AC 2010-1538: INNOVATIONS IN FLUID MECHANICS LABORATORY THROUGH THE APPLICATION OF INDUSTRIAL SCALE EQUIPMENT AND EDUCATIONAL SOFTWARE TOOLS

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Innovations in Fluid Mechanics Laboratory through the Application of Industrial Scale Equipment and Educational Software Tools

Abstract

Texas A&M University at Qatar, TAMUQ, is a newly funded school of engineering whose first class of undergraduate students graduated in 2008. As the university is located in the heart of the Middle East, TAMUQ students are primarily from neighboring and Asian countries with very diverse educational and cultural backgrounds. Teaching engineering sciences in such a new and culturally diverse environment introduces many opportunities for innovation. However, there are many challenges that are unique to TAMUQ. Because of their varied backgrounds and pre-college educational experience, students find it more difficult to link classroom theory with physical results and applications. Integration and application of coursework from one class to the next has also proven difficult.

Learning Thermo-Fluid materials for many engineering students can be daunting, no matter their previous background. Thermo-Fluid laboratories are often the first place students have a chance to make the physical real-world connection between the theory learned in class and actual application. In some Fluid Mechanics laboratory experiments are conducted using off-the-shelf educational stations. Our approach is to integrate the Fluid Mechanics laboratory with industrial equipment and tools in order to allow students to engage their classroom based theoretical knowledge in an industry-like setting. Junior level students design digital data acquisition systems in conjunction with more traditional physical sensors in order to accomplish their laboratory goals. Students will also apply commercially available software to design and conduct an experiment in the laboratory. Students are required to conduct simulations for a real case flow field using commercially available software then validate the results using the industrial scale systems in the lab.

The use of industrial scale equipment, application of both automated and manual measurement devices, and application of simulation in experiments is a new challenge for the Regional students. This paper introduces the newly built Fluid Mechanics Laboratory at TAMUQ and discuses the experimentation scheme used in the laboratory.

Introduction

The previous decade has seen increasing interest in how engineering education is conducted within the Middle-East, specifically in the Persian Gulf region (the Region). Within the last ten years much has been written specifically about the challenges engineering education, especially from an outcomes based Western perspective, face in the Region. Key difficulties include differences in the students' pre-college educational experience as well as significant cultural differences within the classroom between the faculty and the student.[1-5] The growing number of Western universities opening branch campuses or having been contracted to establish

universities in the Region, however, is a testimony to the intrinsic interest in higher education. This has provided more opportunities for students seeking higher education within the region. The goals of the Regional students are similar to that of their US counterparts for most part: they want to be prepared to fill the growing needs of the local industry, in this case mainly oil and gas, without the need for overseas migration in order to obtain their education. Given their diverse backgrounds and their attendance to a certified Western higher education system, successful graduates will be capable of pursuing engineering projects on the local and global scale.[6]

Despite the drive of the Regional students to enter engineering disciplines, summaries of industry views on Regional engineering graduates reveal that they are seen to be especially deficient in terms of hands-on experience, team work, and independent critical thinking.[7] It is therefore especially important to foster any industry links with the students—including the simulation of day-to-day practice and equipment in order to provide realistic hands-on experience. Laboratory courses are the best place to connect text book materials with real world experiences and applications. The laboratory setting furthermore allows group work and the laboratory reports which by nature require critical thought to complete.

The objective of this paper is to describe the general challenges of higher education in Qatar, discuss the differences between TAMUQ and the historical Regional teaching styles. The newly built fluid mechanics laboratory is described and the result of the student experience in the laboratory is discussed. Lessons and conclusions will then be drawn from the overall experience.

Higher education challenges in Qatar

Qatar, with a native population of less than four hundred-thousand and an expatriate population of over a million, has seen tremendous change in the last 10 years. It has become the world's largest LNG exporters and holds the highest GDP per capita in the world. The rampant globalization of their society, stemming from their world-wide business associations and increase in foreign workers and services, combined with the increased wealth of the country has fostered a rich environment for higher education for the indigenous and Regional peoples. The first attempts at establishing a Regional engineering educational program began in 1968 when Qatar, Bahrain, Oman, and Abu Dhabi founded the Gulf Technical College in Bahrain with help from the British government. Engineering education facilities were not established inside Qatar until the mid-70s.[8] Since then the Qatari government has signed agreements with multiple foreign schools from North America and Europe as well as established its own programs. Six top US universities have been invited, forming Education City, to establish and support higher education programs in the country. The primarily natural gas based economy has highlighted the need for in-house engineering abilities and talent. Thus engineering is a natural draw for Qatari citizens. Texas A&M University at Qatar was founded in the fall of 2003 as one of the six US universities within Education City and as the only US engineering college in Qatar. TAMUQ has the highest

