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Go with the Flow! Design and testing of a modular kit for at-home hands-on fluid dynamics instruction

Giorgio Arzate-Juarez, University of Maryland College Park

Giorgio Arzate-Juarez is a fourth-year mechanical engineering student with a strong interest in aerodynamics and fluid mechanics.

Daniel Boback, University of Maryland College Park
Annabelle Diep, University of Maryland, College Park

Annabelle Diep is a second-year computer engineering student. She aspires to become a software engineer and work in the cybersecurity field.

Anna E Dyson, University of Maryland College Park
Jeyadave Nuntha Kumar, University of Maryland College Park

Jeyadave Nuntha Kumar is a fourth-year aerospace engineering student pursuing minors in Mathematics and Global Engineering Leadership. His research interests are in numerical analysis and computational fluid dynamics, with a focus on developing and validating high-fidelity simulation methods.

Vrunda Patel, University of Maryland, College Park

Vrunda Patel is a second-year undergraduate student majoring in mechanical engineering. She takes part in fluid dynamics and analytical chemistry research focusing on fabrication and prototyping.

Terrence Pierce, University of Maryland College Park
Joshua Sambrano, University of Maryland College Park

Joshua Sambrano is a junior undergraduate student majoring in aerospace engineering. He aspires to work in the manufacturing industry and engage in manual design.

Siloe-Noah Selebangue, University of Maryland College Park
Alayna Isabella Sheahy, University of Maryland College Park

Alayna Sheahy is a junior undergraduate majoring in chemical engineering. Her academics has focused on core principles of transport phenomena, reaction engineering, and thermodynamics, which she hopes to apply to applications in drug development and delivery.

Shravan Suresh, University of Maryland College Park
Marklin Yi, University of Maryland College Park
Andrew Elby, University of Maryland, College Park

Andrew Elby's work focuses on student and teacher epistemologies and how they couple to other cognitive machinery and help to drive behavior in learning environments. His academic training was in Physics and Philosophy before he turned to science (partic

Dr. Ken Kiger, University of Maryland, College Park

Go with the Flow! Empowering hands-on individual fluid dynamics education

G Arzate-Juarez, D Boback, A Diep, A Dyson, J Nuntha Kumar, V Patel, T Pierce, J Sambrano, S Selebangue, A Sheahy, S Suresh, M Taesun Yi, A Elby, K Kiger

University of Maryland, College Park

Hands-on laboratory experiments are a standard component of many introductory college-level courses in fluid dynamics. When done well, such exercises form a key component of an active-learning framework [1], providing an opportunity to reflect on and test students' conceptualization of theoretical tools central to the subject. Traditionally, these instructional experiments are performed in a dedicated laboratory space with large and expensive equipment, which often limits the opportunities for students to work creatively with the devices and critically explore the principles they are tasked with testing.

One way to mitigate the shortcomings of a centralized laboratory would be to provide experimentation kits that each student can use on their own or in pairs, potentially in spaces outside a dedicated laboratory. The obvious challenges to this approach are size and cost, though they are continually reduced by the advancement of more sophisticated consumer technology. The inspiration for this work stems from our institution's success with flipping the mechanical engineering electronics course sequence to "at-home" labs in 2015 using miniature USB oscilloscopes, function generators, and Arduino microcontrollers. While we were not the first to see the benefits of this approach (see, for example, [2]), we quickly appreciated students' enhanced interest and sense of mastery of the material, as evidenced by the increased use of electronics and sensors in their senior capstone design projects. Two recent studies demonstrating the effectiveness of "at-home" kits are given by [3] and [4], the latter of which studied a cohort of 290 students, demonstrating an enhanced appreciation of learning outcomes, intellectual challenge, and understanding of the concepts in practical applications.

To adopt a similar approach to fluid dynamics laboratories, the primary hurdle comes from producing compact and inexpensive devices with sufficient precision to achieve the learning objectives. One literature-based example is Starks, et al [5], who developed a series of 18 low-cost exercises that ranged from uncertainty analysis to momentum flux from a fan. Our current work is enabled by the advent of consumer-grade miniature ducted fans and motor controllers used in the remote-controlled aircraft industry and low-cost DC power supplies created for residential LED lighting applications. Using a set of readily available off-the-shelf components (motor, ducted fan, motor controller, power supply), we made the basis for a modular kit to enable six key experiments that use the same fan housing: 1) manometry with velocity and flow rate measurement, 2) momentum flux thrust stand, 3) drag measurement wind tunnel, 4) pipe flow losses, 5) fan characteristics, and 6) boundary layers and flow separation. The current work reports on the detailed design of the thrust stand and manometer components and the preliminary results of testing the prototype device with small focus groups of students. Currently, the tests have been conducted with the student co-authors as preliminary test subjects, with plans to expand to groups of students not familiar with the project as the project progresses. Student feedback informs our refinement of the experiment design and guiding materials used to enable student self-completion of the labs, aiming to encourage creative exploration and promote a deeper understanding of the fundamental principles.

Kit design constraints and objectives

Given the apparent benefits demonstrated by individualized exploration via hands-on engagement in other technical areas, we were motivated to see if similar benefits could be brought to instruction on the fundamentals of fluid dynamics that would serve as a focus or complement to a college-level calculus-based sequence in mechanics. Given the breadth of topics covered in a typical undergraduate fluid dynamics course, as well as the relatively large number of majors that require this topic of study, we set forth the following design goals:

1) The kit should readily address multiple topics that are commonly taught.
2) The kit should be low-cost (target similar to a textbook) but high quality.
3) The kit should produce results of sufficient accuracy to reinforce the principles being studied convincingly.
4) The kit should permit creative exploration of the subject in addition to prescribed technical exercises and demonstrations.

