Should We Turn Down the Thermostat?
A Practical Test of Newton's Law of Cooling

Introduction/Purpose:

Energy can be transferred from hot bodies to cooler ones by conduction, convection and radiation; in this lab, you will study conduction and convention. You will test the validity of Newton's Law of Cooling by applying it to investigate the practical matter of turning down a home thermostat to save energy.

Apparatus:

Light bulb in socket with cord attached, DC Power Supply, Power strip with on/off switch, Large insulated container, Stainless steel thermometer probe, LabPro interface, Voltage probe, PC with Logger Pro software

Theory:

A. Conduction

The heat transfer can be viewed on an atomic scale as an exchange of kinetic energy between molecules in heat conduction. Less energetic (colder) molecules gain energy by colliding with more energetic (warmer) molecules. The manner in which heat is transferred through a material can be understood by examining what is happening to the atoms of the material. Initially the atoms in the material are vibrating about their equilibrium positions. As one end of the material is heated the atoms near that end begin to vibrate with larger and larger amplitudes. These atoms collide with their neighbors and transfer some of their energy in the collisions. Slowly, the atoms farther away also increase their vibrations and heat is transferred through the material.

It has been found experimentally that the rate of heat transfer is proportional to the area of the sample and the temperature gradient:

$$P_{Conduction} = \frac{\Delta Q}{\Delta t} - kA\frac{(T_2 - T_1)}{\Delta x} \qquad (1)$$

A	is the cross-sectional area through which heat flows;
T_2	is the temperature on the hotter side of the conducting substance;
T_1	is the temperature on the cooler side of the conducting substance; and
k	is the thermal conductivity of the substance

The proportionality constant, k, depends on the material. Metals have a higher thermal conductivity because they have more free electrons to carry energy and electric insulators have a lower thermal conductivity due to relying heavily on lattice vibrations to transfer energy.

B. Convection

While conduction takes place in both solids and fluids, convection occurs only in fluids. Unlike conduction, convection involves the flow of matter, not just energy. Circulating currents transfer parcels of fluid between regions of different temperature, where the fluid transfers energy by conduction with the surrounding fluid. A common example is a convection oven where the heating element (gas or electric) is below the food and heated air rises to contact it and transfer energy to it. Once cooled, the air falls back toward the heating element to once again be heated.

The model for convection is very similar to that of conduction since most of the temperature change takes place via conduction from a solid across a thin boundary layer of fluid (in this case the fluid is air, however the behavior is essentially the same for either gases or liquids). The boundary layer is like a fluid skin that clings to the solid surface. However, the thickness of the boundary layer is not a fixed quantity, but depends upon such things as the viscosity of the fluid and its flow speed, which may be related to temperature.

Sir Isaac Newton is credited (perhaps wrongly) with taking advantage of this similarity in developing an approximate model for convective heat transfer. Not surprisingly, it strongly resembles the model for conduction:

$$P_{Convection} = \frac{\Delta Q}{\Delta t} = -Ah(T_{Object} - T_{Surroundings}) \qquad (2)$$

The proportionality constant, *h*, is called the heat transfer coefficient and vary from ~5 W/m^2-^{o}C for free air to as high as 100,000 W/m^{2*o}C for forced condensing steam. The difference between free and forced fluid flow, for example using a fan, can be as high as a factor of 100.

C. Newton's Law of Cooling

Both equations (1) and (2), which obviously have similar mathematical forms, are known as Newton's Law of Cooling. The salient features are that the rate of thermal energy transfer is directly proportional to the temperature difference and also to the cross sectional area through which heat is transferred. While conduction and convection dominate for this experiment, it can be shown that for small room-temperature range differences between an object and its surroundings, the equation for blackbody radiation that has a (T^4-T_0^4) dependence for temperatures in Kelvin can be approximated by a simple difference in temperature as well. Thus, Newton's Law of Cooling is an approximation that applies to virtually all types of heat transfer for temperatures near room temperature.

Integrating Newton's Law of Cooling leads to an exponential:

$$\Delta T = \Delta T_o e^{-\frac{hAt}{mc}} \tag{3}$$

where ΔT_0 represents the initial temperature difference, and ΔT is the temperature difference at some subsequent time *t*. The quantities *m* and *c* are the mass and specific heat of the object whose temperature is changing. Comparing equations (1) and (2), we see that The heat transfer coefficient *h* is, in the case of conduction, simply the ratio of the thermal conductivity of the substance to its thickness, $k/\Delta x$.

D. Turning down the Thermostat

The claim that a substantial amount of energy could be saved if people turned their home thermostats down from 75°F to 65°F across the country is frequently made. In this lab experiment you will investigate the percentage of energy that could be saved as a result of such a change.

