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An Optimized Elbow Project for Undergraduate Mechanical Engineering Students

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I am a mechanical engineering major in my last year at Oral Roberts University, and my name is Benitha Ndayisenga. I have a keen interest in developing and upgrading mechanical systems, and I have been actively involved in several engineering projects during my academic career. The elbow project can enhance the learning chances for undergraduate mechanical engineering students. After graduating, I want to work in mechanical engineering and utilize my experience to help the sector grow.

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An Optimized Fluid Flow Elbow Project for Undergraduate Mechanical Engineering Students

Abstract

This paper presents the testing of an experimental setup for measurements of pressure drop in the flow for an optimized 90-degree elbow. The optimized elbow was designed using Sculptor software and experimental pressure drop measurements at different flow rates were compared with Ansys Fluent simulations of the flow field. It was discovered that a maximum reduction in pressure drop by 64% could be achieved using an optimized design in comparison with the constant cross section elbow. The paper will include a description of student outcomes, student involvement and an assessment of student learning.

Introduction

An optimized elbow in fluid flow refers to a bend or turn in a fluid pipeline that has been specifically designed to minimize turbulence, pressure loss, and energy consumption. The optimization of an elbow in fluid flow is achieved through careful consideration of the fluid velocity, density, and viscosity, as well as the diameter and shape of the pipeline. By carefully designing the angle, radius, and curvature of the elbow, engineers can reduce the amount of friction and turbulence that occurs within the pipeline, which in turn reduces the pressure drop and energy consumption associated with the flow of fluid. The use of optimized elbows in fluid flow systems is essential for maintaining the efficiency, safety, and performance of these systems, and for reducing the overall cost and environmental impact of fluid transport.

For incompressible flows in pipes and ducts of HVAC systems the head loss (energy dissipated in a fluid system due to friction) and associated pressure drop is expressed by McQuiston, Parker and Spitler [1]. The head loss can be determined for piping systems with elbows and valves. The standard circular cross section 90-degree elbow design is known to not be optimized for pressure drop, see Baukal, Gershtein and Li [2].

Yin et al. [3] completed a study of low-resistance optimization of 90 degree elbows using double guide vanes and achieved a maximum resistance reduction of 38.1 %. Sarstedt et al. [4] used topology optimization for fluid flows employing local optimality criteria. Sculptor is based on Arbitrary Shape Design (ASD) and allows CFD designers to create their own shape parameters. The software performs a smooth volumetric deformation, eliminating remeshing the grid for the desired shape change. Sculptor software has been used for mesh morphing in optimization for aerodynamic design of automotive car styling by Ando and Takamura [5]. Jackson, Newill and Carter [6] showed a CFD model of an imported 90-degree elbow and a created ASD volume. The ASD volume was closely fitted to the elbow and they showed the symmetric deformation of the elbow using two control points. More recently, Matsson [7] used Ansys Fluent and Sculptor to optimize the 90-degree elbow flow and found a substantial reduction in pressure drop. Sculptor has also been used in design optimization of combustion equipment by Smith and Landon [8] and Smith et al. [9], [10].

The purpose of this project is to introduce students to gain experimental experience with measurements of pressure drop in pipe flows and to be introduced to design optimization for fluid flows. Sculptor optimization software in combination with Ansys Fluent software was used to find designs of a 90-degree elbow that have improved efficiency and associated lower pressure losses in comparison with the standard elbow, see Figure 1.

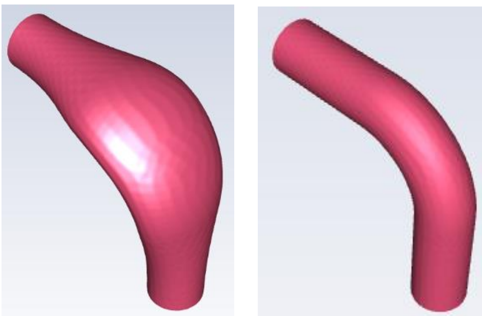

Figure 1. Example of optimized and standard 90-degree elbows [7].

Theory

The temperature dependence for the dynamic viscosity of air can be described using the following equation

$$\mu = aT^b \qquad (1)$$

where the constants are $a = 2.791 \cdot 10^{-7}$ and $b = 0.7355$, and T (K) is the temperature of the air. The density of air is given by the ideal gas law expressed as

$$\rho = \frac{p_{atm}}{RT} \qquad (2)$$

where p_{atm} is the atmospheric pressure and R = 287 J/(kg K) is the gas constant. The Reynolds number is defined as

$$Re = \frac{UD\rho}{\mu} \qquad (3)$$

where U (m/s) is the average velocity and D = 0.04445 (m) is the inner diameter of the pipe. The pressure coefficient can be expressed as

$$K = \frac{\Delta p}{\frac{1}{2}\rho U^2} \qquad (4)$$

where Δp (Pa) is the pressure drop from the inlet to the outlet of the elbow. The outlet of the elbow will be at atmospheric pressure and the inlet of the elbow will be at a higher pressure than the atmospheric pressure. The percentage difference between experimental results and Ansys Fluent results for the pressure coefficient can be determined as

$$Percent\ Error = 100 \cdot \frac{|K_{Exp.} - K_{Fluent}|}{K_{Fluent}} \tag{5}$$

Experimental Set-Up

Students used an existing experimental setup for measurements of pressure drop in elbow flows. They also 3D printed an optimized design of an elbow and compared pressure drop measurements with CFD simulations.