Fluid dynamics is a course that primarily focuses on understanding how to model the behavior of a fluid system in motion. As a result, any proper kit will need to have a means to put fluid in motion. Although the topic of hydrostatics is a key element, it is typically used as a scaffolding construct due to its usefulness in illustrating how pressure exerts forces on objects, as well as making a connection to manometry. We discounted water as the primary dynamic working fluid due to the inherent mess and cleanup this would inevitably entail. Working with air would require either a pressurized reservoir or a powered fan. The limited run time of a reservoir makes this design option less flexible, particularly when it comes to high-volume flow rate applications. Therefore, we settled on pursuing a design powered by a fan system.

The first two of the above design goals recommend a modular approach that uses inexpensive components available off-the-shelf from a broad consumer market segment, with the central element being the fan system (impeller, motor, controller, and power supply). However, when combined with the third goal of providing accurate results, this becomes a reasonably restrictive constraint if one is tied to using a pitot tube and water manometer to measure the fluid velocity. As an order of magnitude illustration, consider the force generated by the scalar momentum flux of air of density ρ_a, moving perpendicularly across a control surface *A* at speed *V* that scales as:

$$F \propto \rho_a V^2 A \tag{1}$$

If one wishes to measure the velocity using a Pitot tube and a water manometer, the velocity can be related to the column of water of height *h* supported by the stagnation pressure:

$$\rho_w g h = \frac{1}{2}\rho_a V^2 \quad \text{giving} \quad V = \sqrt{\frac{2\rho_w g h}{\rho_a}} \tag{2}$$

Substituting this into the force expression gives:

$$F \propto 2\rho_w g h A$$

Assuming the variables are independent of each other and that the uncertainty in the water density and gravitational constant is negligibly small in comparison to the height of the column of liquid and the area, propagation of uncertainty calculation would indicate [6]:

$$\frac{\delta F}{F} = \left[\left(\frac{\delta h}{h} \right)^2 + \left(\frac{\delta A}{A} \right)^2 \right]^{1/2} \tag{3}$$

This implies that the relative uncertainty in measuring the height of the fluid and the positioning of the pitot tube (which determines the effective area) will play equal roles in contributing to the overall uncertainty. Ignoring the area for the moment, practical limitations on measuring a column of liquid at its best are on the order of ±1 mm due to typical visual acuity, parallax effects, and variability of the meniscus within the manometer tube. A 5% relative error would require a height of $h = 20$ mm and a velocity of 18 m/s. Dropping this to 1% would require a column of 100 mm and a velocity of 40 m/s. Even this estimate is likely to be a significant underestimate when factoring in the contribution of the area and the fact that for a practical measurement, a summation is required that convolves the absolute error of both the local liquid column height uncertainty as well as the area due to the integral nature of the net force:

$$F = \int_{CS} \rho_a V^2 dA \approx 2\rho_w g \sum_{i=1}^{N} h_i dA_i \tag{4}$$

The above velocity requirements place stringent constraints on the desired fan. For many years, the inexpensive fan market has been almost exclusively defined by cooling fans for personal computers. These fans can produce stagnation pressures only on the order of 10 mm or so, which is nearly an order of magnitude below what is desired. More recently, the radio-controlled aircraft hobby market has recently made widely available Electric Ducted Fans (EDF) that are far more capable, using rare-earth brushless motors and more advanced impeller designs that are capable of producing static thrusts upwards of 9 N [7], with corresponding stagnation heads well over 100 mm of water. This has been combined with the availability of inexpensive DC power supplies up to 500W for the home LED lighting market. The standard sizes that have evolved for EDF vary from 30mm up to 120mm in diameter, with the current most readily available being 50mm and 64mm variants. Typical components listed in detail in Table 1, shown in Figure 1.

Component	Manufacturer & Model	Cost
DC Power Supply	Supernight 12V-30A DC	\$21.99
Electric Speed Control	HobbyKing X-Car 60A Brushless ESC	\$25.65
Servo Tester	HiLetgo 3Ch digital servo tester	\$3.33
Electric Ducted Fan	FMS 64mm Ducted fan (11-blade) with 2840-KV3900 Motor (3S)	\$39.99

Table 1: Off-the-shelf consumer components that make up the prototype fan core module. The cost listed is based on prices checked in January 2025.

Given the performance and pricing, a 64 mm fan was selected for the prototype development. To provide modular flexibility for different experiments, a clamshell housing was created that incorporates a flow-straightening honeycomb 45 mm long (8 mm cell size) with the fan secured using fixed slot openings to accommodate tabs located on the fan housing (see Figure 2). The fan can be oriented in two positions, such that it either blows through the honeycomb or, in reverse position, sucks air into the honeycomb. The modular components are fixed to the openings using elastic spring clips. For the prototype model, the designs are printed using an HP 580 Powderbed printer with PA12 Nylon feed material.

