A Simple Hairdryer Experiment to Demonstrate the First Law of Thermodynamics

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Abstract:

Equipment for thermodynamics experiments and lab demonstrations can be very expensive. A common inexpensive hairdryer makes an excellent example of an open thermodynamic system, and can be used as an effective piece of lab equipment to illustrate the principles of the first law of thermodynamics.

Heat, work and mass all cross the boundary. From the first law of thermodynamics, the energy into the system has to equal the energy out for steady state. From conservation of mass, the mass in has to equal the mass out for steady state. This experiment requires the student to consider all of the energy terms associated with the hairdryer. The energy going in includes the electric work, the total enthalpy of the incoming air, and the kinetic energy of the incoming air. Energy out includes the total enthalpy of the outgoing air, kinetic energy of the outgoing air, and any heat transfer from the case to the ambient. Potential energy differences between the inlet and outlet are also considered. By accounting for all of the energy terms the students begin to recognize what is most significant and what could be neglected.

One of the difficulties encountered in this test arises from the fact that the air velocity and the air temperature across the nozzle exit are not constant. Students are required to take data at multiple points and treat the area around each point as a separate outlet. After flow rate calculations are made for each area, the total rate is determined by summing the individual rates. The same process is used when calculating the total enthalpy leaving at the nozzle.

The energy terms usually balance within a range of about 1.5% to about 15%. The amount of error usually depends on the patience and diligence of the student group doing the experiment. The students are asked to report on any possible sources of error they recognize while doing the testing.

I. Introduction:

A common hairdryer makes an excellent example of an open thermodynamics system. Figure 1 shows the energy terms that are involved in a first law analysis. For a steady state condition the total energy in must equal the total energy out. In this lab the students attempt to measure all of these energy terms and then compare the energy in with the energy out to show that the hairdryer obeys the first law.
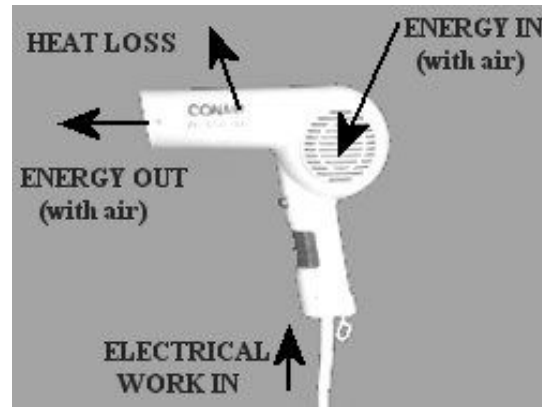
Figure 1

The energy into the hairdryer includes the electric work, the total enthalpy of the incoming air, and the kinetic energy of the incoming air. Energy out of the hairdryer includes the total enthalpy of the outgoing air, kinetic energy of the outgoing air, and any heat transfer from the case to the ambient. Potential energy differences between the inlet and outlet are also considered. The students learn through their calculations that some of the terms involved are very significant to the overall energy balance and some are almost negligible. The students also learn through the experiment that things going on inside the case, or system boundary, are not factors in the external energy balance.

II. Equipment:

Figures 2 and 3 show the equipment that is used to conduct this lab.

- Hair dryer (figure 2)
- Stand for mounting hair dryer (figure 2)
- Custom made holder for five thermocouples with thermocouples attached (figure 2)
- Custom made pitot tube holder with pitot tube and differential pressure gauge (figure 2)
- Two digital multimeters (figure 3)
- Any device for reading the thermocouples (figure 3)
- Infrared thermometer (figure 3)
- Dial calipers (figure 3)

Figure 2

Figure 3

The custom thermocouple holder and pitot tube holder are made out of high temperature pvc pipe. They are machined to fit inside the nozzle of the hair dryer. Both devices can be rotated to place the measuring devices at various locations in the outlet. On the thermocouple holder there are five thermocouples equally spaced across the diameter. The pitot tube holder has a loose fitting clamp to hold the pitot tube in any position across the diameter of the device.

