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A Senior Design Project on the Kelvin-Helmholtz Instability

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A Senior Design Project on the Kelvin-Helmholtz Instability

Students designed a Kelvin-Helmholtz instability test set up for the fluids laboratory. This paper describes a project where a group of two undergraduate engineering students in the senior design course designed, built, and tested a Kelvin-Helmholtz fluid flow apparatus for visualizations of instabilities. The paper will also provide details of outcomes for the project, faculty observations, and assessment of student work.

The two senior students had to choose materials, minimize production cost, and determine fabrication techniques for the apparatus. The same students designed the apparatus using SolidWorks, and ANSYS Fluent software was used by a third student who was not on the senior capstone team to simulate the Kelvin-Helmholtz instability.

Introduction

This project involved the design, building and testing of a Kelvin-Helmholtz instability apparatus by undergraduate engineering students. The laboratory will enable students to conduct visualizations of the waves that develop due to the instability.

The Kelvin-Helmholtz instability is a classical problem originally studied by Helmholtz[1] and Kelvin[2]. The mechanism causing the instability has been studied in detail by Lamb[3], Bachelor[4], Drazin and Reid[5], Chandrasekahr[6], Craik[7], and many others. The Kelvin-Helmholtz instability can appear at the interface of two fluid layers flowing with different velocities and with different densities. For a complete review of this instability, please see Thorpe[8]. Thorpe[9-12] found that the Kelvin-Helmholtz instability can be generated and visualized by tilting a tube that contains two fluids at different densities.

Theory

We will look at the inviscid theory for the Kelvin-Helmholtz instability in terms of a sinusoidal disturbance between two fluids with velocities U_1, U_2 and densities ρ_1, ρ_2.

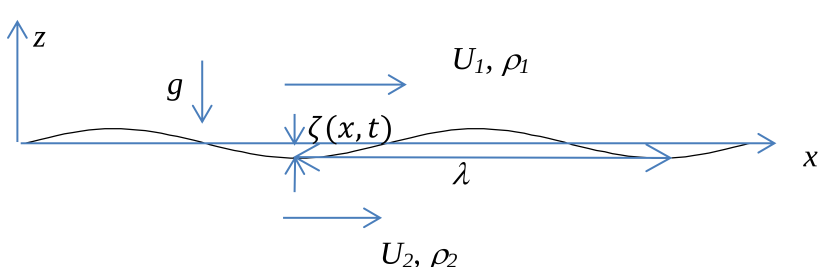


Figure 1. Development of Kelvin Helmholtz instability from a perturbation

We find the following equation for the frequency from inviscid theory

$$\omega = \frac{1}{2}[k(U_1 + U_2) \pm \sqrt{\frac{4(\rho_2-\rho_1)gk}{\rho_2+\rho_1} - k^2(U_1 - U_2)^2}] \quad (1)$$

The frequency is complex with the associated growth of Kelvin-Helmholtz instability waves when the expression under the square root is negative

$$\frac{4(\rho_2-\rho_1)g}{\rho_2+\rho_1} < k(U_1 - U_2)^2 \quad (2)$$

Using the definition of wave number as inversely proportional to the wave length

$$k = \frac{2\pi}{\lambda} \quad (3)$$

We find that waves are amplified and develop when their wave length fulfill the condition as shown in equation (4). A boundary below or above the interface can destabilize the flow as shown by Hazel[13].

$$\lambda < \frac{\pi(\rho_1+\rho_2)(U_1-U_2)^2}{2g(\rho_2-\rho_1)} \quad (4)$$

Experimental Set-Up

The design constraint that the students had to follow was that the design had to be safe to use and user friendly. Furthermore, it was important to keep the cost down as much as possible and within the given budget. The two fluids chosen for the apparatus were picked due to being inexpensive and having the necessary densities and dynamic viscosities to allow the Kelvin-Helmholtz instability to form in the chosen geometry. Originally, the student group's project definition of completeness included constructing two apparatuses of different scales but as the semester continued, time constraints and funding became an issue. It was therefore decided upon to focus attention on only one apparatus.

