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BYOE: Hands-on and Low-Cost Fluid Mechanics Lab for Exploring Pressure Loss in Pipes

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Kayla Lenz is a Ph.D. candidate in Mechanical Engineering at the University of North Carolina at Charlotte, where her research focuses on nanomaterials for biomedical and health-related applications. Her broader academic background includes extensive experience in thermal fluid sciences, having served as a teaching assistant for both a Thermal Fluids Lab (TFL) and Heat Transfer course. As the lead teaching assistant for TFL, she supported the transition from the original pipe flow experiment to the redesigned hands-on system, working closely with Dr. Bachman to troubleshoot and refine the setup. She led weekly lab sessions, guiding students through experimental procedures, data analysis, and conceptual understanding of fluid mechanics principles. Her combined research and teaching experiences reflect an interest in connecting fundamental engineering concepts to real-world applications while enhancing student learning through interactive laboratory design.

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Abstract

It is well documented that hands-on experiences can aid in student learning, with educational institutions often showcasing their lab courses to demonstrate the abundance of interactive opportunities offered to their students. However, not all lab exercises are created equal, and just because it is a lab experiment does not mean that it should be categorized as 'hands-on.' This "Bring Your Own Experiment" (BYOE) paper explores a low-cost and interactive replacement for an aging fluid mechanics lab that explored pressure loss in pipes. The original lab only required students to click a button on a computer, initiating the automatic digital recording of thousands of differential pressure readings and limiting student involvement and engagement. In contrast, the new lab requires students to physically catch streams of water with buckets under various flow rates and piping configurations. The increase in interactivity between these experiments bolsters student engagement, and the simplicity of the replacement experiment allows students to more easily connect complex principles to real world outcomes. Altogether, the success of this simple apparatus can serve to motivate others into exploring their own low-cost yet effective lab alternatives, with the end goal of improving student learning. To showcase the merits and effectiveness of the new lab, the experiment will be set up and demonstrated at the 2026 American Society for Engineering Education conference.

Introduction

To facilitate optimal learning in an academic setting, it is essential to acknowledge and accommodate inherent psychological constraints using evidence-based pedagogical approaches. Understanding the physiological limitations of working memory and implementing theories such as load reduction instruction (LRI) can inform improved instruction methods for students. The primary focus of LRI is reducing the cognitive burden on individuals as they learn [1]. LRI encompasses five key principles: (1) reducing instruction difficulty during initial learning (2) proper instructional support and scaffolding (3) ample structured practice (4) appropriate instructional feedback and (5) guided independent learning [1]. LRI practically translates to pedagogical techniques such as hands-on or movement learning, visual learning, group learning, and simplified learning.

Hands-on learning utilizes multimodal resources as the sensory functions (e.g., sight, sound, touch, taste, smell) work in unison to support stronger sensory perception [2, 3]. Heise et al. compared a hands-on class with a non-hands-on and saw improved test scores, improved motivation, and increased capacity for transfer for the hands-on class [4]. Capacity for transfer refers to the ability to apply newly learned topics to different contexts. This capacity is enhanced when initial learning is less focused on memorization and more on visual and mathematical understanding [4]. Such a skill is particularly important in engineering fields because of its inherent experimental and interdisciplinary nature.

Visual learning is where individuals learn through images, diagrams, charts, colors, and more. This may be coupled with hands-on learning for an even greater enhancement of working memory, explained by LRI principle 2 mentioned above. From Heise et al.'s study, they found that although both groups had the same cognitive gains (which the authors explain could have been from a low sampling pool), students themselves significantly prefer the hands-on method due to >50% preferring visual learning [5].

In this work, the experiment originally used for exploring pressure loss in pipes in a fluid mechanics lab did not adequately implement the pedagogical strategies discussed above for enhanced learning. Despite being a lab course, the original experiment lacked hands-on activity as the only physical role was to turn a few valves and allow a computer to collect all data. Typically, only one person in each small group would turn the valves, leaving others with no hands-on opportunities. Coupling this with the lack of visual stimuli, as all pipes in the system were opaque providing no intuitive understanding as to where and how water was flowing, there was little to no implementation of multimodal effects. Collaboration was also limited as the data collection process was fully digitized, resulting in minimal opportunities for coordinated efforts. Unnecessary extraneous load was a continuous problem amongst students and teaching assistants as the piping configuration was complex with many unused components, the computer program frequently failed and required system restarts, and data conversion into a usable Excel format for post processing was challenging due to a non-user-friendly interface. These factors hindered students from focusing on the primary learning objectives of the experiment.

The new experiment was designed to address these downfalls using low-cost centrifugal pond pumps, PVC tubing, and hardware store buckets to analyze pump performance and learn about head loss. During operation, water is pumped from the main bucket through a known length of tubing that is held at specific height levels while students measure the flow rate by catching the water with another bucket; as the height of the tube's outlet is raised, the flow rate that can be generated by the pump decreases. Plotting the measured flow rate versus the head required to achieve said flow yields a basic pump performance curve that can be used to predict future operation or make design decisions. The nature of the experiment is hands-on in every aspect, as various diameter tubes must be chosen and held at different heights and water is physically collected in a bucket and transferred to a weighing scale. The various physical requirements warrant different roles for the students (i.e., timekeeper, bucket holder, pump operator, tube holder), making each person's role feel critical to the collection of data and fostering collaboration to successfully complete the experiment. The transparent PVC tubing gives students more control and confidence with manipulating the piping configuration, and visually observing the bucket fill up at different rates fosters a more intuitive, engaging, and satisfying experience. Beyond the pedagogical improvements, the new experiment had practical improvements as it was cheaper to build and repair, and took up less space, increasing accessibility across institutions with diverse socioeconomic resources and lab capacities. While the increased hands-on requirements of the new lab could raise concerns in regards to accessibility for students with diverse accessibility needs, several of the roles used in the current implementation of the lab, such as the "timekeeper" or "pump operator" roles, are less physically demanding yet critical tasks. Additionally, the pump selection could be modified to achieve the same experience over a smaller height range, ensuring the lab is within reach for all students. Safe operation of the new lab is also critical, with the main concerns being that all electrical components remain out of contact with water and preventing any part of the equipment from tipping over. Strategies to address these include clear labeling of components that must avoid water exposure, proper allocation of roles so that those handling electrical components do not perform tasks involving water, securely fastening all electrical components, and building a wide enough base for the entire apparatus to prevent tipping.

Device Fabrication and Operation

In order to demonstrate the principles of pump performance, frictional loss through pipes, and application of the mechanical energy equation, a combination of readily available components was assembled. The device fabricated for this lab (shown in Figure 1 and detailed in the BOM provided in Appendix A) utilizes a small (400 gph) submersible pond pump to generate a low volume flow that varies measurably over a small output height range (increase in gravitational head). This allows students to visualize the impact that the gravitational head has on the flowrate of a system.

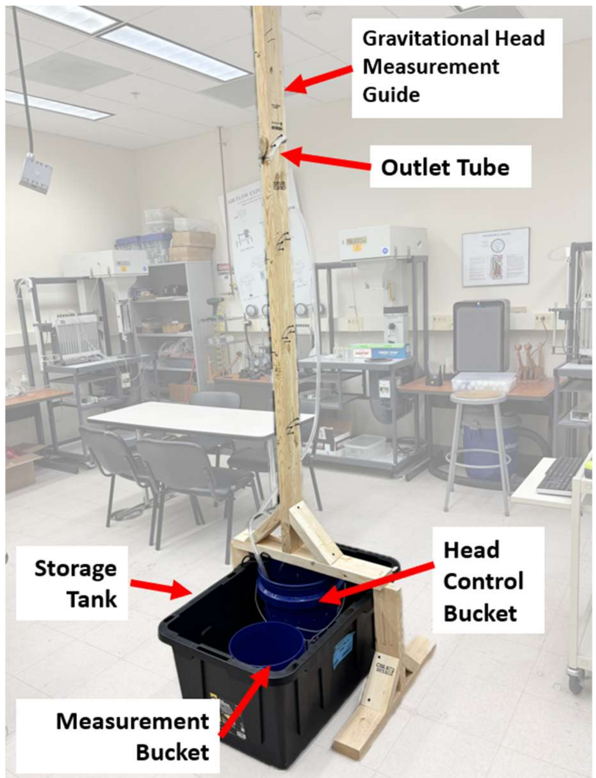

Figure 1: Photo of the entire test apparatus. The system consists of 3 buckets, tubing, pumps and a height measurement guide.

