An In-Class Demonstration Used as an Introduction to the First Law of Thermodynamics for an Open System

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Abstract:

The First Law of Thermodynamics for an open system is a core topic in any first course in thermodynamics. A typical approach to teaching this topic might begin with explaining what an open system is followed by a qualitative discussion of the energy interactions across the system boundary. The bulk of the presentation(s) focus on the mathematical formulations needed to solve various open system problems. Usually this leads to examples involving a group of classic open devices such as turbines, pumps, etc.

Studies have shown that in-class demonstrations as well as other interactive methods are often more effective ways of helping students gain deeper understanding of subject matter than lectures alone. This paper describes an example of the use of an in-class demonstration to help students better understand first law concepts for open systems. This particular demonstration is more than a "show and tell" for the students. It involves the students in the presentation through the use of worksheets and discussions as the demonstration progresses. It typically uses up a complete class period.

Briefly, the demonstration described in this paper uses a pair of hair dryers as the open systems. Students are asked to predict how the output temperatures will change as switches are move into a variety of combinations. (There is a switch for the power and a separate switch for the fan speed). A LabView VI is used to monitor this on a screen in the room for the whole class to see. Various things occur during the demonstration that appear to violate the first law. In addition to these apparent violations, the students are also confronted with two hair dryers that do not act the same way. In fact, the temperature outputs are significantly different, not just in magnitudes but also in the direction of temperature changes as switch positions are changed. Through interactive discussions and the worksheets the students are challenged to reason out what is happening. This paper describes the demonstration and the work sheets used in class along with the expected outcomes of the exercise.

Introduction:

The first law of thermodynamics for open systems is a fundamental topic in any introductory course in thermodynamics. Typically this would be taught through a series of lectures including theory and sample problems. Modern pedagogical research has shown that lectures along are not necessarily the most effective way of presenting concepts such as this[1][2]. In class demonstrations, lab exercises and other hands-on experiences can help students to get a better understanding of the underlying principles. Even classroom demonstrations have been shown to be ineffective in improving learning[3]. They did observe, however, that when the students are actively involved in a classroom demonstration that there can be significant improvement in learning.

The exercise described in this paper is designed to actively involve students in a classroom demonstration. The exercise actively engages the students by having them make predictions about the outcomes of the test, then to discuss how the results compare with their predictions. If their predictions are wrong they attempt to uncover the reasons why they are wrong. The exercise uses a common hair dryer as the open system.

Hair Dryers as Teaching Tools:

A hair dryer was selected as the system because most students are at least somewhat familiar with the device. It has been shown that when a familiar device is used as a teaching tool it can help to add relevance to a lecture[4]. Students do not have to spend time or effort trying to figure out what the device is and how it works. This allows them to concentrate on the principles being demonstrated rather than on the device itself.

The use of a hair dryer for this exercise is not a novel idea. In fact, hair dryers have often been used as teaching tools. Alvarado has students design their own thermodynamic experiment using a hair dryer[5]. Weltner uses a hair dryer in an experiment to determine the specific heat of air[6]. Shakerin makes use of a hair dryer to demonstrate both the first and second laws of thermodynamics[7]. This author has long used a hair dryer in an experiment where students perform a comprehensive first law analysis[8]. The focus of this hair dryer exercise is twofold. First, it is intended to help students gain a better understanding of the first law concepts. Secondly, it is used to teach a qualitative relationship between mass flow rate and temperatures of fluids crossing the boundary of an open thermodynamic system using a guided inquiry approach.

Equipment:

The equipment need for this demonstration is very simple and inexpensive. There are two hairdryers mounted in custom brackets for ease of use. Thermocouples are mounted in an arrangement to measure the incoming air temperature and the outgoing air temperature. The outgoing air is measured in three places across the hair dryer nozzle. A data acquisition unit (DAQ) digitizes the thermocouple outputs which are then sent to a computer running a custom LabView VI to display the temperatures. A wattmeter is used to measure the total power consumed by the hair dryer. Figure 1 shows a schematic of this set-up. Figure 2 shows the actual hardware.

