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Introducing Bio- and Micro-Technology into Undergraduate Thermal-Fluids Courses: Investigating Pipe Pressure Loss Via Atomic Force Microscopy

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Abstract — **To introduce bio- and micro-technologies into general undergraduate thermal-fluids classes, a hands-on interdisciplinary in-class demonstration is described that juxtaposes classical pressure loss pipe flow experiments against a modern micro-characterization technique, AFM profilometry. Both approaches measure surface roughness and can segue into classroom discussions related to material selection and design of bio-medical devices to handle biological fluids such as blood. Appealing to the range of engineering students populating a general thermal-fluids course, a variety of pipe/hose/tube materials representing a spectrum of disciplines can be tested using both techniques. This in-class demonstration relies on technical content already available in standard thermal-fluids textbooks, provides experimental juxtaposition between classical and micro-technology-enabled approaches to the same experiment, and can be taught by personnel with no specialized micro- or bio-technology expertise.**

I. Introduction

Atomic Force Microscopy (AFM) is a standard micrometer-scale surface visualization profilometry technique used to characterize surface roughness for a range of organic fluid flow phenomena; from evaluating blood platelet adhesion to polymers [1] to measuring bacterial colonization rates on walls of drinking water pipes [2] to estimating pressure loss in oil pipelines [3].

To ensure competitiveness of tomorrow's technical workforce, all engineering curricula must now include exposure to bio- and micro- technologies. Integration of these disciplines into conventional engineering curricula is being achieved through creation of relevant college courses and insertion of concepts into lower division chemistry and physics classes [4]. Simultaneously, however, engineering educators are under pressure to reduce the number of required curriculum hours so that the average student can graduate in four years [5].

In their review article on biomedical engineering education, Harris et al [6] indicate that instructional efficiency improvements are necessary to provide students with adequate understanding of both engineering and biology. According to Harris et al, the biomedical device and biotechnology industries face significant knowledge gaps within their technical staffs. To fill these gaps without increasing curriculum hours, engineering educators must find ways to integrate bio- and micro-technologies into general engineering curricula to endow new graduates with enough technical knowledge to converse with experts in both fields.

This paper illustrates a novel method to efficiently introduce bio- and micro-technologies into an undergraduate engineering thermal-fluids course (for example, the basic energy-thermal-fluids service course taken by non-mechanical engineering majors) without requiring teaching personnel with specific expertise in these areas or development of new class materials beyond content already available in standard energy-thermal-fluids textbooks.

Our approach is to use a hands-on interdisciplinary in-class demonstration to juxtapose the classical estimate for pressure loss in a pipe owing to wall roughness against a modern technique using AFM to visualize pipe wall roughness. To appeal to the broad range of engineering students that could populate a thermal-fluids service course, we use a variety of pipe/hose/tube materials representing a spectrum of engineering disciplines: medical-grade plastic tubing and surgical stainless steel tubing (for biomedical and environmental engineers); hydraulic hose (for fluid-power and mechanical engineers); and new copper tubing and fouled copper tubing (for electrical and architectural engineers). This in-class demonstration, adapted from a conventional mechanical engineering fluids laboratory experiment, is easy and inexpensive to build and provides a natural context for practical discussion and training in bio- and micro-technologies for all engineering students.

II. Literature Review

A. *Classical Engineering Approach to Pressure Loss Evaluation Owing to Pipe Wall Roughness*

In the 1930's and 1940's (before AFM profilometry was used), the impact of wall roughness on pipe pressure loss was evaluated through classical experiments. Nikuradse [7] lined pipes of 250, 500, and 1000 mm inner-diameter with sand grains sifted by known diameter. He then measured pressure drop through the pipes as a function of surface roughness and Reynolds Number. Colebrook [8] studied 16 concrete pipes ranging from 101.6 to 5486 mm in diameter and developed a now-universal empirical friction factor expression. Moody [9] combined the results of Nikuradse and Colebrook to create the 'Moody Diagram' for pipes, which gives friction factor as a function of Reynolds Number

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and surface roughness. Descriptions of these classical experiments and pipe pressure loss evaluation techniques are standard in undergraduate energy-thermal-fluids textbooks.