There are 3 'buckets' used in the design. The largest bucket, denoted as the "storage tank" in Figure 1, is a 27-gallon storage tote that is large enough to contain the water necessary for the lab as well as the majority of the splashing generated during operation. This storage tank has a pond pump (referred to as the Head Control Pump) placed at its bottom with a small length of tubing that extends into the second bucket, referred to as the "Head Control Bucket." The Head Control Bucket is a 5-gallon hardware bucket with holes drilled 6" above (Figure 2) the outlet of the submersible pump (referred to as the Main Pump) that is placed in the bucket; these holes are drilled around the circumference of the bucket such that during steady state operation, water that is pumped into the Head Control Bucket from the larger storage tank drains out of the holes and maintains a constant gravitational head above the Main Pump. The Main Pump removes water from the Head Control Bucket and this water travels through the vinyl tubing before exiting the

Outlet Tube. The stream of water that leaves the Outlet Tube is caught in the third bucket, a simple 2-gallon hardware bucket known as the Measurement Bucket.

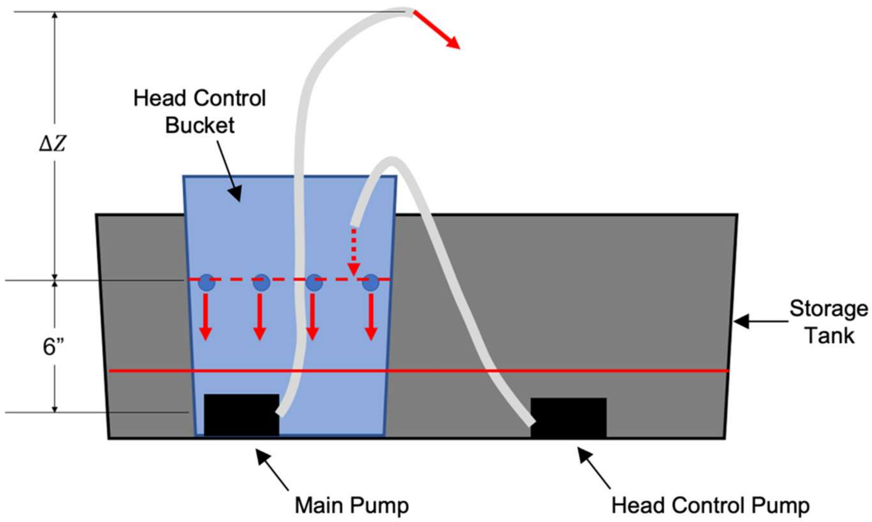

Figure 2: Flow of water throughout the system. Water is pumped from the Storage Tank into the Head Control Bucket. The water level within the head control bucket is regulated by the drain holes drilled into the side, and water is also pumped out of the head control bucket through the outlet tubing. Red arrows indicate the flow of water and red lines indicate water levels.

To ensure that students accurately hold the Outlet Tube at a consistent height, a wooden structure, denoted as the “Gravitational Head Measurement Guide,” was constructed around the storage tank; markings are included on this guide to indicate where 1, 2, 3, 4, 5, and 6 feet of height change from the inlet to the exit of the system (labeled as ΔZ in Figure 2). Appendix B provides a full set of lab guidelines including a detailed protocol for students to follow during experimentation. The following section describes the operation, theory, and data analysis associated with the lab.

Data Analysis and Educational Objectives

The main educational outcome for this experiment is to demonstrate the balance of inputs, outputs and losses in the mechanical energy equation. Applying the mechanical energy equation to the apparatus described in the previous section, starting at the surface of the water in the Head Control Bucket and defining the output as the stream that leaves the Outlet Tubing, yields the following simplified expression for the pump head required for operation:

$$h_s = \Delta z + \frac{V^2}{2g} + f\frac{L}{D}\frac{V^2}{2g} \qquad (1)$$

In this equation, the input pump head (h_s) is balanced by the increase in gravitational head (Δz) and kinetic head ($\frac{V^2}{2g}$) as well as the frictional losses ($f\,\frac{L}{D}\frac{V^2}{2g}$). Before the lab begins, students are asked to generate system curves that represent the pump head required to achieve a desired flow rate at the various output heights that will be explored during experimentation (2' - 6' for the chosen pump). These curves are generated using a Moody Chart and assuming a 10' section of ½" flexible PVC tubing for calculating losses (Figure 3).

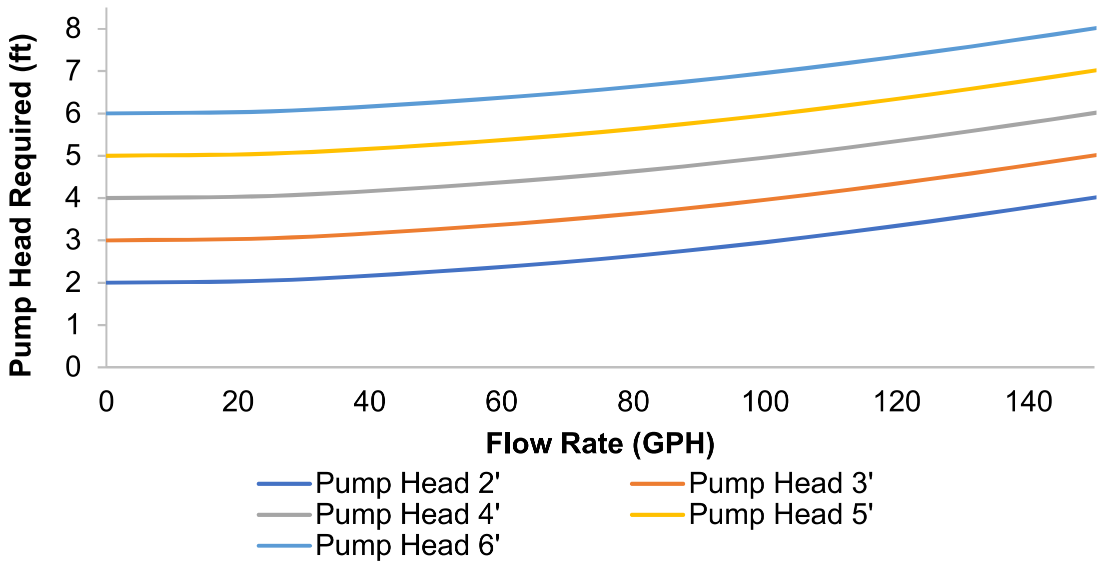

Figure 3: System curves for a 10' section of ½" ID flexible PVC tubing and various gravitational head increases. As the flow rate increases, the pump head required increases due to the added frictional losses within the tubing.

Students are asked to complete these pre-lab calculations to refresh their memory of frictional losses and the mechanical energy equation generally. During the lab, students follow the procedure to collect water in the Measurement Bucket while holding the Outlet Tubing at various heights. By timing the collection and weighing the collected water, students can calculate the flowrate generated at each outlet height. A sample data point would be measuring a flowrate of 135 GPH at an outlet height of 2' through the 10' and ½" PVC tube. With this value, students can plot the data point on their previously generated system curves (placing this data point at the intersection of the 2' Pump Head Curve and 135 GPH flowrate). Fitting a second order polynomial to the data points for each of the height outputs generates a performance curve for the Main Pump as shown in Figure 4; this second order performance curve is consistent with the curve fitting expected in real-world performance measurements. Student data has shown that across multiple trials, the flowrate generated by the system is consistent, varying $\pm$ 2% for the three trials requested.

