AC 2009-712: SIMPLE EXPERIMENTS FOR THE THERMAL AND FLUID SCIENCES

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Abstract:

An NSF funded project called The Engineering of Everyday Things (EET) uses simple, everyday devices to help teach core concepts in the thermal and fluid sciences. Exercises are being developed which can be used for laboratory classes, in-class demonstrations, or as supplemental instruction outside of the class. It is also possible to extend the time spent on the exercise by incorporating portions of them into a standard classroom lecture. The desired outcomes of the exercises are to overcome students' misperceptions and to increase their understanding of the underlying core concept involved in the exercise.

The EET exercises use simple hardware that is either based on consumer items like a hair dryer or a blender, or simple equipment like an open tank of water or a duct with a change in area. The use of familiar or simple equipment is designed to engage students by demonstrating the relevance of their coursework to their everyday lives. Additionally, the use of the simple equipment reduces the need for the students to concentrate on the operation of the equipment and allows them to focus more on the concepts involved. The EET laboratory exercises use a guided inquiry approach to challenge student misconceptions, and to promote deeper understanding through qualitative reasoning.

The purpose of this paper is to give an overview of the project and to present some of our research highlights on student learning gains and attitude change. Details of specific exercises are presented in companion papers. The goal is to develop interest in this approach to instruction and to show faculty how they can easily incorporate these ideas into their lecture-based and laboratory-based classes.

Introduction:

This paper reports on some of the work being done to develop active laboratory exercises to teach core concepts in the fluid and thermal sciences. The authors are currently developing a suite of seven exercises as part of an NSF funded project called "The Engineering of Everyday Things" (EET). In these exercises students are asked to perform experiments using common devices that they are already familiar with. This paper reports on work done to date on exercises using a hair dryer, a blender and a computer power supply. Other exercises which are described in other papers involve such simple devices as a toaster, a tank of water, a bicycle pump and a pipe with a sudden change of area. We believe that the use of simple equipment that is familiar to the students frees the students to concentrate on the principles involved rather than on trying to figure out the equipment. The use of simple equipment is not new. A hair dryer is a very common device used as teaching tools. For example, Alvarado asks students to design their own thermodynamic experiments, one of which is based on a hair dryer[1]. Weltner uses a hair dryer as part of an experiment to determine the specific heat capacity of air[2]. Shakerin describes an experiment incorporating a hair dryer to demonstrate both the first and second laws of thermodynamics[3] and Edwards discusses an experiment to perform a thorough first law analysis of a hair dryer[4]. Other examples of experiments using simple equipment are common. Butterfield describes a laboratory exercise to determine the height of blocks that can be stacked on an elastic base[5]. The only equipment required for that exercise is a set of blocks and a piece of foam. A report from the American Association for the Advancement of Science describes how the use of something that is familiar to the students as part of a demonstration can add relevance to an unfamiliar process or concept[6].

The exercises described in this paper incorporate an active learning pedagogy called guide inquiry. The guided inquiry approach requires the students to be actively involved in the exercise both physically (conducting the tests) and mentally (thinking about concepts and applications of concepts). Most typical laboratory exercises involve well planned activities requiring students to gather data for a particular set of operating parameters using preconfigured instrumentation. The experiments generally have been well tested ahead of time to assure predictable results. These types of experiments are sometimes called “cookbook” exercises. The authors often use these exercises themselves, and acknowledge that there is a place for them in a laboratory curriculum. The hair dryer exercise described by Edwards[4] is one such experiment. However the authors are attempting to extend typical laboratory experiences to include actual learning as well as just demonstration.

Active learning approaches to laboratories are gaining a solid foothold in science classrooms. Inquiry-based learning[7], experiential learning[8], project based learning[9] and various workshop models[10] have all been widely used for teaching physics, chemistry, biology and other sciences. These approaches have been slower to reach into engineering. We are trying to help to extend these approaches into the engineering laboratory. Felder and others have noted that learning individual learning styles need to be recognized when developing educational materials[11,12,13]. The “hands-on” active learning exercises being developed by the authors should be beneficial to students with concrete learning styles. Many, if not most, engineering students fall within this category.

