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UNDERGRADUATE INTERNAL FLOW PIPE FRICTION LABORATORY

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ABSTRACT

Hydrodynamics laboratory experiences have supported the United States Military Academy's civil and mechanical engineering programs for nearly 50 years. A recent effort revitalized and significantly improved the pipe friction hydrodynamics laboratory, a system originally built by the U.S. Army Corps of Engineers Waterways Experiment Station in the 1950s. The experimental apparatus includes a $3\,\mathrm{hp}$ electric pump capable of delivering a steady flow of liquid up to $5.1\,\mathrm{lbm/s}$ fed from a $100\,\mathrm{gallon}\,(\mathrm{US})$ reservoir. The test section is a horizontal copper pipe of $0.75\,\mathrm{in}$ diameter which issues fluid into a transparent, plastic visualization chamber. Mineral oil is the working fluid, chosen for its favorable physical properties that enable a broad range of flow regimes for data analysis and flow visualization. The test section is instrumented with digital pressure gauges and an ultrasonic flow meter, installed as part of the revitalization project. A collection tank on a mass scale provides a manual method for estimating flow rate during experimental trials. The improved laboratory significantly expands the range of data that may be collected, with students now able to accurately measure pressure, temperature, flow rate, and pipe geometric data. Students compute Reynolds number to characterize flow regime, estimate pressure gradient, and predict the friction factor given an estimate for the pipe's roughness coefficient for several flow rates. A pre-laboratory exercise requires students to derive a functional form of the steady-flow mechanical pipe flow equation and employ dimensional analysis to identify the non-dimensional parameters required to achieve dynamic similitude. The upgraded laboratory offers a relevant, comprehensive application to deepen students' conceptual understanding of internal fluid flow, hydrodynamics, and modeling and similarity principles.

KEY WORDS: Hydrodynamics, Undergraduate Laboratory, Pipe Flow

1. INTRODUCTION

The United States Military Academy at West Point educates and trains future Army officers over a four-year, undergraduate education. The mechanical engineering program includes a two-course sequence integrating thermodynamics and fluid mechanics, Thermal-Fluid System I and II. The MC312 Thermal-Fluid Systems II course serves as the experimental methods course for the major. The course involves a significant milestone for demonstrating proficiency in technical communications (TECOM) via the West Point Writing Program's "Writing in the Major" requirement. The course uses the pipe friction laboratory to provide students a robust, hands-on opportunity to conduct experimental work, apply design of experiment (DOE) principles taught in MC312, and write a complete laboratory report.

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Several internal flow hydrodynamics principles can be visualized and demonstrated using the pipe friction laboratory, an experimental apparatus that was designed and constructed by the U.S. Army Corps of Engineers for West Point. The laboratory augments fluid mechanics instruction by demonstrating the different effects temperature and pressure have on a pipe-pump flow system. Data including temperature, pressure, time, and weight are all collected and used to calculate the Reynolds number for a range of test cases across both laminar and turbulent flow regimes. The system contains 110 gallons of mineral oil stored in a reservoir which is pumped into a copper pipe running the entire length of the system. The pipe has six different locations where the pressure is measured using gauges, easily showing how fast the pipe will lose its pressure over the given length. The oil is then deposited into a clear, Plexiglas hood where cadets can visually observe the physical differences between flow rates. Oil is collected into an initial tank that can be closed off via a gate valve. With the tank closed, students can collect a specified amount of oil using a digital scale and measuring how long it takes for the oil to accumulate, measuring the flow rate. A recently added ultrasonic flow meter can also be used to compute flow rate.

Student feedback corroborated the need to re-envision the laboratory. In the semester before the improved laboratory, the course-end questionnaire asked students about their confidence to perform elements of the course. The design of experiment involving the pipe friction laboratory related directly to performance objectives (1), (2), (7) shown in highlighted bold font in Table 1. Students scored themselves well in their ability to apply conservation of mass, energy, and the Second Law of Thermodynamics to improve existing thermal-fluid systems (7) and in their ability to quantify uncertainty in experimentation and take steps to reduce uncertainty (2). Students reported lower confidence in their ability to design and conduct an experiment and analyze and interpret data from an experiment (1). This student feedback supported the update of the DOE laboratory environment as a means to reinforce modern data acquisition techniques with finer precision and deeper ability to conduct a more detailed analysis on a real-world pipe flow system. The re-envisioned apparatus improves on several analog and less precise instruments with modern LabView™ transducers, digital scales, and an ultrasonic flow meter.