Underpinning the pedagogical approach in this paper are the following: 1) no new material need be developed to seed micro- and bio-technology instruction because technical content and supporting homework problems/solutions are already in standard textbooks and 2) the classical experiments of Nikuradse and Colebrook are easily visualized by engineering students enabling comparison between classical and micro-technology-enabled approaches to surface roughness evaluation.

B. *AFM for Pipe Wall Roughness Evaluation*

For industrial applications such as flow through oil pipelines, AFM profilometry has superseded classical pipe pressure loss experiments as the preferred standard to predict friction factor [3]. In leading-edge academic research, AFM is the standard technique to evaluate the impact on flow of surface roughness in micro-channels supporting both laminar flow [10] and turbulent flow [11]. In biological research, AFM has been used to measure bacterial growth in drinking water pipes [2]

Despite its prevalence in industry and university research, AFM and other micro- and nano-meter-scale characterization techniques are only now beginning to be integrated into undergraduate curricula. For example, Asmatulu et al [12] reported beginning a tiny technology undergraduate teaching laboratory in 2007, which includes AFM sample characterization. Despite this important development, creation of these capabilities requires personnel with specialized expertise and facilities with specific micro-characterization equipment.

C. *New Bachelor-Level Micro- and Bio-Technology Engineering Classes and Content Insertion*

One approach to facilitate bachelor-level bio- and micro-technology exposure is to create new courses. For example, Crone et al [4] implemented “Micro- and Nano-scale Mechanics” for an engineering physics program. This course includes hands-on laboratory components enabling students to characterize surfaces via AFM, functionalize surfaces with self-assembled mono-layers, and synthesize nanoparticles. Students then construct micro-fluidic devices and nano-filters using the techniques they learned.

A second approach is to create short general activity modules that can be inserted into existing courses. For example, Ong et al at Arizona State University (ASU) established the “Interactive Nano-Visualization for Science and Engineering Education (IN-VSEE)” project enabling students anywhere in the world to perform micro-characterization and visualization remotely via the Internet using Spanning Probe Microscopy (AFM without the sample under vacuum) [13]. Existing IN-VSEE topics include sphere packing and the relationship between mechanical friction and surface topology. For deeper curriculum customization, remote users can mail in their own samples for interrogation or request samples be made at ASU.

While some colleges and universities now have AFM or SPM capability, others do not. To implement the exercise proposed here at institutions without in-house AFM/SPM capability, the ASU IN-VSEE capability could be used to visualize roughness of tube/hose/pipe samples studied using the classical pressure-drop experiment we describe.

III. Theory

A. *Surface Roughness Magnitude Orientation Calculation*

To orient students to the physical scale of surface roughness in terms of parameters familiar in a generic thermal-fluid course, the following orientation exercise is instructive. The velocity profile for turbulent fluid flow through a pipe is characterized by three unique regimes (ordered here from the pipe center to the pipe wall): the turbulent core, the overlap layer, and the viscous sub-layer. One hallmark of turbulent pipe flow is that its core is inertia-dominated while viscous effects remain important only near the pipe wall (i.e., the ‘no-slip’ condition). The greatest influence on the shape of the turbulent velocity profile arises when wall roughness height, ε, is of the same magnitude as the viscous sub-layer thickness.

Turbulent pipe flow viscous sub-layer velocity profile shape is approximated by the following expression,

$$\frac{\bar{u}}{u^*} = \frac{yu^*}{\nu} \text{ for } 0 < \frac{yu^*}{\nu} \leq 5 \tag{1}$$

where $\bar{u}$ is the average flow velocity and u^* is the “friction velocity”. The ratio of these parameters is a dimensionless figure of velocity. Moreover, y is the distance from the pipe wall and ν is the fluid kinematic viscosity. The ratio of these parameters multiplied by u^* is a dimensionless figure of distance from the pipe wall.

