Web-Based Digital Experiment in Chemical Engineering

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Many concepts in engineering courses can be difficult to understand when first seen, and interactive simulations can be an effective way to help students understand such concepts. As indicated in the National Academy 2022 report on New Directions for Chemical Engineering [1]. "In its interactive mode, this kind of visualization would allow students to design and control the behavior and performance of such systems, to explore how they respond to perturbations in parameters or conditions, and to address and resolve safety and ethical matters in the practice of engineering without risking any direct physical or professional consequences of their actions." The report further states that "The chemical engineering classroom of the future will leverage modeling and simulation to expand student understanding."

To help improve student learning in chemical engineering, as suggested in the National Academy Report, we have created web-based, interactive digital experiments (WIDEs). Some WIDEs are identical to Low-Cost Desktop Learning Modules (LCDLMs) created at Washington State University [2-4]. Digital and physical experiments are compared in the same classroom, where half the student groups use a physical experiment and other half use the corresponding digital experiment. The LCDLMs have been used previously during 50-minute class periods in classrooms, where the instructor provides one module for every 3-5 students. In those studies, the LCDLMs improved student learning [5-7]. The WIDEs were prepared for chemical engineering courses: fluids, heat transfer, material and energy balances, and thermodynamics, but many of the WIDEs are also appropriate for mechanical engineering courses.

Web-based interactive digital experiments (WIDEs) are simulations that allow students to conduct experiments and investigate system behavior by testing responses to changes in model input. The WIDEs are programmed using JavaScript and HTML. They play in web browsers so that students can use them directly on laptops and tablets without downloading software or plug-ins. The objective of these WIDEs is to enable students to understand important concepts and skills. For the WIDEs that are mimics of the currently-available LCDLMs, the simulations' interactive graphics are essentially identical to the physical experiments. Students adjust valves and other equipment, take measurements (e.g., by collecting samples and reading meters), and analyze data. The digital measurements include noise in the data, just as in the physical experiment.

Studies have shown that virtual laboratories have advantages over physical laboratories, and WIDEs are expected to have similar advantages:

- Available at any time or location [8], including to students working remotely or at institutions that are resource-limited, and multiple students can use them simultaneously [9].
- Able to run experiments that are time-consuming for a physical laboratory [8], [10]. Procedures that take a few seconds in a virtual laboratory would require many minutes in a physical laboratory.
- Cost-effective; virtual laboratories are less expensive than physical laboratories and easier to maintain, update, and improve [9].
- Able to make abstract phenomena more visible [11], [12].
- Allow students to try different conditions without damaging equipment [9] or exposing

themselves to hazards [9], [10].

In addition, WIDEs have advantages over LCDLMs because they are easily scaled for use at multiple universities, instructors do not need to transport experiments to class, and they are easier to maintain and update.

Some might question if students might not learn hands-on skills if WIDEs were used in place of LCDLMs. However, the equipment used in LCDLMs is much smaller than industrial equipment, so it is not clear how the skills in using LCDLMs translate to industrial equipment. Also, it is not clear what hands-on skills chemical engineers need in industry.

Previous studies observed that student learning using virtual experiments was at least as good and, in some studies, better than physical experiments [12-16]. Those physical experiments in previous studies were mostly ones that were carried out in an undergraduate laboratory, whereas the LCDLMs and WIDEs can be carried out in a 50-minute class period in most cases. Another significant difference in the current study from previous studies is that the WIDEs were prepared so they are identical to LCDLMs.

WIDEs topics:

Thirty WIDEs have been created to date and posted online on https://learncheme.com/virtual-laboratories/; they cover a range of topics. Nine WIDEs are direct mimics of LCDLMs created at Washington State University and posted on https://labs.wsu.edu/educ-ate/desktop-learning-modules/. Three planned WIDEs will also be direct mimics of LCDLMs. The WIDEs were programmed at the University of Colorado Boulder (CUB). The WIDEs that are mimics of the LCDLMs used the LCDLMs worksheets with slight modifications. The remaining WIDEs and their worksheets were created at CUB. The heat transfer WIDEs, all of which are mimics of LCDLMs, are:

- Cross-flow heat exchanger
- Double-pipe heat exchanger
- Evaporative cooling
- Kettle boiler
- Shell-and-tube heat exchanger
- Radiative and conductive heat transfer (planned)

The fluids WIDEs are listed below. The ones that are mimics of LCDLMs have an asterisk.