III. Test Set-up:

Figure 4a shows the hairdryer mounted on the stand with the thermocouple holder in place. Figure 4b shows the same set-up except that the pitot tube holder is mounted. The hairdryer is mounted with the outlet nozzle in a horizontal position.

| Figure 4a | Figure 4b |

IV. Test Procedure:

Before coming to lab the students are to prepare a data sheet for recording all of the data. The data that is required includes:

- Barometric pressure
- Ambient temperature
- Inside diameter of the outlet
- Any measurements needed to determine the inlet area
- Electrical work in: Voltage and current
- Mass flow rate and enthalpy out: The outlet is divided into 17 equal area regions (figure 5). Within each of these regions the outlet temperature and the differential pressure across the pitot tube are measured. The reason for dividing the outlet into regions is because the temperatures and velocities have large variations across the outlet due to the locations of the internal components. This method gives much better results than using an average value across the cross-section.
- Heat out: Surface temperature of the nozzle and length and diameter of the heated area

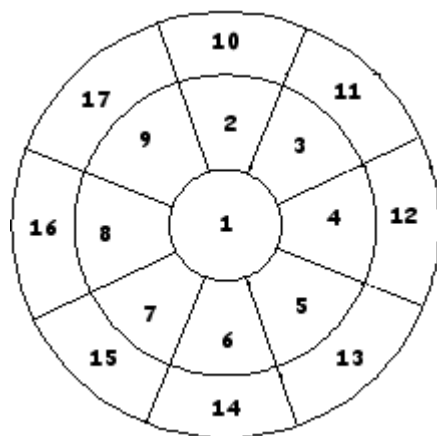Table 1 shows the test procedure given to the students.

Figure 5

V. Calculations

The basic first law of thermodynamics for the hairdryer can be written as:

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

Consider each term in the equation:

Electric Work In:

$$\dot{W}_{elec} = Voltage * Current \quad \text{(Equation 2)}$$

Students measure both the inlet voltage and current for this equation. A hairdryer is designed to produce heat, so a high power factor is desired. Most hairdryers have a power factor very close to one. A power factor of one is assumed for this experiment. This assumption has been tested for the particular hairdryer used in this test by observing the voltage and current input on an oscilloscope and noting a negligible phase shift. Most typical hairdryers should exhibit the same characteristics.

Heat Transfer:

$$\dot{Q} = hA(T_s - T_\infty) \quad \text{(Equation 3)}$$

- h is the convection coefficient. This number is given to the students as 5 w/m^2-^0C. More advanced students calculate this number based on a correlation for a horizontal cylinder in natural convection. The area is estimated based on the students' judgment about how

much of the nozzle is actually warm. The surface temperature is measured using an infrared thermometer. The temperature varies across the surface, so the students must make a judgment about what to use as an average temperature. No effort is made to break the nozzle surface into regions of different temperatures, mainly because the heat loss through the nozzle is quite low and the extra effort would not be worth the extra time it would take.

Specific Enthalpy In:

$$h_{in} = CpT \quad \text{(Equation 4)}$$

Cp is the specific heat of the incoming air, given to the students as 1.004 KJ/kg-^{0}C. More advanced students are required to look this number up based on the ambient temperature. The temperature T is the absolute temperature of the incoming air (room temperature) in K.

Specific Enthalpy Out: h_{out} is calculated using equation 4, but the temperature used is the temperature for each data region in the outlet. More advanced students look up specific heat values at the measured temperatures instead of using the given standard value.

Velocity Out:

$$V_{out} = 22.3\sqrt{\frac{\Delta p}{\rho}} \quad \text{(Equation 5)}$$

The velocity is calculated for each data region. In this equation Δp is the differential pressure across the pitot tube in inches of water. ρ is the density of the air in kg/m^3 which is calculated from equation 6. The constant is a correction factor for the inconsistent units. More advanced students are required to perform their own unit conversions.

Air Density:

$$\rho = \frac{21.33 P_b}{9/5(T) + 492} \quad \text{(Equation 6)}$$

In this equation P_b is the barometric pressure in inches of mercury and T is the temperature of the air in the data region measured in ^{0}C. The other constants are conversion factors so the units of density are kg/m^3. The constants are correction factors for inconsistent units. More advanced students are required to perform their own unit conversions.