enrollment of any university in Education City with 390 students for the 2009-2010 academic year. 43% of the students are native Qatari, and the majority of the rest of the students are from the Region.[10]

Most of the students in these colleges come from the regional and Arab states where collegiate preparation practices have remained largely unchanged from the previous decades.[4,7,11] Namely, students from the Arab Gulf States have typically had pre-college experiences that have stressed memorization over application and come with deficits in understanding in mathematics and sciences. Other common difficulties include time management and the ability to efficiently prioritize their required tasks.[5] It is not atypical for students to spend between one to two years in an academic bridge program in an attempt to bolster their English skills and these abilities before embarking on their four year undergraduate campaign.

The students at TAMUQ share many of the same pre-college experiences. Despite their great enthusiasm and natural talents, one can easily highlight challenges that have been echoed in the past. English being the second language, reading comprehension hurdles as a result of cultural differences and a lack of self-supported reading, lack of hands on experience, a general lack of confidence in abilities, and lack of independence are all still present in varying degrees.[4,5,8, 12] These issues are readily apparent in science and engineering laboratories where the acquired theoretical knowledge in the class is to be used and understood via the application of physical equipment and devices. This requires a transformation of theoretical material into practical applicative work and finally back into theory when reducing data and conclusions in their reports. This manipulation of theory and application proves to be extremely challenging for the students.

The Fluid Mechanics Laboratory layout has been setup in a manner consistent with other laboratories on campus.[13] The laboratory space is ample and robust. The fluid mechanics laboratory itself is composed of a $20.5m^2$ working area with an adjacent teaching and computer simulation room. The large dedicated laboratory floor space allows for constant advancement of equipment whether due to increased enrollment or increasing functional capacity. Students are given the chance of using industry scale devices in the laboratory and are given increasing responsibilities as the term progresses in terms of setting up equipment and writing their data acquisition programs. The final culminating task is to simulate a set of previously conducted experiments using computational fluid dynamics (CFD) software packages.

Historical Regional Teaching Style

The Regional teaching styles have historically relied on rote memorization and reproduction, a carryover from the regional cultures as well as a result of the extreme pace of the modernization that has carried through much of the Region.[4,7,9] The regional teaching style is upheld by local accreditation schemes, reliant on strictly planned and adhered curriculums.

The generalized Regional accreditation scheme, as described by Thompson,[5] require strict adherence to a highly structured and pre-set curriculum. This curriculum regulated model increases the difficulties in enabling faculty to make minor changes within the class without having to pass through an accreditation review panel. It does, however, clearly set a measurable metric by which all programs can be judged, one reason for its popularity.

Outcome based accreditation programs on the other hand such as ABET differ in that minimal guidelines are presented and the accreditation of the program is based on the results produced by the students. Accreditation review and acceptance comes after students have gone through the program rather than before it. Because there are minimal guidelines the curriculum is more open to interpretation and change, as long as proper documentations and outcomes are met. Thompson states that the less rigid educational programs, such as those under ABET certification, will encounter difficulties in establishing themselves in the Region due to an inherent conflict between the regulated model and outcome-based model.

TAMUQ follows the same educational practices that have been established at the main campus in College Station, TX. In 2008 TAMUQ underwent the initial ABET reviews. ABET accreditation was conferred upon TAMUQ during the 3rd quarter of 2009. It is currently the only ABET accredited university in Qatar, and one of few in the Region. ABET accreditation is both a symbol and metric by which the flexibility and strength of the outcome based model TAMUQ uses can be seen. The outcomes based educational model has allowed faculty to make the required changes in the laboratory in order to facilitate the adoption of the physical course materials and methods.