The original apparatus that the students designed is shown in Figure 2a). The fixed support was designed first. Next, the group continued with designing the remaining parts such as the lids, top support, and the connection between the tube and the apparatus. The original design was a truss frame with hollow metal square tubes and cables. For several reasons the decision was made to instead use a circular pipe, eliminating the cables from the final design. The frame was modified so that it would have a relatively low center of gravity and a T-shape. This design allows for easy transportation of the apparatus that has four casters. The tube is mounted in an enclosure that prevents the tube from rotating more than 8 degrees. The final design is shown in Figure 2b). Static structural testing of the designed frame was made using the SolidWorks Simulation software.

Once the design was complete, the construction phase began. The frame was welded together and once the apparatus was complete, the testing phase was ready to begin. All the data and pictures from the tests were collected using multiple video cameras. The students attached a ruler to the apparatus as a reference length scale. At first the group tried to use vegetable oil and water for the fluids but the decision was made to switch to fresh and salt water as the fluids. Initially, blue food coloring was used for the salt water and the fresh water was left uncolored. However, during testing the instability was only slightly visible and the contrast between the two fluids was not great. In the next step the salt water was colored orange and the fresh water was colored blue. The students went through the video frame by frame analyzing the results.

The experiments were carried out in a tilted circular tube where the maximum angle of tilt was 8 degrees. The clear polycarbonate tube had an inner diameter of 196.85 mm and an outer diameter of 203.2 mm. The length of the tube was 2400 mm so that the length to inner diameter ratio was 12.2. The tube can be tilted about a horizontal axis that is located 240 mm below the centerline of the tube. The tube is also supported by a base structure made of welded 60 mm OD steel tubing. The transparent tube is locked to a support box that is attached to the pin for the tilting motion. The tube has a Plexiglas lid with an o-ring inserted at both ends.