Since the edge of the viscous sub-layer exists at $yu^*/\nu \approx 5$, manipulation of (1) enables estimation of the distance from the wall defining the viscous sub-layer height, δ,

$$\delta = \frac{5D}{\text{Re}_D \sqrt{\frac{f}{8}}} \tag{2}$$

where D is the pipe inner diameter, Re_D is the Reynolds Number, and f is the friction factor. Inserting representative numbers arising from data obtained during the experiment (in our case: D = 0.011 meters, Re_D = 10,000, f = 0.033) gives $\delta = 8.6 \times 10^{-5}$ m or 8.6 μm. From a biological fluid flow perspective, this representative viscous sub-layer is roughly the size of a human erythrocyte (red blood cell), about 7 μm [14]. Since viscous sub-layer height, δ, is similar in magnitude to wall roughness height, ε, this example can segue to in-class discussions surrounding biological fluid interactions with tubing walls. *Can erythrocytes get caught or trapped in the roughness groves of metallic tubing? What impact might this effect have on blood running through a dialysis machine? How might the choice of tubing material to carry biological fluid impact patient health or recovery* *time?* This exercise provides orientation for students, allowing them to combine familiar macro-scale parameters like pipe diameter and Reynolds number to realize a micro-scale result, surface roughness. They can then compare roughness height to sizes characterizing biological systems to extrapolate material selection design rules that promote improved patient health.

B. *Dimensional Analysis: Friction Factor Functional Relationship*

The Buckingham-Pi Theorem, a standard engineering non-dimensionalization technique, applied to variables relevant to turbulent pipe flow, yields the functional relationship linking pressure loss per unit pipe length, ΔP_l, with surface roughness, ε. Empirical observation indicates a functional relationship exists such that

$$\Delta P_l = \phi(\varepsilon, D, \bar{u}, \rho, \mu) \quad (3)$$

where D is the pipe diameter, ū is the average pipe flow velocity, and ρ and μ are the fluid density and dynamic viscosity respectively. Applying Buckingham-PI non-dimensionalization yields the following functional relationship among dimensionless terms

$$\frac{2D\Delta P_l}{\rho \bar{u}^2} = \phi\left(\frac{\varepsilon}{D}, \frac{\rho D \bar{u}}{\mu}\right) = f \quad (4)$$

where φ(ε/D, ρDū/μ) is called the friction factor, f. The same result can be obtained analytically by combining the Darcy-Weisbach Equation with conservation of energy.

The pipe flow pressure loss experiment we describe measures ΔP_l as a function of D, μ, ρ, and ū. Mass flow rate, measured via digital scale and timer, gives ū, but ε remains unknown. This approach allows students to generate their own raw data and then use existing published relationships for (4) to determine the surface roughness of their samples based on fluid flow measurements. These ε values, measured using this classical fluid mechanics experiment, are then verified by looking at AFM micrographs of the same pipe/hose/tube samples tested.

IV. Experiment

A. *Pipe Flow Pressure Loss Experiment*

The fluid flow pressure loss apparatus, pictured in Fig. 1, runs liquid tap water at ambient temperature and pressure through a 18.29-meter-long coil of pipe/hose/tube. To demonstrate a variety of materials with a range of surface roughness, the coil can be easily swapped between medical-grade plastic tubing, surgical stainless steel tubing, hydraulic hose, new copper tubing, and fouled copper tubing to explore how roughness impacts pressure loss. In the classroom demonstration apparatus, a submersible pump draws water from a reservoir, and flow rate is regulated via metering value to access a range of Reynolds Numbers. A pressure gauge at the coil inlet measures input pressure. A manometer attached to the end of the coil reads outlet pressure. The water exhausts into a plastic bucket isolated from the lab bench atop an Ohaus NVT 1601 portable digital scale. Rate of water accumulation is measured via stopwatch, and water temperature is monitored using an immersed K-Type thermocouple and hand-held reader. Water accumulation rate and temperature data respectively determine average pipe flow velocity (ū) water density (ρ) and kinematic viscosity (μ). The coil inner diameter (D) is measured via micrometer before the coil is attached; the copper used here had D = 0.011 meters. All these values combine to form the Reynolds Number as well as the values in the dependent Pi term. The pressure loss per length (ΔP_l) in the dependent Pi term is found by reading the difference in inlet and outlet pressures and dividing by the coil length, which is determined in advance by unfurling it and using a tape measure.

Figure 1. Experimental apparatus for fluid pipe flow pressure loss and surface roughness evaluation.

B. *Surface Roughness Measurement*

AFM samples are prepared by cutting 5 mm x 5 mm samples from each pipe/hose/tube material used to make test coils for the fluid flow pressure loss apparatus. Tubes should be chosen with large enough radius of curvature that samples lay flat on the AFM stage. A sample AFM micrograph, Fig. 2, shows a new copper surface.