In the experiments, the inlet flow to the elbow was supplied from a B-Air Koala KP-1200 centrifugal blower that was connected to sections of screens and honeycomb followed by a contraction before entering the straight pipe section, see Figure 2.

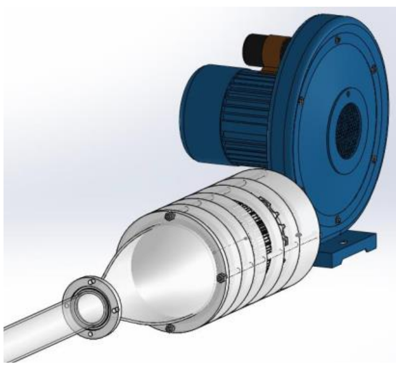

Figure 2. Centrifugal blower with settling chamber, contraction and pipe section.

The contraction was 3D printed together with the four supports for the horizontal pipe as shown in Figure 3. The pipe was made of clear polycarbonate tubing for durability and transparency. The inner diameter of the pipe was D = 44.45 mm and the total length was 8 ft. The end of the straight pipe section was connected to the elbow. Students used 90-degree elbows with the same inner diameter as the straight pipe section. Pressures were measured by students before and after the elbow in order to determine pressure drop. The Furness Controls FCO 510 Micromanometer was used to measure pressure drop at different flow rates and Reynolds numbers.

Figure 3. Experimental setup and SOLIDWORKS model for measurements of pressure drop.

Ansys Fluent

Ansys Fluent is a computational fluid dynamics (CFD) software that provides a comprehensive solution for simulating fluid flow, heat transfer, and other related phenomena. It's widely used in various industries, including aerospace, automotive, chemical, and electronic design, among others. Ansys Fluent allows users to model complex fluid flow problems, including turbulent, multiphase, and reacting flows, and predict the behavior of fluid systems under different conditions.

Ansys Fluent was used to simulate the flow in the standard and optimized 90-degree elbows [7]. Ansys Fluent Meshing was launched in double precision, standalone mode and the workflow type was chosen as a watertight geometry, see Figure 4.

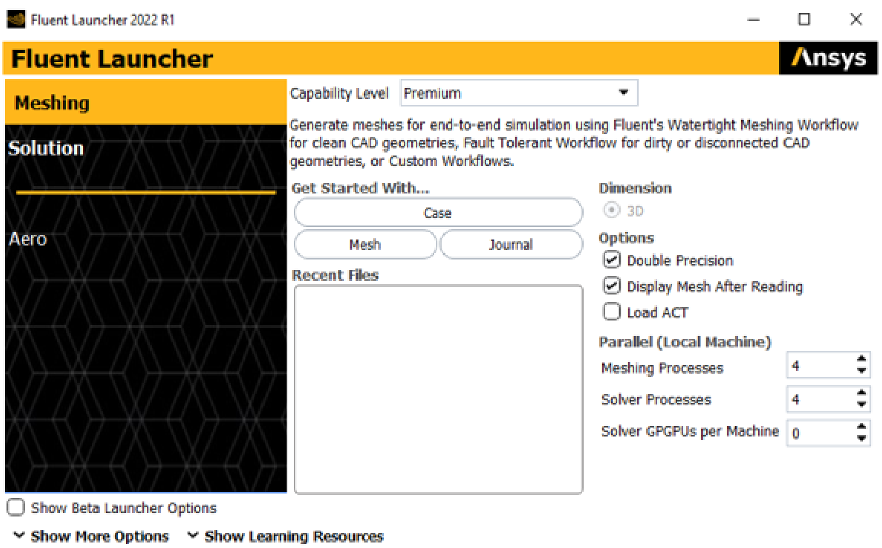

Figure 4. Ansys Fluent Launcher window [7].

The elbow geometry was imported and a surface mesh was generated, see Figure 5.

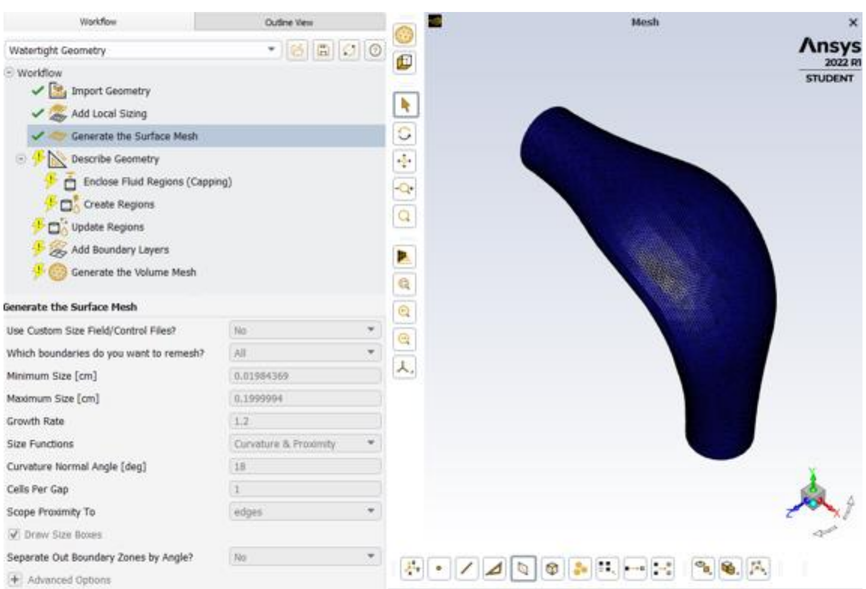

Figure 5. User interface with generated surface mesh in Ansys Fluent for optimized elbow [7].