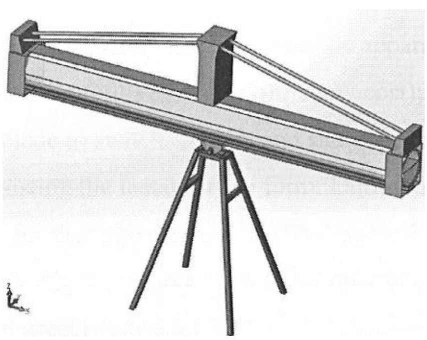


Figure 2a). Original design of apparatus

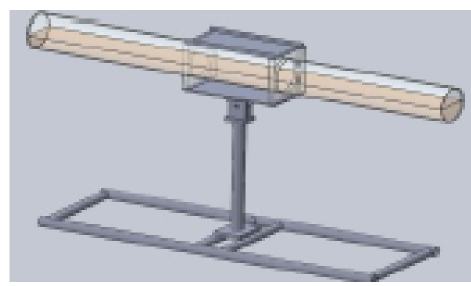


Figure 2b). Final SolidWorks design

Figure 2c). Finished experimental set-up

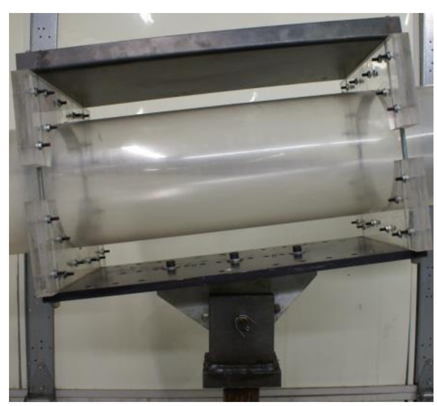


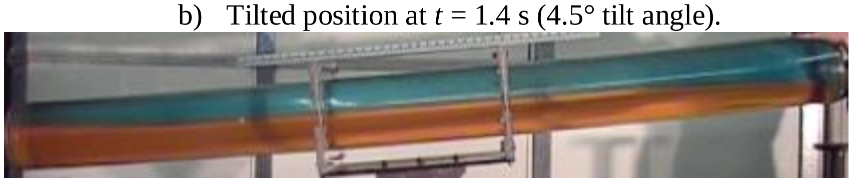
Figure 2d). Support structure for tube

The tube was slowly filled with fresh water and salt water from an open valve connected at one end of the tube so that the two fluids did not mix. Orange dye was used to color the bottom layer of salt water and blue dye was used to color the top fresh water layer in order to create a visible interface between the two fluids. The tube was slowly tilted off the horizontal to an 8° tilt angle in 3.5 s. Waves developed after the tilt angle had been set and the growth of the waves is visible in Figure 3. When the tube has reached the 8° tilt angle, we see that the displacement of the interface between the two fluids is most evident at both ends of the tube and that the interface in the middle section has not moved. The waves started to develop in the middle one-third section of the tube and it took approximately 3 seconds for the waves to amplify and break down. At the end of the sequence of the pictures we see that the heavy fluid has gathered to the left and the lighter fluid is positioned above the heavier fluid as expected.

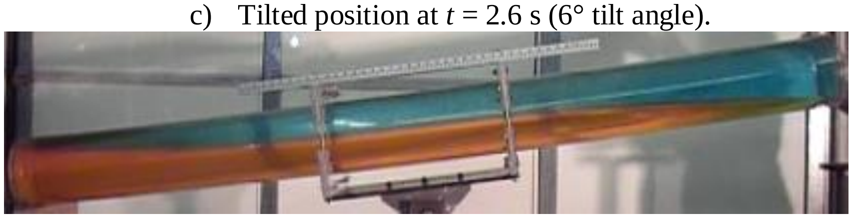
Figure 4 is showing a close up view of the instability. The wave length was determined to be approximately $\lambda = 0.09$ m and the corresponding wave number $k = 0.07\ \mathrm{m}^{-1}$. In comparison, inviscid theory using equation (4) predicts that the Kelvin Helmholtz instability is amplified for all wave lengths smaller than $\lambda = 1.1$ m.

a) Horizontal position at $t = 0$ s.

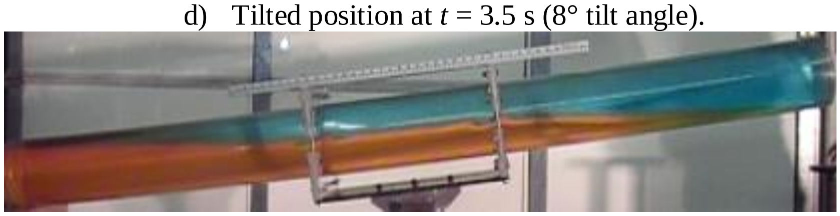
b) Tilted position at $t = 1.4$ s (4.5° tilt angle).



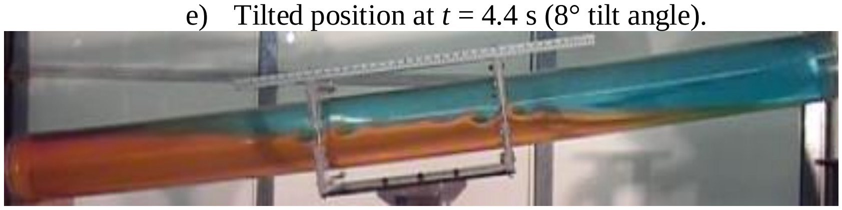
c) Tilted position at $t = 2.6$ s (6° tilt angle).



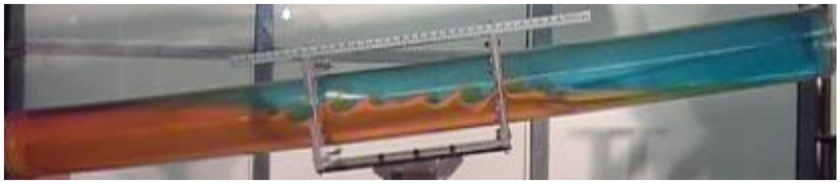
d) Tilted position at $t = 3.5$ s (8° tilt angle).



e) Tilted position at $t = 4.4$ s (8° tilt angle).



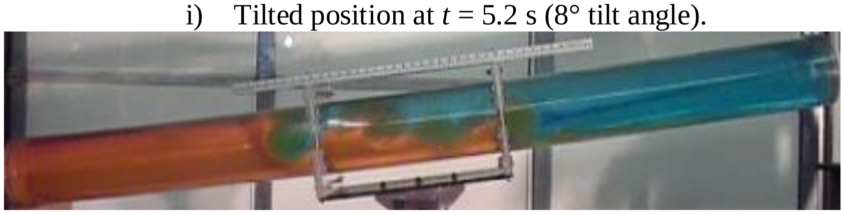
f) Tilted position at $t = 4.6$ s (8° tilt angle).