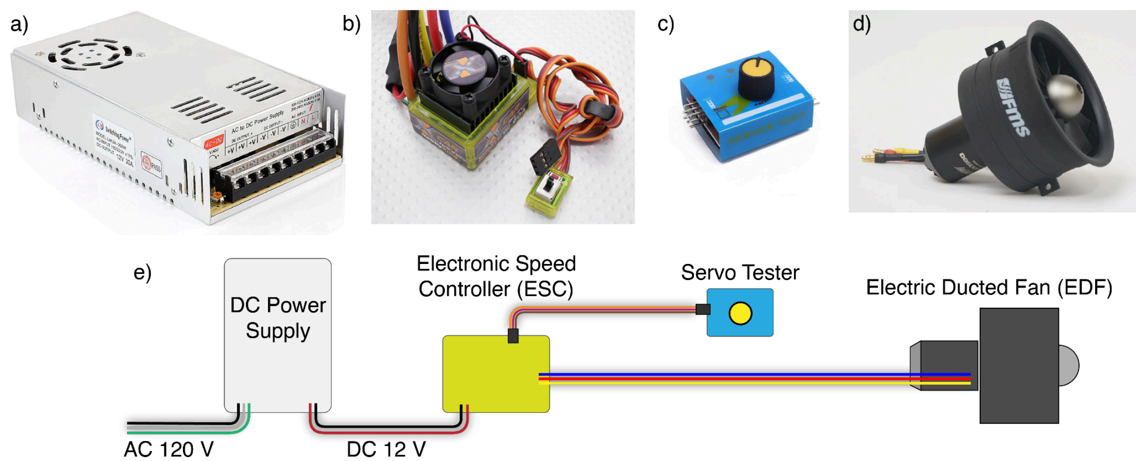

Figure 1: a) DC Power Supply, b) Electronic Speed Controller (ESC), c) Servo Tester to provide fan speed signal, d) 64 mm diameter Electric Ducted Fan (EDF), and e) wiring connection schematic.

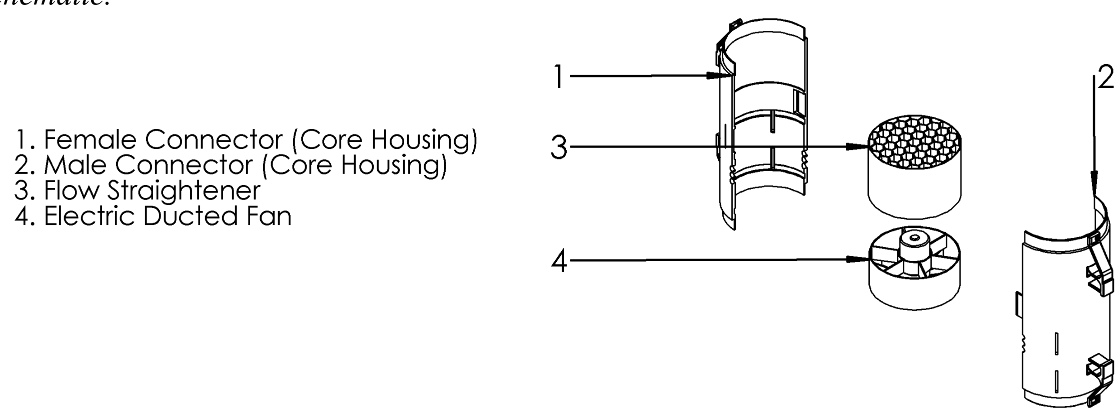

Figure 2: Exploded View of the Fan Core Module.

The central fan housing provides a versatile foundation for various experiments with minimal additional investment. These experiments align with the learning objectives commonly found in introductory fluid mechanics courses, typically aimed at sophomore- and junior-level students. The key topics supported include:

1) Basic Manometry and Pressure Measurement: Fundamentals of measuring fluid pressure.
2) Bernoulli Equation: Exploring work-energy relations for steady, incompressible, inviscid flow.
3) Pitot Tube Applications: Using a pitot tube to measure velocity profiles.

4) Control Volume Analysis: Investigating momentum flux, forces exerted by fluids, and mass flux considerations.
5) Pipe Flow Losses: Modeling and predicting major and minor losses in confined flows.
6) External Flow: Examining drag forces on immersed objects.
7) Boundary Layers & Separation: Understanding the development and growth of boundary layers in favorable and adverse pressure gradients.
8) Fan Characteristics: Analyzing flow rate, pressure, and efficiency of fans.

Figure 3 depicts renderings of specific components that have been designed to create suitable test beds for these goals, and experimental development of their prototypes are in various stages of completion. Currently, the thrust stand, pipe flow major and minor losses and the wind tunnel with drag balance have initial prototypes available for testing. Within the current work, we report on detailed tests demonstrating the performance of the thrust stand, and plans for reporting on the other modules are in development for future presentations.