Boundary layers were added as directed by the Ansys Fluent workflow and a volume mesh was generated, see Figure 6.

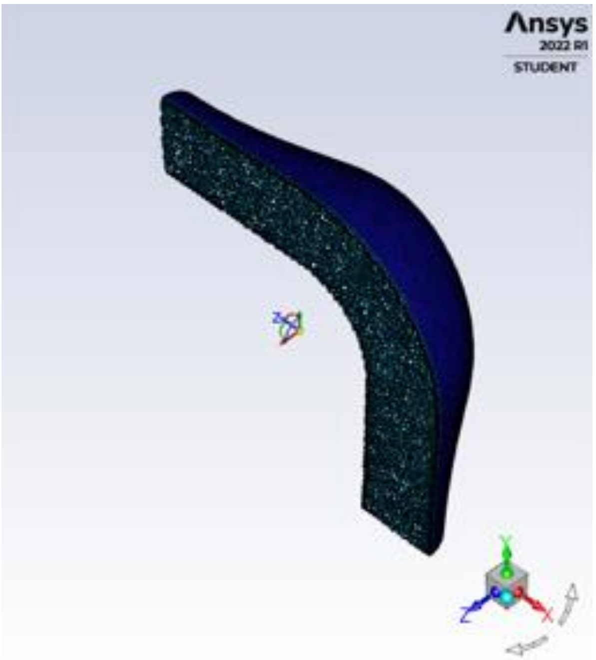

Figure 6. Generated volume mesh in Ansys Fluent [7].

Next, Ansys Fluent Solution was initiated and a k-epsilon turbulence model was used. The properties of air in the simulations was defined to align with properties of air in the experiments. The velocity magnitude in the pipe was set and a sand-grain surface roughness of the elbow was introduced. For the solution method, a coupled scheme was used for the pressure-velocity coupling and the spatial discretization gradient was set to the least-squares cell-based method. The residuals for all equations was set at an absolute criteria level of 1e-4. The flow in the elbow was initialized and the flow solution was iterated until the residuals reached the required level, see Figure 7.

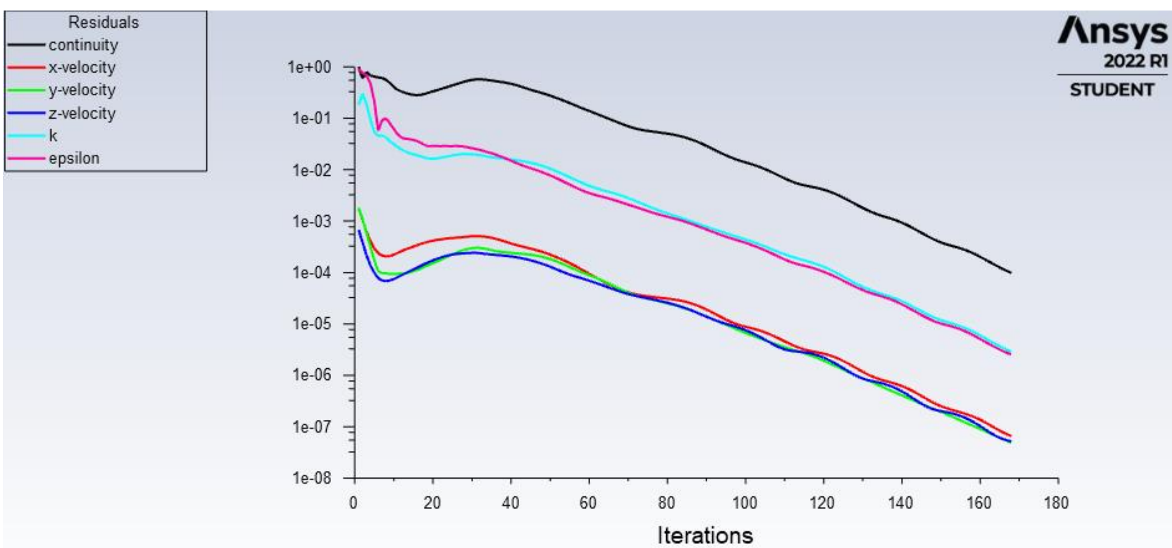

Figure 7. Residuals from simulation of flow in optimized elbow [7].

During the post-processing phase the static pressure contours and velocity magnitude were plotted as shown in Figure 8 and surface integral reports were generated of area-weighted average static pressure and pressure coefficient were generated at inlet and outlet.