The rest of this paper concentrates of a description of each of the three exercises – blender, hair dryer, and computer power supply, as well as some assessment of the results to date. This is an ongoing project to develop the exercises and the assessment instruments, so the data collected thus far is being used not only to determine learning gains among the students but also as feedback to the authors to assist in making improvements to the test procedures and worksheets. Our ultimate goal is to develop interest in this approach among engineering faculty and to demonstrate how they can be incorporated into both lecture based and laboratory based courses. Final dissemination will be through a project website and possibly through workshops and seminars.

Overview of the Suite of Exercises:

There are seven exercises currently being developed by the authors. This section gives a brief overview of these exercises, primarily focusing on the purpose of the exercise and a general description of the procedure.

1. Hair dryer: The purpose of the hair dryer exercise is to teach a qualitative as well as a quantitative relationship between mass flow rate and temperatures of fluids crossing the boundary of an open thermodynamic system. This exercise is described in more detail below. An early description of the exercise was given by Edwards at the 2008 ASEE national conference[14].

2. Blender: There are several learning objectives for this exercise. First, to help the students to recognize and describe the roles of heat, work, and energy storage in the operation of a food blender. Secondly, to get the students to identify and qualitatively describe the relationship between terms in the first law of thermodynamics and the physical parameters affecting the performance of a blender. Finally, we want to get the students to use qualitative reasoning to predict and verify the changes in measurable system parameters (temperature, power input) that result from changing blender speed, quantity of liquid in the blender, and initial temperature of the liquid in the blender. This exercise is also described in more detail below.

3. Computer Power Supply: The computer power supply exercise is somewhat unique among the suite of exercises for a couple of reasons. The exercise itself requires a piece of test equipment that is not available at every campus. It can be built at a reasonable price (around $6000), but that is well beyond the equipment costs needed for the other six exercises. Also, the principles being taught by this exercise are not fundamental concepts, but they are common concepts needed for a lot of engineering work. More detail about this one is provided below. There are several learning objectives for this exercise. Instead of listing them all here they will be listed in the section below dealing with the power supply.

4. Tank Filling: The tank filling exercise is described in more detail in other papers which are available from the authors. The tank filling exercise deals with the hydrostatic equation. The learning objectives for this exercise are:
    - Identify a pressure transducer and explain its role in measuring/transmitting pressure values to a data collection system.
    - Identify the fluid properties and other physical variables that determine the pressure at some depth in a tank partially filled with water and open to air.
    - Predict the trend in pressure with tank depth.
    - Compute the pressure at any depth below the free surface of a tank partially filled with liquid.
    - Predict how the relationship between pressure and depth changes with the shape of the tank.

5. Toaster: Radiation is an important concept that is poorly understood[15]. The toaster exercise is used to demonstrate several things:
    - The surface finish of an object affects the rate of radiation heat transfer (emissivity). Black and shiny pieces of simulated toast are use to show that the black toast both heats up faster while it is in the toaster and cools down faster once it is removed from the toaster than the shiny toast.
    - In still air radiation can be the dominate form of heat transfer as evidenced by comparisons of the rate of cooling. However, in moving air, radiation effects can be overpowered by convective effects. This is shown by placing the heated pieces of toast in an air stream caused by a fan. The cooling rates then become essentially the same.

    This experiment is more complex than the others because of the more difficult concepts that are involved. This one would be recommended for more advanced classes. More details on this exercise are given in other papers available from the authors.

6. Sudden Expansion: As with radiation, the Bernoulli equation is also an important concept that is poorly understood[15]. A common misperception is that pressure in a flowing duct must always decrease in the direction of flow. Another misperception is that the Bernoulli equation can always be applied to a fluid flowing in a duct. This exercise addresses these issues. A sudden expansion in a duct is sized so that a decrease in velocity actually causes an increase in pressure downstream. Also, applying the Bernoulli equation at an upstream and downstream cross-section shows that something else is involved besides just the terms in the equation. This leads to minor losses and the loss across the expansion. The hardware costs for this experiment are among the highest among the suite of exercises shown here. More details on this exercise are given in other papers available from the authors.

7. Bicycle Pump: The bicycle pump exercise is in an early stage of development. It was inspired by work done by McDermott, et.al., about student understanding of ideal gas compression[16,17,18]. After the students complete the exercise they should be able to estimate the work and instantaneous power input during compression, compare the work and power inputs for an insulated and non-insulated pump, and write an energy balance equation for the pump. The concepts involved are more advanced than for some of the other exercises, so this one is recommended for more advanced classes. More information can be obtained from the authors.