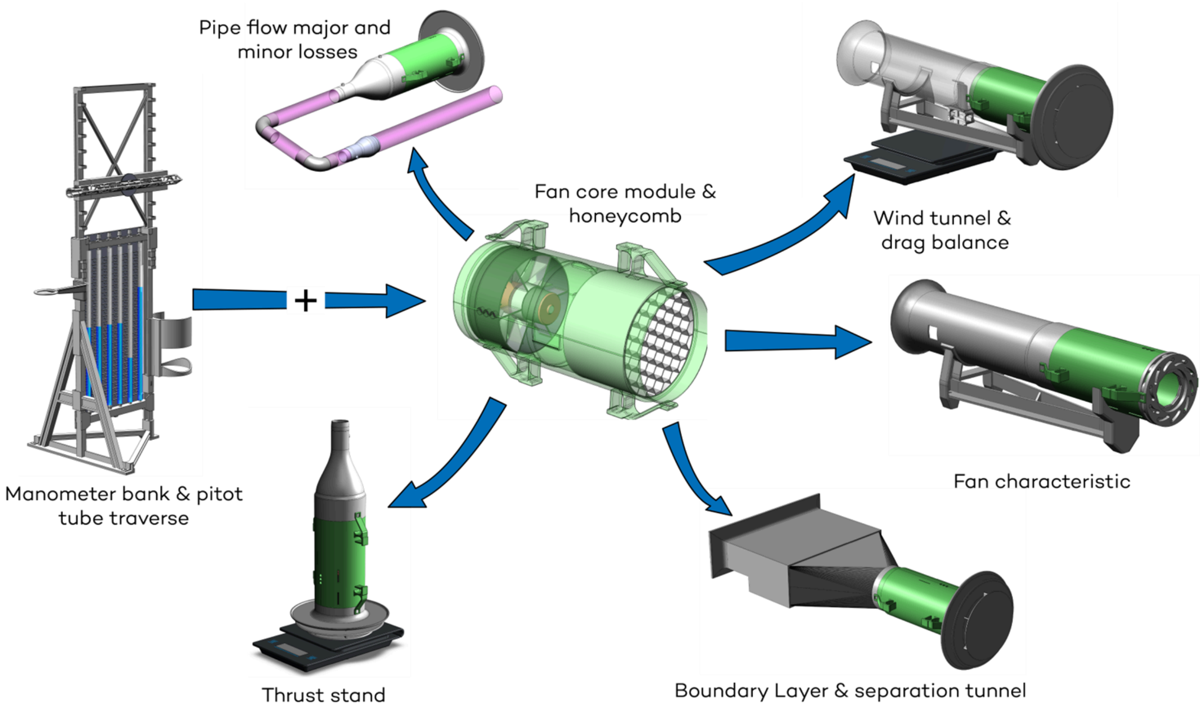

Figure 3: Experiment Options for the Fan Core Module.

Each module would have specific technical learning outcomes related to their intended focus, but could be broadly categorized along the following lines:

1. Design of an experimental procedure for data collection
2. Assessment of potential sources of error and contribution to uncertainty
3. Development and implementation of post-processing procedure to calculate derived quantities
4. Comparison of results to expectations provided by theory or independent relevant data

5. Reflection on the behavior demonstrated in the experiments and success or failure of models used to represent the experimental conditions
6. Reflection on how explored phenomena may be relevant to broader applications

When considered as a whole, these items can readily be organized and linked to several different ABET learning outcomes, specifically:

1. an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.
6. an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.
7. an ability to acquire and apply new knowledge as needed, using appropriate learning strategies.

The majority of the outcomes fall within outcome (6), but items (1) and (7) are readily adjacent depending on the prompts that are provided to the students. This will be a subject for further detailed development once the initial prototypes have completed development.

Thrust Stand Experiment - manometer tube bank & momentum flux of a free jet

The first module completed is a thrust stand designed to verify momentum conservation principles via integration of velocity profiles across the exit of a free jet and compared to the net force exerted on a mass balance.

Initially, a very simple intake with no vanes and a straight tube exit pipe (without honeycomb and nozzle) were used. Due to the wake of the motor housing and power cables, a careful two-dimensional mapping of the exit flow was needed to calculate the momentum flux. The best agreement obtained was more than 30% different from the mass balance reading, following several hours of tedious work. This prompted a redesign of the apparatus, creating a carefully vaned intake to minimize axial flow components, and adding a honeycomb section and smooth nozzle contraction (8.5:1 contraction ratio) to remove swirling components and the wake of the fan motor.

Although only a single manometer tube is needed for the current module, it is anticipated that other modules may wish to measure multiple pressures simultaneously. As a result, the design created space for six tubes. The manometer bank also provides a secure mounting point for a traverse and pitot tube holder (see Figure 4). This requires a stable platform that permits accurate pitot tube placement along the diameter of the nozzle exit with millimeter precision. Early work demonstrated that the simple placement of the pitot tube on a freestanding support was not accurate enough and resulted in tedious machinations as the stand was moved in small increments, resulting in imprecise and unsatisfactory results.

The current design uses a dovetail slide with a rack-and-pinion to position the pitot tube relative to the manometer frame. The pitot tube consists of an 18G needle with a 90-degree bend and a Luer lock fitting (IntelliSpense 18Gx1.5” tip 90 degree bend Pink). A ring guide was created to ensure the placement of the traversing profile across the diameter of the nozzle. The ring permits close-tolerance (better than 1 mm) non-contact locating of the manometer stand relative to the nozzle. To facilitate downstream measurements, the manometer stand can also be fitted with a vertical extension frame on which the traverse mechanism can be repositioned.

In addition to the momentum flux experiment, this module supports observation – via the measured velocity field – of the growth of the jet and the entrained ambient air. The experiments can be thorough, permitting exploration of uncertainty propagation or questioning assumptions about flow symmetry. The nozzle can also be used to explore aspects of the Bernoulli equation using the pressure taps at its base and exit or to enable fun activities like levitating ping-pong balls, which get the user thinking about unsteady drag and lift forces.