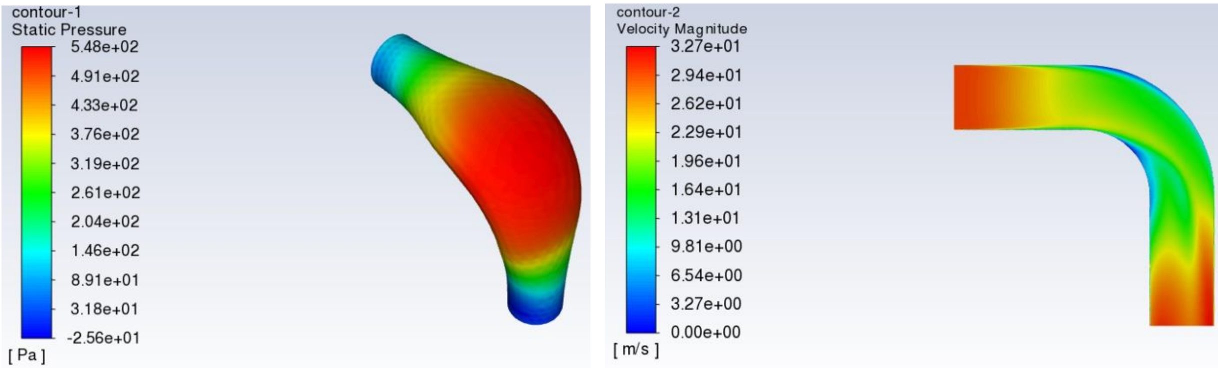

Figure 8. Contours of static pressure and velocity magnitude [7].

A batch-job was created in Ansys Fluent to run the simulations for different Reynolds numbers. Based on batch jobs and experimental results, a comparison could be made between standard and optimized elbows for the pressure drop and pressure coefficient as shown in Figures 9a), 9b). The Objet24 PolyJet 3D printer with VeroWhite Plus printing material was used to print the optimized elbow design.

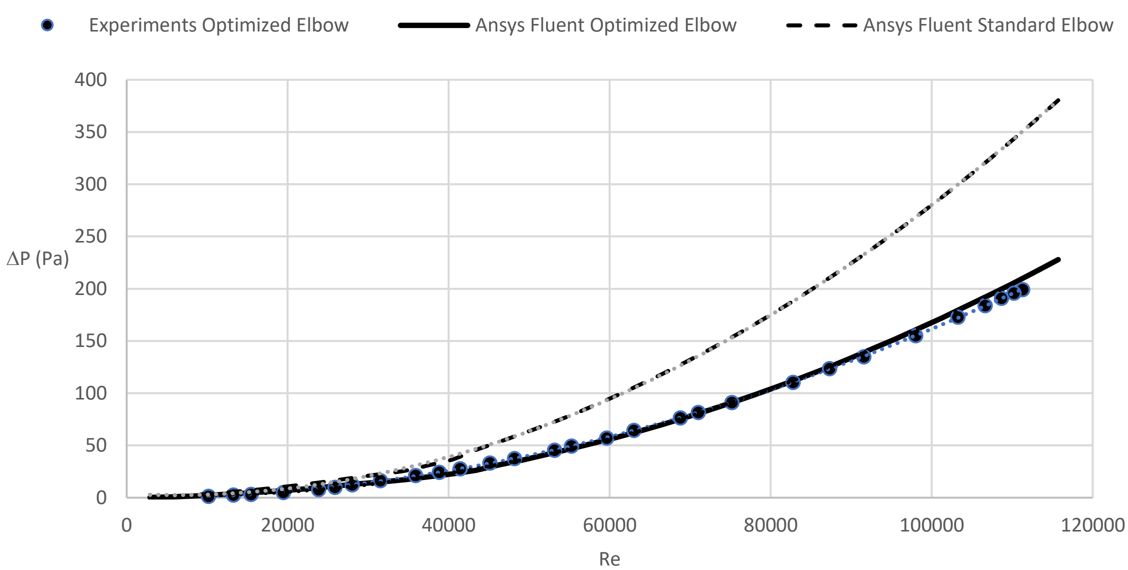

Figure 9a) Pressure drop versus Reynolds number for optimized elbow experiments [7].

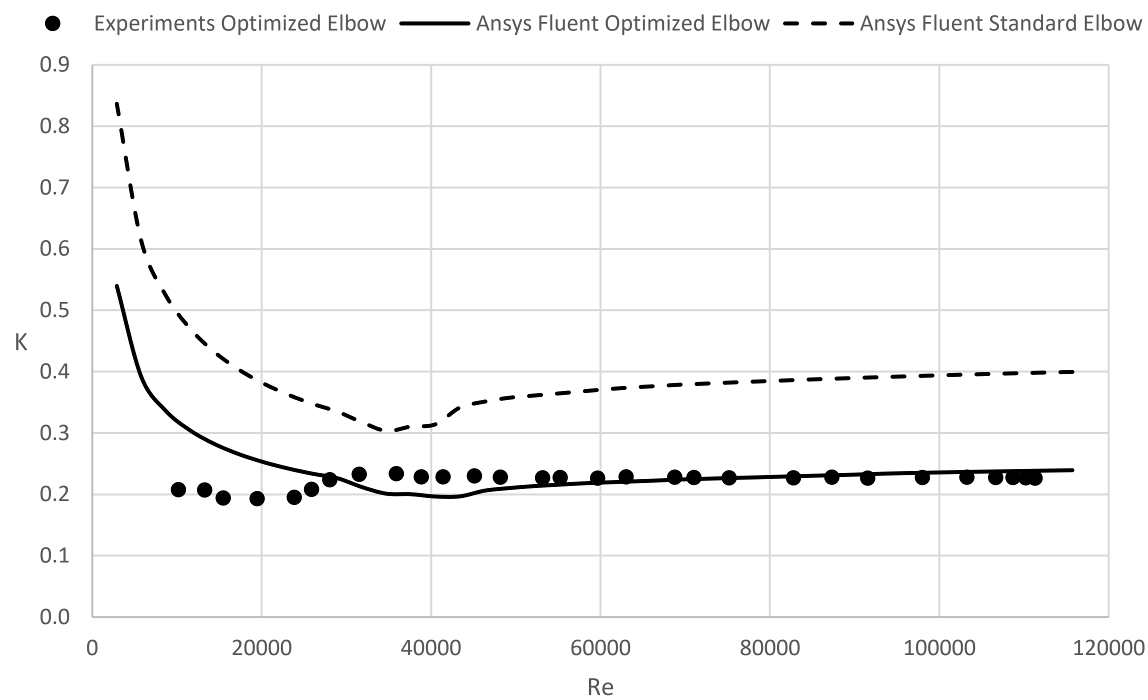

Figure 9b) Pressure coefficient versus *Re* for standard and optimized elbows [7].