Implementation of the Exercises:

The exercises are designed to be implemented in a three step process. The first step is to make a simple and short in class demonstration designed to 1) expose student misperceptions about the topic, and 2) get the students' interested in the topic. The second step is to deliver a traditional lecture on the material where the students can learn the theory and basic problem formulations. The third step is a more extensive lab experience with the same equipment that was used for the demonstration. Questions are posed during the exercise designed force the student to think about core principles instead of just typical problem solving. These lab exercises are not graded. This takes the pressure off the students to be "right", and gives them more freedom to let you know what they are really thinking about. This process can be problematic. In the course of this research there have been times that the authors have had to visit classes being conducted by other instructors in order to run the in-class demonstrations. This needs to be timed to correspond to the lecture on the material. Additionally, the other instructor needs to be willing to cooperate. Since scheduling can be a problem the lab exercises can, and have, been run without the in-class experience first. Once these exercises are fully developed it is anticipated that the class instructor will be incorporating them directly into the curriculum thus eliminating the scheduling problems.

Hair Dryer Exercise:
The purpose of the hair dryer exercise is to teach a qualitative as well as a quantitative relationship between mass flow rate and temperatures of fluids crossing the boundary of an open thermodynamic system. Figure 1 shows a schematic of the apparatus, figure 2 shows a photograph of the test set-up and figure 3 shows a simplified schematic of the hairdryer.

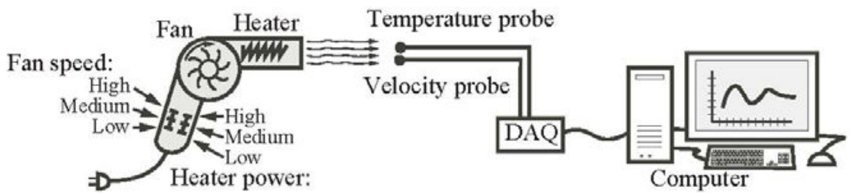
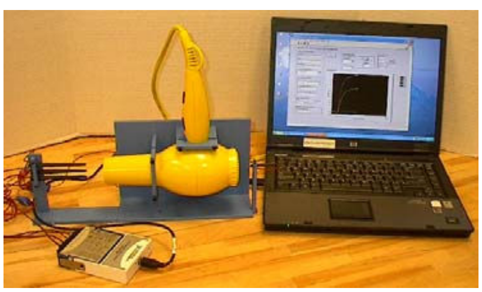


Figure 1 – Hair Dryer Exercise Schematic



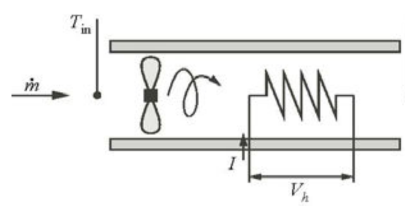


Figure 2 – Test Set-up

Figure 3 – Hair Dryer Schematic

The first law of thermodynamics for the hair dryer can be written as:

$$\dot{W}_{elec} - \dot{Q} + \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{2}}{2} + gz_{in}\right) - \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{2}}{2} + gz_{out}\right) = 0 \qquad (1)$$

If the heat transfer rate and the kinetic energy and potential energy terms are assumed to be negligible then equation 1 is simplified into equation 2.

$$\dot{W}_{elec} = \dot{m}_{out}h_{out} - \dot{m}_{in}\, h_{in} = 0 \qquad (2)$$

The enthalpy terms (h_{in} and h_{out}) depend on the air temperature. The mass flow rate in has to equal the mass flow rate out (continuity equation). Also, the inlet temperature remains constant, so the inlet enthalpy remains constant. The variable parameters are the input power and the mass flow rate. If the input power increases the outlet enthalpy or air temperature would have to increase for a constant mass flow rate to maintain the equality in equation 2. If the mass flow rate increases for a constant input power then the outlet enthalpy or air temperature would have to decrease to maintain the equality.

The hair dryer exercise is designed to teach this core concept to the students. The students run the hair dryer for all of the combinations of fan speed and heater power settings that are available and plot two trend lines. One shows outlet temperature vs. fan setting for a constant heater setting and the other shows outlet temperature vs. heater setting for a constant fan setting. The students are asked to predict the results before they actually run the experiment. After the students have individually predicted the results it is a good idea to discuss the predictions and get a class consensus prediction. The predictions should be similar to figure 4.