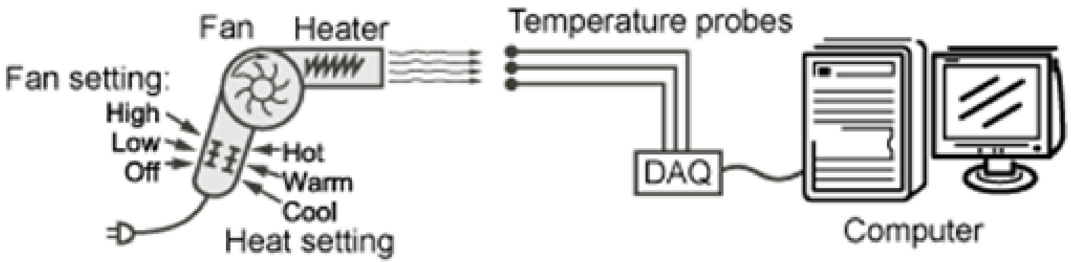

Fig. 1: Schematic of the exercise set-up

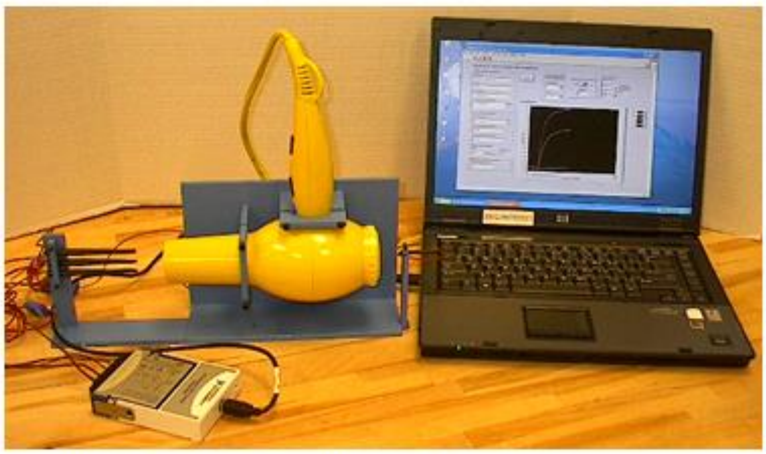

Fig. 2: Apparatus used for the hair dryer exercise

Notice the various hair dryer settings. There are two switches on the handle. One controls the fan setting, with off, low and high options. The other controls the heater setting, with cool, warm and hot options. When the hair dryer is set on the cool setting there is no power directed to the heaters. It is important to recognize this because it factors into the results of the exercise.

As mentioned above, there are two hair dryers that are used for the demonstration. One of the devices has been modified so that the controls work differently from a stock hair dryer. They give dramatically different results, one of which seems to contradict the first law of thermodynamics. This will be discussed below. Part of the exercise is for the students to try to make sense of the results.

Theory:

A simple schematic for a hairdryer is shown in Figure 3. It is made up of three basic parts: a resistance heater, a fan and an enclosure. Most of the energy consumed by the hair dryer is used by the resistance heater while a smaller amount is used by the fan. As air is blown across the heater it gains energy from the heater causing the temperature to increase. A small amount of the temperature increase can also be attributed to the power consumption of the fan motor. Even though the power consumed by the fan is small, it is interesting to note that the effect of this small increase is observed later as part of the exercise. It turns out to be an important part of the analysis of the data.

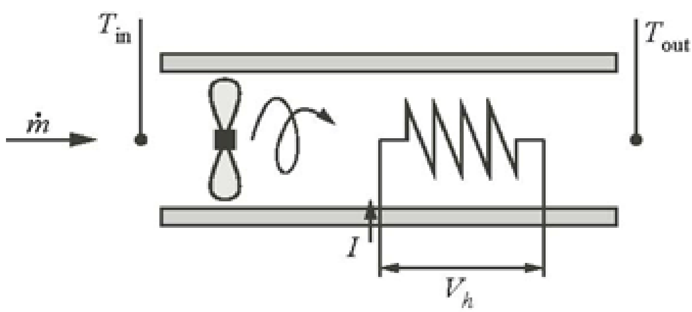

Fig. 3: Simplified schematic of a hair dryer

The first law of thermodynamics for the hair dryer can be written as shown in Equation 1[9].