- Blood cell sedimentation*
- Fluidized bed*
- How fast does a tank empty?
- Hydraulic loss in a smooth pipe*
- Rising 3D-printed quarter
- Venturi meter*
- Viscous flow around a rotating rod
- Viscous flow in two connected pipes

- Fluidized bed with enzyme reaction* (planned)
- Glucose analyzer* (planned)
- Non-Newtonian hydraulic loss (planned)

The material and energy balances/thermodynamics/separations WIDEs are below.

- Absorption column separations
- Adiabatic flash drum with binary liquid feed
- Adiabatic gas expansion between two tanks
- Chemical equilibrium in the Haber process
- Chemical equilibrium N_2O_4 dissociation
- Determine Antoine constants
- Effectiveness of liquid-liquid extraction
- Mass and mole balances in a reactor
- Material balances in liquid-liquid extraction
- Material balances on a CSTR
- Material balances on a stripping/absorption column
- Measure heat capacity with a calorimeter
- Ranque-Hilsch vortex tube
- Reverse osmosis
- Single-effect evaporator
- Stripping column separations
- Unsteady-state mass balances for a 2-phase, ternary system
- Unsteady-state material balances on a CVD reactor
- CO_2 adsorption in a packed bed (planned)

WIDE examples:

Images of three WIDEs appear below along with photos of two LCDLMs. The first WIDE (Figure 1) is a counter-current shell and tube heat exchanger with hot water on the tube side and cold water on the shell side. Rates of heat transfer are determined by measuring temperatures and flow rates, and heat transfer coefficients are calculated. This WIDE is a mimic of the LCDLM in Figure 2.

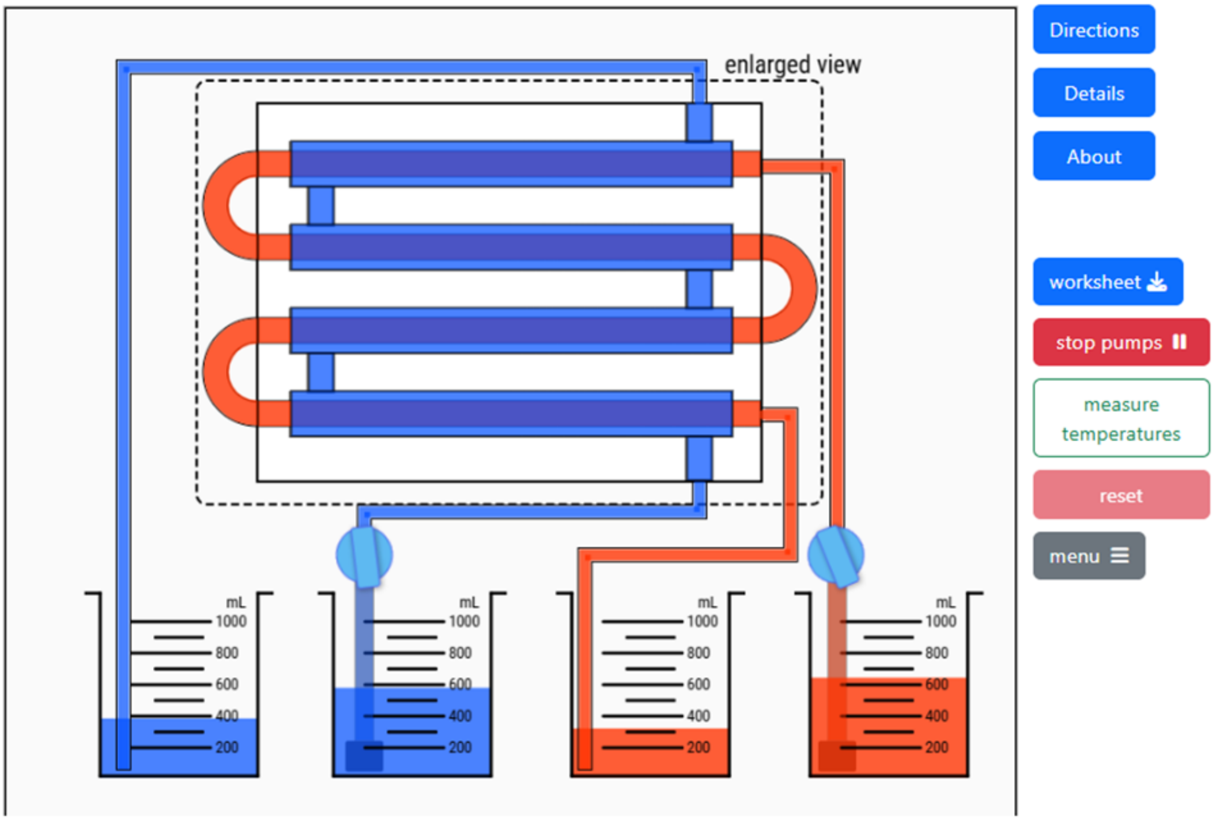

Figure 1. Shell and tube heat exchanger WIDE. Cold water (blue) is fed to the shell side and hot water (red) is fed to the tube side.