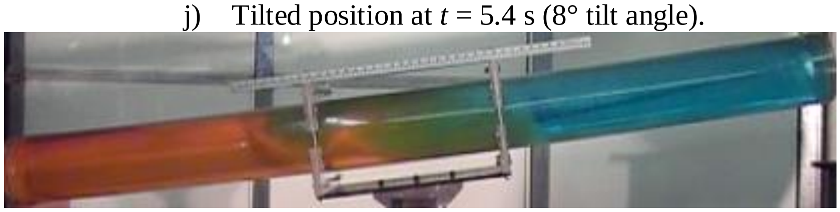
g) Tilted position at t = 4.8 s (8° tilt angle).

h) Tilted position at t = 5.0 s (8° tilt angle).

i) Tilted position at t = 5.2 s (8° tilt angle).



j) Tilted position at t = 5.4 s (8° tilt angle).



k) Tilted position at t = 6.0 s (8° tilt angle).

Figure 3. Development of the Kelvin-Helmholtz instability over time

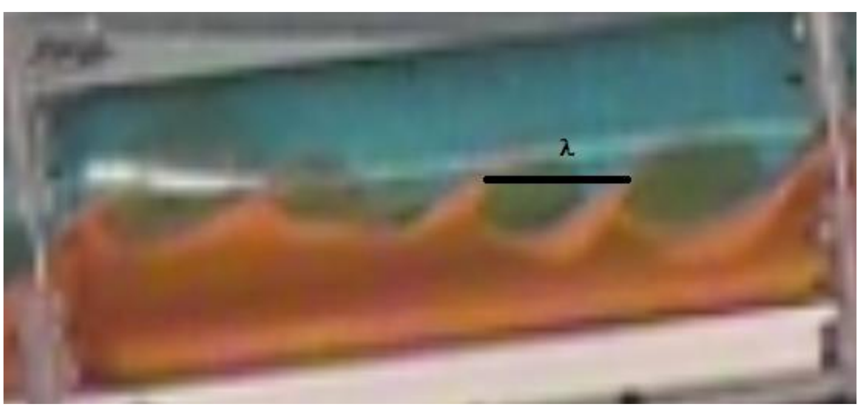


Figure 4. Magnified view of the Kelvin-Helmholtz instability

ANSYS Fluent Flow Simulations

The simulations of the Kelvin-Helmholtz instability were performed using ANSYS Fluent software. These simulations considered a volume of water with a density of 998.2 kg/m^3 resting above a volume of liquid salt-water with a density of 1074.9 kg/m^3. The corresponding dynamic viscosity values used were 0.001002 kg/m·s for the water and 0.001259 kg/m·s for the salt-water, see Sharqawy, Lienhard, and Zubair[14]. The instability developed naturally without any need for artificial triggering. The contours function in the graphics and animations tabs were used to provide volume fraction visualization as the solver was running, providing a movie of the simulation.

The general settings chosen in ANSYS Fluent were a pressure-based solver with absolute velocity formulation for a transient study in the 2D plane space. The multiphase model used in Fluent was a volume of fluid model with two Eulerian phases and default settings for volume fraction parameters. The primary phase was set to the water and the secondary phase was the salt-water phase. Gravitational acceleration was set in the general settings of Fluent with an X component of -1.36529 m/s^2 and a Y component of -9.71453 m/s^2 in order to simulate an 8 degree tilt angle of the tube.

The rectangular computational domain was the same as the projected area in the experiments with dimensions *width* x *height* = 2400 mm x 200 mm which was used in all of the trials. The flow region was evenly split with the fresh water on the top and the salt water below which was a standard setting. The computational domain was meshed using a biased mesh in the vertical direction, see Figure 5a). The simulation was run with a time step of 0.01s during 650 time steps for a total of 6.5 s. Surface tension interaction between the two layers was set to 0.00148 N/m.