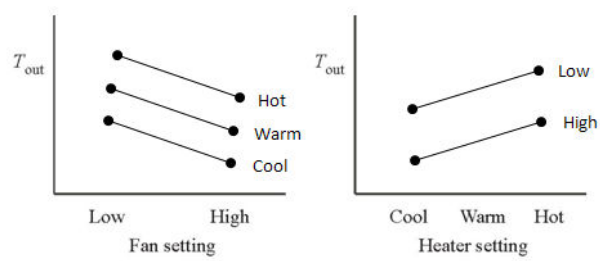


Figure 4 – Pre-exercise predictions

The predictions in figure 4 come from the first law of thermodynamics (equation 2). After the students run the experiment and plot the data there is a surprise waiting for them. An increase in flow rate (fan setting) causes an increase in temperature. This provides a wonderful teaching moment. What is going on? Is it possible that a simple hair dryer violates the first law of thermodynamics? A second hair dryer is provided for them to test. Another surprise is waiting. This one shows that the temperatures go down as predicted for the warm and hot settings but goes up for the cool setting. Now they are faced with not only conflicting data but with data that appears to violate the first law of thermodynamics. The students have to devise some test to determine what is happening. This forces them to think about the entire energy balance concept. It is not unusual for them to come up with the correct reasons for the apparent "problems" when they engage in a discussion with the rest of the class.

The correct reason for the increase in temperature when the fan is turned up is that the hair dryer is wired to increase the power to the heater when the fan speed increases. They discover this by comparing power readings on a wattmeter. The other hair dryer does what is predicted because it has been re-wired to have independent controls for the fan and heater setting. Again, this can be discovered by reading the wattmeter. The final dilemma is that the temperature still goes up for the cool heater setting. Once again the wattmeter can provide the answer. On the cool setting the heater is not powered, so the increase in temperature is caused by an increase in the power to the fan. The apparatus used for this experiment lends itself to other experiments that could be used as follow-up exercises. For example, an energy balance for the hair dryer or mapping of the temperature profile in the air jet at the outlet.

Blender Exercise:
The purpose of the blender exercise is to relate heat, work and energy storage to the operation of a blender. Figure 5 shows a schematic of the test apparatus. The core principles are the first law of thermodynamics for a closed system. The blender exercise provides a good example of thinking of the first law as a rate equation, not just as a relationship between equilibrium end states. An important aspect of this exercise is to make the students think about relationships between important parameters. This is done through the use of a qualitative reasoning exercise using ratios to predict the effects of changes in parameters.

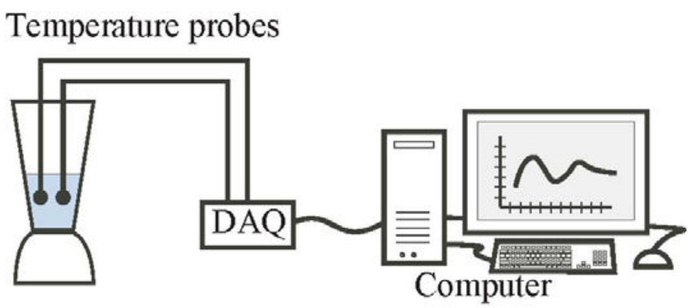


Figure 5 – Blender Exercise Schematic

An important aspect of any first law analysis is the selection of a system boundary. This is not an easy task for a blender. In our exercise the students are trying to balance the energy into the blender with the energy storage in the water. Figure 6 shows several different system boundaries that might be selected depending on what is being analyzed. These options are the springboard into a discussion of which on is appropriate for the analysis we are trying to do. What can the students readily measure (input wattage, water temperature)? None of these options is ideal for the data that is going to be collected. What can we do to keep the experiment simple, minimize error and obtain results that are sufficiently representative of the real life situation to be a teaching tool?

Students conduct various experiments to discover relationships between work and energy storage. They vary the mass of the water and keep the power to the blender constant, and then they vary the power to the blender and keep the mass of the water constant.

After the data is collected they are introduced to qualitative reasoning. In this case it consists of taking ratios of terms to show how the various parameters are related.