Figure 2. Shell and tube heat exchanger LCDLM.

The next WIDE (Figure 3) is a packed bed of particles in which water flows up through the bed, and as the flow rate increases, the bed fluidizes. Pressure drops across the bed, the height of the bed, and flow rates are measured. This WIDE is a mimic of the LCDLM in Figure 4, which shows conditions where the bed fluidizes.

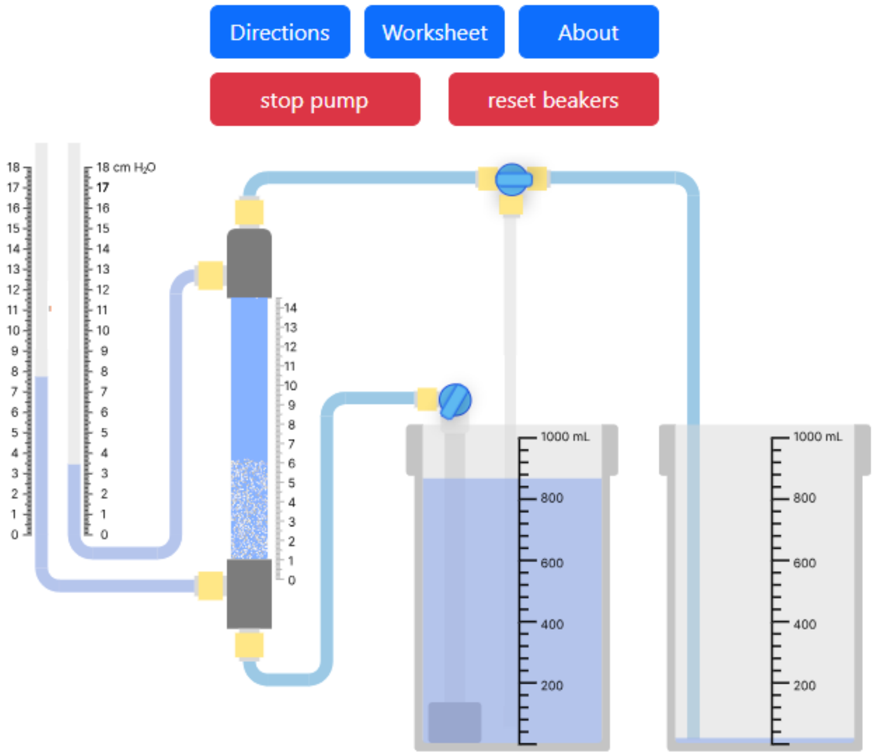

Figure 3. Fluidized bed WIDE in which water from the feed tank flows up through the bed. The manometer on the left measures pressure drop across the bed and water collects in the beaker on the right.

The third WIDE (Figure 5) is adiabatic gas expansion between two tanks and is appropriate for a material and energy balances course or a thermodynamics course. Gas at high pressure on the left expands into an evacuated tank on the right when the user clicks on the valves to open them. The temperatures and pressures recorded after pressures equalize between the two tanks allow calculations based on mass balances, energy balances, and the ideal gas law.