The streamwise development of waves including the volume fraction during the simulation is shown in Figure 5b). The waves are clearly visible and they only appear in the middle third section of the tube as was also the case in the experiments. At the end of the simulation, most of the heavier salt water fluid has moved towards the left end of the tube and the lighter fresh water fluid is concentrated on the right hand side of the tube. The wave length of the instability in the simulations was 0.15 m which is 67 % larger than in the experiments.

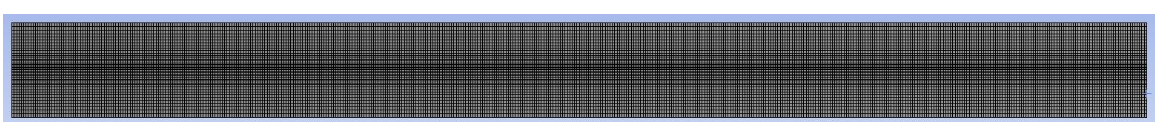
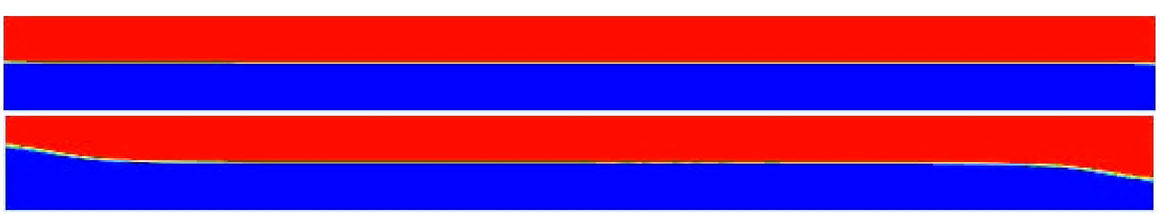