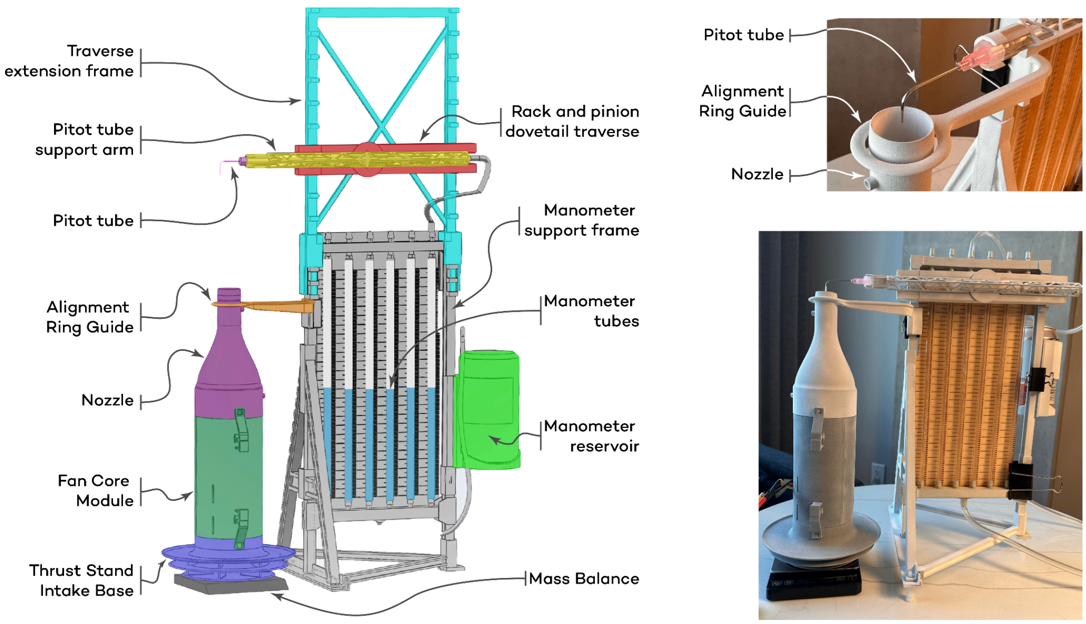

Figure 4. Assembled manometer bank and traverse mechanism, showing guide ring and traverse extension. b) close up image of nozzle exit and ring guide, along with pitot tube. c) detail of traverse extension and

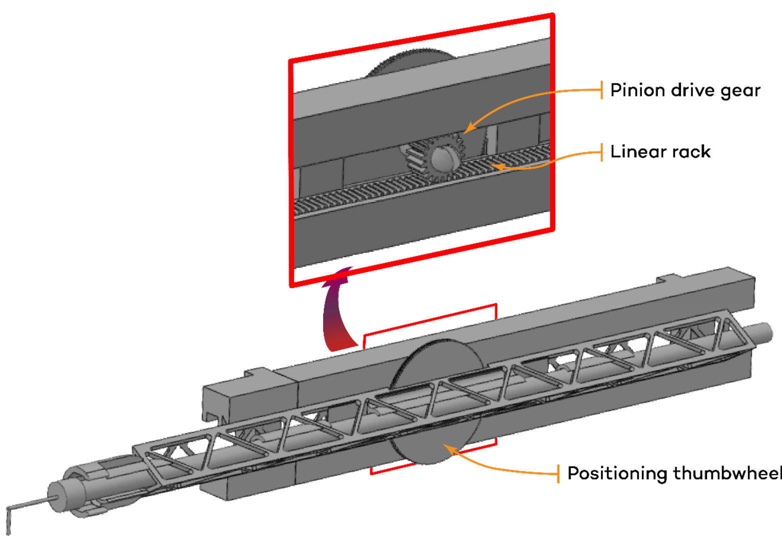

Figure 5: Detail of dovetail traverse with rack and pinion positioning. The gear ratio is such that one revolution of the thumbwheel moves 32 mm. The wheel is marked with divisions that permit reliable positioning at 1 mm increments. Total range of the traverse is 100 mm.

Verification testing of thrust stand prototype

Preliminary validation and verification of the thrust stand module design were carried out by comparing forces measured by the mass balance with the momentum flux calculated from the jet velocity profiles. Since the thrust stand intakes air through the radial- and transverse-vaned base module and exhausts it into the ambient environment through an axial aligned circular nozzle, a simple control volume analysis demonstrates that the thrust can be determined from the momentum flux through the nozzle exit. Figure 5 depicts a cross-section of the relevant control volume around the thrust stand. The top of the control volume can readily be extended further downstream to permit use of velocity profiles in the downstream sections.

The momentum equation,

$$\frac{\partial}{\partial t}\iiint_{\forall}\rho\vec{v}d\forall+\iint_{CS}\rho\vec{v}(\vec{v}\cdot\hat{n})dA=-\iint_{CS}p\hat{n}dA+\iiint_{\forall}\rho\vec{g}d\forall+\iint_{CS}\bar{\bar{\tau}}\cdot\vec{n}dA \tag{5}$$

is applied to the thrust stand control volume. Assuming steady state conditions and inviscid, incompressible, and axisymmetric flow, the resultant thrust produced by the nozzle and read by the scale is given by:

$$F_{thrust}=\int_0^\infty \rho_a v(r)^2 2\pi r dr \approx 2\rho_w g\sum_{i=1}^{N} h_i \Delta A_i \tag{6}$$

where $v = v(r)$ is the axial flow velocity, r is the radial position from the nozzle center, ϱ_a is the air density, ϱ_w is the water density, g is the acceleration due to gravity, and h_i and ΔA_i are the discrete location measurements of the manometer reading and annular area corresponding to the measurement. Using a research-grade manometer and pitot-static tube (Dwyer No. 246: 152 mm range, 0.5 mm scale division; Airflow Developments pitot-static tube: 4 mm diameter, ellipsoid tip), left and right radial velocity profiles were taken at two stations downstream of the nozzle.