Our instrument, a Bruker-Nano AFM, was equipped with a Veeco 1-10 Ohm-cm Phosphorous n-doped Si tip mounted on a cantilever with the following specifications: T = 3.5-4.5 μm, L = 115-135 μm, W = 30-40 μm, f = 246-275 kHz, and k = 20-80 N/m. The AFM was placed in tapping mode at 1.25 Hz and used to profile a representative 10 μm x 10 μm area of the new copper sample. Automated AFM surface interrogation software referenced the lowest valley on the sample to zero. It then reported the tallest peak and the average roughness feature size, as shown in Fig. 2.

V. Results

Average surface roughness of the new copper sample was measured by our AFM to be 0.26 μm with a maximum peak at 0.42 μm, as shown in Fig. 2. While not part of the test used in the thermal-fluids class, our AFM results were independently verified using a Mitutyo SJ-201P profilometer with a 5 μm radius, 90° conical taper angle diamond-tipped probe and 5 mN measuring force. The profilometer measured a 0.40 µm maximum peak with average roughness of 0.19 µm for the same new copper sample.

The apparatus measures ΔP_l as a function of D, ū, ρ and µ; it leaves ε unknown. Empirical formulas are available to ascertain friction factor, f, for turbulent pipe flow at known surface roughness and Reynolds Number. For example, the Colebrook Equation [8] is preferred for its accuracy.

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}_D\sqrt{f}}\right) \tag{5}$$

Since the friction factor, f, is known from (4) based on measurements from the pressure loss experiment, (5) is solved for ε to provide empirical surface roughness from the classical fluid flow experiment for comparison to the AFM result. Using a fouled copper pipe sample, we estimated $\varepsilon_{\mathrm{Colebrook}} = 49.6 \pm 20.8$ µm by taking the average of 17 runs and using twice the standard deviation to estimate uncertainty to a 95% confidence interval.

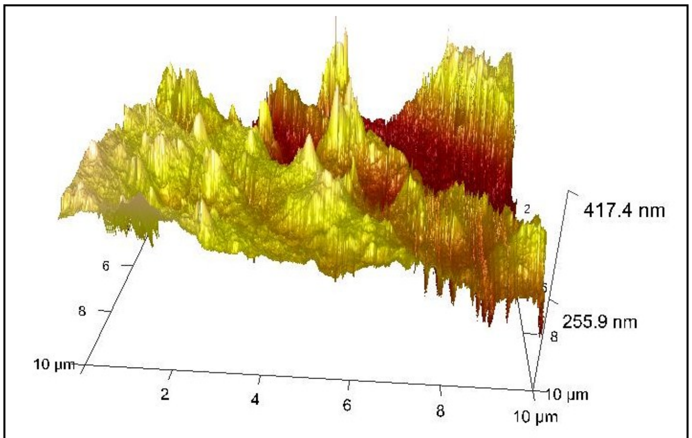

Figure 2. AFM micrograph decipeting surface features and average roughness of a new copper surface.

VI. Discussion & Conclusions

As expected, a significant difference (two orders of magnitude) in average surface roughness was found between the new copper sample (ε ≈ 0.26 µm) and fouled copper pipe (ε ≈ 50 µm). Corrosion on the fouled copper pipe wall substantially increased roughness; our measured roughness corresponds to literature values for copper exposed to fresh water; 18-50 µm [15]. Increased wall roughness is reflected in larger pressure loss per unit length than would be measured for new copper pipe. By comparing roughness of surgical stainless steel and plastic medical tubing to copper, this result can segue into class discussions about material choices with respect to energy conservation and pressure loss in fouled pipe. *Why must air conditioner evaporators be replaced at regular intervals to ensure efficient operation?* It is expected that AFM surface roughness results will agree within experimental uncertainty to empirical pipe flow results. However, the functional relationship in (4) does not include coil radius of curvature as a parameter, and fully-developed turbulent velocity profiles do skew when fluid moves around a corner. So some mismatch between the two roughness results is expected from this effect.

An interdisciplinary in-class demonstration has been described to contrast classical pipe flow pressure loss experiments against AFM profilometry to promote bio- and micro-technology training in general thermal-fluids engineering classes. This demo is an important example of how bio/micro content can be inserted into standard engineering courses without increasing curriculum hours or demanding development of new material beyond content already available in standard thermal-fluids textbooks.

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