While the first experiment primarily allows students to explore the effects of gravitation on pump performance, they are also able to explore frictional losses by varying the tube lengths and

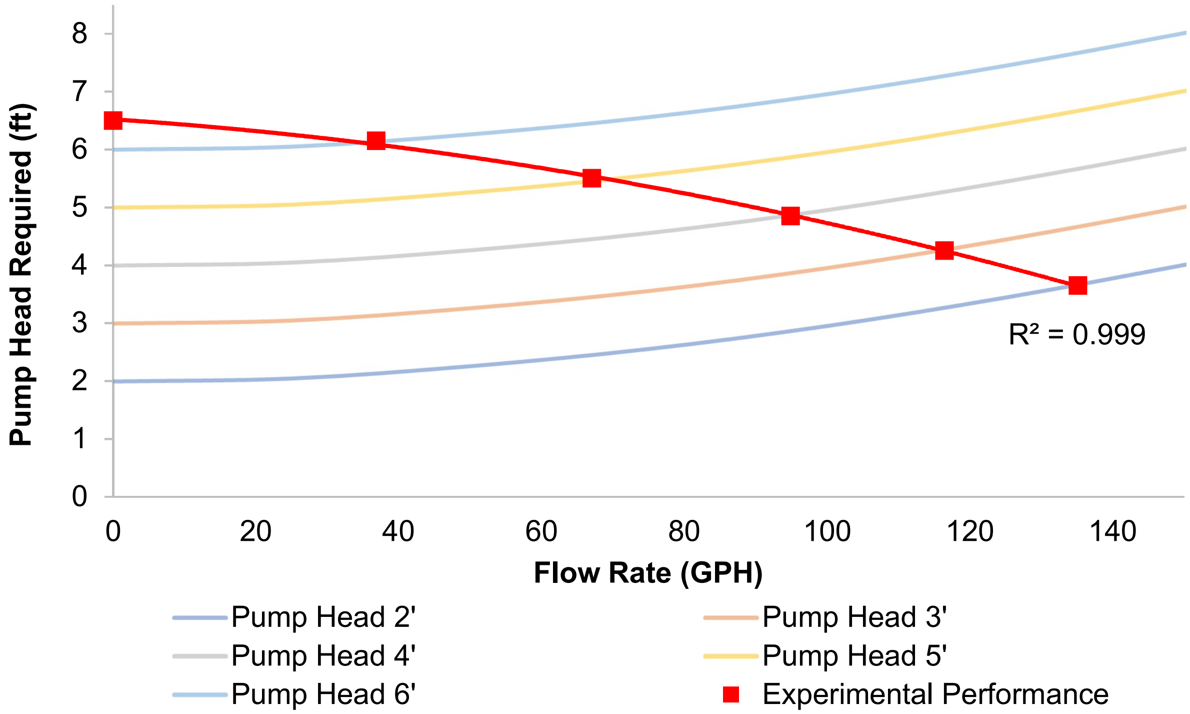

Figure 4: Pump performance curve overlaid with the system curves for a 10' section of ½" ID flexible PVC tubing and various gravitational head increases. The performance curve demonstrates the characteristic decline in available head as the flow rate increases.

diameters. During the lab, students are asked to swap the 10' section of ½" tubing for, first, a 50' section of ½" tubing, and also a 10' section of ¾" tubing. By swapping the tubing, students can see how additional length, or a less resistive (larger diameter) tube impacts the flow rate. As expected, the flow rate decreases with an increase in pipe length, and the flow rate increases noticeably with a larger diameter Outlet Tube.

Conceptual questions are paired with the lab, asking students to consider the real-world impacts of these piping design decisions. While classroom introductions to pipe flow and losses describe how changes in piping systems can impact the operation, this experiment allows them to visualize these impacts. The closing section of this paper discusses future changes and modifications that could be made to the lab to allow students to further explore these concepts, as well as student and TA feedback for the new experiment compared to the previous one.

Future Work and Instructional Observations

Future work with this experiment looks to expand the exploration of pumping phenomena. To explore minor losses in pipes, additional bends could be incorporated along the length of the pipe as it extends up the wooden column (See Figure 5). These bends would increase turbulence and flow separation within the pipe, which would be reflected by changes in water collection. Equation 1 could be expanded to account for these minor losses and students may explore whether assuming no minor losses (which is frequently done in engineering curricula) is reasonable for this application. Additionally, valves, expansions, or contractions could be placed along the length of the pipe to further impede the flow and allow exploration of minor losses in piping systems. The performance of the pump can also be explored in more detail by measuring power consumption and considering the efficiency of the device itself.

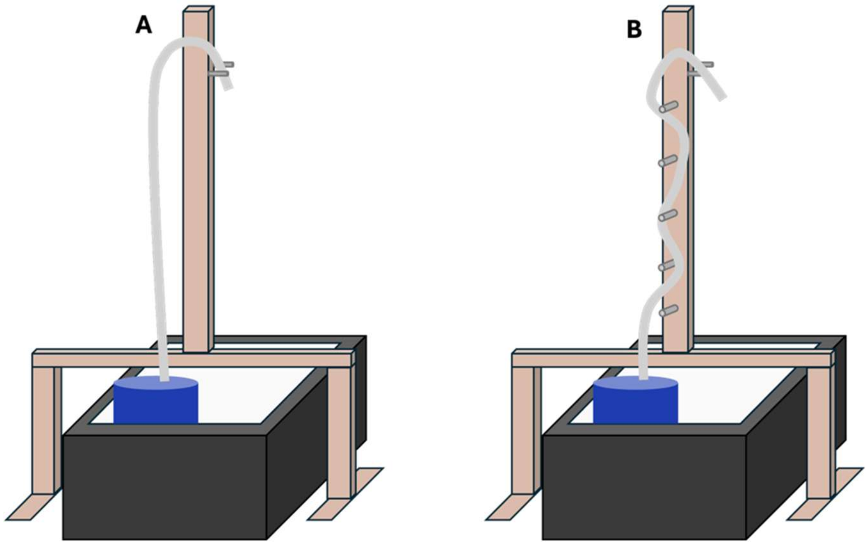

Figure 5: Proposed set up for modifications for exploring minor losses using screws to weave and bend the pipe. (A) "Straight" pipe with no significant minor losses. (B) "Bent" pipe with significant minor losses.

Arguably one of the best indicators of the success of a new lab is based on feedback from students and TA's who interact with the experiment most frequently. Attempts to solicit feedback from students was unsuccessful, however a comparison of average grades on the complete notebook assignment (includes pre-lab and post lab analysis) provides rudimentary insight into the quantitative success of the new lab. In the semester prior to switching to the new experimental set up, the average was 91.3, whereas the first semester with the new lab produced an average of 94.5. Furthermore, feedback from the TAs, some of whom took the course previously and interacted with both the new and old systems, has shown positive outcomes. When asked, one of the current TAs stated:

"I took TFL in my undergrad during the first semesters of the pandemic, and so I would say my experience in the lab was poor overall in that the rushed transition to online materials certainly made it so that very little was learned in the lab. I do think the lab you developed conveys key topics and demonstrates a thermal-fluid system effectively in a system that is simple to operate. It's easy to order replacement parts, and itself only requires ~10 items versus the probably ~100 of the old setup. Students can immediately see the change in flow rate as a function of the utilized head in the system."

This TA also indicated that scoring for this lab was higher than similar labs in the course. Other TAs who had experience running both the old lab and the new one noted the following:

"Students were much more engaged with the new lab compared to the previous pipe flow experiment. I noticed with the previous experiment, students appeared bored with nothing to do besides watch. With the new lab, it was nice to see everyone had a specific task and there was a lot more collaboration among the group."

"As the TA, I was much more confident in my students' ability to independently operate this lab experiment compared to the previous one. In all honesty, I performed most of the equipment operation tasks with the previous lab, since we've had many experiences in the past of students accidentally turning the wrong valve and damaging the pump. With the new lab, the only "risk" is the chance of getting some water on the floor, which worries me much less as a TA than costly equipment damage."