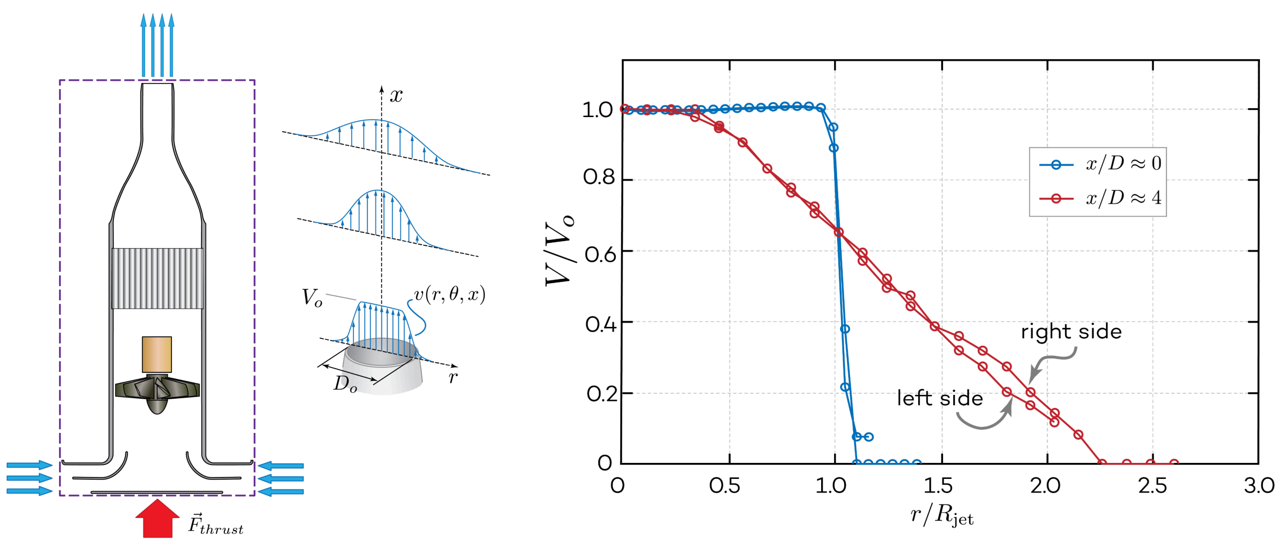

Figure 5: Thrust stand control volume for momentum flux calculation (left). Radial velocity profiles at two downstream stations using research-grade pitot tube and manometer (right).

Noting *x/D* as the distance from the nozzle exit normalized by the nozzle diameter, Figure 5 also shows velocity profiles immediately at the exit and four diameters downstream. At $x/D = 0$, the profile follows a top hat shape with very thin shear regions near the nozzle edges, with close agreement between the left and right profiles. The average deviation between complementary sides is less than 2% over the complete profile, and less than 0.5% when limiting the comparison to $r/R_{jet} < 1$. Uniform velocity at the nozzle exit validates the combined effects of the flow straighteners upstream of the nozzle and the geometry of the nozzle contraction. The agreement suggests that the assumption of axisymmetric flow is reasonable.

At $x/D = 4$, the jet retains a small amount of the potential core (region of uniform velocity for $r/R_{jet} < 0.3$) and the streamwise velocity decays steadily in the radial direction. Left and right profiles at $x/D = 4$ agree within 1.5% for $r/R_{jet} < 1.5$, and then differ by 5% in the last quarter of the profile. Possible explanations for this error are the introduction of 1) uncertainty from repositioning of the pitot tube lab traverse mechanism due to its limited 25 mm traversing length, 2) uncertainty in reading the fluctuating velocity due to turbulent mixing, and 3) slow temporal fluctuations of the driving fan voltage.

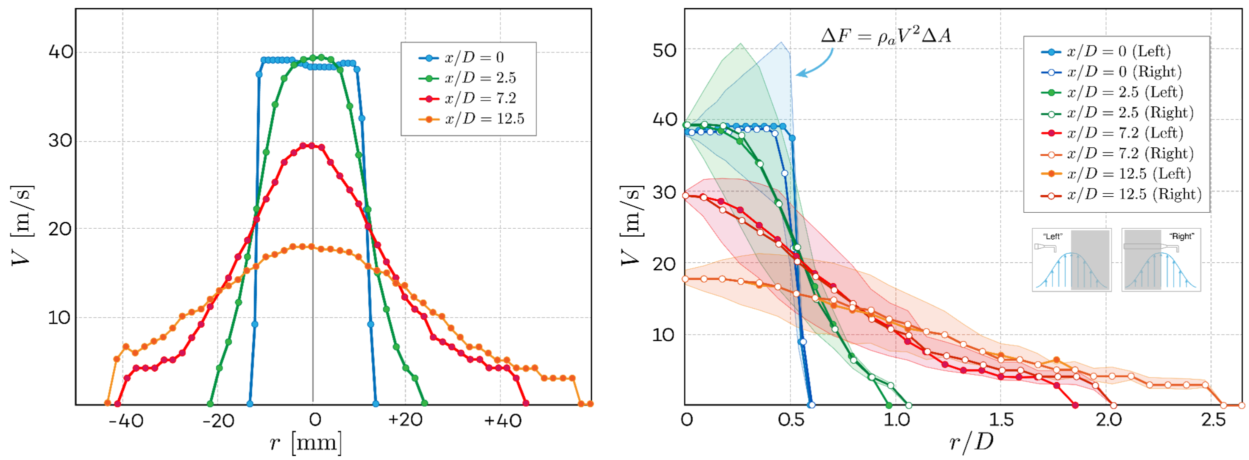

Figure 6: (left) Radial velocity profiles at four downstream stations (x/D = 0, 2.5, 7.2, and 12.5) shown across the full span. Note that the traverse limit prevented measurement at locations r < -40 mm. (right) Radial velocity profiles with the left-side profiles mirrored across the centerline, and corresponding force contribution $\Delta F = \rho_a V^2 \Delta A$.

Additional testing was done using the manometer tube bank and pitot tube assembly developed specifically for the module. As shown in Figure 6, four profiles were completed at different downstream stations x/D = 0, 2.5, 7.2, and 12.5. The profiles demonstrate a high degree of symmetry, typically agreeing to better than 2%. However, there are several noticeable exceptions:

1. The profiles are truncated for $r < -40$ mm due to the limit stops on the traverse, see x/D = 7.2 and 12.5.
2. There appears to be a systematic bias in portions of the profile between the left and right sides, with the left profile slightly lower near the centerline and slightly higher as the profile decays in the outer region.

The cause of this difference is currently unclear and requires further testing. Given the results using the research-grade instrumentation do not exhibit this behavior, it is believed that the difference stems from the procedure and/or configuration of the pitot tube system. For example, the support arm of the pitot tube extends into the flow as the pitot tube measures the right profile. The blockage created may slightly alter the flow and result in the observed distortion. It may also result from hysteresis effects of the water wetting the tube as it is displaced and then re-wets on opposite sides of the profile.

