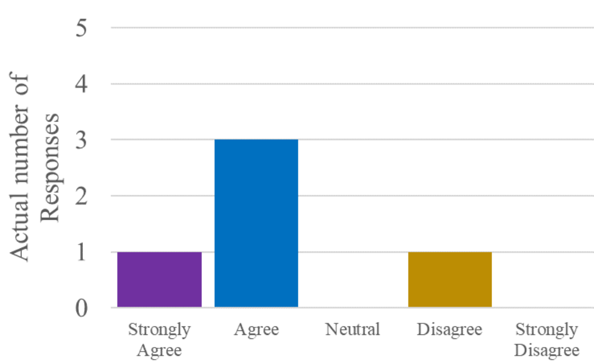
Survey Results from teaching assistants (5 participated from 7)

The survey from the TAs consists of in total 8 Likert scaled questions in 2 categories along with 3 open-ended questions.

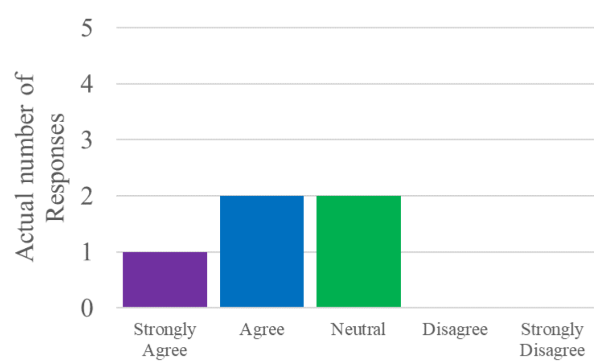
Likert-scale Questions:

Category 1: Usefulness of Resources Provided for the Lab Exercise
Question1: Students understood the working principles of the equipment used for the centrifugal pump lab setup (operation of the pump, the pressure transducer, the flowmeter, and the valves).
Question 2: The lab manual was a useful reference for the students to understand the centrifugal pumps lab exercise.
Question 3: Total time allocation (2+2=4 hours in the lab) was sufficient to perform the lab properly.
Question 4: After finishing the lab exercise, students were able to answer the questions in the lab manual.
Question 5: The lab setup was designed properly to accommodate all of the students in each lab section.

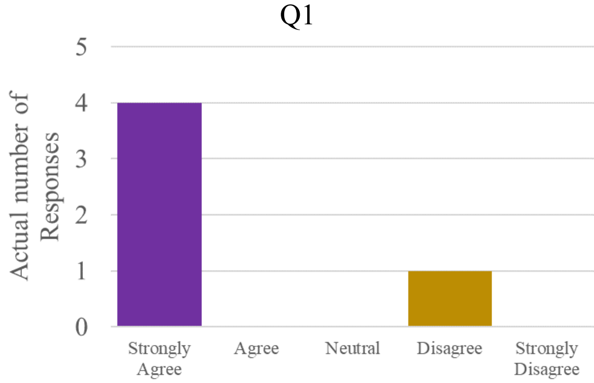
Category 2: Evaluation of the Coherence of this Exercise within the Lab Course
Question 6: The centrifugal pumps lab exercise was scheduled in a reasonable place in the semester with respect to the other lab exercises.
Question 7: Writing the previous lab reports prepared students well to write this lab report.
Question 8: The grading rubric was fair and easy to use.



