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Exploring Open Lab Experiences to Enhance Fluid Mechanics Education

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Enhancing Fluid Mechanics Learning through Open-Ended Lab Experiences: A Pilot Implementation

Abstract

In mechanical engineering and mechanical engineering technology education, bridging the gap between theoretical concepts and practical applications is critical for promoting student learning and engagement, particularly in core technical subjects such as fluid mechanics. This study explores the pilot implementation of a series of open-ended lab experiences in an advanced fluid mechanics course, aimed at enhancing students' learning of fluid flow in pipelines. Open-ended labs give the students the freedom to develop their own experiments instead of following a more guided step-by-step procedure and provide students with hands-on opportunities to explore fundamental fluid dynamics concepts and encourage active learning. A preliminary evaluation of the efficacy of these open-ended lab experiences was conducted using a direct assessment of the lab assignment's components and an anonymous indirect assessment in the form of a survey. The survey questions focused on the students' perceptions of their learning experiences, classroom and project engagement, confidence in applying theoretical concepts, and the perceived relevance of lab activities to practical applications. Findings revealed that 50% of the reporting students felt "very satisfied" or "satisfied" with the open-ended lab experience, while 83% found the experiences "extremely effective" or "effective" in enhancing their understanding of core fluid mechanics concepts. These results suggest that while satisfaction levels vary, students felt the labs were highly effective and thus achieved their primary educational objectives. The pilot study supports further implementation of open-ended lab experiences and contributes to the growing conversation on innovative engineering education strategies by demonstrating the value of experiential learning approaches, particularly the integration of entrepreneurial mindset learning (EML) into laboratory experiences.

Why open-ended labs?

The decision to introduce open-ended labs into our curriculum was inspired by the insights gained from the Summer 2024 Engineering Mechanics in Lab and Design workshop series, hosted by the University of Illinois Urbana-Champaign and supported by the Kern Family Foundation. During this workshop, we had the opportunity to explore in more depth the concept of open-ended labs, engaging with experts and educators who have successfully implemented such activities in their own teaching practices. The moderators, who were experienced in running open-ended laboratory activities, shared their valuable perspectives on the positive outcomes observed in their students. They emphasized how they not only enhance students' understanding of theoretical concepts but also promote critical skills such as creativity, independent problem-solving, and teamwork, skills that are essential for future engineers and align with the 3C's of an entrepreneurial mindset, Curiosity, Connections, and Creating Value.

The authors were particularly inspired by how open-ended labs provide students with a deeper, more personalized learning experience, allowing them to experiment with real-world problems, refine their engineering judgment, and develop solutions that may not have a single, clear-cut answer. By participating in these discussions and reflecting on the practical applications demonstrated in the workshop, the authors became convinced of the importance of integrating open-ended lab experiences into their own teaching practices. They recognized that these labs could transform traditional learning environments into spaces where students take ownership of their education, bridging the gap between theoretical knowledge and its application in complex engineering systems. Moreover, the workshop highlighted the long-term benefits of such approaches, including enhanced student engagement, increased retention of engineering principles, and better preparation for the demands of modern engineering careers. With these insights in mind, the authors felt compelled to introduce open-ended labs into their fluid mechanics course, believing that they would provide students with the opportunity to engage in more meaningful, hands-on learning that mirrors the challenges they will face in professional practice [1-5]

Pilot Implementation in an Advanced Fluid Mechanics course

The pilot of the open-ended lab was introduced in the Fall 2024 semester as part of a mechanical engineering technology program's fluid mechanics course. This course is the second in a sequence of two fluid mechanics courses, designed to build upon foundational concepts and provide more advanced knowledge of fluid behavior. It is a 4-credit hour course, with 3 credit hours dedicated to lecture-based instruction and 1 credit hour allocated to hands-on laboratory experiences. The timing of this course in the students' academic journey is significant, as it is often one of the final courses taken in their program, making it particularly important for reinforcing key engineering concepts and preparing students for professional practice. There were 17 students enrolled in the course, most of whom were in their final semester before graduation. As such, the course offered a unique opportunity to implement the open-ended lab, allowing students to integrate their prior knowledge from earlier courses and apply it to more complex, real-world fluid mechanics problems. Given that this course is situated at a critical juncture in the students' education, it was seen as an ideal setting for introducing an open-ended lab, where students could engage in meaningful, hands-on problem-solving experiences that would not only solidify their technical understanding but also help them develop the critical thinking, teamwork, and design skills necessary for success in their future careers. By placing this open-ended lab at the end of their academic program, the pilot aimed to provide students with a capstone experience that would challenge them to apply their learning in innovative and practical ways, fostering a deeper, more integrative understanding of fluid mechanics.