Sculptor

Sculptor Morph and Sculptor Morph Analysis provides real-time morphing technology for STL files, point cloud data, CAD data and analysis mesh data. Arbitrary Shape Deformation (ASD) technology can be used to find even better designs than shown in Figures 8 – 9. The case file from Ansys Fluent can be imported directly to Sculptor, see Figure 10a).

To find a new design to further optimize the elbow, a software called Sculptor was used, which is an application built to modify the geometry of CFDs. It does this by creating a control volume surrounding the mesh with numerous control points that can be manipulated to morph the mesh into the desired shape as shown in Figure 10a).

With the control volume defined, the next step is to create custom control groups which allows the user to designate exactly how the geometry can be changed. Then the user needs to open the optimizer. To optimize a design, Sculptor takes what the user defines as an improvement and produces numerous iterations of slight modifications based upon the control groups created earlier. Each iteration is loaded into Fluent and analyzed via a command prompt line and a script file. The results of this analysis were read by Sculptor with a transcript file, which then makes another iteration and repeats the process.

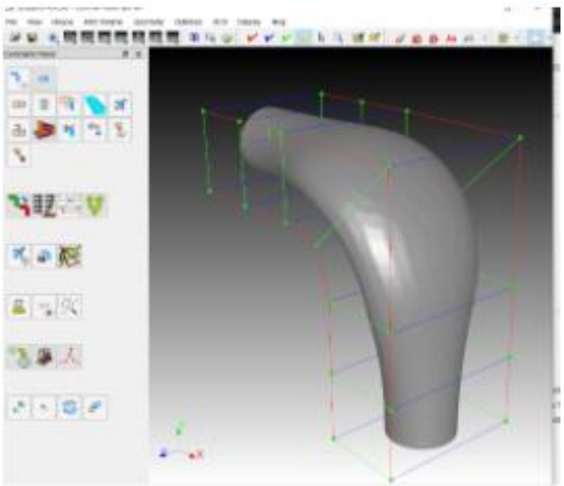 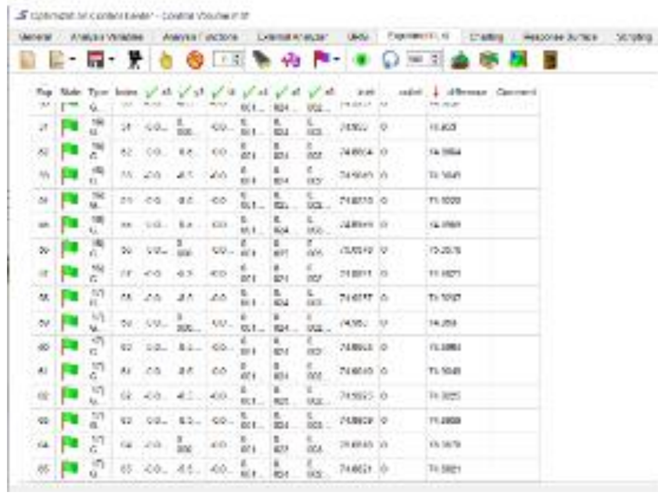

Figure 10a) Elbow control volume defined   Figure 10b) Sculptor optimizer results

With the results of each iteration displayed, as shown in Figure 10b), the run containing the most optimized design can be opened and exported as an STL file to be made ready to 3D print.

An example design with pressure drop 32.86 Pa is shown in Figure 10b). This pressure drop can be compared with 91.14 Pa for the original standard elbow design. This is a remarkable decrease of 64% in pressure drop for the optimized design.

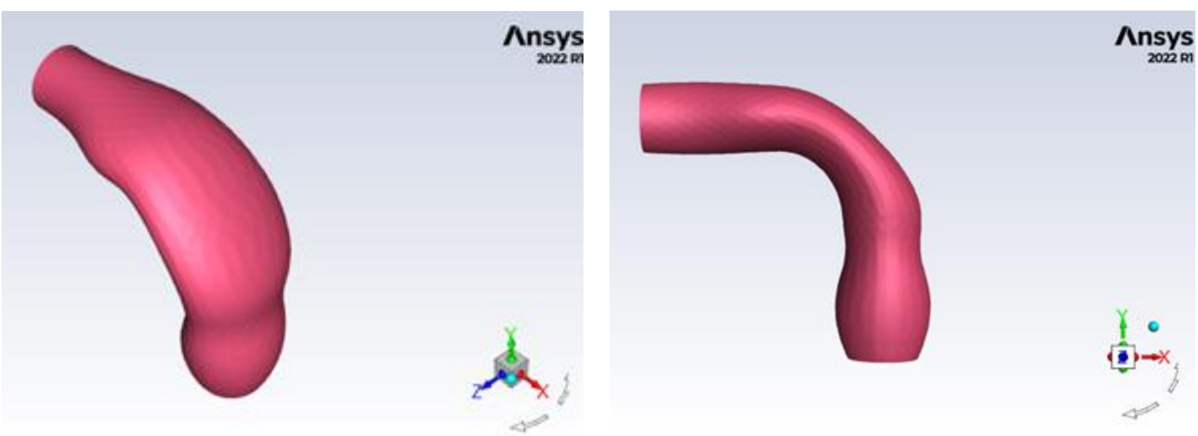

Figure 10b) Optimized elbow design from Sculptor and Ansys Fluent [7].