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

Where:

$\dot{W}_{elec} = Electric\ work\ input\ (watts)$

$\dot{Q} = Heat\ loss\ from\ the\ housing\ (watts)$

$\dot{m}_{in} = Mass\ flow\ rate\ of\ the\ incoming\ air\ (\frac{kg}{sec})$

$\dot{m}_{out} = Mass\ flow\ rate\ of\ the\ outgoing\ air\ (\frac{kg}{sec})$

$h_{in} = Specific\ enthalpy\ of\ the\ incoming\ air\ (\frac{joules}{kg})$

$h_{out} = Specific\ enthalpy\ of\ the\ outgoing\ air\ (\frac{joules}{kg})$

$v_{in} = Velocity\ of\ the\ incoming\ air\ (\frac{m}{sec})$

$v_{out} = Velocity\ of\ the\ outgoing\ air\ (\frac{m}{sec})$

$g = Acceleration\ due\ to\ gravity\ (9.81\ \frac{m}{sec^2})$

$Z_{in} = Elevation\ datum\ for\ the\ incoming\ air\ (m)$

$Z_{out} = Elevation\ datum\ for\ the\ outgoing\ air\ (m)$

By the time the students are exposed to this exercise they have already had an introductory class in the theory. They have already seen this equation, and have used it for several homework problems. This exercise forces them to apply qualitative reasoning to the equation in order to make their predictions. This is an important step in helping them to get a better understanding of the relationships between the factors in the equation.

Required Student Predictions:

Pre-exercise the students are asked to make predictions about the relationships between the outlet temperature and the air flow rate through the device. They are asked to predict what effect changing the flow rate of the air will have on the outlet temperature if the power setting remains unchanged. Physically, this is done by leaving the heat setting untouched while the fan setting is changed from low to high. They are given the choices shown in figure 4 for their prediction. The correct answer is d – as the flow rate goes up the outlet temperature should go down linearly.

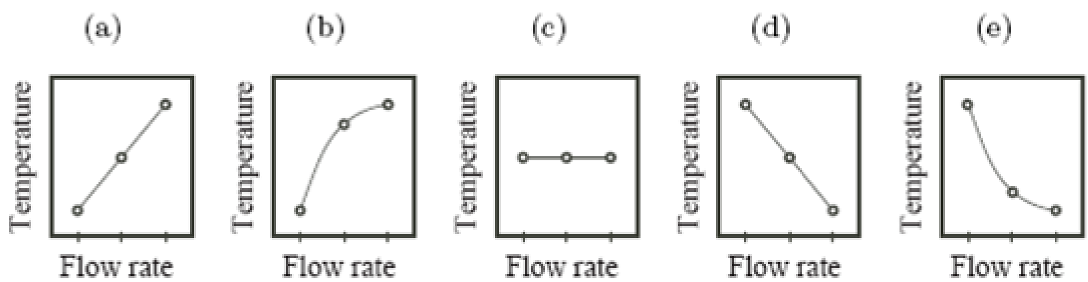

Fig. 4: Effect of air flow rate on outlet temperature

After their predictions are made the first hairdryer is run. Figure 5 shows the results.

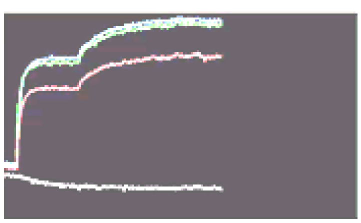

Fig. 5a – Heater setting Cool

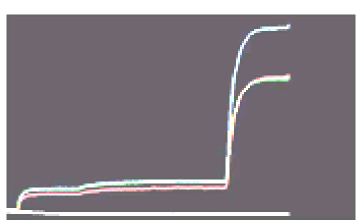

Fig. 5b – Heater setting warm, fan setting low

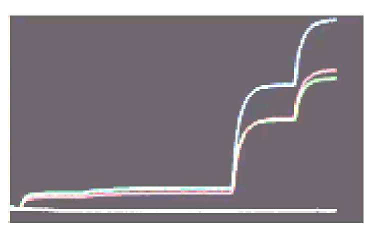

Fig. 5c – Heater setting warm, fan setting high

There are a couple of important observations to be made at this point. First, the temperature of the outlet air goes up even though the heaters are not turned on (Fig. 5a). Some students are surprised by this which makes this a good point for a class discussion. When the heaters are turned on to "warm" the temperature rises dramatically. This is an expected result. Finally, as the fan setting is turned up to high the temperature rises. This is a very unexpected result, and seems to contradict the first law of thermodynamics.

At this point the second hair dryer is tested to verify the results from the first. Figure 6 shows the results for this hair dryer.