- Lab Assignment #1: Develop and Execute an Experimental Procedure for Analyzing Fluid Flow in Pipelines.

The primary objective of this open-ended lab was to engage students in designing and executing a comprehensive experimental study to explore the impact of varying pipeline configurations on fluid flow. Specifically, the students were tasked with investigating how different factors such as pipe diameter, the presence of elbows, and pipeline material influence key fluid dynamics parameters, such as flow rate and pressure drop. These factors are critical in real-world engineering applications, where the design of pipelines and fluid transport systems plays a central role in optimizing energy efficiency, minimizing losses, and ensuring system reliability.

To complete the lab, students were encouraged to use the existing fluid mechanics setups available in the fluids lab. They were asked to first conceptualize their experimental procedures and determine methods for capturing data. They were encouraged to approach the problem with creativity and independent judgment, designing experiments that would allow them to isolate and manipulate the variables of interest, while maintaining control over factors like flow conditions. The open-ended nature of the lab meant that students had the flexibility to choose from a range of pipeline configurations, test different combinations of pipe diameters, lengths, and bends, and predict how each modification would influence the system's behavior.

To support their experimentation, students were provided with a detailed handout that outlined the core objectives of the lab and the expected deliverables. Upon completing the experiments, students were asked to submit a comprehensive lab report summarizing their methodology, data analysis, and conclusions. The report required them to not only present their experimental results but also critically evaluate their findings in relation to theoretical predictions, providing insights into the real-world implications of pipeline design. This process fostered a deeper understanding of fluid flow in practical systems and reinforced the importance of clear communication, both in terms of technical writing and in presenting complex scientific findings to peers and instructors. The handout given to the students is included as Appendix 1 for reference.

Two lab sessions were dedicated to this open-ended laboratory assignment, each serving a distinct purpose in ensuring the students successfully completed their tasks. The first session was focused on familiarizing students with the existing laboratory equipment and setup. During this session, students were given an overview of the fluid mechanics lab, which included hands-on interaction with the various instruments and apparatuses that would be used in their experiments. In addition to providing students with the practical prerequisite knowledge of using the lab, this initial session also provided an opportunity for students to engage in team discussions, where they collaboratively brainstormed and developed a detailed plan for their experiments. They reviewed the objectives, considered potential challenges, and determined the experimental methods they would employ to investigate the effects of varying pipeline configurations on fluid flow. This collaborative planning process allowed students to refine their approach, allocate roles within their teams, and ensure that they were well-prepared for the data collection phase.

The second session was dedicated to executing the experimental procedures and collecting the necessary data. Armed with their finalized experimental plan, students carried out their investigations by setting up the pipeline configurations and measuring key parameters such as flow rate and pressure drop. During this session, students worked together to ensure that the data was collected accurately and systematically, while troubleshooting any issues that arose with the equipment or experimental conditions. In addition to gathering data, students were also required to begin analyzing their results in real time, comparing their findings with theoretical predictions based on fluid mechanics principles.

At the conclusion of the second session, students were expected to compile their findings into a comprehensive lab report. The report required them to not only present their raw data and analysis but also interpret the results, making connections to theoretical models and discussing any discrepancies or unexpected outcomes. This final deliverable allowed students to demonstrate their ability to synthesize experimental data, draw conclusions, and communicate their findings effectively, reinforcing both their technical and written communication skills. By structuring the lab in two distinct phases, one focused on preparation and team collaboration, and the other on data collection and analysis, students were given the opportunity to engage with the material and experience the full cycle of an engineering project, from planning to execution and reporting.