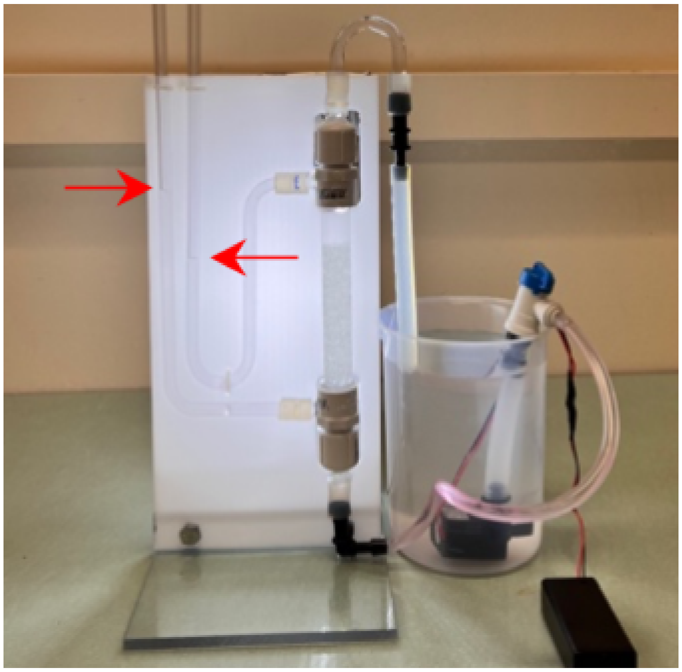

Figure 4. Fluidized bed LCDLM

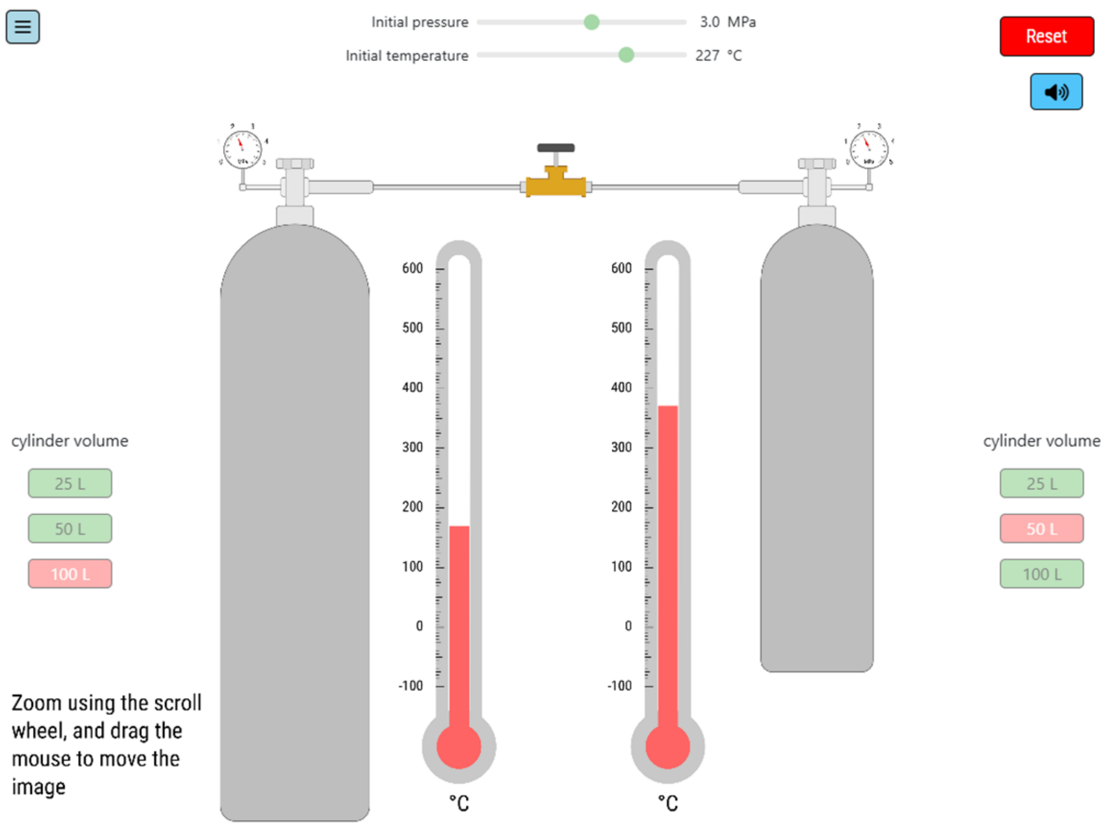

Figure 5. Adiabatic Gas Expansion between Two Tanks WIDE. The final condition, after opening the valves so that pressure equalizes between the two tanks, is shown. Initially only the left tank contains gas.

WIDEs content:

All WIDEs are browser-based and play in multiple browsers and on PCs, Apple computers, and iPads. Each WIDE contains brief directions that are accessed by clicking on the blue rectangles labeled Directions in Figures 1 and 3. In some WIDEs, such as in Figure 5, the Directions button is in a hamburger menu, which is in the upper left corner of the figure. Likewise, each WIDE contains an About section in the same format as the Directions. Sliders, such as those at the top of Figure 5 for initial pressure and temperature, allow students to change parameters. Buttons, such as those in Figure 1 for stopping pumps, measuring temperatures, and pouring back water from the outlet beaker to the inlet beaker, allow students to control the WIDEs. Most WIDEs contain a red Reset button, as seen in Figures 1, 3, and 5 so students can re-start an experiment. As seen in the lower left of Figure 5, students can zoom in with a scroll wheel; this allows the pressure gauges to be read and the final temperatures to be accurately read. Likewise, students can zoom in for the WIDE in Figure 1 to allow accurate measurements of the volumes in the beakers. For the WIDE in Figure 3, students can zoom in to accurately measure the pressure drop across the fluidized bed, the height of the bed, and the volumes in the beakers.