However, one TA did note that while the systems allows for a more intuitive understanding of the principles of pump power and head loss, the lack of formal equipment (flow meters, valves, etc.) could be a hinderance to students as they transition to industry. This point is well taken and future work can investigate how these more complex systems could be integrated into the simple design to achieve a good balance for the students.

References:

[1] A. J. Martin, "Using Load Reduction Instruction (LRI) to boost motivation and engagement," 2016: British Psychological Society Leicester.

[2] M. Mavilidi, K. Ouwehand, A. D. Okely, P. Chandler, and F. Paas, "Embodying learning through physical activity and gestures in preschool children," in *Advances in cognitive load theory*: Routledge, 2019, pp. 103-118.

[3] L. Radford, "On the role of representations and artefacts in knowing and learning," *Educational Studies in Mathematics,* vol. 85, no. 3, pp. 405-422, 2014.

[4] D. Heise, "Asserting the inherent benefits of hands-on laboratory projects vs. computer simulations," *Journal of Computing Sciences in Colleges,* vol. 21, no. 4, pp. 104-110, 2006.

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Appendix A: Bill of Materials and Alternatives for Device Fabrication and Experimental Design

The bill of materials shown below provides the basic materials that are needed for assembly of the apparatus as described. Items not included in the BOM include a small scale that is likely to be present in a laboratory setting.

Table A1: Bill of Materials as purchased for the new experiment. A digital scale that was already in the lab is not included on this list, as well as screws and zip ties that are likely to be had on hand.

Item	Vendor	Unit Price ($)	Qty.
27 Gallon Tote (Storage Tank)	Hardware Store	9.98	1
5 Gallon Bucket (Head Control Bucket)	Hardware Store	4.98	1
2 Gallon Bucket (Measurement Bucket)	Hardware Store	3.28	1
400 GPH Pump	E-Commerce	19.99	4
½" Tubing x 100 ft	E-Commerce	38.99	1
¾" Tubing x 10 ft	E-Commerce	19.45	1
2x4 x 8' Lumber	Hardware Store	4.77	3

Hardware components for this experimental setup were sourced from Lowe's and additional E-commerce items were obtained through Amazon. It is important to note that four pumps are included in the "Pump" E-Commerce purchase. In the current experimental setup, three separate pumps are utilized for each of three testing scenarios (1/2" x 10' or 50', and 10' x ¾" tubing), and one pump is used to maintain the inlet head. Assigning separate pumps to each testing scenario helps distribute wear and tear for maintaining long term use. However, during any given test, only two pumps are operating simultaneously (one for head control and one for the active testing scenario). Several other options exist to reduce operational expenses and increase accessibility of the experiment to institutions where cost is a prohibitive factor. A single pump could be used with the large storage tank (Figure A1). As long as the water level in the storage tank is measured, then the head at the inlet will be known, and the large volume of water in the storage tank will avoid variations in water level throughout the measurement process. Additionally, although the wooden height guide makes it convenient for students to measure and aim the outlet tub, markings on a wall adjacent to the testing setup could be utilized as well; this would drastically reduce the physical footprint of the system as well.

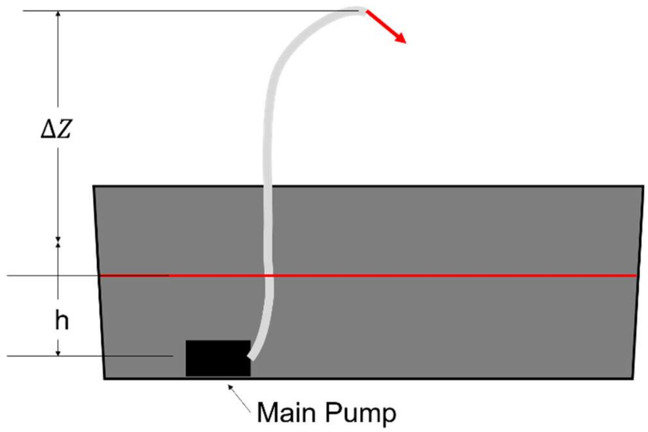

Figure A1: Diagram of the simplified single pump system. With a sufficient and known head in the storage tank, there is no need for a secondary Head Control Pump as used in the initial design. Red arrows indicate the flow of water and red lines indicate water levels.

In terms of flowrate measurement, a scale is currently used. However, a graduated measurement device could be used as the catch basin, which would remove the need for a scale. These changes, in combination with the use of a single pump where students swap the outlet tubing for various experiments would significantly reduce the build cost and could enable instructors to build multiple setups so that more students can conduct the experiment at the same time.

To further increase the usefulness of this design, educators could create other simple setups that demonstrate fluid mechanics principles. For example – if the head control bucket in the current experiment was raised up out of the storage tank, then a small hole drilled at the bottom of the bucket would drain water. This draining can be used to demonstrate Bernoulli's Principle in a free jet (Figure A2).

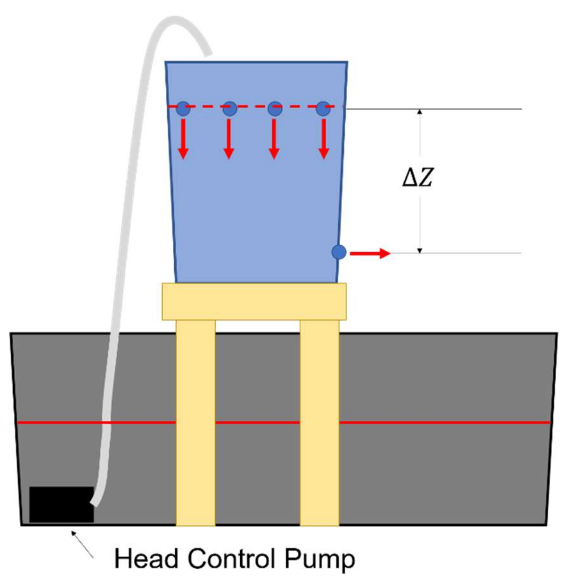

Figure A2: Schematic of modified system that explores free jet flow from an orifice. Red arrows indicate the flow of water and red lines indicate water levels.

Appendix B: Sample Lab Guidelines for Instructional Use

A Self-Contained lab protocol that could be implemented in a course is provided below.

Pipe Flow Lab Guidelines

Objective

The objective of this lab is to explore the mechanical energy equation and its application to viscous pipe flow. We will also explore pump performance curves.

Theoretical Background

The Mechanical Energy Equation

The mechanical energy equation (1) describes a concise balance between a limited number of fluid mechanics factors that enables users to estimate flow rates and size piping systems.

$$\frac{p_{out}}{\rho g} + \frac{V_{out}^2}{2g} + z_{out} = \frac{p_{in}}{\rho g} + \frac{V_{in}^2}{2g} + z_{in} - h_L + h_s \quad (1)$$

As it is written in equation 1, the mechanical energy equation balances pressure, kinetic, gravitational, loss and shaft 'heads.' Fluid heads are used to represent the energy of the system as a combination of static fluid columns, whose heights are proportional to the various forms of energy (kinetic, potential, pressure, etc.). Selection of appropriate inlet and exit points for the system you are analyzing allows you to simplify many of the terms in this equation. Alternatively, knowing design parameters of the desired fluid system (end position, desired pressure, desired flow rate, etc.) can allow us to solve for the other system variables. oftentimes we are concerned with calculating the pumping power required to achieve the desired flow characteristics. The term h_s represents the pump head (the s subscript refers to shaft work in traditional fluid mechanics texts). The head provided by a pump can be related to the power of the pump and the flowrate of the system using the following relationship:

$$h_s = \frac{\dot{W}}{\dot{m} g} \quad (2)$$

Where, $\dot{W}$ is the power required by the pump, and $\dot{m}$ is the mass flow rate of fluid through the system.