- Lab Assignment #2: Develop and Execute an Experimental Procedure for Identifying the Resistance Coefficient of a Standard 90º Elbow

The second open-ended lab tasked students with calculating the resistance coefficient for a standard 90° elbow, a common component in fluid transport systems. This lab, handout in Appendix 2, provided students with an opportunity to explore the impact of pipe fittings on fluid flow, an essential aspect of designing efficient piping networks. To complete the assignment, students first needed to select any experimental set-ups currently available in the lab. As before, once the students decided on a methodology for their experiment and data on flow rates, pressure measurements before and after the elbow, and other relevant variables, students used the data to calculate the resistance coefficient and compared their experimental results with expected theoretical values. The open-ended nature of the lab allowed students to explore various factors that could influence the results, such as fluid velocity, pipe material, and roughness. Additionally, they were encouraged to discuss potential sources of error and reflect on how their experimental setup might be improved. This open-ended lab not only reinforced students' understanding of energy losses in fluid systems but also emphasized the importance of experimental design, data analysis, and the application of theoretical concepts to real-world engineering challenges.

Assessment

To assess the effectiveness of the open-ended labs and to gauge students' perceptions of their impact on learning, both direct and indirect assessment methods were employed. Direct assessment was carried out through grading the students' lab reports, which evaluated their ability to design the experimental methodology, collect and analyze data, and draw conclusions based on theoretical principles. The grading criteria focused on the clarity of their experimental strategy, accuracy of data collection, application of fluid mechanics concepts, and the quality of their final report, including proper presentation of results and critical analysis. In addition to this direct assessment, an indirect evaluation method was used through a voluntary anonymous survey conducted at the end of the lab sessions. This survey aimed to capture students' feedback on the open-ended lab experience, specifically regarding how the experiments influenced their understanding of fluid mechanics, enhanced their problem-solving skills, and contributed to their overall learning. The survey asked students to reflect on aspects such as the level of engagement during the labs, the usefulness of open-ended tasks in promoting critical thinking, and their perceived preparedness for real-world engineering challenges. By combining both direct measures of academic performance and indirect feedback on students' learning experiences, the assessment provided a comprehensive understanding of the educational impact of the open-ended lab format. This data is valuable for refining future lab sessions and ensuring that these types of learning experiences effectively contribute to students' development as capable, independent engineers.

- Direct Assessment: Lab Reports

The direct assessment of student performance, as reflected in the lab report grades, revealed interesting trends when comparing various lab formats. For the first open-ended lab, which involved investigating the effects of pipeline configurations on fluid flow, the average class grade was 70%, indicating that students found this open-ended, self-directed format somewhat challenging, particularly in terms of experimental design, data analysis, and drawing conclusions. In contrast, the second open-ended lab, which focused on calculating the resistance coefficient for a 90° elbow, saw a significant improvement, with the class average rising to 82%. This suggests that students became more comfortable with the open-ended approach after their initial experience and were able to better apply the fluid mechanics principles to real-world problems. The lab that required students to use the newly learned HydroFlo pipeline design software had an average grade of 77%, which indicates that while students were engaged with the new technology, they faced challenges integrating software-based simulations with their hands-on experimental data. Finally, the more traditional, guided lab, which followed a structured procedure, resulted in the highest average at 85%. This higher average reflects students' ability to follow predetermined steps with greater ease, though it may also indicate that the more open-ended labs presented a steeper learning curve that took time for students to master. Overall, these comparisons highlight how students tend to perform better in traditional, guided formats, but also show that they improve and gain confidence in open-ended labs over time, especially when these labs build upon previously learned concepts and tools.

- Indirect Assessment: Anonymous Survey

The students were asked to complete an anonymous survey to assess their perceptions of the newly introduced lab experiences. Only six students (35%) participated in the survey, and while we recognize that this may not fully represent the entire cohort, we believe the feedback still provides valuable insights including enhancing and refining future lab experiences.

When asked how effectively the open-ended labs enhanced their understanding of fluid mechanics concepts, the responses were varied: 33% of students were "very satisfied," 17% were "satisfied," and 50% selected "neither satisfied nor dissatisfied." This suggests that while some students found the open-ended labs highly beneficial for understanding theoretical concepts, others felt neutral, indicating potential room for improvement in engagement or clarity.

Regarding the effectiveness of the labs, 67% of students found them "very effective," with an additional 17% considering them "extremely effective" and another 17% rating them as "somewhat effective," indicating a generally positive perception of how the labs helped reinforce the course content. While the students found the labs effective, other factors beyond effectiveness influenced their overall satisfaction, leading to a lower satisfaction score, such as lack of structured guidance, understanding concepts, and time management.