All WIDEs contain a PDF worksheet file that downloads when the user clicks on the blue worksheet button (Figures 1 and 3) or on the blue button in a hamburger menu (Figure 5). Worksheets contain:

- Student learning objectives
- Questions to answer before starting experiments
- Equipment diagrams and explanations of the equipment
- Step-by-step experimental procedures and tables to record measurements
- Explanations of equations and calculations
- Questions to answer after completing the WIDE

Several worksheets contain more detailed homework problems. Currently, about half of the WIDEs contain short screencasts that demonstrate how to use the WIDEs, and all will contain screencasts in the future.

Some WIDEs are like desktop experiments, whereas others are like small-scale laboratory experiments. WIDEs contain animated diagrams of the equipment that show behaviors such as:

- fluid flow
- fan rotation
- a rotating stirrer
- particles that move in a fluidized bed
- valves that can be opened or closed
- switches that turn on and off
- movable digital thermometers

Rotameters, bubble flow meters, or mass flow controllers measure gas flow rates. Liquid flow rates are measured by timing the change in volume of liquid in a beaker or the change in weight in a beaker. Mass flow meters/controllers also measure liquid flow rates. Manometers, analog pressure gauges, or digital pressure gauges measure pressures or pressure differences. Concentrations are measured with meters or simulated GCs.

Comparison of WIDEs and LCDLMs:

In this paper, the only rigorous, direct comparison available between learning with the WIDE and the corresponding LCDLM is for the Hydraulic Loss in a Smooth Pipe experiment. About half of the student groups in the class completed the activity using the LCDLM, and the other half used the WIDE version. Students were tested immediately before and immediately after the activity using the same pre-test and post-test. The questions, which are in the Appendix, featured different scenarios relevant to the topic of hydraulic pressure head loss. Scenarios included two tanks of water with different pressures connected by a horizontal pipe of constant diameter and a coiled pipe of constant diameter where the inlet was at a greater height than the outlet. The purpose of these questions was to gauge whether students understood three main points: 1) Water flows from high pressure to low pressure. 2) Since water is incompressible, the volumetric flow rate of water is the same entering and leaving a pipe. Even in the coiled pipe of constant diameter where gravity is a complicating factor, water flows at a constant velocity. 3) Head loss due to friction is linear in a smooth pipe.

The results of the pre-test and post-test and their differences are shown in Figure 6. Learning within each condition was evaluated using a two-tailed paired t-test (pre vs. post). To compare the two instructional formats directly, learning was summarized using growth scores (post − pre), and gains for the LCDLM and WIDE groups were compared using a two-tailed Welch two-sample t-test (unequal variances). The difference in learning gains between the LCDLM ($n = 11$) and WIDE ($n = 9$) groups was not statistically significant ($p = 0.35$).