Table 1 Student self-assessment to perform course objectives.

COURSE OBJECTIVE	SCORE
(1) Design and conduct an experiment, as well as analyze and interpret data from the experiment	**4.35**
(2) Quantify uncertainty in experimentation and take steps to reduce uncertainty	**4.39**
(3) Analyze the performance of internal combustion engines and associated automotive systems	4.48
(4) Analyze the performance of gas turbine engines	4.48
(5) Analyze the effects of compressibility on flow	4.33
(6) Analyze the forces that an external fluid enacts on an object (lift and drag)	4.41
(7) Apply Conservation of Mass, Energy, and the 2nd Law to improve existing thermal-fluid systems	**4.48**
(8) Apply the Concept of Exergy to analyze existing thermal-fluid systems	4.28

Laboratory experiences represent a significant part of engineering education at the undergraduate level. Laboratories augment classroom instruction and help students apply theory to real-world scenarios while teaching them skills necessary for a career in engineering and help students develop an understanding of the physical phenomena represented by modeling, understand assumptions, approximations, and simplifications, and subsequently apply simplified models to more realistic situations and complex geometries [1–6]. The Engineering Accreditation Commission of ABET has consistently integrated practical application of engineering principles within its student outcomes that are ideally fulfilled through the use of laboratories and other hands-on activities, including designing and conducting experiments, analyzing and interpreting data, and using techniques, skills, and modern engineering tools [7]. In recent years, virtual and remote laboratory experiences have emerged in response to the cost of developing or maintaining costly laboratory equipment and the development of new technologies [8–13]. Physical and virtual laboratories play a central role in the engineering curricula at the U.S. Military Academy at West Point [14–21].

2. EXPERIMENTAL APPARATUS

The main components of the pipe friction laboratory are shown in Figures 1, 2, and 3. A pump drives mineral oil through a copper pipe lined with pressure gauges. The inner diameter of the copper pipe is $d_m = 0.75 \pm 0.05$ in. Students estimate the roughness of the copper pipe (drawn tubing), while the mineral oil's density is estimated from a chart or computed using Sutherland's law. Three valves control the oil flow rate. A tank located at the copper pipe exit, shown in Figure 3, can be used to accumulate mineral oil to estimate mass flow rate. Figure 2 shows the pump and the three valves that control the flow rate through the copper pipe by diverting some of the mineral oil immediately back to the oil reservoir. The green valve, which controls the flow of oil from the reservoir to the pump, should remain fully open while the pump is operational. The remaining two valves can be used to vary the flow rate through the copper pipe. An ultrasonic flow meter was added as part of the laboratory upgrade, which can measure flow rate to a precision of $0.01\,\mathrm{lbs}$. The flow meter replaces a tank and valve system with accumulated fluid weighed on a balance scale. New pressure transducers collect data at $100\,\mathrm{Hz}$, also improving precision.