If Newton's Law of Cooling applies, then the amount of energy lost in a given time by a system (e.g., a house) to its surroundings (e.g., the outdoors) is approximately proportional to the temperature difference between the system and its surroundings.

Let's assume that a typical winter outside temperature is 30°F = -1.1°C. A warm house at 75°F = 23.9°C needs to have a certain amount of heat added per unit time to maintain the temperature difference between it and the outside. If, instead, the thermostat is set at 65°F = 18.3°C, less heat is required.

For these values, the temperature <u>difference</u> between the warm house and the outside is 23.9°C - (-1.1°C) = 25.0°C.

The corresponding <u>difference</u> for the cooler house is 18.3°C - (-1.1°C) = 19.4°C.

The thermostat in a typical house works by monitoring the temperature at some location. For example, if the thermostat is set to 75°F, the thermostat will turn on the furnace when the temperature is about 1°F below the desired temperature; in this case it will turn on when the temperature drops below 74°F. Once the furnace is on, the house will start to warm up. When the temperature is about 1°F above the desired temperature, in this case about 76°F, the thermostat turns off the furnace. Thus, for a typical house during a winter night, the furnace will turn on and off a number of times as the temperature swings by a few degrees Fahrenheit around the set-point of the thermostat. You will be modeling this type of temperature control in this experiment.

Procedure:

1. Obtain a light bulb (about 100 W, with a known power output) in a holder, and plug it into the power strip. Test that the bulb works when you turn on the power strip, but then turn it off. Make sure the DC power supply is turned on and plugged into the same outlet strip.

2. Turn on your computer, log in to the physics domain, and start the Logger Pro program. Load the template file SAVEENERGY from the f:\classes\class2 folder.

3. The Logger Pro graph will display two quantities *vs*. time: the first quantity is the temperature in °C and the second is simply a voltage. The voltage goes from zero when the light bulb is turned off, to a positive value when the light bulb is turned on and will help you determine the length of time the light bulb was on and off.

4. Determine the temperature of the room in which you are working using your thermometer.

5. Place the light bulb and the thermometer inside the container, now known as your "house." Position the thermometer so that it reads the air temperature in the house. Close up your house.

6. Calculate the target temperature for the warm and the cool house. For the warm house, add 25.0°C to your measured room temperature.

   The target warm temperature = room temperature + 25.0°C is _____ °C.

   For the cooler house, by add 19.4°C to your room temperature.

   The target cooler temperature = room temperature + 19.4°C = _____ °C.

7. Designate two members of your group to be (1) the thermostat, and (2) the thermometer reader. The thermostat is responsible for turning the light on and off. The thermometer reader monitors the temperature and lets the thermostat know when to turn the light on or off.

8. First, you need to heat the house up to the desired temperature. The thermostat turns on the light until the thermometer reads the target temperature for the warm house. (Don't start taking data with Logger Pro yet!)

9. As soon as the target temperature is reached, turn off the light in the house.

10. When the house temperature reaches 0.5°C below the warm target temperature, the thermostat turns on the light. At the same time, begin collecting data, by hitting the “Collect” button, in Logger Pro to keep track of the temperature and the time elapsed when the light is on.

11. When the house temperature reaches 0.5°C above the warm target temperature, the thermometer reader tells the group. The thermostat turns off the light.

12. Repeat Procedures 10 and 11 for exactly 20 minutes. At this point, Logger Pro will stop acquiring data. Be sure to save your data.

13. In order to do the second part of the experiment, the system needs to start at the cooler target temperature. It may help to “take the roof off of your house” for a few seconds, but don’t let it get below your new, lower target temperature.

14. Once the house has cooled to 0.5°C below the cooler target temperature, turn on the light bulb, press “Collect” in Logger Pro and repeat Procedures 10 through 12 using the cooler target temperature. Again, save your Logger Pro data.

15. Finally, see whether additional energy can be saved by insulating your house (for example, use a jacket or heavy sweater) and adding “weatherstripping” to better seal leaks. Run the experiment for 20 minutes and save your Logger Pro data.

Analysis:

1. Using the data from your first two trials (heating and cooling to maintain target temperatures), compute the percentage of energy saved by lowering the thermostat setting to the lower target. Using Newton’s Law of Cooling as represented by equation (2), calculate the percentage of energy that is expected to be saved. How do your measured savings compare to the expected energy savings?

2. By what percentage do the energy savings increase when the house is better insulated?

Questions

1. Were you surprised by the percentage of energy saved? Why or why not?

2. Does the percentage of energy saved depend upon how well insulated your “house” was? Theoretically? Experimentally? Compare your results with other groups in your class who used different styles of “houses”.

3. How would a change in your original assumption of 30°F = - 1.1°C for a typical winter temperature influence the percentage of energy saved? Based on your results, estimate the percentage of energy saved by turning down the thermostat 10°F from 75°F when the outside temperature is -20°F on a brisk winter night.