The average of the left and right profiles is compared to existing data in the literature in Figure 7. The majority of literature on turbulent jets focuses on the self-similar region well beyond the potential core, which typically focuses on x/D > 20. Near-field measurements are needed at downstream stations that closely replicate the current profiles and also closely mimic similar boundary conditions (domain size, exit nozzle). Such conditions are found in the work of Iqbal and Thomas [8], which provide comparable measurements using hot-wire anemometry at downstream locations *x/D* = 3 and *x/D* = 7. The profiles agree surprisingly well (to within 5% at all points based on centerline velocity), with little variation noticeable between the *x/D* = 7.2 and 12.5 locations when normalized in this manner. This is consistent with the fact that typically the mean velocities tend to collapse earlier than the higher order moments.

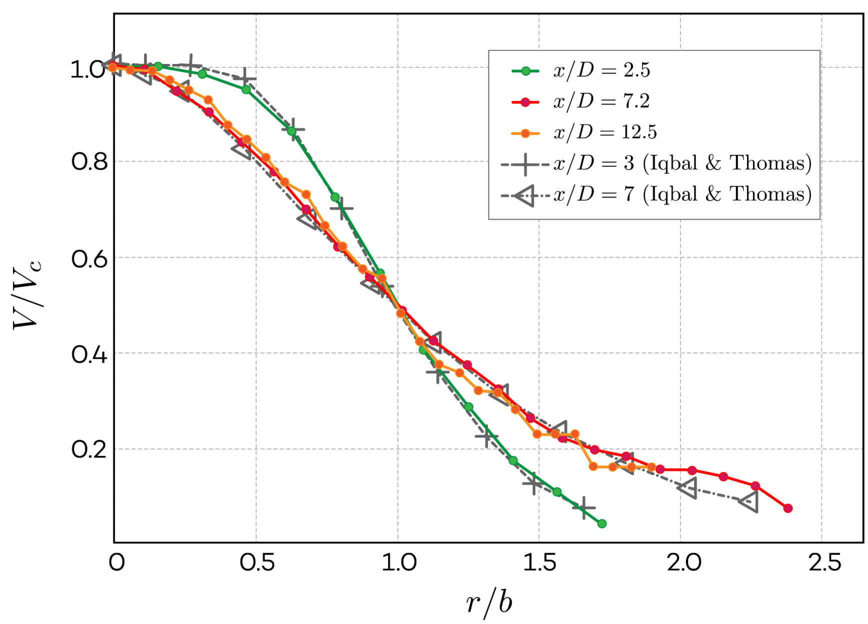

Figure 7: Comparison of normalized velocity profiles to Iqbal & Thomas [8], with V_c being the centerline velocity of the profile, and b is the radial position where V/V_c = 0.5.

The last observation is the impact of the manometer resolution on the resulting velocity and momentum flux calculations: the tails of all the profiles exhibit an unrealistic decay dictated by the 1 mm resolution of the manometer. This implies that any velocity below approximately 4 m/s is unreadable with the current system. This also implies a significant increase in the relative uncertainty of the measurement as the profiles decay towards zero. The significance of this can be observed by the colored shaded regions surrounding each curve in Figure 7, which represent the local contribution of that measurement to the overall momentum flux.

Profile	$\mathbf{F_{thrust}}$ (N)	$\mathbf{F_{scale}}$ (N)	Error (%)
x/D = 0 (left)	0.705	0.695	1.55
x/D = 0 (right)	0.688	0.695	-0.96
x/D = 4 (left)	0.655	0.726	N/A*
x/D = 4 (right)	0.692	0.726	-4.62

*Table 2: Comparison of measured momentum flux to force measurement using research-grade pitot tube and manometer. *Profile is truncated and not representative of complete measurement.*

Profile	$\mathbf{F_{thrust}}$ (N)	$\mathbf{F_{scale}}$ (N)	Error (%)
x/D = 0 (left)	0.790	0.787	0.37
x/D = 0 (right)	0.688	0.784	-12.3
x/D = 2.5 (left)	0.694	0.780	-11.0
x/D = 2.5 (right)	0.707	0.781	-9.46
x/D = 7.2 (left)	0.760	0.779	-2.44
x/D = 7.2 (right)	0.785	0.766	2.51
x/D = 12.5 (left)	0.700	0.770	N/A*
x/D = 12.5 (right)	0.755	0.768	-1.57

*Table 3: Comparison of measured momentum flux to force measurement using kit prototype pitot tube and manometer. *Profile is truncated and not representative of complete measurement.*

The profiles shown in Figures 6 and 7 were integrated using equation (6), calculated numerically as a discrete summation using a trapezoidal rule. The results are compared to the corresponding mass balance readings in Table 2 and 3, respectively. For the research grade instrumentation, the thrust force calculated using the momentum flux agrees with the mass balance to within 2% for the profile at x/D = 0. For the profile at x/D = 4, only the right side was complete enough to compute the thrust force reliably, and agreed with the mass balance reading to within 5%.

The results for the profiles measured using the prototype instrumentation are more mixed, with deviations (averaged across both profiles where available) of -6%, -10%, 0.1% and -2%, respectively for x/D = 0, 2.5, 7.2 and 12.5. On the whole, these are encouraging results and give confidence that the experiments would be worthwhile. The x/D = 2.5 case is the only trial that exhibited a greater deviation than we feel is acceptable for the project target goals. Further testing of repeated trials as well as varying the procedure are planned.