If we write the First Law for each experiment we get:

$$m_1 c_1 \left(\frac{dT}{dt}\right)_1 = \dot{Q}_1 - \dot{W}_1 \qquad\qquad m_2 c_2 \left(\frac{dT}{dt}\right)_2 = \dot{Q}_2 - \dot{W}_2$$

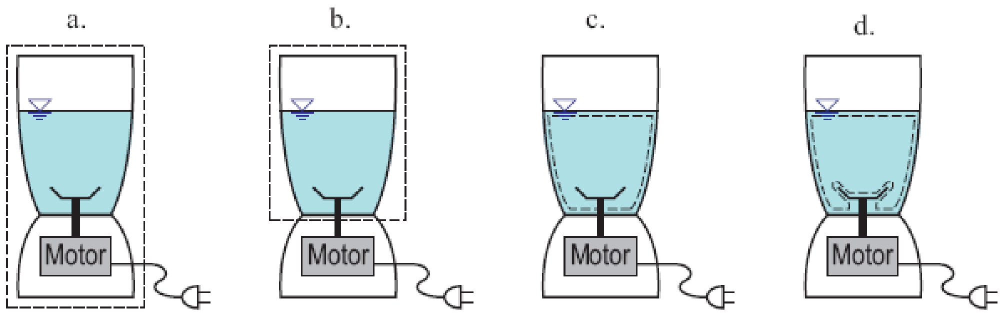
Taking the ratio of these two instances of the energy equation gives:

$$\frac{m_2 c_2 \left(\frac{dT}{dt}\right)_2}{m_1 c_1 \left(\frac{dT}{dt}\right)_1} = \frac{\dot{Q}_2 - \dot{W}_2}{\dot{Q}_1 - \dot{W}_1} \qquad (3)$$

The students complete this analysis by rearranging terms to describe each of the sets of data. It is assumed that the rate of heat loss (or gain) is negligible for both cases. They then use their equations to check if their data makes sense.

Heat transfer is addressed through a group discussion focusing on the question of what temperature water to use for the exercise. What effects would be expected by starting with cold water, room temperature water and hot water?

An important aspect of this exercise is the use of qualitative reasoning to look at the relationships among the key variables (heat, work, energy storage). Qualitative reasoning is a procedural skill that is closely related to conceptual understanding, making a good fit with the goals of our exercises. Using qualitative reasoning helps the students develop both an understanding of the relationships among the variables in this exercise and a tool they can use in other areas. In this particular exercise they learn that the rate of change of the water temperature is proportional to the power input and inversely proportional to the mass of the water. Having discovered this relationship for themselves through both qualitative reasoning and experimentation the students have a better sense of what should happen in other situations outside the lab. A weakness among most students is the lack of the ability to judge for themselves if results of lab exercises or calculations make sense. This ability comes from life experiences. Qualitative reasoning is one way to build a library of general relationships to help one make sense out of things.



	Work input	Heat Input	Energy Storage
a.	Electrical work enters the control volume through the wires.	Small heat loss from outside surface of pitcher because the air is calm and the thick walls of the pitcher heat up slowly.	Energy storage occurs in the motor, blades, pitcher, and water, but only water temperature is measured.
b.	Work enters through the rotating shaft.	Small heat loss from outside surface of pitcher because the air is calm and the thick walls of the pitcher heat up slowly.	Energy storage occurs in the blades, pitcher, and water, but only water temperature is measured.
c.	Work enters through the rotating shaft.	When pitcher is cooler or warmer than the water, significant heat transfer is caused by the vigorously mixed water.	Energy storage occurs in the water, and is indicated directly by water temperature.
d.	Work applied to system surface by shear stress between blades and water.	When pitcher is cooler or warmer than the water, significant heat transfer is caused by the vigorously mixed water.	Energy storage occurs in the water, and is indicated directly by water temperature.

Figure 6 – Selection of an Appropriate System Boundary

Computer Power Supply Exercise:
The computer power supply exercise is different from the others in that it is not teaching a particular core principle, but is teaching an important concept common to a wide range of mechanical and electrical devices. The general concept is that many devices do not operate with a fixed output, but that the output depends on external parameters. In this exercise a fan is used to demonstrate this concept.

There are several learning objectives for this exercise:

- Recognize that the flow rate of fans depends on the flow resistance that the fan must work against.
- Recognize that the flow rate vs. flow resistance relationship for a fan is a well-defined and intrinsic characteristic of the fan, and can be shown graphically as a “fan curve”.
- Plot the “fan curve” for a fan using an air flow bench.