Figure 5a). Details of the mesh used in simulations



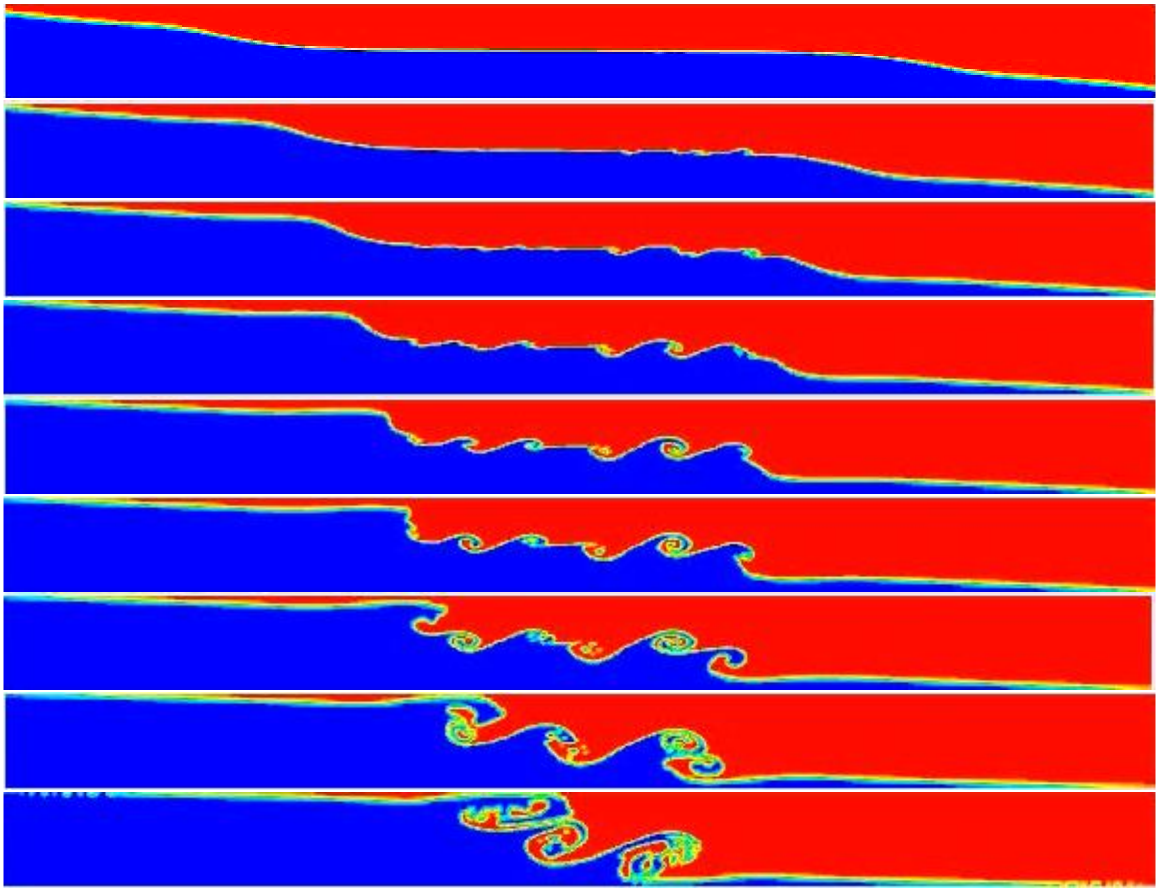


Figure 5b). Contour of volume fraction for water at t = 0.0, 1.4, 2.6, 3.5, 4.3, 4.7, 5.0, 5.2, 5.4, 5.6, 6.0 and 6.5 s.

Student Involvement

Students have been involved in all phases of this project including design, building and testing of the Kelvin-Helmholtz instability project. All engineering student are required to complete a capstone senior design project. Design and building was accomplished during fall semester while testing and ANSYS Fluent simulations were started during the following spring semester.

The students worked on the senior design project outside of scheduled class hours. Weekly progress reports were submitted and contributed to 5% of the course grade while the written project progress report contributed to 10% of the course grade. This project is now included as ANSYS Fluent simulations of the Kelvin-Helmholtz instability in the Finite Element Methods course and will be included as a lab in a new special topics course titled Hydrodynamic Stability.

Students designed the apparatus using SolidWorks® software. SolidWorks® Simulation software was used for structural simulations of the final design. Moreover, students have been involved in the building of the apparatus under supervision of the technician at the engineering department.

Student Response

Through this simulation and research, the third student involved with ANSYS Fluent flow simulations gained knowledge of key tools used in industry. The student was exposed to various techniques of meshing and solver setup, which will be useful in his later career.

This project also sparked an interest in further research for the student. Research skills such as thinking creatively and documenting procedures and results were bolstered. The student involved with the flow simulations is now able to model a physical situation and produce repeatable results. Failure in producing results has become a tool rather than a setback, the student realizing that each failure teaches something new about the capabilities of the software and the complexity of the phenomena being studied.

Assessment and Outcomes for the Capstone Senior Design Project

The overall objective was to engage the students in a capstone senior design project. For the Senior Design and Research course, the students submitted a written project proposal (10% of the final grade) and a written research report (5% of the final grade). Furthermore, the students made an oral project proposal (10% of the final grade) and an oral research presentation (5% of the final grade). An overview of the final grade contribution of the senior design project is shown in Table 1.

	Evaluation Procedures
Oral Research Presentation	5%
Written Research Report	5%
Oral Project Proposal	5%
Written Project Proposal	10%
Resume	5%
Design Process Quiz	5%
Professional Ethics Quiz	5%
Oral Project Progress Report	10%
Written Project Progress Report	10%
Weekly Progress Reports	5%
Project Progress	15%
Individual Contribution to Project Progress	15%

Table 1. Final grade contribution for different parts of the senior design project

The student performance was assessed based on written reports but also on weekly progress reports and achievements in relation to the definition of completeness for the capstone senior design 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 evaluation of the project progress and of individual contribution was determined by the project advisor and was based on the quality, timeliness, and thoroughness of the work. The evaluation of the seminar presentations was determined by the entire faculty and based on the quality, organization, clarity, and style of the presentation. The project 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 capstone senior design project described in this paper contributed to certain university course outcomes and proficiencies/capacities such as intellectual creativity, critical thinking, communication skills, leadership capacity and interpersonal skills as shown in Table 2. Table 2 is copied from the syllabus of the Senior Design and Research as an example. The project was not the only component that contributed to Table 2 for this course. Other evaluation procedures such as quizzes determined the final level of contribution as shown in the table.