The TAMUQ Laboratory

Each laboratory session started with the possibility of a quiz, followed by a lecture, and then the experiment itself where the students worked individually and as a group. Due to the class size participation could be more easily fostered during both the lecture and the laboratory. Rather than relying on off-the-shelf turn-key solutions, four out five experiments were fabricated in-house from industrial components, such as pumps, flow meters, controllers, and data acquisition systems. The purpose of this was to allow the students to investigate specific fundamentals of fluid mechanics while exposing them to industrial settings and providing them with a realistic hands-on experience. The laboratory allows students to investigate internal and external flows through experimentation and CFD simulation. Figure 1 shows students at one of the flow loops.

Figure 1: Students at a flow loop station. Pump, Coriolis and magnetic flow meters, and water reservoir visible.

In total, students were required to prepare six full technical report, five experiments and one simulation. Table one details the laboratories, objectives, and equipments used for the whole laboratory. While the laboratory format itself is not particularly novel—other universities have used realistic or industry equipment with or without academic or industry related software tools to great effect[14-17] —their usage in this context presents forward progress in terms of Regional education. It is also worth noting that active and problem based learning styles are almost necessitated by the laboratory format itself—these are strong methods of engaging students that many students themselves prefer.[18,19] The Appendix contains an abridged example of a laboratory handout.

Lab #	Name	Objective	Equipment Used
1	Calibration of Pressure Transducer and Calibration of Flow meter	Introduction to DAQ tools and methods, hydraulic flow loop, flowmeters, and laboratory practices. Students calibrated digital pressure transducers and a variety of flow meters (magnetic, vortex, Coriolis, and turbine). They became familiar with and use the general uncertainty estimation for the devices used in the lab and its propagation in the experimental work.	Hydraulic flow loops, deadweight pressure transducer calibrators, various flow meters
2	Bernoulli's Apparatus: Fluid Velocity and Pressure	Study principles of conservation of energy in fluid mechanics via a Bernoulli's device. Students are given the opportunity to use traditional pressure measurement methods in this experiment.	Hydraulic flow loops, custom diverging/converging nozzle, high head tank (2m), manual U-Tube manometer bank
3	Impact of a Jet	Study principles of conservation of momentum using the hydraulic reservoirs and different jet nozzles.	Hydraulic flow loops, differing PVC nozzles (width, L/D ratio, angle of impact), digital scale
4	Pressure Drop in Pipes	Determine major and minor loss coefficients by measuring pressure drop in hydraulic flow loop. In this experiment student use industrial scale piping, pumps, valves, and connections. The set ups are design in a way	Hydraulic flow loops, digital pressure transducers, various PVC fittings/pipe diameters/lengths

		that students can visually experience concepts such as pressure head and its loss in a piping system.	
5	Pressure Distribution over a Cylinder	Determine pressure distribution along the cylinder surface, up and downstream velocity profiles, calculate drag coefficient based on pressure distribution and using conservation of momentum	ELD Wind tunnel, HVAC damper actuators, PVC cylinders, pitot-probes, differential pressure transducers
6	Simulation of Internal and External Flows	Use CFD to simulate laboratories four and five. Compare experimental and simulated results. Comment on the placement of pressure transducers in laboratory 4. Students are required to discuss the possible differences they may see between the numerical results and those obtained earlier in experiment.	Solidworks CFD Suite

Table 1: List of Laboratories, objectives, and respective equipment. DAQ: Labview Data Acquisition. ELD: Engineering Laboratory Design.

The full report for each experiment requires the necessary background theory and governing equations, documentation of the experimental setup and procedure, data reduction and analysis along with proper presentation of data. This is followed by the discussion, with proper uncertainty analysis, and conclusion. Students were expected to observe and explain the theoretical trends provided in their report via experimental data and discuss possible deviation from theory.

The major fluid dynamic set ups that are utilized in the lab can be divided in two groups of internal and external flows. The internal flow equipment is composed of five fluid flow loop stations, each includes a large $1.25m^3$ water container (330 USG) used as a water reservoir. The flow loops were completed with 5 HP Dwyer pumps as well as industrial scale Coriolis, vortex, turbine, magnetic flow meters, and various Setra pressure transducers. All flow loops were constructed using 2" PVC with the ability to connect pressure transducers and flow meters to Labview modules or multimeters. This setup is capable of producing stable volumetric flow rates between 5-130 GPM with a maximum pressure of 45 PSI.