Flow Characterization

The Reynolds number is an important non-dimensional number in fluid mechanics that can provide insights into the flow dynamics. Many phenomena can be calculated as functions of the Reynolds number, including things like the drag/lift coefficient, friction loss coefficients, heat transfer coefficients, and more. The Reynolds number can be calculated as a function of the pipe diameter using the following relationship [1]:

$$Re_D = \frac{\rho V D}{\mu} \tag{3}$$

Where the fluid density is, ρ, the average velocity (obtained from experimental volumetric flow rate measurements) of the flow is, V, the pipe diameter is, D, and the fluid viscosity as a function of temperature is, μ.

Head Loss

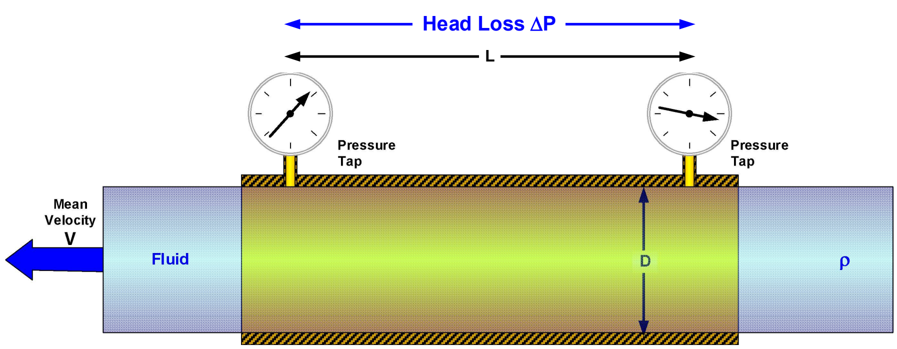

Figure 1: Head Loss in a Pipe

Head loss (Figure 1) refers to the loss of waterpower due to friction within a pipeline. The head loss (as a pressure), represents the pressure loss due to viscous effects in the piping system. The head loss can be calculated if the dimensionless Darcy friction factor (H.P.G. Darcy, 1803-1858), ***f***, is known. The head loss associated with viscous friction in straight sections of pipes can be described as follows [1]:

$$h_L = f\frac{L}{D}\frac{V^2}{2g} \tag{4}$$

Where, ***D***, is the pipe diameter or hydraulic diameter (for non-circular conduits), ***f***, represents the friction factor, ***L***, is the length of pipe, and lastly, ***V***, is the mean velocity throughout the cross-sectional area in which the fluid passes.

When the flow is laminar, the resistance is determined by the viscous shear stress solely and is independent of the pipe surface roughness. The friction factor, ***f***, for fully developed laminar flow may be equated as [1]:

$$f = \frac{64}{Re_D} \tag{5}$$

When the flow becomes non-laminar, the friction factor incorporates both the viscous stresses and the relative roughness of the pipe. The quantity used to measure the roughness of the pipe is called the relative roughness, which equals the average height of surface irregularities (ε) divided by the pipe diameter (D), For the flexible PVC tubing used in this experiment, the roughness can be taken as 0.0015 mm.

The following Colebrook (C.F. Colebrook), equation is employed to obtain the friction factor [1]:

$$\frac{1}{\sqrt{f}} = -2log_{10}\left(\frac{\epsilon/D}{3.7} + \frac{2.51}{Re_D\sqrt{f}}\right) \tag{6}$$

Unfortunately, this is a reciprocal equation which is difficult to solve without numerical tools. Fortunately, if the relative roughness of the pipe, ϵ/D , and the Reynolds number are known, then ***f*** may be determined from the Moody chart (L.F. Moody, 1880-1953, Figure 2. Next page). A good rule of thumb is that values taken from the Moody chart are roughly $\pm$ 10% from the real-world losses.

You may also remember the concept of minor losses (related to bends, contractions, valves, etc.). The system used in this lab attempts to avoid these losses, and so we will neglect their discussion in this background. However, analysis of real-world systems required you to consider both major and minor losses.

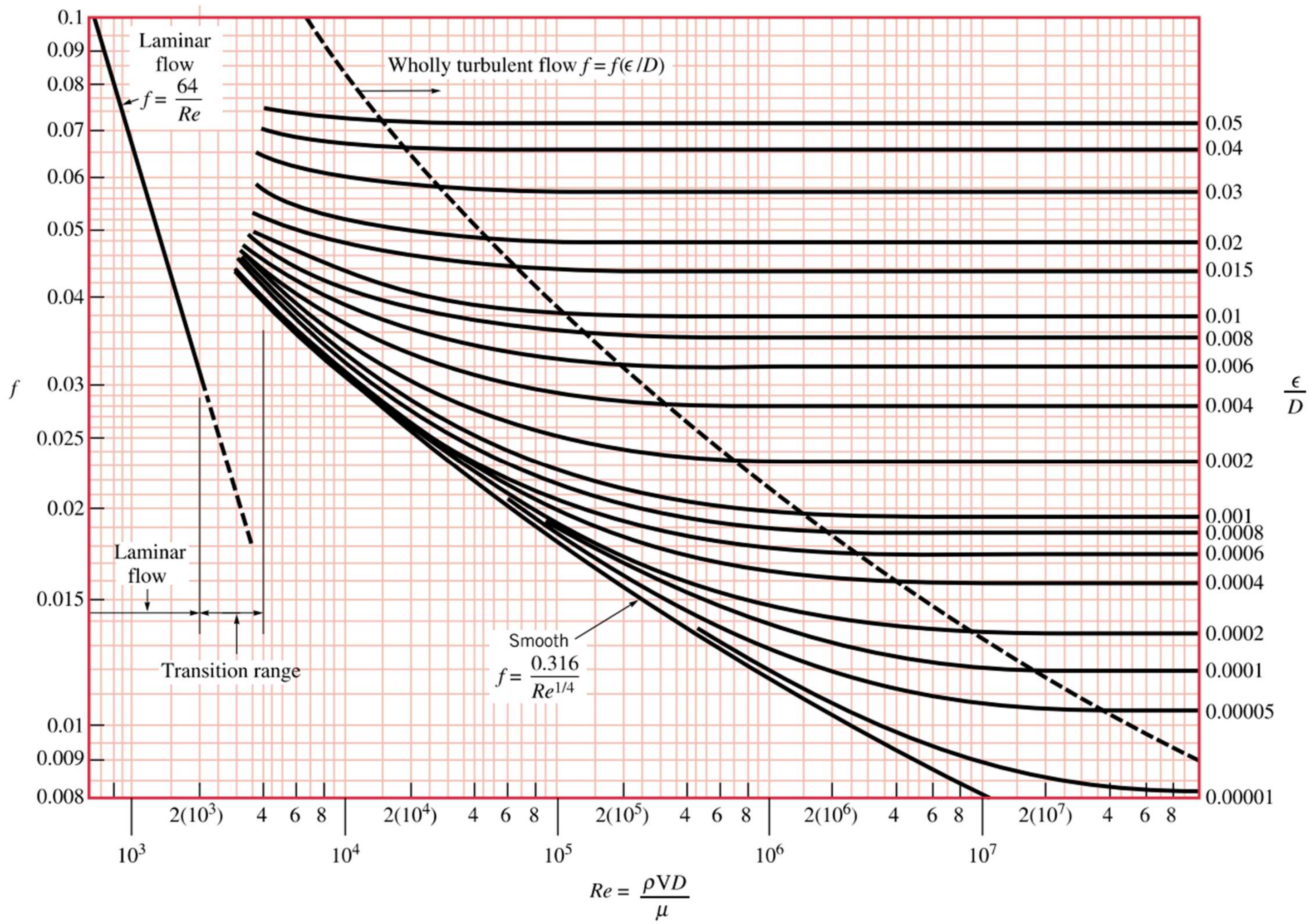

Figure 2: Friction Factor as a Function of Reynolds Number and Relative Roughness for Round Pipes-The Moody Chart [2]

Pump Performance Curves and System Curves

In order to predict what the flow in a piping system will look like, we need to analyze the mechanical energy equation. Unfortunately, the head provided by a pump is not constant with respect to the flowrate produced. In order to circumvent this problem, pump manufacturers will provide pump performance curves (as shown in Figure 3) to aid in the design of fluidic systems. Pump performance charts provide a convenient way to understand the energy that the pump can provide to the fluid within the range of flow rates that the pump can generate.