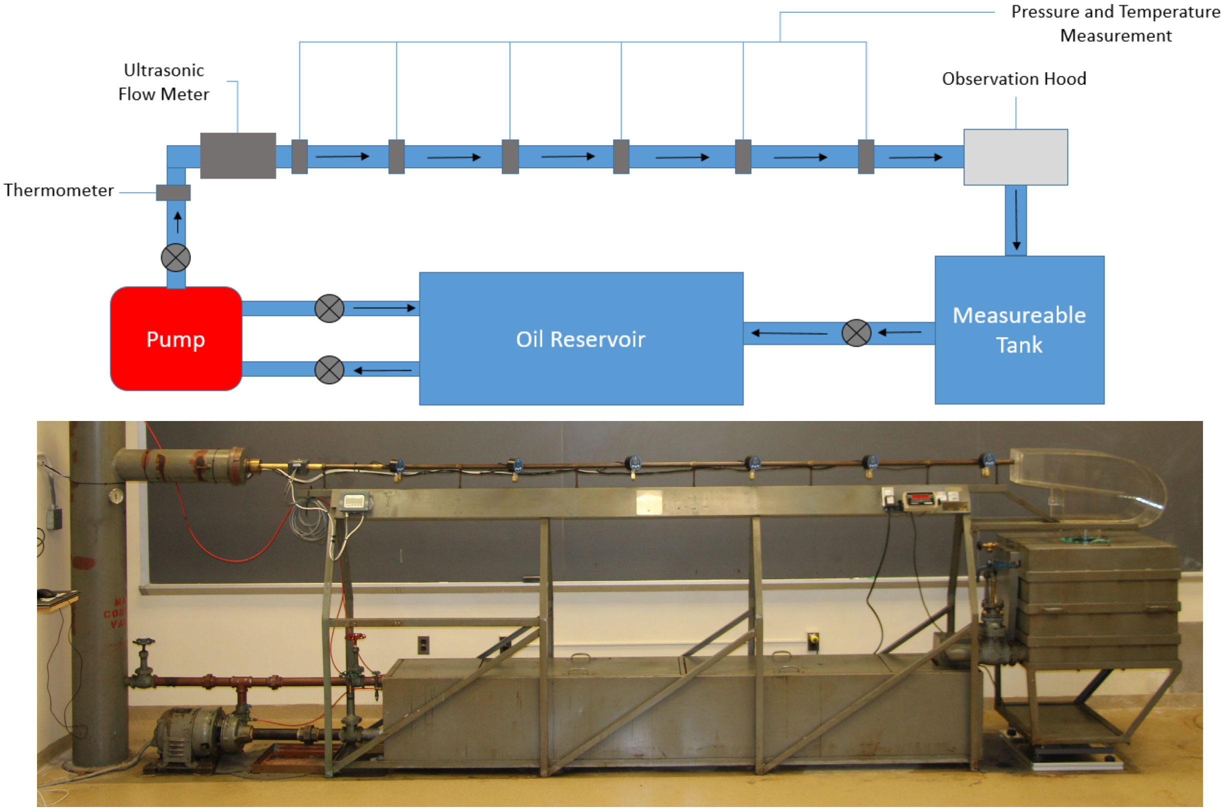


Fig. 1 Pipe Friction Laboratory: schematic showing flow direction (top); actual device (bottom).

3. PIPE FLOW THEORY

In this laboratory experience, the experimental setup comprises a pump issuing mineral oil, an incompressible fluid, at steady state through a pipe of uniform, circular cross section. The pipe within the instrumented test section is level and parallel to the ground, thereby experiencing no change in elevation. The variable of interest in this experiment is the pressure gradient, ∇P, which depends on properties of the flow (density, ρ, dynamic viscosity, μ, and mean velocity, V) and pipe geometry (diameter, d, and mean roughness height, ϵ). Using dimensional analysis, a functional relationship can be written as

$$\frac{\nabla P d}{\rho V^2} = \mathcal{F}\left(\frac{\rho V d}{\mu}, \frac{\epsilon}{d}\right), \tag{1}$$

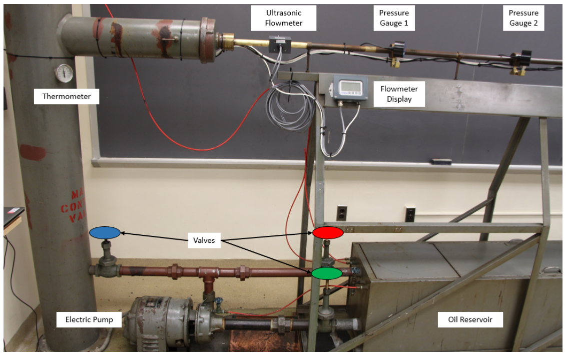


Fig. 2 Upstream section of PFL.

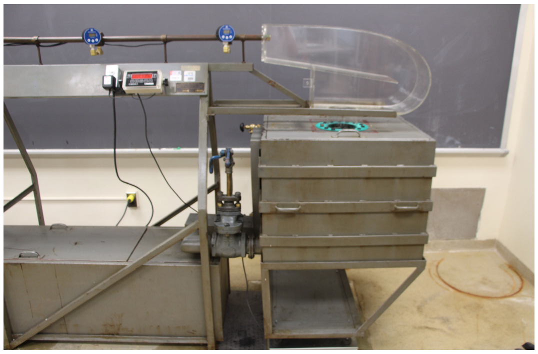


Fig. 3 Downstream section of PFL.

which reduces the number of terms requiring investigation from five ($\rho,\ \mu,\ V,\ d,\ \epsilon$) to two ($\rho V d/\mu$ and ϵ/d). The first term on the right-hand side of Equation 1 is the dimensionless Reynolds number based on diameter, Re_d.