The external flow equipment was primarily composed of an Engineering Laboratory Design wind tunnel with a working test section of 0.3x0.3x0.6m and a maximum linear free stream velocity of approximately 7.2 m/s. For the purpose of the external flow experiment a cylinder with a pressure tap on one face was mounted to a rotating damper actuator and allowed to rotate around its axis. This allowed the pressure at any point along the surface of the cylinder to be measured. One group measured the pressure along the first 90˚ rotation and another group measured the pressures around the second 90˚ rotation. This gave the students the chance to investigate the uncertainties that arise between different users' attempts to acquire data from the same system. They were to share data and independently construct and reduce their data. The free stream static pressure was measured upstream of the cylinder. A pitot-probe mounted on a traversing system allowed the velocity profile behind the cylinder to be measured. Pressure taps were connected to differential Setra pressure transducers which interfaced with Labview. Appendix A shows an example of the hand for one of the experiments provided to the students.

Students were then tasked with simulating the external and internal flow experiments they had previously conducted in laboratories 4 and 5. They were directed to make appropriate measurements of the test apparatus and set up their simulations in the CFD suite in SolidWorks. In order to introduce the students to the CFD suite an example tutorial was written for a potential external flow scenario. A video-stream showing how to use the suite was also created. While students have been exposed to SolidWorks multiple times in the past, as the CFD suite was new, extra time was allotted for this laboratory and students were given access to laboratory computers and facilities.

Enrollment for the fluid mechanics laboratory reached a branch campus record of seventeen students in one class. Students were broken into groups in two sections. These groups met once every other week to receive the laboratory lecture and conduct separate experiments. Laboratory handouts were provided to the students prior to the class in order to prepare them for the laboratory tasks. In order to try to foster proper preparation for the class an extrinsic incentive, quizzes on the handout material, were given during the class. Reports were due 12 days after the lab; before the next laboratory meeting time. Given almost two weeks time for preparation of each report, in depth objectives were set and a relatively large amount of material was covered for each laboratory.

Successes

Despite the challenges associated with this laboratory there were strong successes, although less quantitative. There was a general strong interest in the equipment and how they related to and functioned in relation to the task to be studied. Some students consistently showed strong interest towards all aspects of the laboratories including the auxiliary equipment that was critical to the functioning of the laboratory although not central to their understanding of the concepts at hand. Given the small class size we were able to oblige.

The CFD modeling exercise allowed the students to see how commercial computational tools can complement and successfully model real-world physical examples via their previous experiments. Figures 2 through 4 below show an example of one group's experimental and CFD results along with a picture of their CFD mesh. These figures are straight from one group's report and represent their experimental and simulation results in determining the pressure distribution along a cylinder in cross-flow. Text and arrows were added.

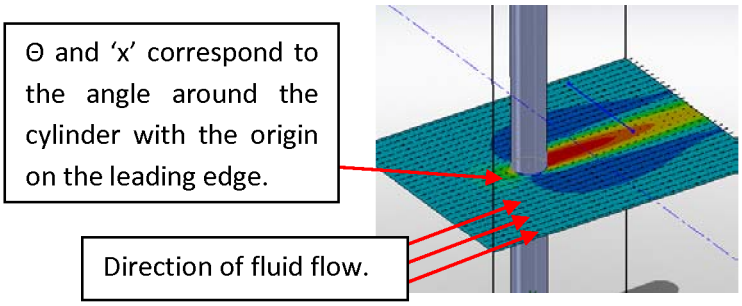

Figure 2: CFD mesh and X-Y velocity profile. Θ and 'x' in the graphs below correspond to pressure around the cylinder at the indicated diameter.