Mass Flow Rate Out:

$$\dot{m}_{out} = \int \rho V dA \quad \text{(Equation 7)}$$

The students do not take enough data to perform this integration, so the integration is replaced with a summation across the data regions. (Equation 8)

$$\dot{m}_{out} = \sum_{i=1}^{17} \rho_i V_i A_i \quad \text{(Equation 8)}$$

In this equation ρ is the density of the exiting air as determined by equation 6, V is the exit velocity as determined by equation 5, and A is the area of the region of interest. The exit is divided into 17 equal regions, so A becomes the total exit area divided by 17. Since the air is forced through the custom thermocouple and pitot tube fixtures, the inside diameter of the fixtures is used to calculate the total exit area.

Velocity In: The students are told to use a velocity in of zero because the inlet area is much larger than the exit, so the velocity will be very low. More advanced students use the continuity equation which says that the mass flow rate in equals the mass flow rate out. From this information the inlet velocity can be calculated from equation 9.

$$\dot{m}_{in} = \rho_{in} V_{in} A_{in} \quad \text{(Equation 9)}$$

Where ρ_{in} is the density of the room air, V_{in} is the inlet velocity, and A_{in} is the total inlet area. The velocity is assumed to be constant across the inlet area. The students are required to take any necessary measurements to determine the total inlet area.

Potential Energy: The vertical distance between the center of the inlet and the center of the outlet is measured. This elevation change is used to calculate the potential energy change.

Miscellaneous Information: Many of the equations above contain correction factors for unit conversion. As mentioned, these factors are not provided for more advanced classes. However, some of the measurements still contain inconsistent units, such as the measurements for the heated area of the nozzle, the nozzle diameter, and the measurements for the inlet area. The students must recognize inconsistent units throughout the calculations and make conversions as needed.

VI. Data and Results:

 Table 2 shows a typical set of data taken for this lab. Notice that there are four temperatures given for region 1. When the thermocouple fixture is rotated the center thermocouple remains in region 1, so data is taken in four different positions of the fixture. The data does not stay constant because the center thermocouple is not perfectly centered. The four readings are averaged for the region.

With this set of data the total mass flow rate through the hairdryer is .01417 kg/sec, the total energy of the air exiting the nozzle is 4830 watts, the heat loss is 0.7 watts, the total energy of the air entering the hairdryer is 4182 watts, and the electric work input is 832 watts. This gives a total of 4801 watts out and 5014 watts in for a 4.2 % error.

These values are typical for the lab. The errors can range from about 1.5% to about 15%. The amount of error usually depends on the patience and diligence of the student group doing the experiment.

The students are asked to report on any possible sources of error they recognize while they are taking the data. Factors that contribute to the error include difficulty in positioning the pitot tube accurately, no true steady state condition for the hairdryer (although it does reach a reasonably stable condition after about 2 minutes), and a slight leakage of air from separation in the plastic housing.

DATA		
PHYSICAL CHARACTERISTICS		
Fixture Inside Diameter = 1.485 in = 0.037719 M		
Air Inlet Area of Dryer = 3.55 in^2 = 0.00229 M^2		
Elevation Difference Inlet/Outlet = 0.75" = 0.01905M		
ELECTRICAL CHARACTERISTICS		
Input Voltage (low speed) = 113.3V		
Input Current (low speed) = 7.34A		
HEAT LOSS DATA		
Average Temp. of Nozzle = 34^{0}C		
Length of Heated Surface = 2.459 in		
Outside Diameter of Nozzle = 1.975 in		
MISC. DATA		
Room Temperature = 20^{0}C		
Barometric Pressure = 29.82 in Hg		
Region	Temperature (^{0}C)	Diff. Press. (in H$_2$O)
1	75.2	0.30
1	71.4	-
1	65.8	-
1	59.3	-
2	73.4	0.30
3	110.9	0.32
4	84.6	0.31
5	96.3	0.27
6	74.3	0.34
7	69.0	0.39
8	72.2	0.38
9	75.5	0.32
10	55.4	0.35
11	86.2	0.25
12	69.4	0.24
13	68.9	0.31
14	61.8	0.34
15	41.2	0.30
16	45.5	0.30
17	57.1	0.35
Table 2		

VII. Tips for Implementation:

For those considering implementing this test, here are a few helpful tips

- The custom thermocouple and pitot tube fixtures are made from high temperature PVC pipe.