- Recognize that the flow rate vs. flow resistance relationship for a system is a well-defined and intrinsic characteristic of the system, and can be shown graphically as a flow impedance curve.
- Plot the flow impedance curve for a system using an air flow bench.
- Recognize that it is impractical to measure the flow impedance curve for a large system, Calculations or simulations must be used to determine these curves.
- Determine the actual operating point of a fan by superimposing the fan curve on the system impedance curve.
- Recognize the relationships for flow rate and pressure for fans in parallel and fans in series.

Fan catalogs often rate fans by their maximum flow rate and/or maximum pressure output. These ratings can be very deceiving. The fan will never produce the maximum flow or the maximum pressure output, and will certainly never produce both at the same time. The flow rate produced by a fan varies depending on how much back pressure there is in the system it is attached to. This relationship is shown on what is called a characteristic curve for the fan, or a fan curve.

The back pressure in the system varies by the amount of air flowing through it. This can also be plotted as a system characteristic curve known as a flow impedance curve. Superimposing the two curves will indicate the actual operating point for the fan (Figure 8). This operating point will be at the intersection of the two curves which is the only point at which the component characteristics match.

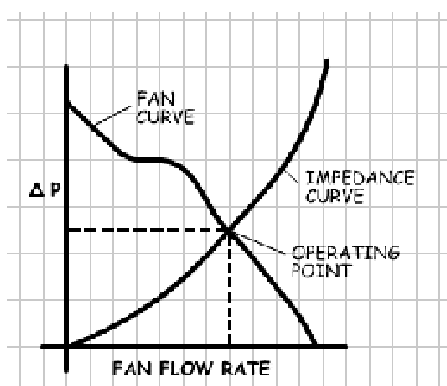


Figure 7: Operating point for a fan

Notice that the operating point is significantly lower than the maximum rated flow rate. Also note that the back pressure is significantly lower than the maximum rated pressure for the fan. This is very important information to have for any system to assure that the system specifications are met.

The pressure drop across fans in series is the sum of the pressure drop across each of the individual fans. The flow rate remains the same as for an individual fan (Figure 8). For parallel fans the pressure drop remains the same as for an individual fan, but the flow rate is multiplied by the number of fans in the parallel configuration (Figure 9).

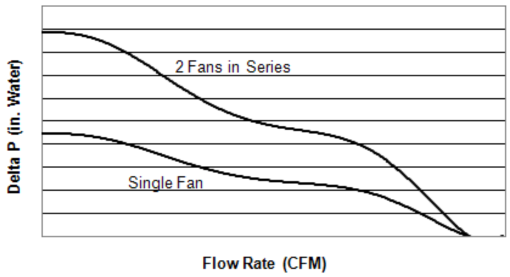


Figure 8: Fans in series

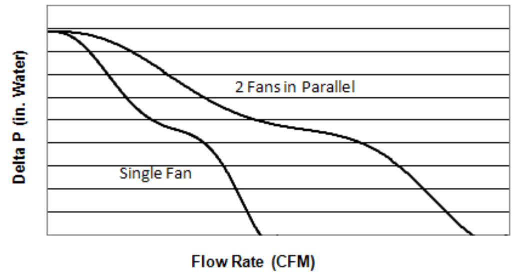


Figure 9: Fans in parallel

In actual operation the series configuration will never reach the theoretical maximum pressure and the parallel configuration will never reach the theoretical maximum flow rate. This is due in large part to flow interference that is set up when the fans are placed too close together, which is common in a real application.

During this exercise the students are taught to use an air flow bench to take data for both fan curves and flow impedance curves. They then collect data for the following devices:

- The fan curve for a fan that has been removed from a computer power supply,
- The impedance curve for the power supply housing,
- The actual operating point of the fan when it is installed in the power supply housing,
- The fan curve for two fans identical to the power supply fan which are in a series configuration,
- The fan curve for four fans identical to the power supply fan which are in a parallel configuration.

Figure 10 shows the air flow bench which is used for the testing and figure 11 shows the computer power supply mounted on the flow bench. Details of how to conduct the operating point test for the power supply using the flow bench can be found in a separate paper by Edwards[19].