Testing with students

Once the prototype development is complete, the next step will be to conduct feedback trials with students to both assess the effectiveness in achieving the goals of the project (comprehension and interest/engagement with material), as well as to improve the functioning of the prototype. To date, all student testing has been completed internally with the authors as test subjects, as this group represents a mix of undergraduate students from sophomore to senior level, some of which have fluid dynamics as a requirement, and others who do not but have an interest in the topic. The prototype presented is the results of 3 prior iterations, from which lessons related to implementation of the traverse, as well as redesigns of the nozzle, honeycomb and intake section have all been implemented.

With the current iteration, student feedback indicates that operation of the motor controller is non-intuitive, and that the assembly of the manometer bank/pitot tube support is subject to errors that can result in a compromised rigidity. When assembled correctly, however, the positioning provided by the rack-and-pinion and the nozzle guide ring worked well and with a high degree of precision. Lastly, reading the manometer accurately was also a challenge, as was evident by low-speed regions of the profiles. Assembly time varied depending on the proficiency of the individual students, ranging from 10 minutes to nearly an hour. Note that these results reflect assembly without a set of written instructions, only verbal communication and occasional visual demonstration from their peers. In the future, these initial insights will be used to guide survey questions to assess student frustration and potential learning insights that the assembly process can provide. Part of the benefit of assembling the device is to develop an appreciation of how the system functions, and understanding the role that some of the design details play in making everything work.

The documentation to enable student use is currently under development, but the plan is for materials to be provided in three components: pre-lab, instruction manual, and post-lab. Prior to starting the experiment, students are given a pre-lab document, allowing them to review key concepts, procedures, and safety protocols. It is anticipated that this material will likely require an hour to read and process. The pre-lab will start with an explanation of learning goals, which is to explore the relationship between the velocity of a fluid and pressure measured by a pitot tube, and then to apply that measurement to a control volume analysis to calculate the force exerted by the fluid on the device. Students will be tasked with measuring velocity profiles at different downstream locations, as well as across diameters transecting various quadrants of the exit plane. By analyzing these velocity measurements, they will be able to determine the momentum and mass flux of each profile, and relate the result to the force measured by the mass balance.

The pre-lab prompts students to consider important concepts like the definition of mass flow rate and mass flux, as well as the relationship between flow direction and inflow/outflow. Additionally, the document highlights the significance of assumptions by reviewing how Reynolds number can help justify assumptions and the use of Bernoulli's equation to calculate the velocity using the pitot tube. The pre-lab also aims to clarify seemingly minor, but relevant information, such being careful with the wiring harness to minimize loads bypassing the mass balance reading, taring the mass balance and checking the reading after conclusion of the experiment to ensure there has not been any drift, and using the guide ring carefully to also make sure the nozzle does not come in contact with it.

After completing the pre-lab, students are provided with an instruction manual that details the process of assembling the thrust stand. This manual provides a clear and organized list of parts, assembly instructions, activities, questions, and assessments to guide students through each phase of the experiment. Students are given materials, such as images of each component and step-by-step assembly instructions to ensure proper setup of the thrust stand. Key activities include assembling the core housing, inserting the flow straightener, and attaching the fan to the system, followed by adjusting the speed using the electronic control knob. Throughout the process students are encouraged to reflect on key questions including flow symmetry and the relationship between velocity and pressure at different positions. Assembly is expected to require no more than 20 minutes with the final design, and taking the data may vary from 40 minutes to several hours depending on how meticulous and comfortable the students are in operating the equipment.

The post-labs are designed to guide student processing of the raw data, evaluate students' understanding of key fluid dynamics concepts and the effectiveness of the experiment in achieving learning objectives. These questions cover a range of topics, such as determining if the flow is axisymmetric, assessing the accuracy of assuming uniform flow at the exit of the duct, and analyzing the widening of velocity profiles downstream due to mixing, all while considering how the flow behaves along the centerline. Additionally, the students are tasked with calculating the mass and momentum flux at different positions, observing how these quantities change along the duct. Setting up the calculations will require significant scaffolding for new learners, and will likely represent a significant fraction of the post-lab effort. Lastly, students would ideally be asked to calculate the uncertainty in their measurements to ensure they grasp the full scope of the experimental process and can assess the validity of their results. These post-lab questions help gauge the clarity and usefulness of the handout and ensure that the learning objectives were met. Completing all of the post-lab objectives is likely to require several hours of effort.

Following internal testing, we plan to expand the testing to students not involved in the design process. This will provide a fresh perspective on the handout and ensure that it resonates with the intended audience. The primary target group of this phase will be students currently enrolled in or have already completed a fluid dynamics course, as our kits are designed to complement this curriculum. This kit could also be used to augment instruction on measurement and instrumentation in general, not just fluid mechanics. Although the current design uses a water manometer and pitot tube to measure pressure and velocity, we are currently exploring the use of inexpensive, but highly precise, digital barometers (see for example the Adafruit DPS310, which has a reported precision of 0.2 Pa and costs $7, https://www.adafruit.com/product/4494) read using an arduino microcontroller to measure the pressure. These potentially can increase the precision by more than an order of magnitude over a simple water manometer. There are also hot-wire anemometers that may work well, and recent implementation of using smartphone cameras to conduct particle image velocimetry[9] would provide a range of inexpensive methods to explore the various advantages and disadvantages of different instrumentation approaches.

Conclusions

The current work summarizes the motivation and progress toward the design and testing of a modular, low-cost fluid dynamics experimentation suite targeted toward use in an introductory undergraduate hands-on learning and experimentation module.Challenges, such as securing the fan module and addressing non-uniform flow outputs, were identified and tackled through iterative design processes. Notable solutions included the integration of honeycomb structures to reduce turbulence and ensure flow uniformity, the exploration of modular designs for fan mounts focusing on secure, adaptable mechanical connections rather than traditional fasteners, and the identification and mitigation of potential hazards (e.g. capacitor failures, fan noise) which were addressed through improved material selection and design refinements.

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