When asked about the most engaging activity, 85% of students cited the HydroFlo lab, highlighting the appeal of using simulation software in conjunction with practical experiments, while only 17% found Lab 1 more engaging. This aligns with comments about the increased relevance of software tools in professional engineering environments, suggesting that students appreciate the opportunity to work with real-world applications. Regarding the balance between theoretical and practical work, responses were evenly split: 33% felt the balance was "just right" and another 33% found it both theoretical and practical, while 17% felt it was too theoretical or too practical. This indicates that while many students were content with the balance, there is a noticeable variation in their preferences.

The survey also gauged collaboration, with 33% of students feeling the open-ended lab format "absolutely" encouraged more peer interaction. The remaining students had more mixed responses, suggesting that while collaboration was fostered, there may be room to enhance teamwork dynamics in future sessions, which led to frustration. One student specifically mentioned that the lab environment had a dominant leader and little interaction or challenge within the group;he/she felt that they were not actively engaged in the learning process andteam members did not contribute equally, affecting satisfaction. In terms of confidence in applying learned concepts to real-world engineering problems, 50% of students felt "moderately confident," 33% were "very confident," and 17% felt "not so confident," reflecting a generally positive outlook on how the labs prepared them for professional challenges. While the majority of the students reported being confident, those who found the labs difficult or lacking in clear direction expressed low or moderate levels of confidence. This gap in confidence likely contributed to some students reporting some level of dissatisfaction.

In terms of challenges, the most common issues were lack of guidance (cited three times), difficulty in understanding concepts (twice), and time management (once), with one student reporting "none." These comments suggest that while the open-ended nature of the labs was valuable, students faced hurdles related to guidance / structure, and conceptual clarity. However, these types of challenges also exist in the real-world and the labs are intended to simulate similar environments. Part of the learning experience requires students to problem solve through the collaboration process. Regardless, the feedback was largely positive, it also pointed to areas where the open-ended lab format could be further improved, particularly in terms of guidance, conceptual clarity, and equipment validation. Moreover, the evidence from direct and indirect assessments supports further exploration and expansion of open-ended labs in the curriculum.

Conclusion

The combination of direct and indirect assessments provides valuable insights into the effectiveness and reception of the newly introduced open-ended lab experiences in this advanced fluid mechanics course. The direct assessment, based on students' lab report grades, revealed a range of performance, with the first open-ended lab averaging 70%, the second averaging 82%, and a lab utilizing the HydroFlo pipeline design software achieving a 77% average. This indicates an overall improvement in students' ability to engage with open-ended tasks as they progressed through the course, although challenges remained, particularly with the integration of new technologies and software. The higher average in the traditional guided lab (85%) suggests that students performed better in a more structured environment, underscoring the value of both guided and open-ended approaches in fostering learning.

The indirect assessment, collected through a voluntary anonymous survey, revealed mixed yet generally positive feedback. A significant portion of students reported that the open-ended lab experiences enhanced their understanding of fluid mechanics concepts, with 67% rating the labs as "very effective" or "extremely effective." However, the 50% of students who selected "neither satisfied nor dissatisfied" suggests that there is still room to improve engagement and clarity, particularly in making the lab experiences more universally impactful. Students found the HydroFlo lab particularly engaging, with 85% of participants noting its relevance to real-world engineering practice, which aligns with feedback emphasizing the value of software tools in professional settings. Nonetheless, challenges such as a lack of guidance and insufficient collaboration, difficulty in understanding concepts, and time management issues were noted, indicating areas where additional support could enhance the lab experience. Furthermore, while many students felt confident in applying what they learned to real-world problems, a substantial portion expressed moderate confidence, reflecting the need for continued efforts to ensure that students feel fully prepared for professional applications. More diverse activities, structured guidance, and better equipment could help address these concerns and lead to a more satisfying lab experience.