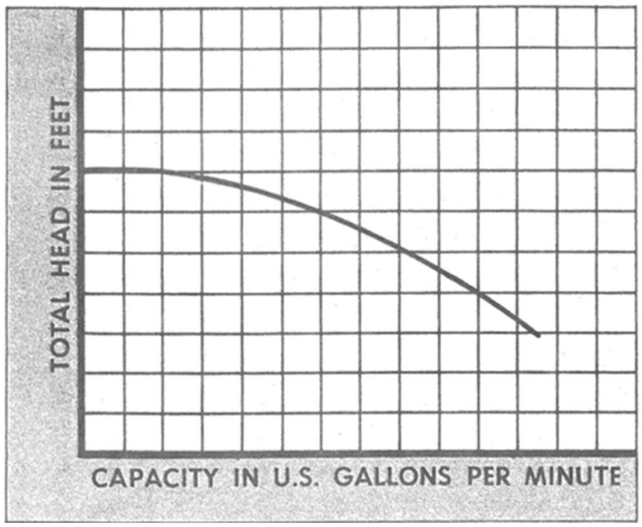

Figure 2: Typical head capacity curve [3]

In order to use these curves, you can first determine the flowrate that you want to operate at; oftentimes, the flowrate is a known value. Once you know your target flowrate, you can perform a loss analysis by analyzing the mechanical energy equation; consider the kinetic, potential, pressure, and friction energies that you will need to provide to the fluid using the pump. Once you have tallied these heads, you can compare them to the available head as indicated on the pump performance curve. A simplified example follows:

System Curves:

In the simplified example above, we determined the total head required to achieve the desired flowrate and compared this with the pump performance curve. Since the total head required was less than the available pump head at the desired flowrate, we said that the pump may work for our application, if the additional pump head/flowrate is acceptable for our application. In many cases, we want to determine the specific operating point for our pump; that is, we want to find the exact point where the head required to overcome system parameters (kinetic, gravitation, pressure and head loss) intersects the pump performance curve. This idea brings about the concept of a system curve. This concept of a system curve is depicted in the graph shown below:

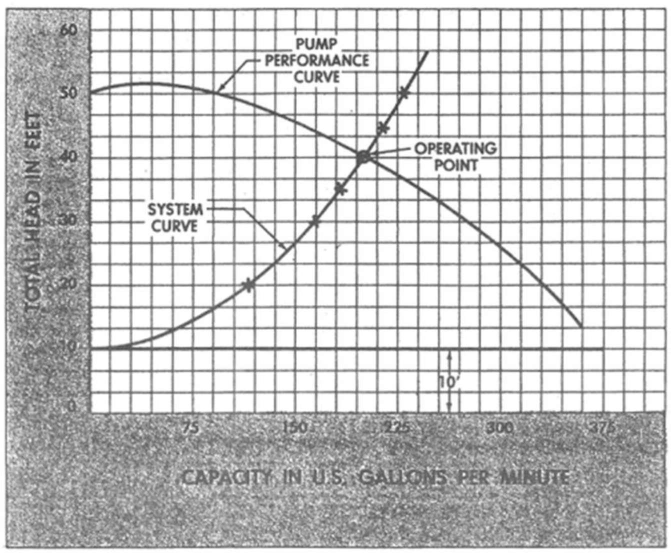

Figure 4: System curve intersection with pump performance curve

The system curve depicts the head required to move fluid through the system as a function of flowrate. As shown in the figure above, there is a constant head of 10’ added to the curve; this vertical shift is due to a constant 10’ of head required for gravitational lift. From the y-axis, the curve then slopes upwards, owing to the fact that as the flowrate increases, so does the head loss (and kinetic head). The intersection point of the system curve and the pump performance curve indicates the operating point for a system.

Apparatus

The device used in this lab (Figure 5) was built specifically for this experiment. It utilizes a small pond pump (Zoronk – 400 GPH submersible water pump) to generate a low volume flow that varies (measurably) over a small output height range (increase in gravitational head). This allows us to visualize the impact that gravitational head has on the flowrate of a system.

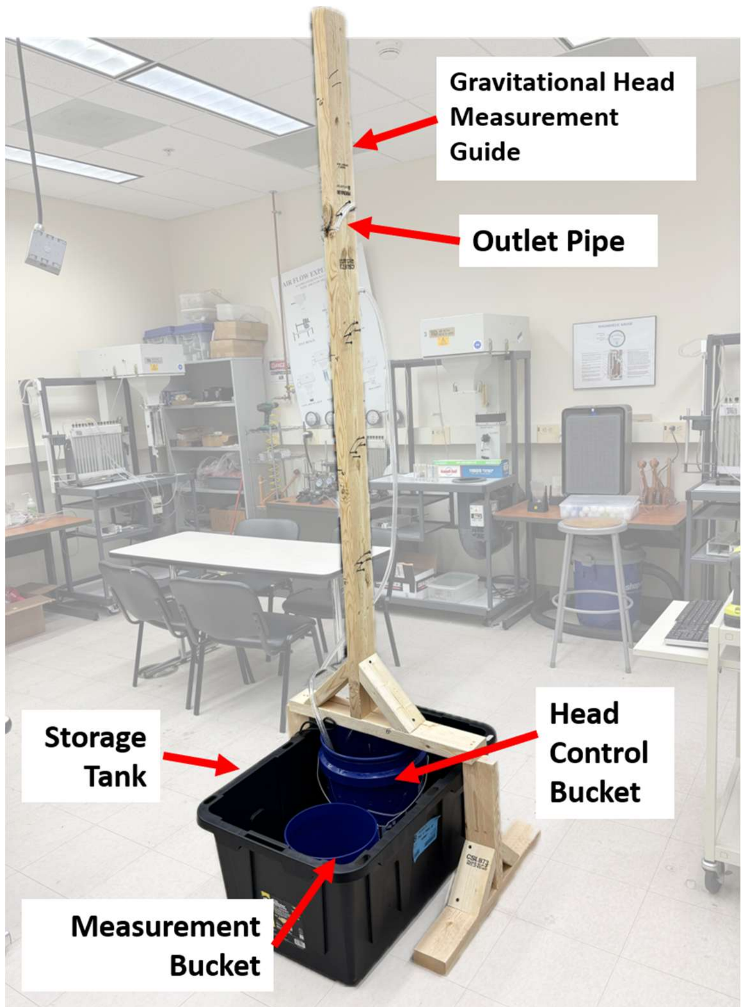

Figure 5 – photo of the entire test apparatus

Apparatus Description

The apparatus for this experiment consists of several key components as described below:

Buckets:

There are 3 main buckets used in the device. The largest is the storage tank which is used as a reservoir for the experiment and the return for the water leaving the outlet tube. The second bucket is the head control bucket which has been drilled with holes that are 6" above the pump. When the water in the head control bucket rises to the holes, the water flows out, thus providing a constant head for the main pump. The third bucket is the measurement bucket which is used to 'temporarily' collect the outlet flow and determine the flow rate.

Pumps:

There are two pumps used in the device (Figure 6). The first pump (head control pump) sits in the bottom of the storage tank and continuously pumps water into the head control bucket. This pump maintains the water level in the head control bucket. The second (main pump) is located within the head control bucket and is connected to the outlet pipe. The main pump moves water through the outlet pipe and generates the flow we are measuring in the device. Both pumps are the same model (as listed above).

The switch on the surge protector used to power the system is connected to both pumps. Turning on the power supply will start both water streams. ENSURE THE WATER LEVEL IS ABOVE BOTH PUMPS AND THAT THE PIPES ARE ALWAYS DIRECTED BACK INTO THE STORAGE TANK BEFORE TURNING ON THE POWER.