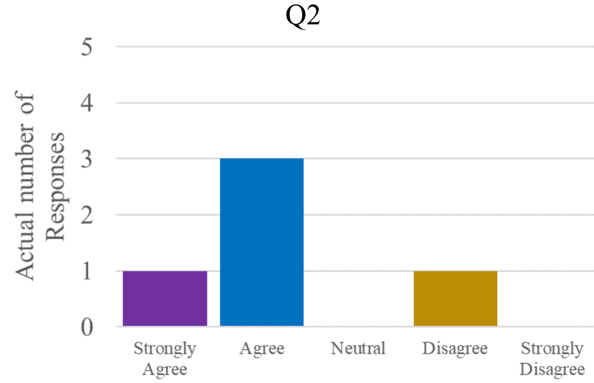
Q1



Q2



Q3



Q4

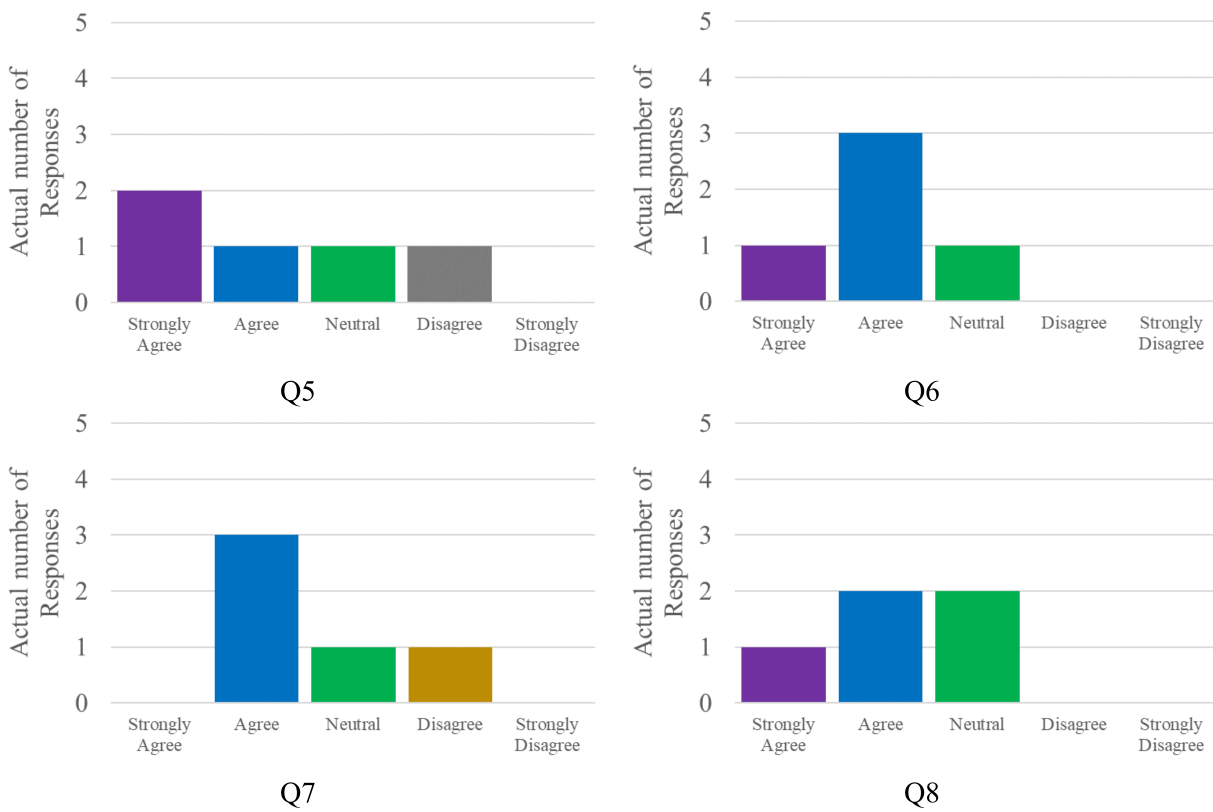


Figure 16. TA survey report on Likert scaled questions

Open-ended Questions:

Question 1: What aspects of this lab exercise do you feel were most useful or valuable to the students?

1. Comparing the different combinations of centrifugal pumps was useful.
2. Understanding the concept of head in a flow and how varying flowrates is usually used in similar experiments.
3. Building the setup by themselves and assembling each orientation
4. they could see the impact of putting pumps in parallel vs. series configuration
5. The relations ships of pressure and flow rate in different pump configurations.

Question 2: List the challenges (if any) that you faced while leading the students through the lab exercise.

1. A major challenge was the fact that there was too much resistance downstream of the pumps such that the flow rate was not able to get high enough to collect important data.
2. N/A
3. I had no challenge with running the experiments
4. Leaks through different fittings were a bit challenging to overcome.
5. Some fitting were too light that at high flow rate it just snapped out.

Question 3: How do you feel this lab exercise could be improved?

1. Better pump circuit design would be the best starting place for improvement.
2. The questions in lab manual can be more specifically relevant to this experiment, instead of a general pump performance experiment. The best efficiency point was not reached in all experiments due to not enough flow rate. It would be better if students can reproduce the performance curves similar as in the lab manual.
3. I think by having a stronger pump to go to higher flow rates
4. by emphasizing the difference of parallel vs. series configuration for students
5. Better fittings and more permanent setup.