Considering this system to be single inlet - single exit, a reduced form of energy conservation written in "head" form (all units of measure in terms of length) becomes,

$$\frac{P_i}{\rho g}+\frac{v_i^2}{2g}+z_i=\frac{P_e}{\rho g}+\frac{v_e^2}{2g}+z_e+h_p+h_L \tag{2}$$

where P is fluid pressure, ρ the mass density assumed to be constant for incompressible fluids, v is mean flow velocity, z is elevation from some designated reference datum, g is the gravitational acceleration constant. Subscripts i and e represent inlet and exit stations, respectively, while h_p is the energy added by a pump and h_L the head loss. Head loss comprises both major losses, per the Darcy-Weisbach equation [22], and minor losses, as

$$h_L=\left(f\frac{L}{d}+\sum_i K_i\right)\frac{v^2}{2g} \tag{3}$$

where f is the Darcy friction factor, L the pipe length, D pipe diameter, and K_i minor loss coefficients. In the case of the pipe friction laboratory, minor losses can be assumed negligible because pipe is straight, uniform in diameter and composition throughout the test section. Combining Equations 2 and 3, neglecting minor losses, and applying incompressible flow assumptions for a uniform, horizontal pipe illustrates that the laboratory's flow at steady state is simply a balance between a driving pressure gradient and shear stress, as

$$P_1-P_2=\left(f\frac{L}{d}\right)\frac{v^2}{2g}. \tag{4}$$

Approximating the pressure drop over pipe length as a pressure gradient, as $\frac{P_1-P_2}{L}\approx\nabla p$ and re-arranging results in an expression for the Darcy friction factor,

$$f=\frac{\nabla P d}{\frac{1}{2}\rho V^2}. \tag{5}$$

Combining Equations 1 and 5 reveals that the friction factor depends on the Reynolds number and the relative roughness, as

$$f=\frac{1}{2}\mathcal{F}\left(Re_d,\frac{\epsilon}{d}\right). \tag{6}$$

Students assume fully-developed flow, with no further change in velocity profile in the direction of flow after the hydrodynamic entrance length, but are encouraged to explore sources of error which includes the invalidity of this assumption for some regimes. The exact form of the functional relationship, $\mathcal{F}(\ )$, was determined through numerous high-quality experiments for a range of Reynolds numbers and relative roughness values. The results of these experiments are presented in the Moody diagram, an exact equation from Poiseuille's Law for laminar flow and an empirical expression proposed by Swamee and Jain [23] used for a wide range of turbulent flows,

$$f \;=\; \frac{64}{Re_d}\ (laminar) \quad \text{or} \quad f = 0.25\left[\log\left(\frac{\epsilon/d}{3.7} + \frac{5.74}{Re_d^{0.9}}\right)\right]^{-2}\ (turbulent). \tag{7}$$

In the pipe friction laboratory, students attempt to replicate these experiments using the experimental apparatus and an experimental procedure. In small groups, students develop an experimental procedure, collect data, perform analysis, and report results and accuracy/uncertainty.

4. LABORATORY EXPERIENCE

The pipe friction laboratory requires students to demonstrate their ability to design and conduct an experiment, analyze and interpret data, and communicate technical results in a complete technical report. The laboratory experience is divided into several components and requirements, some of which are collective and some individual exercises. Students individually complete a pre-laboratory assignment prior, then groups of three or four students collect data during a one-hour laboratory period with an instructor and technician. Students work within assignment groups to analyze data and submit a collectively authored analysis assignment to be graded by instructors. Finally, each student prepares and submits a full technical laboratory report, individually authored.