Elbow 3D Printing

After designing the new elbow in Sculptor, the next step is to convert the design/mesh to an STL elbow file that can be 3D printed. To do that the optimized elbow STL file needs to be opened in SOLIDWORKS. Initially, the elbow's diameter is 0.03868 in. Using the scaling option to scale the model up by 45.24 to get the required dimensions 1.75 inch for the inner diameter of the elbow opening. Next, using the boss-thicken function, a thickness of 0.375 in. can be added to the object.

The file can be saved as a SLDPRT and then uploaded into Fusion 360. Adding a mesh-BREP enables the user to create a sketch. Using the create sketch option one can create a 3-point circle to make a lip for the elbow. Once the circle with diameter of 2 inches is drawn, one can use the extrude-cut option to create a lip with a depth of 0.375 inch. Next, extrude-cut the hole of diameter 1.75 inch through the entire elbow to allow airflow. The document can be saved and sent to print on the 3D printer. The da Vinci 1.0 Pro 3D printer takes around 40 hours to fully print the optimized elbow design.

Student Involvement

A group of six students worked together on the optimized elbow project during the Spring semester of the 2022 academic year. This project began with the testing of a variety of elbow designs using the setup shown in Figure 3. The goal of this preliminary testing was to compare the effects of a variety of factors on the pressure drop Δp and the pressure coefficient K values for the different designs. The factors included the material used to 3D print elbows, the effects of coating the elbow, and different elbow designs. The experimental data obtained were tabulated and plotted for proper comparison. A couple of the comparison plots obtained are seen in Figure 12a) – 12b).