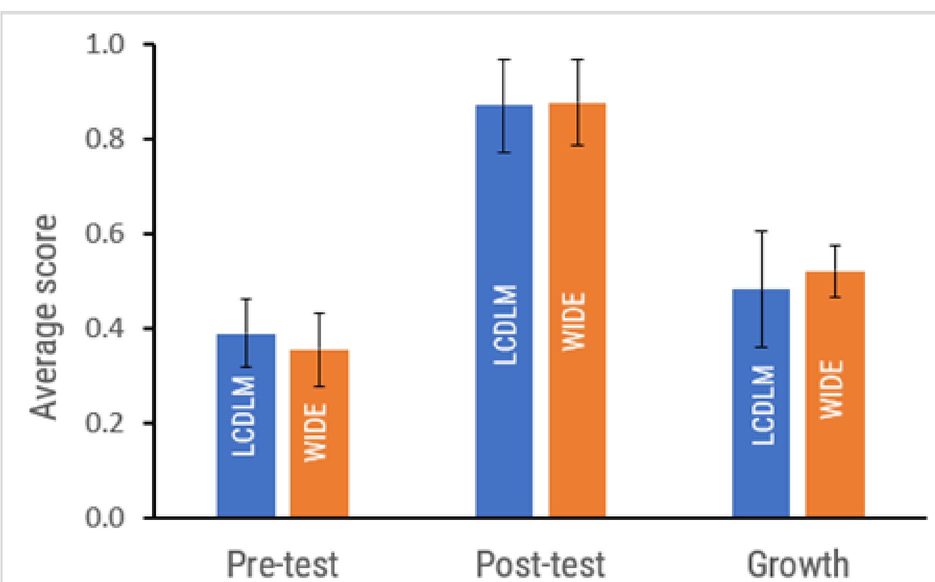

Figure 6. Average student scores for pre- and post-tests and the difference between pre- and post-tests when the Hydraulic Loss in a Smooth Pipe LCDLM and the corresponding WIDE were compared.

Summary and outlook:

WIDEs have the potential to be used both in classrooms and as part of homework assignments. Currently 30 WIDEs are available on the LearnChemE website and more will be added in the next few months. Many of the WIDEs have already been improved as students have evaluated them and identified changes. This effort to evaluate and improve them will continue. The results of the comparison in class between a LCDLM and the corresponding WIDE are encouraging as they support our premise that digital interactive experiments may be as beneficial as physical experiments for improving student learning outcomes. Further assessments will be presented at the 2026 ASEE conference.

Acknowledgments:

This project was supported by the National Science Foundation (NSF DUE 2336987 and DUE 2336988). Most of the WIDEs were programmed by Drew Smith, Sanjay Kavatooru, and Neil Hendren. Sanjay Baskaran and Jackson Dunlap each programmed one WIDE. Michelle Medlin implemented the WIDEs on the website. The worksheets for WIDEs that are mimics of LCDLMs, and the pre- and post-test surveys, were developed at Washington State University by the co-authors and by Dr. Prashanta Dutta and prior PhD research assistants: Drs. Arshan Nazempour, Jacqueline Gartner, Negar Beheshti Pour, Kate Dahlke, Olivia Reynolds, and Kitana Kaiphanliam.

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Appendix: Questions for the Hydraulic Loss in a Smooth Pipe experiment

1. Water flows through a pipe from Tank 1 to Tank 2. The water level in each tank is indicated at an instance in time. Assuming steady-state flow, select the correct graph below of **velocity** versus **distance** down the pipe.

- o Exponential decay of velocity to a high value
- o Linear velocity decreases
- o Exponential decay of velocity
- o Linear velocity increases
- o Constant velocity

2. Your answer to question 1 is because…

- o The velocity increases near the pipe entrance because of the pressure gradient but accelerates slowly at the pipe exit because of friction.
- o The velocity increases down the pipe because of the pressure gradient.
- o The force of friction reduces the velocity of the liquid.
- o The cross-sectional area is constant; thus, the velocity is constant to conserve mass.
- o The velocity decreases near the pipe entrance due to friction and then decelerates since friction is reduced when it moves slower.

3. In a steady state system, fluid is flowing from a tank with a constant liquid height, h, at some pressure, P, through a pipe to the atmosphere. Which graph represents the relationship between pressure and **distance** in the pipe?

- o Exponential decay of pressure to a high value
- o Constant pressure
- o Exponential decay of pressure
- o Linear pressure decrease
- o Linear pressure increase

4. Your answer to question 3 is because...

- o Frictional losses within the pipe will decrease velocity nonlinearly, so pressure must also decrease nonlinearly.
- o Frictional losses within the pipe will decrease pressure linearly.
- o The fluid is not accelerating, so the pressure must be constant.
- o Frictional losses within the pipe will increase pressure.
- o The fluid speeds up through the pipe, so pressure must decrease.

5. Excessive pressure (head) losses are observed in a section of piping with constant diameter. Select the option that could be explored to reduce the head losses in the piping section, assuming turbulent flow.

- o Increase the fluid velocity.
- o Decrease the pipe diameter.
- o Increase the pipe diameter.
- o Use a piping material with a higher relative roughness to decrease the friction factor.

6. Fluid flowing inside the coil. Assuming the coil has a constant diameter, what would happen to the fluid velocity as the fluid flows from the top to the bottom of the coil?

- The velocity will increase because the fluid is flowing downwards and is driven by gravity.
- The velocity will remain constant because the pipe has a constant diameter and mass must be conserved.
- The velocity will decrease because of friction on the pipe walls.
- The velocity will remain constant because the increase in velocity due to gravitational forces is counterbalanced by the decrease due to friction.