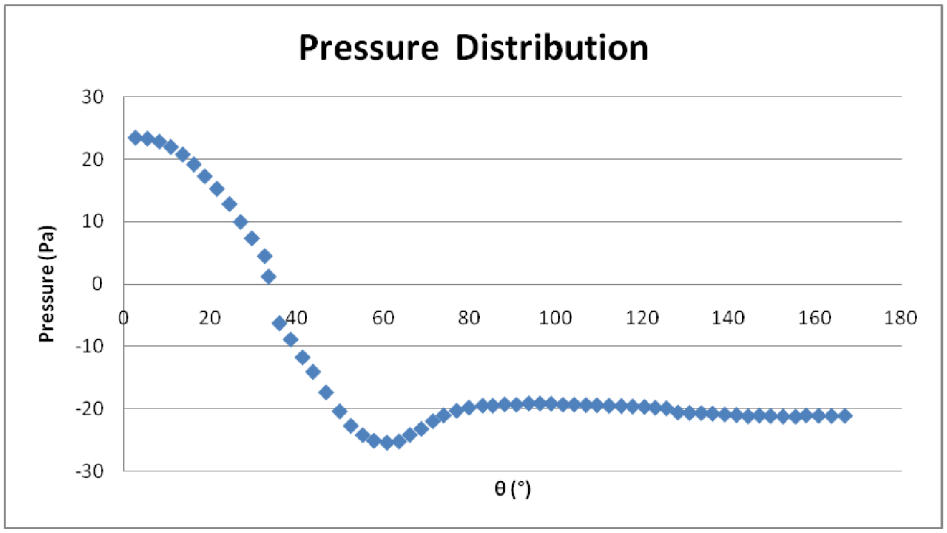

Figure 3: Experimental Results for Pressure Distribution around a Cylinder in Crossflow.

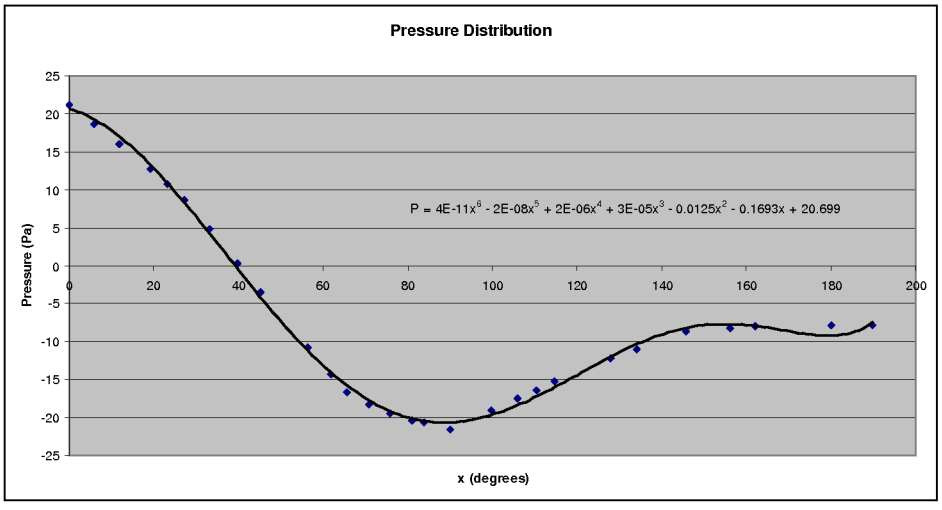

Figure 4: CFD Results for Pressure Distribution around a Cylinder in Crossflow. The line of best fit was added by the students.

Figure 2 shows the graphical results of one group's external flow simulation. Despite minor differences between the experimental and simulated results these results show a good agreement

between their experimental results, figure 3, and their simulation, figure 4. This allowed the students to validate both their experimental data and begin to grasp the modeling potential of the software. Not normalizing their experimental data to 180˚ and errors in normalizing the other groups' data largely account for the shift between the experimental and simulated results.

Challenges

While hardly case-specific, time management skills remained a critical student attribute that requires definite improvement. As the semester progressed it became apparent that the students were starting their laboratory reports in the last hours before they were due. E-mails would be sent one to two hours before the lab was due asking for clarification or help. This was certainly detrimental to their understanding of the subject material as they rushed to quickly apply theoretical concepts to their results. This caused frustration for them as they could not prepare their reports in a self-satisfactory form. Time management problems were very apparent during the final laboratory.

During the last laboratory students were to simulate the two previous labs, pressure drop in pipes and external flows. As the CFD suite was new, students were given three weeks time in order to complete the laboratory. While the objectives clearly stated that the students must simulate both previous laboratory experiments—this was also reiterated during the laboratory lecture—only one of the four groups did so. The rest of the groups simulated only one laboratory. Several groups tried to contact either the coordinator or professor for clarification in the days before the deadline during a school vacation period where the instructors had previously revealed they would be unavailable. This was also done despite the fact that they had already had two weeks to start their assignment. This is a strong indication of challenges relating to personal thoroughness, reading comprehension, and time management.