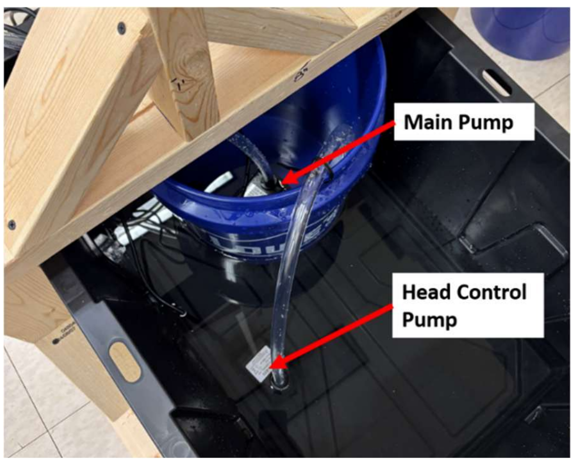

Figure 6 – Photo of the pumps used in the apparatus

Test Stand:

The test stand has been designed to provide easy testing of various outlet pipe positions (Figure 7). The height measurements denoted on the test stand (2-6 feet) are measured from the top of the water in the head control bucket; that is, the measurements on the test stand directly provide the **change** in height you will use in the mechanical energy equation. Although the guide screws added to the system generally hold the pipe in place, **one member of the team MUST hold the outlet pipe at all times to ensure that the flow is always directed back to the storage bucket.** At higher heights, you may also need to hold the last feet of the outlet pipe to ensure that there are no kinks in the system at the guide screws that would introduce unwanted pressure losses into the system.

As indicated by the dashed lines in the photo, please attempt to make the outlet of the pipe as close to the height measurement line as possible; this will ensure an accurate gravitational head measurement.

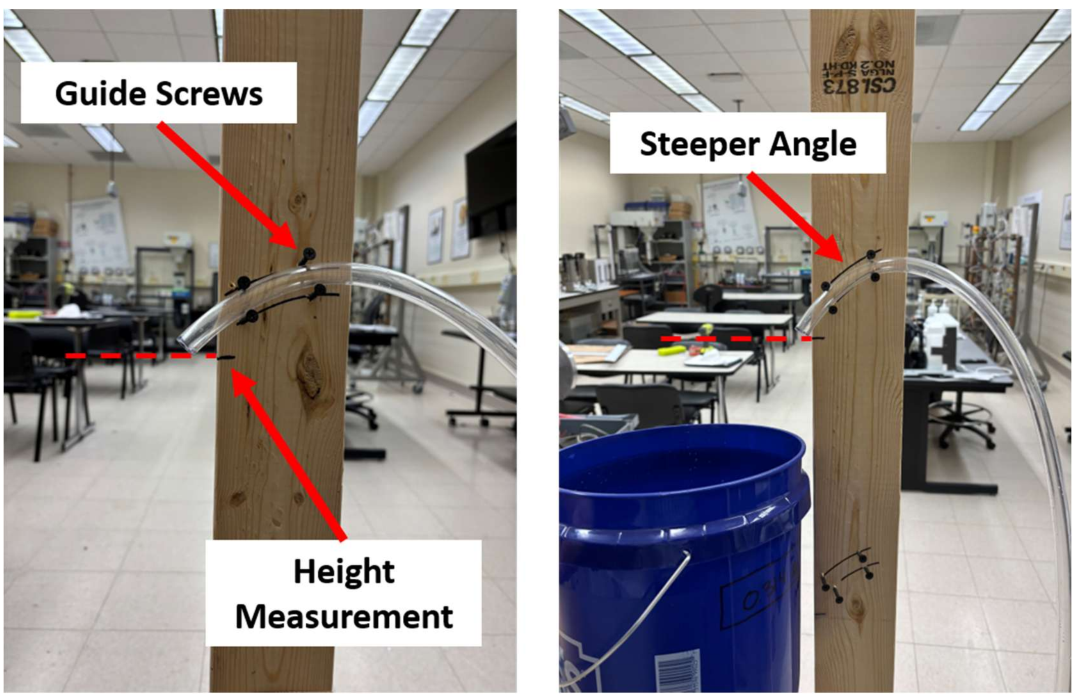

Figure 7 – (left) Example of the height guides used to ensure accurate head measurement. (right) Demonstration of the steeper angle required at greater heights to ensure the flow returns to the storage tank

Theory applied to the experiment

The mechanical energy equation paired with calculation of the friction factor allows us to predict the flowrate for various conditions. Applying Equation 1 to the apparatus as modeled in the schematic shown below yields the following relationship:

$$h_s = \frac{V_{out}^2}{2g} + \Delta z + h_L \tag{7}$$

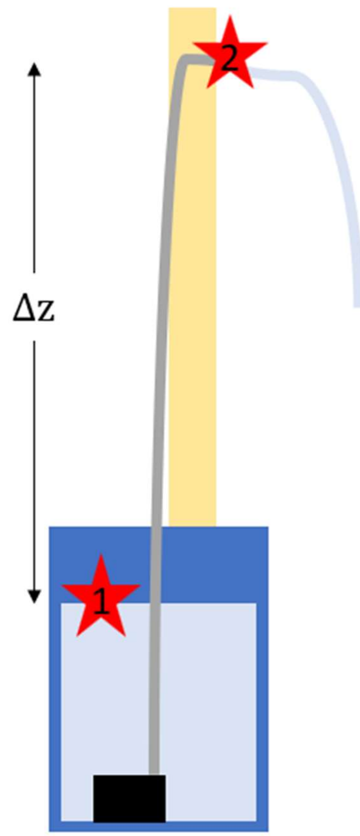

Figure 8 – Schematic of the device with initial and final points for energy equation analysis.

There is negligible kinetic energy on the inlet side since we keep the water level constant. There is no pressure on either side of the system since both are exposed to the atmosphere. The height change is determined relative to the water surface and the outlet of the tube, and the head loss depends on the system flowrate. The pump head depends on the flowrate, so the equation is not easily solved without the performance curve; the goal of the lab is to generate a performance curve for the small pond pump we are using.

Pre-Lab Calculations

For this lab, you are required to complete a handful of sample calculations BEFORE coming to lab. Your TA will verify that these have been completed when you arrive to lab. Lack of completion will result in a 0 for your pre-lab notebook score for the lab.

The main issue with the pump we are using is that we don't know how much head it can provide at a given flowrate (we do NOT have a performance curve); as such, we don't know if it will achieve the performance we need. With that in mind, our goal is to develop the performance curve. The way will do this is by varying the height of our outlet pipe (changing the gravitational head). As we raise the outlet pipe, the flowrate will decrease. By measuring the flowrate produced when varying the gravitational head, we will be able to calculate the head required and produce a performance curve. The annoying part of this problem is that the pump head required to move fluid out of our pump to a given height is a combination of the gravitational head, the kinetic head, and the head loss. Luckily for us, we have equations to calculate each of these values:

$$h_s = \Delta z + \frac{V^2}{2g} + f\frac{L}{D}\frac{V^2}{2g}$$

Once we know what flowrate is produced at a given height, we can calculate each of the terms on the RHS of the equation above. The sum of these heads (gravitational, kinetic and loss) **represents the system curve for our system**, and we can equate this to the head the pump produces at each flowrate.

Fortunately, we don't need to wait to see what our pump does to calculate the system curve; that is, the head loss for a given flow (certain flow rate through a certain pipe) is independent of the pump being used. The goal of these pre-lab calculations is to determine how much pump head it will take to produce different flows through the same pipe we will use in lab (a 10' section of ½" ID flexible PVC tubing) and draw various system curves. As the outlet height is increased, the gravitational head increases; as the flowrate increases, the loss and the kinetic head increase. The following steps guide you through the creation of a required system curves.

In preparing for lab, please complete the following calculations:

1. First, using the Moody chart, determine the head loss for pumping water ($\rho = 1.95 \frac{slug}{ft^3}, \mu = 0.000022 \frac{lb \cdot s}{ft^2}$), and a 10' section of ½" ID flexible PVC tubing (roughness – 0.0015 mm), fill in the following table (hint: make an excel spreadsheet to automate everything except getting the friction factor from the Moody Chart).

$$Kinetic\ Head = \frac{V^2}{2g}$$

$$h_L = f \frac{L}{D} \frac{V^2}{2g}$$

Table 1: Head calculations for a 10' section of ½" ID flexible PVC tubing.