- Figure 6 shows the thermocouple fixture. Five thermocouples are spaced across the opening (labeled 1-5). The arrow on the bottom left is pointing at a shoulder on the fixture. The PVC pipe is turned down to fit snuggly inside the hairdryer nozzle. The fixture can be rotated in 45^0 increments to collect data from each of the 17 regions of the exit.
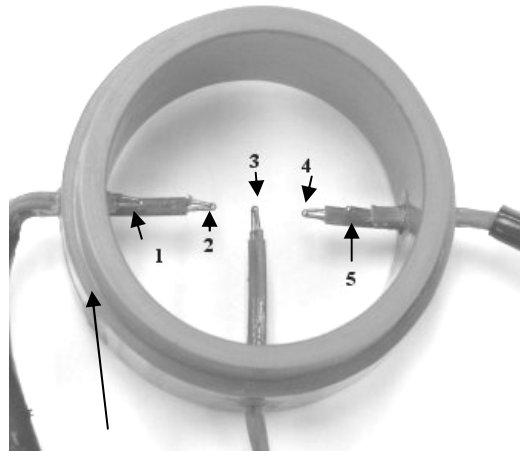

Figure 6

- Figure 7 shows the pitot tube fixture. The fixture is made in two pieces. Again, a shoulder is turned on the PVC pipe so it fits snuggly into the hairdryer outlet. A small slot is machined into each piece to hold the pitot tube. Care must be taken when tightening the bolts holding the two pieces together so as not to crush the pitot tube. The center of the pitot tube is positioned on a radius to locate it in the center of one of the outlet regions. The fixture can then be can be rotated in 45^0 increments to collect data from 8 of the regions of the exit. Notice the tape placed near the end of the fixture. This is marked in 45^0 increments to facilitate correct placement.

Figure 7

- An ammeter has to placed in the electrical line at some point. It is helpful to have an extension cord with one of the wires pre-cut to accommodate the ammeter.

- The thermocouple readings and the pitot tube readings for each region must be linked to each other. It seems like a simple task to keep this straight, but most student groups have a lot of trouble arranging their data sheets to keep these pairs connected. It is important to carefully observe how the students are recording their data so the proper pairs are used for the calculations later.

- Consistent units must be stressed throughout.

- It is important to keep the students focused on looking for possible sources of error. Many groups include this in their reports as an afterthought, and the reasons they present are often less than insightful.

- It is helpful to the students to make sure they recognize which energy terms are significant and which ones contribute very little to the overall energy balance.

VIII. Conclusions:

This lab offers the students an excellent demonstration of the first law of thermodynamics at a very low cost for equipment. Most of the instrumentation is available in any typical lab. The hairdryer cost is negligible, and the two custom holding fixtures are very simple to make.

The students learn several things from this lab. Primarily they get a hands-on experience with the first law. They get a sense of which terms in the energy equation are significant and which might be considered negligible. The potential energy change and the heat loss through the nozzle combine for less than .002% of the total energy exchange. When these terms are dropped from calculations in a lecture the students have a better understanding why that can be done. It also teaches them that the energy balance addresses the energy interactions between the system and the external environment. Only the energy crossing the boundary needs to be considered, not the things going on inside the boundary.

This lab can be used either after or before the first law of thermodynamics is introduced in the classroom. When it is used after the material is covered in a lecture the students understanding of the material is enhanced by the experience. Often it is more valuable to conduct the lab before the material is introduced in class. The students' curiosity about the topic is raised by doing the experiment. When the theory is covered in a lecture, particularly if it is soon after the lab, the students can relate to what is being taught, and tend to have more questions, helping to stimulate class discussion. This lab has been used for several years at Penn State Erie with very good success.

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Robert Edwards is currently a Lecturer in Engineering at The Pennsylvania State University at Erie where he teaches Statics, Dynamics, and Fluid and Thermal Science courses. He earned a BS degree in Mechanical Engineering from Rochester Institute of Technology and an MS degree in Mechanical Engineering from Gannon University.