The effects of a strongly grounded memorization-based education are still heavily apparent. Figures 3 and 4 were the best prepared set produced by the students. While all students successfully simulated this part of the laboratory most did not convert their axis in the simulations graph to match the experimental results. Basic plotting guidelines had been made clear on multiple occasions. However, it was still apparent that when faced with a new challenge it was difficult for the students to adapt their prior knowledge to the scenario at hand. This had appeared many times throughout the class in different circumstances and each time the students had to be specifically corrected about a specific fault in order to ensure they changed it in the future.

Assessment

Our efforts in the new fluid mechanics laboratory were successful in supplementing the course material, providing useful hands-on experience, giving the students some sense of scale in "mechanical engineering", and applying software which can successfully simulate engineering scenarios. Not all students were able to fully internalize the lessons in the laboratory as per our

intentions because of the required time and concentrated effort laboratories take. Due to their pre-college education there is also a strong resistance to accepting the world as less-than-perfect—it seems that real errors and uncertainties are just beginning to be understood and uncovered by these students during this laboratory.

Students made extensive use of Labview through writing their own data acquisition programs and wiring all their modules. This contrasts with the 2nd experiment where the students used a manual manometer bank. In both cases students were initially frustrated by the fluctuations in their reading—a product of their limited exposure to hands-on experimentation. Students eventually learned to interpret their results, computational averaging their data in Labview or mentally averaging their manometer readings. Correctly knowing when and how to average a system's output is a key "engineering sense" that is invaluable to develop which these exercises aided in establishing.

Even though laboratory handouts were always available before class very few students came to the laboratory having read them. Students who had not read the laboratory handout generally did not attempt to read it during the class or laboratory time—they much preferred to rely on an instructor or one of their peers to find out what they should be doing. The syllabus had indicated that there would be three "pop" quizzes throughout the semester. Students performed poorly on the first quiz, averaging 52%. This encouraged them however to more actively read the laboratory handouts and familiarize themselves with laboratory theory and practice before hand. The 2nd and 3rd quiz scores rose to 65% and 75% respectively and students were more prepared during the laboratory. While this is not directly an intrinsic motivator for the students, the quizzes in this case provided an effective behavioral modifier as students take great pride from their standing in class.

The most prominent lessons are that even with seemingly strong equipment a purely 'technical fix' is not entirely feasible in providing the desired student outcomes in terms of material comprehension. Cultural sensitivity, especially in terms of stressing personal responsibility and the importance of critically reading distributed materials is still ultimately required. Time management skills need to be addressed and actively taught, however possible, much earlier in their academic careers.

Conclusions

New experimental equipments and methods have been established in the fluid mechanics laboratories at TAMUQ. Industrial scale equipment is used in the laboratory along with student driven CFD simulations of laboratory experiments. While the equipment used during this laboratory elicited strong positive responses from the students, care needs to be taken to provide the right direction and instruction in order to motivate the students to work in a timely fashion. In general, working with industrial scale equipments such as the pumps, piping, flow meters, and commercial data acquisition systems seemed to give them a general feeling of connection

between university and industry and their future role. CFD simulations, when conducted properly, showed students the possibilities of industry software tools in realistic physical modeling situations. Additional sensitivity needs to be given surrounding required objectives and expected results from the experiments.

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Appendix A

Example laboratory handout. This handout is abridged and does not include the experimental procedure or data charts and tables.

Fluid Mechanics Laboratory (MEEN 345) Experiment 4: Pressure Drop in Pipes

Fall 2009 Rev 1.5

1. Introduction

Fluid flow study in tubes and pipes is one of the most important topics of fluid mechanics. HVAC systems in buildings, oil and natural gas transport, even arterial blood flow are all examples of closed conduit flow. In each of these cases the energy put into the fluid at the beginning of transport does not equal the energy of the fluid at the exit. The change in energy of the fluid is caused by losses which are divided into two groups: major and minor. These losses show themselves in the system as a drop in the fluid pressure flowing in the pipe. These need to be evaluated accurately for a given flow rate in a system in order to be able to choose proper pumps in order to correctly facilitate the material transport.