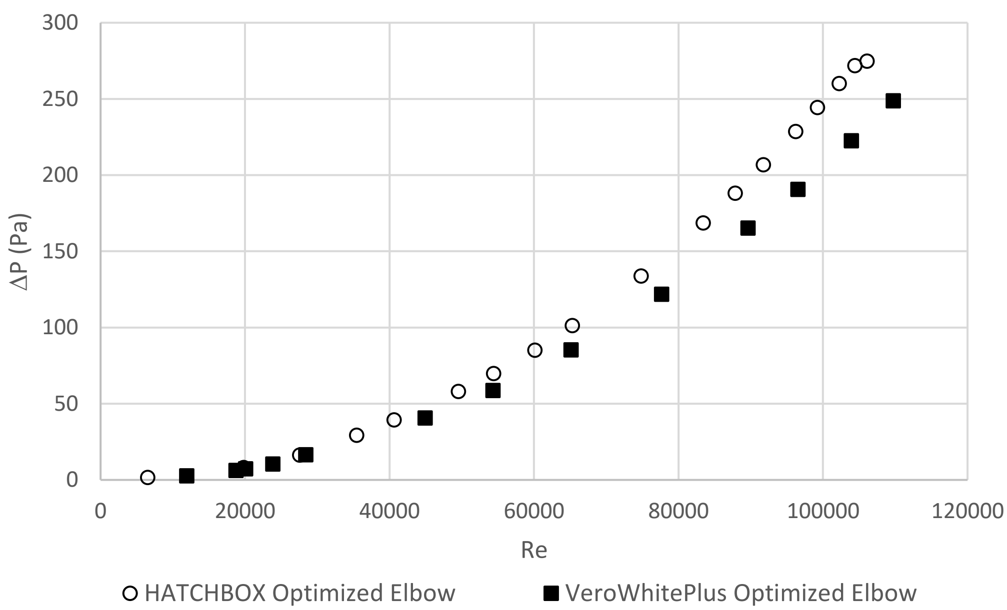

Figure 12a) Pressure drop comparison for two different 3D printing materials

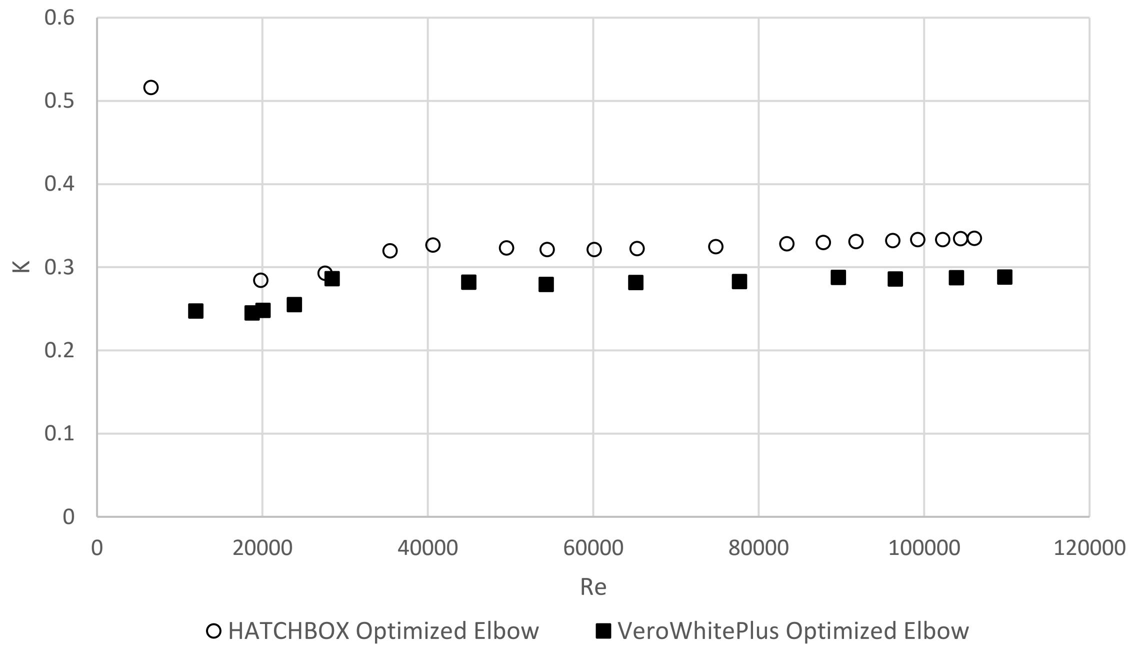

Figure 12b) Pressure coefficient comparison for two different 3D printing materials

While some students ran these tests, others worked on achieving a new optimized design in Sculptor. First, the students created custom control groups, allowing them to define the parameters of the design geometry that could be modified to optimize the design. The software then ran multiple iterations with small modifications to the control groups, allowing the students to identify the design with the most optimized result. The design found during the course of the semester project is seen in Figure 13. The students then used this design to obtain a velocity magnitude contour plot in Ansys to observe the changes in velocity magnitude of air through the elbow as seen in Figure 14. This was also compared to other previously obtained velocity magnitude contours for the standard 90-degree elbow. The optimized design generated by Sculptor resulted in a pressure drop of 74.89Pa, which is a 23.6% increase in efficiency.

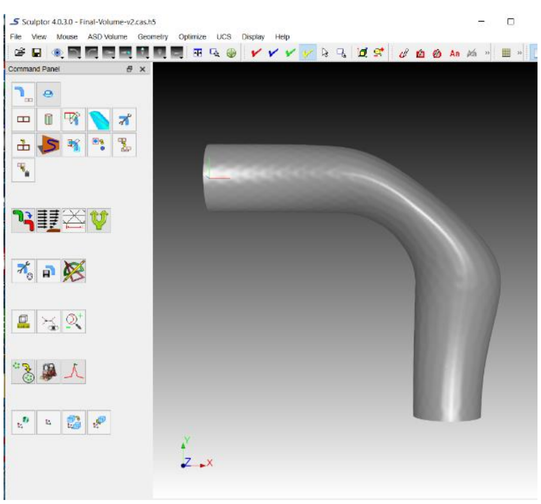

Figure 13. Student optimized elbow design in Sculptor

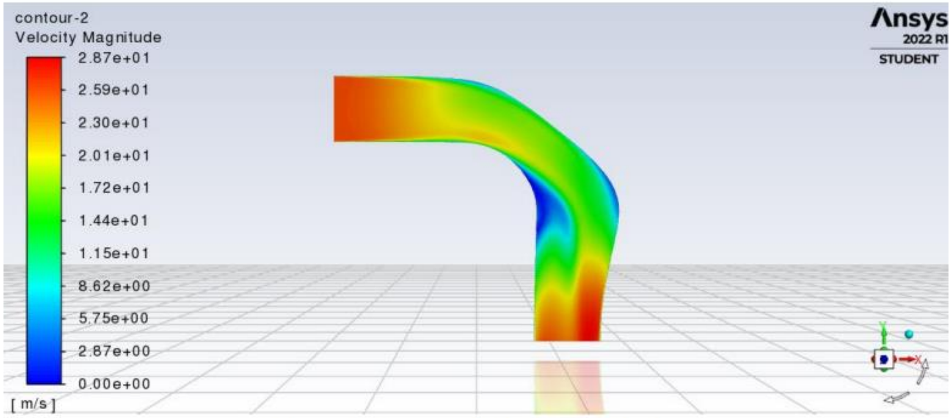

Figure 14. Velocity magnitude contour for student optimized elbow design

In the final steps of the project, the students attempted to 3D print the optimized design as shown in Figure 13. Throughout this process, the students encountered a variety of issues related to the meshing and scaling of the designed elbow. After 3D printing the elbow, the students were responsible for cleaning out the support material from the interior. This was done using a hammer, screwdriver, and special sanding tools. It was particularly difficult to clean out the interior of the bend due to its irregular geometry. Upon cleaning the elbow, the students fractured the elbow. Although they tried to seal the fracture with glue, it is possible that this fracture still had a significant negative effect on the prototype due to its ability to cause undesirable air leaks during testing. As the students continued the process of cleaning out the elbow, they also noticed an issue in the elbow's print. The internal radius of the elbow was a lot smaller than all the elbows that they had previously tested in the lab, making it impossible to compare the efficiency of the elbow with other previously tested optimized and standard elbow designs. In this situation, it would have been better for the students to reprint the elbow for a proper design comparison, but they were unable to do so due to lack of time.