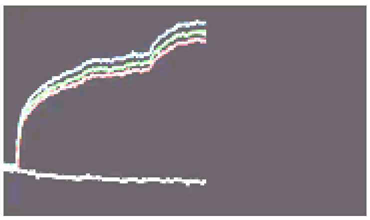

Fig. 6a – Heater setting Cool

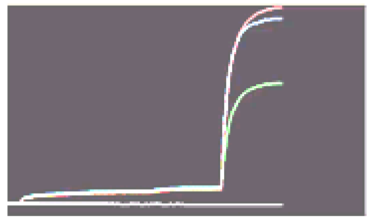

Fig. 6b – Heater setting warm, fan setting low

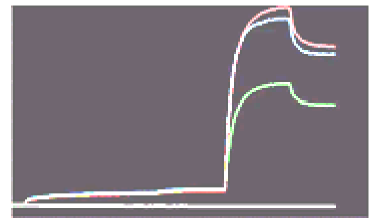

Fig. 6c – Heater setting warm, fan setting high

While these tests are being run the input power to the hair dryer is being recorded for the various switch settings. Figure 7 shows the wattage values for a typical run.

Hair Dryer		Low	High
1	Cool	70	110
	Warm	422	875
2	Cool	67	108
	Warm	555	597

Fig. 7 – Typical data table

Comparing Fig. 5c with Fig. 6c there is an obvious difference. The second result tends to properly demonstrate the first law, but the first one seems to contradict it. The remainder of the class period is used to discuss these results, and to give the students an opportunity to make sense of what they are seeing.

Analysis of the Data:

The results are very surprising based on the predictions. First, note that the temperatures go up for both hair dryers when the heaters are set on cool. Usually the group prediction is that there will be no change in the temperature for that setting. Figure 8 shows an energy diagram for a hair dryer. The first law of thermodynamics states that for steady state the energy in has to equal the energy out. Neglecting heat loss, the energy leaving with the air has to equal the sum of the energy coming in with the air and the electrical work input. Therefore the temperature of the outgoing air will be higher than that of the incoming air due to the electrical input to the blower. Additionally, when the fan speed is increased it requires more power, increasing the outgoing temperature even more. This is exactly what is shown in Figures 5a and 6a. Most students eventually recognize this relationship on their own.

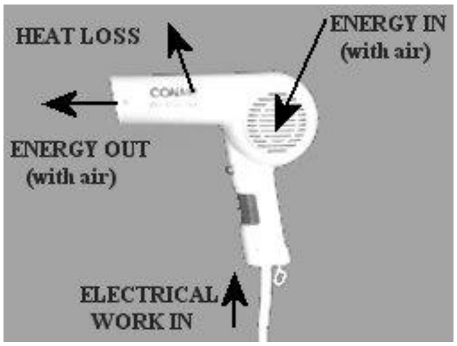

Fig. 8 – Energy diagram for a hair dryer

Now the students are left with the bigger problem. When the heaters are turned on (warm or hot), the hair dryers not only behave differently from each other, but one of them appears to violate the first law of thermodynamics. They need to consider the data (Figure 7) to resolve this issue. Notice that for both hair dryers, the power required to change the fan speed from low to high is around 40 watts. (This can be determined by looking at the cool power setting, because no power is going to the heaters.) Looking at the warm setting, you can see that it takes about 450 watts to increase the fan speed for the first hair dryer while the second hair dryer it takes only about 40 watts. Eventually the students notice that the power for the first one is significantly higher than for the second one, and conclude that it must have some effect on the results. They rarely notice that the power to increase the fan alone is 40 watts. Eventually, through discussing this dilemma as a group, the students begin to understand why the hair dryers act differently in terms of the outlet temperature characteristics.

It is interesting to note that even after the discussion period there is still confusion about how this all relates to the first law of thermodynamics. The students are asked which of the hair dryers obeys the first law. The majority say that the second one does because it follows the predictions, whereas the first one does not. They sometimes find it hard to believe that both of them do. It must be explained to them that the variations from the predictions are not caused by a failure to obey the first law but by the fact that the first one does not follow all of the assumptions that went into the prediction. Specifically, the heaters are not held at constant power. It needs to be emphasized at this point that everything has to obey the first law of thermodynamics, and that apparent violations must have some type of explanation behind them.

At the end of the exercise the students are told that one of the hair dryers has been modified. They are asked which one they think was changed. Most students assume that the first one was modified because it does not follow their first law predictions. In reality, it was the second one that was modified. Several hair dryers were tested by the author, and all of them behaved like the first one. Some of the students have suggested that one reason the manufacturers might design them that way is because if the temperature of the outgoing air were to go down when the fan is turned up that many users would assume the unit was broken.

Summary

The exercise described above has been successfully used in one 50 minute lecture period. Student participation is significantly higher than it is during a standard lecture indicating that they are getting engaged. The results to date have been encouraging, but more work needs to be done to verify that the exercise enhances their learning experience.

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