Students complete the pre-laboratory assignment, an individual exercise, and submit the assignment during the laboratory period. Course faculty encourage students to meet within their group to discuss and finalize a collective experimental procedure prior to the laboratory period. Students must derive Equation 1 using the step-by-step method, and derive Equation 5, starting from an expression for conservation of energy, Equation 2. The final pre-laboratory requirement is the development of a detailed step-by-step experimental procedure. Guidance for students is provided as a series of questions for consideration:

- What do you need to measure to calculate the friction factor?
- Do you need to know the dimensions of the lab setup? Which dimension(s) in particular?
- How will you determine the mean velocity in the pipe?
- Does any of the equipment need to be calibrated?
- Does it matter when you determine the tare weight for the balance scale?
- How often should you check the mineral oil temperature?
- How many flow rates would you like to consider? How many trials for each flow rate?
- Will you consider both laminar and turbulent flow rates?
- What are the upper and lower limits for Reynolds number with this setup?
- How will you determine the uncertainty for each measurement?
- What steps can you take to reduce uncertainty in your reported results?
- How can you test the repeatability of your results?

After conducting the experiment and obtaining measurements, students work as a group to analyze their results. An instructor provides feedback on the data analysis portion before students communicate their results in an individual final report in a standard publication style format with extensive appendices [24]. Throughout the experience students are required to communicate the limitations of their experiment by quantifying uncertainty and questioning the validity of their assumptions [24]. Students submit their raw data and calculations as separate appendices to the final report. Students must include equations showing how to calculate the friction factor and its uncertainty based on measured quantities using the method of Kline and McClintock [25] in another appendix. Students plot the pressure versus the pipe location, with uncertainty bars, for each flow rate with emphasis on clear, distinguishable data and legible labels. Students are given intellectual freedom to choose the number of figures required to best present the data. Students also create a plot that presents friction factor versus Reynolds number for each flow rate. This plot should include the friction factor estimated from the experiments as well as the approved solution from the Moody diagram and associated equations; all data points should include uncertainty. Next, students are required to identify which measurement contributes most to uncertainty. Particular emphasis is placed on students to ensure the reader understands how a measurement was identified as the greatest contribution to uncertainty. Students then consider four fluid-material combinations to assess their ability to achieve full similarity with the pipe friction demo setup. Each combination represents a real-world pipe system, including an (1) oil pipeline, (2) a ventilation duct, (3) a natural gas line, and (4) a water supply line, through the following fluid-material combinations: (1) Water-Galvanized Iron, (2) Crude Oil-Commercial Steel, (3) Air-Sheet Metal, and (4) Natural Gas-Smooth Steel with associated material/fluid properties, flow rates, and roughness factors.

Table 2 Prototype cases for which students must determine whether it is possible to accurately predict pressure drop using the pipe friction demo equipment.

	Fluid	**Density** [lbm/ft^3]	**Dynamic Visc.** [lbm/(ft-s)]	**Diameter** [in]	**Velocity** [ft/s]	**Material**	**Roughness** [ft]
1	Water	62.3	6.54 E-04	1.0	2.0	Galvanized iron	0.00050
2	Crude oil	58.1	3.13 E-03	22.5	0.5	Commercial steel	0.00015
3	Air	0.0749	1.23 E-05	12.0	12.0	Sheet metal	0.00050
4	Natural gas	0.300	7.39 E-06	3.0	0.8	Smooth steel	0.00002

Finally, students must determine the pressure gradient, $\nabla P\,[\mathrm{psi/ft}]$, for each of the fluid-material combinations. The students approach may use the Moody diagram and associated equations, should include uncertainty, and should clearly indicate the Reynolds number, relative roughness, and friction factor for each case. Students are given intellectual freedom to use whichever computer program they wish to make the plots and are expected to provide derivations of the equations they used in an appendix.

5. TECHNICAL WRITING COMPONENT

The West Point Writing Program (WPWP) supports students, faculty, and staff as they pursue the study of writing and communication across the curriculum, in every discipline and department, at the United States Military Academy. Its overarching goal is to cultivate institutional awareness of the writing process and effective writing practices, and especially to provide students with continuity and coherence in their education so that all graduates are thoughtful, agile, and clear communicators prepared to answer the various demands of their professional environments and succeed as Army officers [26]. The program aims to provide students with continuity, depth, and coherence in their education as writers and communicators. As part of this program, Writing-in-the-Major (WiM) courses specifically emphasize the intensive study and practice of discipline-specific writing. Faculty prepare students to write in particular modes and genres, address specialized audiences, and understand fully the subjects, methods, and communicative aims of the course and discipline. MC312 Thermal-fluid Systems II serves as the class for this program requirement where the pipe friction laboratory report serves as the signature writing event (SWE) for both the Chemical and Mechanical Engineering

Divisions WiM requirement [24, 26].