In this laboratory you will investigate the effects of various factors in major and minor losses on the pressure (and thus energy) of a fluid.

2. Theory

Major loss is due to the energy loss in the pipe due to the friction of the fluid with the wall. In addition to fluid density, ρ, it is related to the pipe wall characteristics such as length L, diameter D, and pipe inner surface roughness, in addition to the fluid velocity V. The pressure loss due to major losses is obtained:

$$\Delta P = f \frac{L}{D} \rho \frac{V^2}{2} \qquad \text{eq. (1)}$$

where f is the friction factor. Minor losses are the term used for losses due to bends, contractions, expansions, valves and other obstructions in the flow field. The pressure drop due to minor losses can be expressed as:

$$\Delta P = K_L \frac{V^2}{2} \rho \qquad \text{eq. (2)}$$

where K is minor loss coefficient for the device.

Typical values for K_L are given throughout chapter 8 of Munson and Young.

In order to determine the total pressure losses within a system, the summation of the major and minor losses are needed:

$$\Delta P = \sum \rho \ f \frac{l}{D} \frac{V^2}{2} + \sum \rho K_L \frac{V^2}{2} \qquad \text{eq. (3)}$$

The friction factor, f, is dependent on the surface condition of the conduit, conduit diameter, D, and Reynolds number. In order to calculate f the surface roughness of the material, ε, must be known. In the case of most non-fouled plastics and glasses it can be approximate as 0.0, in other words, smooth. If the material was not smooth, the surface roughness would have to be known. The relative roughness, $\frac{\varepsilon}{D}$, for the pipe is then calculated. In both cases the Reynolds number for the pipe and fluid are calculated. A Moody chart can then be utilized (see page 434 in Munson).

If the flow is turbulent (Re>2000) then the Colebrook equation can be used:

$$\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{\frac{\varepsilon}{D}}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \qquad \text{eq. (4)}$$

The Swamee-Jain equation is an approximation of the Colebrook equation and is slightly easier to use if you are using a circular conduit:

$$f = \frac{.25}{\log\left(\frac{\varepsilon}{3.7D} + \frac{5.74}{Re^{.9}}\right)^2} \qquad \text{eq.(5)}$$

In many cases it is still quickest to use a Moody chart.

3. Laboratory Objectives

The specific reportable objectives of this experiment are to:

- Draw a schematic for the flow loop indicating all the components and their characteristics parameters such as length and diameter. Indicate the flow meter and number the location of the pressure sensors.
- Calculate the L/D ratio for each test section.
- Create a plot for each station at maximum flow rate averaging the pressure at each transducer.
- Plot the total pressure drop in the system, as a function of mass flow rate, for each station.
- Plot the pressure drop for a 90˚ flanged elbow as a function of velocity.
- Determine the $K_{L_{minor}}$ values for the 90 degree elbow, expansion and contraction in $1\frac{1}{4}$" and $\frac{3}{4}$" pipes, ball valve, flange connection, and Micromotion Flow Meter. Compare with literature values (see 4-20ma primer, Munson & Young Ch 8.)
- Compare and discuss the results between the pressure differences in the expansion and contraction sections in $1\frac{1}{4}$" and $\frac{3}{4}$" pipes.
- Perform uncertainty analysis for all calculations, discuss.
- Discuss which losses (major or minor) had the largest impact in this experiment. Describe a different system where the opposite losses have a larger impact.

4. **Experimental Materials**

The experimental materials for Pressure Drop in Pipes are:

- (3) Hydraulic flow loops with Micromotion F Series Coriolis Mass Flow Meter.
    - Station 1 with 2" PVC test section
        - (1) Setra 100 PSIA Pressure Transducer
        - (2) Setra 50 PSIA Pressure Transducers
        - (5) Setra 25 PSIA Pressure Transducers
    - Station 2 with 1 ¼" PVC test section
        - (1) Setra 100 PSIA Pressure Transducer
        - (5) Setra 50 PSIA Pressure Transducers
    - Station 3 with ¾" PVC test section
        - (5) Setra 100 PSIA Pressure Transducers
        - (1) Setra 25 PSIA Pressure Transducer
- (6) Agilent E3634A Power supplies.
- (3) NI PXI-1042Q workstations with peripherals including DAQ input board.
- (3) 200 Ω terminating resistor.