Figure 10 – Air Flow Bench

Figure 11 – Installed Power Supply

After all of the data is collected the students plot each of the curves. There are two types of comparisons the students are asked to make. First, the intersection of the fan and impedance curves for the power supply is compared with the data for the actual operating point. Secondly, the fan curves for the series and parallel configurations are compared to theoretical curves. The students are asked several reflection questions to try and make sense from the results.

It is fairly obvious from the size of the flow bench that it is not easy to bring it into a classroom for a short demonstration. Figure 12 shows a device that was built for in-class demonstrations.

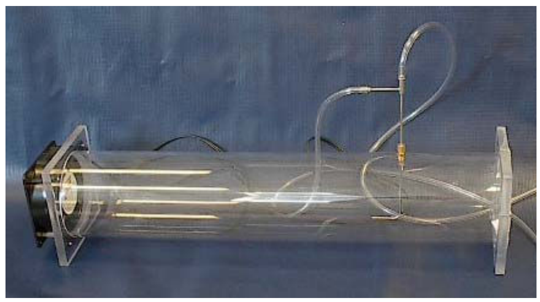


Figure 14 – In Class Fan Demonstration Device

The device consists of a fan mounted on a length of tube and a pitot tube mounted to measure the velocity. A LabView VI is used to display the velocity and to calculate the flow rate of the air through the tube. Figure 13 shows a schematic of the test set-up. The students are given the nameplate data from the fan, including the rated flow rate, and asked, among other things, to predict if the measured flow rate will closely match the rating. When it does not they are asked to try to make sense from the information. This in-class demonstration leads into a lecture on fans, fan laws, and ultimately the full exercise described above.

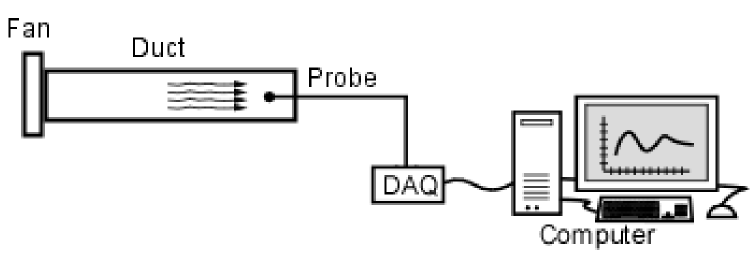


Figure 13 – In Class Fan Exercise Schematic

Challenges for the Future:

The information given in this paper is a snapshot of the current state of this research. There are many challenges to face for future improvements. R. Streveler, T. Litzinger, et.al.[20] give a very good overview of the research being done in the area of teaching concepts to students in order to improve their understanding of the material and to be able to apply higher level thinking to their problem solving. They list several areas where engineering students struggle with basic concepts such as heat vs. energy. They conclude that much has been done in the area of conceptual knowledge and misconceptions in science, but little has been done in the field of engineering. They make several recommendations for future research in this field, one of which is the development of "learning experiences that help student learn difficult concepts in engineering science". The exercises being developed by the authors are a small part of that recommended research. We recognize that the exercises in their present form leave room for improvement, and we intend to continue making needed improvements. In order to do that there are several challenges that lie ahead.

Not all faculty members at our own schools, and surely at others as well, are convinced that this kind of active learning approach to learning is a good approach. Others are not impressed by the exercises simply because they use unimpressive equipment. One of our challenges is to find ways to convince others that this is a sound pedagogical approach which will improve student learning. This challenge extends not just to other faculty but also to students. Our approach requires students to take more responsibility for their own learning, and many do not seem to be ready for that. It is our experience that some students in traditional laboratory environments are able to avoid putting in much effort while relying on classmates. In an active lab environment they cannot do that, so those students tend to dislike this approach.

The authors are not experts in doing educational research. We have come a long way since the beginning of the project in terms of creating exercises which provide reliable feedback to assess gains in student learning, but we need to continue to improve in that area. While the exercise worksheets are being continuously improved already, we need to rely on ongoing experience running the labs to help us continue to improve and update the worksheets, particularly in the area of assessment.

Ultimately there are several things we would like accomplish. We want to refine our suite of exercises to provide a pedagogically sound, easily assessable set of experiments. They should be interesting enough so the students are motivated to do their best work. We need to put in an extra effort to prove that they are effective in increasing the understanding of the concepts they are designed to teach. We feel we have a good start toward reaching these goals, but more work needs to be done.

Acknowledgements

This work is supported by the National Science Foundation under Grant No. DUE 0633754. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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