Technical communications emphasizes four characteristics, amplifying the institution's general writing guidance – clarity, concision, precision, and consistency. These characteristics are best described within the element of technical style and are described below.

- **Clarity.** Technical writing should be clear, direct, accurate, factually correct and simple. Avoid ambiguity (confusing or multiple meanings), vagueness (no meaning at all), and redundancy.
- **Concision.** Technical writing should be concise, using correct terminology. Avoid wordiness and redundancy. The use of figures, tables, and other graphics can make technical communications more concise while also aiding the reader in understanding the message or visualizing results and analysis.
- **Precision.** Correct use of technical terminology is essential in technical communication. Using incorrect terms will confuse readers and also detract from the substance element. For example, if an author uses the term ”reliability” but describes the theory of “similarity”, a reader will be confused and may question the author's conceptual understanding of fundamental topics related to the work and credibility.
- **Consistency.** This characteristic plagues many undergraduate student works, particularly technical work. Work must be consistent in voice, tense, and tone throughout. Authors should employ parallelism when using lists (enumerated or itemized), tables, and charts. Consistently punctuate lists and captions throughout the work.

The final graded requirement for the pipe friction laboratory is an individually-authored, full laboratory report requiring students to explain their experiment to an unknown reader. Students are told to assume the reader knows less about the experiment than them and are instructed to guide the reader through an extensive discussion section to explain detailed context behind the process and analysis as they build to final results. The report must include an abstract, methods section, results section, discussion section, conclusion section, and appendices to include: (A) step-by-step derivation of dimensionless groups; (B) relationship between ∇p and the Moody friction factor; (C) the Moody diagram; (D) pipe friction demonstration components; (E) experimental procedures; (F) governing equations and calculation of uncertainty; (G) kinematic viscosity of mineral oil; (H) experimental measurements; and (I) any additional appendices, as needed.

Faculty are available for writing reviews and conferences to help students draft their reports, thereby satisfying institutional requirements for WiM courses to address writing-to-learn (WTL) pedagogies. Some examples of WTL pedagogies used in this report include:

- Faculty help explain a major writing assignment by distributing and discussing relevant guidelines and examples.
- Students are asked and equipped to complete planning or prewriting activities inside or outside of class in relation to a major writing assignment, including annotating, brainstorming, freewriting, blogging, clustering, dramatizing, concept-mapping, outlining, etc.
- Students are asked to iteratively draft one or more key components of a major writing assignment inside or outside of class in a process called scaffolding. Examples may include theses, hypotheses, introductions, methods or results sections, literature reviews, conclusions, abstracts, charts, tables, figures, or other discrete elements.

Three key elements of feedback in the process are faculty feedback on ungraded drafts or pieces of drafts that students may use to revise before submitting a major writing assignment; team-based peer-to-peer assessments and collaborative workshops; and finally a self-reflection component that students complete via their Cadet Writer ePortfolios.

Faculty rate student work as *Excellent* (E), *Satisfactory (S)*, *Marginal* (M), or *Non-proficient* (NP) for each of the five elements and an overall rating. Each NP rating must be accompanied by comments. Any overall NP rating must be remediated to satisfy the institutional writing requirements.

6. INITIAL ASSESSMENT OF STUDENT LEARNING

Initial laboratory results show a significant reduction in error and uncertainty using the modernized apparatus, illustrated in Figure 4. Kinematic viscosity of the mineral oil was experimentally determined via Poiseuille's law to be $0.00037547\,\mathrm{ft}^2/\mathrm{s}$. Flow exhibits turbulent features at a Reynolds numbers above 4000 with new mineral oil. The improved laboratory improves accuracy, with experimental values closer to accepted values in the Moody diagram as illustrated in Figure 4. Upgraded instrumentation also reduces measurement uncertainty.