This project still brought important insight for the students involved. The students learned to use Sculptor, a software that they can greatly benefit from when coupled with Ansys. This project gave the students real-world experience with 3D printing, experimental measurements, and comparison studies. The students were also able to examine a variety of 90-degree elbow designs and test new, potentially pioneering designs. This, at its core, was an experience that delved into the core of the engineering design process.

Student Assessment

The overall objective was to engage students in a fluids related project. This project was therefore included in the fluid mechanics course during the Spring 2022 semester. For this course, the students wrote the final project report. The course project contributed to 10% of the final grade in the fluid mechanics courses.

The student performance was assessed based on written final report but also on weekly progress reports and achievements in relation to the definition of completeness for the project. In the weekly progress reports, students provided evidence of work completed during the past week and include an updated time line for the project. The project final report generally included an abstract followed by an introduction to the topic, a theory section, a results section, a section with conclusions, recommendations for the project, and references.

The project described in this paper contributed to certain university course outcomes such as personal resilience, intellectual pursuit, global engagement and bold vision as shown in Table 1. The project was not the only component that contributed to Table 1 for this course. Other evaluation procedures such as quizzes, homework problems, labs, exams, and final exam determined the final level of contribution.

OUTCOMES	Significant	Moderate	Minimal
Personal Resilience			
An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.		X	
An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.		X	
An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.		X	
Intellectual Pursuit			
An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.		X	
An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.		X	
An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.		X	
An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.		X	
Global Engagement			
An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.			X
An ability to communicate effectively with a range of audiences.			X
An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.			X
Bold Vision			
An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.		X	
An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.		X	
An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.		X	
An ability to apply Christian principles of stewardship.			X

Table 1. Fluid mechanics course inventory for university student learning outcomes

The student learning outcomes specific for the fluid mechanics course were to discuss and explain the following:

A. Demonstrate fundamental concepts of fluids and the forces present in fluids at rest.
B. Use the basic equations governing fluid dynamics to calculate various properties of fluids in motion.
C. Demonstrate dimensional analysis and dimensionless ratios in order to predict actual fluid flow characteristics from measurements made on scale models.
D. Use the governing equations to calculate the properties of fluid flow in closed conduits, over immersed bodies, and in open channels.

The project included components related to outcomes B – D.

A survey was given to the six students who worked on the project. Students rated the extent to which each objective was achieved for them as a result of completing the optimized elbow project., with a score of ten representing extremely helpful while a score of one representing not helpful, even to the slightest. The questions and average scores are included in Table 2.

1. The Optimized Elbow project helped me to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgement to draw conclusions: 9.7
2. The Optimized Elbow project helped me to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, societal, environmental, and economic factors: 7.8
3. The Optimized Elbow project helped me to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives: 8.7
4. The Optimized Elbow project helped me to identify, formulate and solve complex engineering problems by applying principles of engineering, science and mathematics: 8.3
5. The Optimized Elbow project helped me to recognize ethical and professional responsibilities in engineering situations and make informed judgements, which must consider the impact of engineering solutions in global, economic, environmental and societal contexts: 7.0
6. The Optimized Elbow project helped me to communicate effectively with a range of audiences: 6.5
7. The Optimized Elbow project helped me to acquire and apply new knowledge as needed, using appropriate learning strategies: 8.5

Student Recommendations

The completion of this project was hampered by several factors. The most significant was the time lost due to complications with the Sculptor software. A possible solution to minimize the time loss is to explore multiple optimization software that the team can divide time in to potentially making progress even if the use of another software fails.

The other major issue was removing the support material when the elbow was printed. Due to the geometry of the part and limitations of the 3D printers available, the elbow was completely filled with support material and a considerable amount of time was devoted to cleaning out the material. There are a few solutions to this problem. The first is to purchase a printer with a larger print area so that an optimal print orientation can be found that minimizes the support material printed inside the elbow. Another solution would be printing the elbow in two halves, thus making removing the support material easier. A third solution is purchasing a dual extruding printer with a water-soluble material used as the support material. The fourth possible but more inconvenient solution is further shrinking the scale of the elbow so that it could fit optimally in the printers available.

It would have also been beneficial to have a more efficient method of measuring the pressure drop including the use of National Instruments LabView software. When the pipe flow average velocity was low the pressure difference fluctuated a lot. A better approach for determining average values of pressure drop at lower velocities would be desirable.

Benefits of Reproducing this Project in a Classroom Setting

Reproducing this project in a classroom setting can benefit engineering students significantly. Firstly, utilizing Sculptor software to replicate this project has the potential to generate new and innovative elbow designs that still need to be tested or discovered. Through testing and simulations, engineering students may discover a groundbreaking elbow design. However, one of the main issues with these designs is that their geometries can be challenging to produce and manufacture on a large scale. Therefore, students may discover a design that introduces minimal complexities and closely resembles existing elbow designs with only slight modifications that can significantly enhance the elbow's effectiveness and efficiency.

This project is an excellent introduction for students to a partially unsolved engineering problem. It allows students to engage in the engineering research, design, and development phases. Moreover, students who aspire to pursue graduate-level education may find this project intriguing as it can help familiarize them with the research environment. Notably, this project accomplishes the course's learning outcomes and provides students with practical experience applying fluid dynamics principles to real-world systems.

Conclusion

This paper has shown a project where the students designed, built and tested a 90-degree elbow measurements apparatus and compared experiments with Sculptor and Ansys Fluent simulations. The project offered an opportunity for students to experience classroom learning together with real-world applications of the optimized design process.

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