Flowrate (gal/hr)	**Velocity (ft/s)**	**Kinetic Head (ft)**	**Reynolds Number**	**Friction Factor (f)**	**Head Loss (ft)**
0					
25					
50					
75					
100					
125					
150					
175					
200					
250					

2. Determine the total head required to pump fluid through this same pipe at various heights.
   a. The total head is a combination of the head loss determined in the last step, the kinetic head, and the gravitational head.
   b. For example, the calculation for a 3' outlet height would be:

$$h_s = 3\,ft + \frac{V^2}{2g} + f\frac{L}{D}\frac{V^2}{2g}$$

3. Plot the total head required versus flowrate for outlet heights of 2, 3, 4, 5, and 6 ft. These are the system curves for various gravitational heads.
    a. Each outlet height will have the same curve versus flowrate, but be shifted up by a value of 1 ft each curve
4. Make the scale on the bottom axis vary by 10 GPH, and the scale for heads vary by 0.5 ft. Include gridlines to make reading the chart easier in lab.
5. Print out your chart as a full page (landscape) and paste into your notebook

The following figure provides an idea of what the system curves you are trying to create should look like (values removed to keep some mystery alive). As the flowrate increases, the head required to achieve that flow does as well. The head required to achieve each extra foot of outlet height (gravitational head) is simply a constant shift of one foot of head.

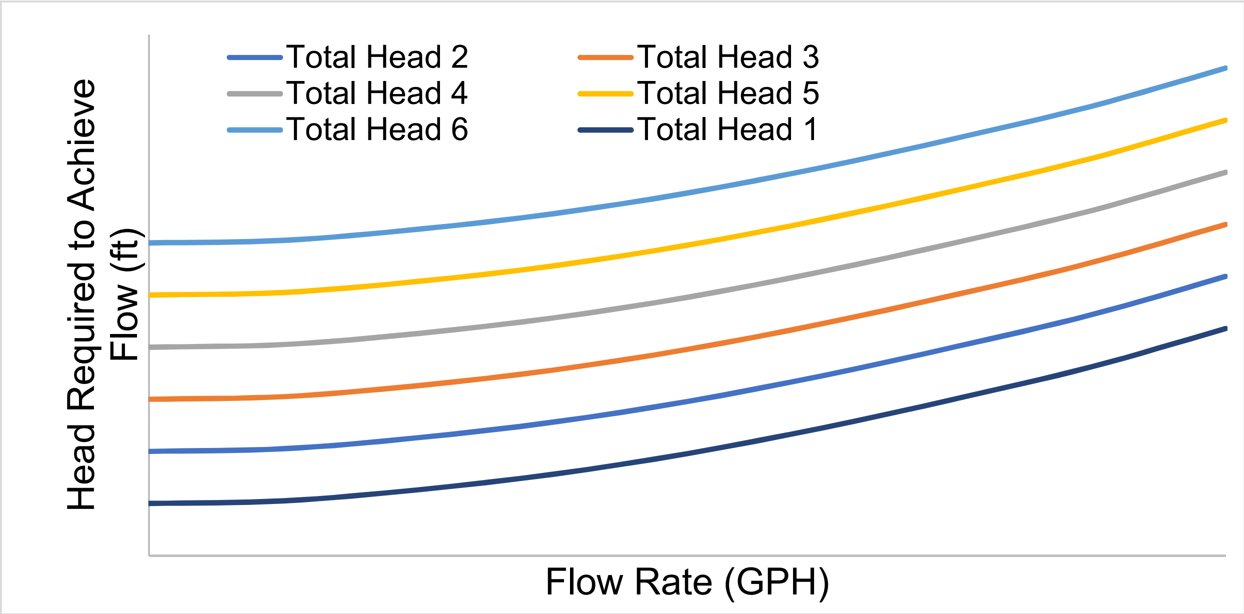

Figure 9: System curves for a 10' section of ½" ID flexible PVC tubing and various gravitational head increases.

Experimental Procedure

To organize the team, it is recommended that the 4 members assume the following roles:

- Member 1 – Testing pipe holder
- Member 2 – Power switch monitor
- Member 3 – Timer
- Member 4 – Measurement bucket holder

Once everyone has decided on their roles, please follow the procedure below:

1. Record the room temperature – we will assume the water temp matches the room temperature and use this to look up fluid properties
2. Ensure that the storage tank has sufficient water. The water should be several inches above the storage tank pump.
3. Zero out the scale with the empty measurement bucket on it
4. Ensure that sufficient water is in the head control bucket. The water should be several inches above the pump, and ideally at the water drainage holes that are 6" above the pump.
5. Route the ½" x 10' testing pipe through the 2' height guides on the test apparatus. Hold the pipe at the appropriate height and angle so the water will return to the large water storage tank.
6. Turn on the system and allow the water to flow for several seconds. Ensure that water has started to leak out of the drainage holes in the side of the testing bucket (this ensures that the starting gravitational head is known and that the dimensions of the device are accurate).
7. Once the system stabilizes, simultaneously start the timer and place the small measurement bucket within the flow of the water.
    a. Collect water for around 15 seconds and stop the watch at the same time the bucket is removed from the stream
8. Turn off the pump until the next trial.
9. Record the fill time and use the scale at the front of the classroom to measure the mass of water added to the bucket during the fill duration. Record the mass.
10. Return the water to the large basin
11. Complete 3 trials at each height from 2-6 feet
12. Disconnect both pumps from the power supply and remove the ½" x 10' tubing pump from the head control bucket. Replace the pump with the ½" x 50' tubing pump. Plug the head control pump and the new test pump back in.
13. Using the 1/2" x 50' tubing pump, measure the flow rate at the 2', 3', and 4' height for three trials each.
14. Disconnect both pumps from the power supply and remove the ½" x 50' tubing pump from the head control bucket. Replace the pump with the ¾" x 10' tubing pump. Plug the head control pump and the new test pump back in.
15. Using the 3/4" x 10' tubing, measure the flow rate at the 2', and 4' heights for three trials.

16. Turn off the system and place all tubes into the buckets. Clean up any water that splashed out of the system.

Results

1. Calculate the average flowrate for each height measured using the 10' x ½" diameter pipe
2. On the same graph that you created for the pre-lab, plot your experimental flowrates for the 10' x ½" tubing. To do so, please:
    a. Go along the x-axis to the average flowrate calculated for a given height.
    b. Trace vertically up on the plot until you intersect with the appropriate total head curve plotted from the pre-lab (i.e. if the data point was for a 4' experimental height, trace vertically until you intersect the 4' head curve)
    c. Connect the new points to generate the pump performance curve
        i. Use the value of 6.5 ft of head at 0 flow for the y-intercept of your plot
        ii. Your plot should slope down from left to right
3. Calculate the average flowrate for the ½" x 50' tubing at each height
4. Calculate the total head required to achieve these flowrates through the ½" x 50' pipe (same calculation you completed for your pre-lab but now $l = 50\ ft$)
5. Plot the data points for the ½" x 50' tubing on your performance curve using the experimental flowrate (x-coordinate) and the theoretical head calculated in the last step (y-coordinate)
6. Calculate the average flowrate for each trial of the ¾" x 10' pipe

Discussion

1. Calculate the uncertainty in your average mass flow rate calculations (kg/s)
2. Do your data points from the ½" x 50' pipe intersect the pump performance curve?
    a. If not, are they close? What errors and uncertainties could contribute to the differences in these values.
3. Would this pump work if I wanted to generate a flow of 90 GPH with an increase in gravitational head of 3.5 ft? Use your pump curve and calculations to support your answer
4. What do the results from the ¾" tubing indicate? What are the real-world implications of these results?
    a. Compare the flows to the smaller diameter pipes – what are the differences? Are these good things?

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