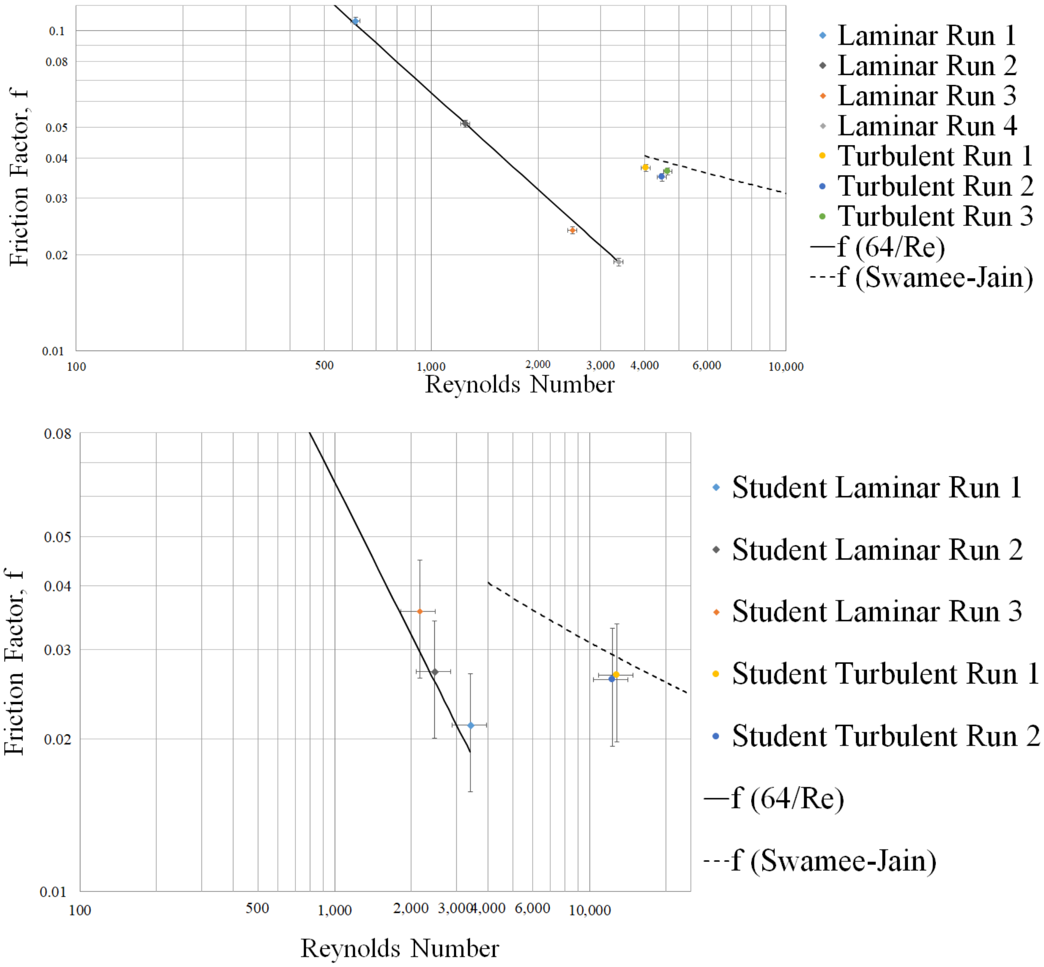
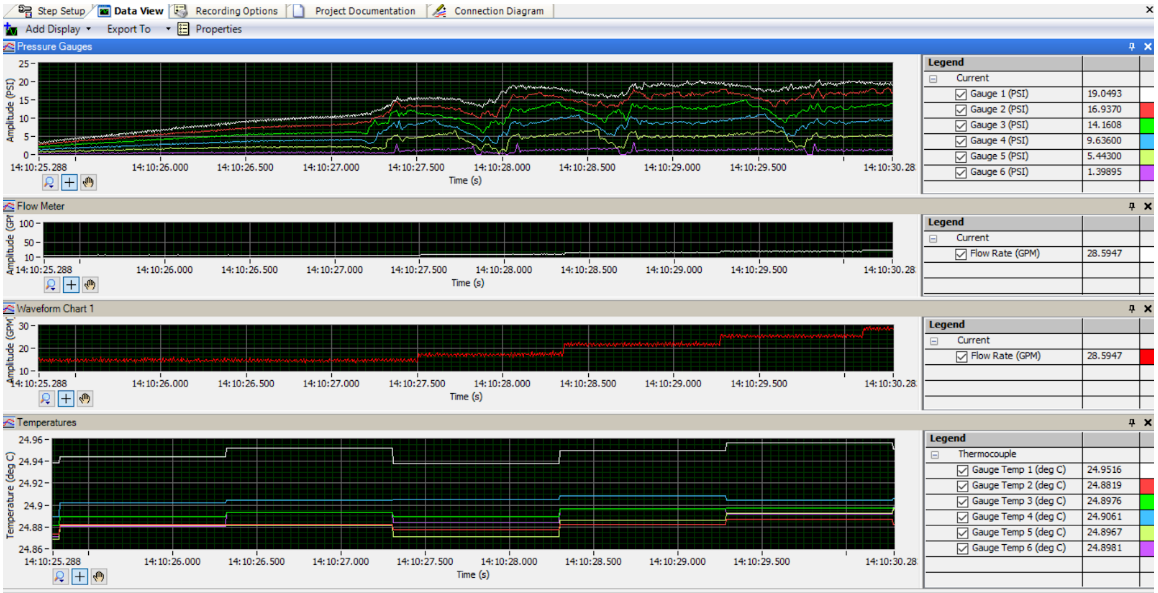