Open-ended labs are a powerful tool for fostering and entrepreneurial mindset in engineering students because they go beyond traditional structured experiments by a) encouraging curiosity, pushing students to ask, “what if?” and “why?” rather than following a preferred set of steps, while also nurturing a lifelong learning attitude; b) fostering creativity and innovation, pushing students to think outside the box, and expose them to failure as a learning opportunity; and c) encouraging making connections between theory and application, by bridging the gap between theoretical knowledge and practical implementation.

Overall, the open-ended lab experiences were well-received, while revealing several opportunities for improvement, especially in terms of balancing theoretical and practical work, enhancing guidance, and refining equipment setups. These findings will be used to refine future iterations of the course, with a focus on providing clearer guidance, increasing collaborative opportunities, and continuing to integrate real-world tools and applications into the lab environment. By addressing these areas, the course can more effectively engage students and support their development into confident, capable engineers.

References:

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Appendix 1

MET 4100 - Lab Assignment #1
Fall 2024

Develop and Execute an Experimental Procedure for Analyzing Fluid Flow in Pipelines

Objective: Design and execute a comprehensive experimental study to investigate how varying pipeline configurations, such as pipe diameter, elbows, and length, affect fluid flow, including flow rate and pressure drop.

Designing the Experiment:

- **Formulate Specific Questions:** Decide what specific questions you want to answer.
- **Select Variables:**
  - **Independent Variables:**
  - **Dependent Variables:**
  - **Controlled Variables:**
- **Design the Experimental Setup:**
  - **Equipment:** Use the existent setups in the fluid laboratory.
  - **Experimental Procedure:** Outline the steps you will follow to conduct the experiment. Include details on how you will vary each independent variable and how you will record your data.
- **Data Collection and Analysis:**
  - Plan how you will collect and record your data. Consider how you will ensure accuracy and reliability in your measurements.
  - Decide on the method for analyzing the data. This might include comparing the results with theoretical analysis and identifying trends or patterns.

2. **Conducting the Experiment:**
   - Collect data systematically for each variable and condition.
   - Ensure all safety protocols are followed during the experiment.

3. **Reporting Your Findings:**
    - **Data Presentation:** Create tables, graphs, or charts to present your data clearly.
    - **Analysis:** Discuss how the results support or refute the hypothesis. Compare the effects of different materials and dimensions on fluid flow characteristics.
    - **Conclusion:** Summarize your findings and reflect on the implications. Consider any limitations of your experiment and suggest possible improvements or further investigations.
4. **Submission:**
    - Submit a written report that includes:
        - Your experimental design and procedure.
        - Data collected and analysis.
        - Discussion of results.
        - Any conclusions and recommendations for future work.

Safety Considerations:

- Handle all equipment and fluids according to safety guidelines.

Notes:

- This is an open-ended assignment; your experimental design can be as simple or complex as needed to address the hypothesis.
- Consider consulting additional resources or references to support your experimental design and analysis.
- You have two weeks to submit your Written Report.

Appendix 2

MET 4100 - Lab Assignment #2
Fall 2024

Objective:

Develop a strategy to calculate the resistance coefficient K for a 90° standard elbow.

Theory:

Energy losses $\boldsymbol{h_L}$ are found to be proportional with the velocity head of the fluid as it flows around a fitting or a valve. Experimental values for energy losses are sometimes reported in terms of a resistance coefficient $\boldsymbol{K}$.

From the previous lectures, we observed that

major losses:

$$h_L/_{major} = f\,\frac{L}{D}\frac{V^2}{2g} \qquad (1)$$

minor losses:

$$h_L/_{minor} = K\frac{V^2}{2g} = f_T\frac{L_e}{D}\frac{V^2}{2g} = \gamma\Delta P \qquad (2)$$

Where f – friction factor; value depending on Re and D/

f_T – friction factor for the fully turbulent regime.

K – the resistance coefficient

V – fluid velocity

L – pipe length

D – pipe diameter

$\frac{L_e}{D}$ – the equivalent length ratio – considered to be constant for a given type of fitting

γ – specific weight

ΔP – Pressure loss / drop

Laboratory Setup:

Use any Fluid Mechanics Demonstration Unit available in NE1430 room.

Show your lab setup including showing all the dimensions required to solve this lab.

Data Collection:

Flow Rate (units you prefer)	***Δh (units you prefer)***	***ΔP (your units)***

Results:

Present your data in tabular and / or graphical form.

Discussions:

Discuss your findings.