Significant Contribution – Addresses the outcome directly and includes targeted assessment
Moderate Contribution – Addresses the outcome directly or indirectly and includes some assessment
Minimal Contribution – Addresses the outcome indirectly and includes little or no assessment
No Contribution – Does not address the outcome

Outcome – Intellectually Alert Proficiencies/Capacities	Significant Contribution	Moderate Contribution	Minimal Contribution	No Contribution
Critical thinking	X			
Information literacy		X		
Global & historical perspectives			X	
Aesthetic appreciation			X	
Intellectual creativity		X		
Communication skills	X			
Interpersonal skills		X		
Leadership capacity		X		

Table 2. Senior design and research course inventory for university student learning outcomes

The student learning outcomes specific for the senior design and research course are to

- Demonstrate, in a controlled environment, the knowledge and skills developed during the previous years of engineering study.

- Become proficient not only in engineering ability but also in both written and oral communication ability.

- Work as part of a team on a design project selected by the team and approved by the advisor and engineering faculty. The team is expected to perform a reputable job of design, implementation, execution, and testing of the project with continuous progress during the duration of the project.

- Successfully complete the design project, which is culminated in a final written and oral report.

- Design a system to meet realistic design constrains and goals, referencing applicable engineering standards.

Student benefits from this project included enabling the students to conduct visualizations of instabilities in fluid flows. Furthermore, to the students benefit the project provided an opportunity to understand the effects of shear on the stability of the flow. While students gained insight into the experimentation of shear flows, insight into the design process and flow simulations was also obtained. The direct comparison between flow simulations and visualizations was beneficial to the engineering students.

Conclusions

This paper has shown a combined experimental and simulation study of the Kelvin-Helmholtz instability. It was shown that the instability develops in the experiments over a time period of approximately 3 seconds when the tube is tilted at 8 degrees from the horizontal. ANSYS Fluent simulations were used to study the spatial and temporal development of the waves as they were developing without being triggered. The cost of building the experimental set-up described in this paper was $1,225. The project cost is detailed in Table 3.

Item	Qty	Description	Vendor	Price
Tube	1	Polycarbonate – Hollow Tube – Clear 8 OD x 7.75 ID – 8 feet	Kmac Plastics LLC	$460.96
Brass Ball Valve	1	3/8” Vented Exhaust 600 WOG 150 WSP Full Port Thread End Forged	Fastenal	$27.10
Plexiglass	2	1” thickness, Clear Plexiglass-acrylic sheet-cast, 7.75” x 7.75 “	Professional Plastics	$28.32
Plexiglass	4	1/2” thickness, Clear Plexiglass-acrylic sheet-cast, 12” x 12 “	Professional Plastics	$71.52
O-ring	2	EPDM O-ring, 9557K262, 1/8 fractional width	McMaster	$8.17
Threaded Rod	1	3/8 in. x 72 in. Zinc Threaded Rod	Home Depot	$5.96
Casters		Everbilt 2 in. Threaded stem with Brake Non-		$17.88

	4	Marking Rubber Caster	Home Depot	
Steel Pipe	1	2" SCH 80 (2.375 OD x .218 wall) A-500 Structural Steel Pipe, 16 ft long	MetalsDepot	\$151.04
Steel Pipe	1	1-1/2" SCH 80 (1.9 OD x .2 wall) A-500 Structural Steel Pipe, 8 ft long	Metals Depot	\$65.28
Steel Plate	1	3/8 inch thick A36 Steel Plate, 1ft x 1ft	Metals Depot	\$39.30
Steel Plate	1	1 inch thick A36 Steel Plate, 1 ft x 1 ft	Metals Depot	\$73.51
Steel Plate	1	1/2 inch thick A36 Steel Plate, 1 ft x 2ft	Metals Depot	\$134.05
Steel Sheet	1	14 GA (0.075") Steel Sheet Hot Rolled, 1 ft x 2 ft	Metals Depot	\$13.44
Aluminum Plate	1	1 inch thick 6061-T651 Aluminum Plate, 1 ft x 1 ft	Metals Depot	\$55.12
Shipping Charges				\$73.25
Total				**\$1,225**

Table 3. Detailed project cost

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