Fig. 4 Pipe friction laboratory experimental data, Reynolds number, Re, versus friction factor, f. Data from recent upgrade (top) and old version (bottom).

Students are now able to visualize the data stream directly on a 55-inch monitor positioned next to the pump and the valve control station. Instructors are able to demonstrate the change in measured parameters associated with various flow regimes, such as an increased pressure gradient and volumetric flow rate that comes with the increase of fluid mass flow rate by further opening the output flow valve as shown in Figure 5.



Legend		
⊟ Current		
☑ Gauge 1 (PSI)	19.0493	⬜
☑ Gauge 2 (PSI)	16.9370	🟥
☑ Gauge 3 (PSI)	14.1608	🟩
☑ Gauge 4 (PSI)	9.63600	🟦
☑ Gauge 5 (PSI)	5.44300	🟨
☑ Gauge 6 (PSI)	1.39895	🟪

Legend	
⊟ Current	
☑ Flow Rate (GPM)	28.5947

Legend		
⊟ Current		
☑ Flow Rate (GPM)	28.5947	🟥

Legend		
⊟ Thermocouple		
☑ Gauge Temp 1 (deg C)	24.9516	⬜
☑ Gauge Temp 2 (deg C)	24.8819	🟥
☑ Gauge Temp 3 (deg C)	24.8976	🟩
☑ Gauge Temp 4 (deg C)	24.9061	🟦
☑ Gauge Temp 5 (deg C)	24.8967	🟨
☑ Gauge Temp 6 (deg C)	24.8981	🟪

Fig. 5 Students can visualize live data changes as the fluid moves through the transition regime from laminar to turbulent flow using NI SignalExpress $^{\text{TM}}$. The information is projected on a 55-inch monitor displaying the pressures, flow rate, and temperatures of the fluid.

7. CONCLUSIONS AND OUTLOOK

The recently revitalized pipe friction hydrodynamics laboratory at West Point offers a relevant, comprehensive experience to enhance the mechanical engineering programs curriculum. The new laboratory also provides the context, experience, and data to fully support the signature writing event for the West Point Writing Programs Writing-in-the-Major requirement for both chemical and mechanical engineering majors. The enhanced laboratory significantly expands the range of data that may be collected, with students now able to accurately measure pressure, temperature, flow rate, and pipe geometric data. The upgraded experience offers a relevant, comprehensive application to deepen students conceptual understanding of internal fluid flow, hydrodynamics, modeling and similarity principles, and technical writing. Future work will explore the effects of altering the current apparatus to enable data collection at several pipe diameters, larger flow rates, and varied fluids.

Faculty agree that the pipe friction laboratory is a premier hands-on student learning experience, one of more than 20 integrated within the civil or mechanical engineering curricula at West Point. The upgraded facility is the product of several months of significant effort on the part of Thermal-Fluids faculty members and Department technicians, working collaboratively on the apparatus, laboratory and supporting equipment, and instrumentation. Finally, several students and interns have contributed to the laboratory upgrades through project-based learning courses or summer internships.

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