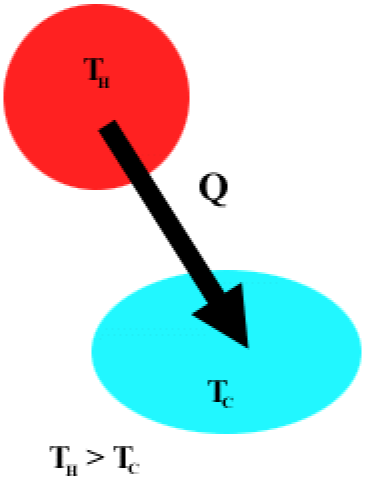
ESA21
Environmental Science Activities for the 21st Century

Energy: R-Factor

Introduction

Confusion About Heat and Temperature

Even though it has been over 150 years since the First Law of Thermodynamics was discovered, we still find that heat is misunderstood. For example, the many environmental science textbooks define heat as "the total kinetic energy of atoms or molecules in a substance not associated with bulk motion of the substance." **THIS IS WRONG!** What these books are describing is the thermal energy of a system. This is a common misconception. While heat is energy, it is not a containable form of energy since, by its very definition, heat is energy that is transferred. In particular, heat is **the energy transferred between objects of different temperature**. The misunderstanding comes from the fact that we often talk about heat leaving or entering an object, which gives people the idea that the object must contain heat. But this is not the case. Once heat enters an object, it increases the internal energy of an object, which is the same result that doing work on the object would produce. The object does not contain the heat or the work; it merely changes its energy because of them.



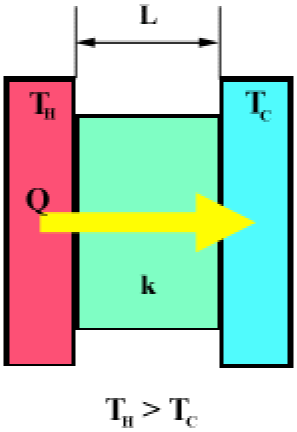
This increase in internal energy can cause numerous things to occur to the object. One of the more common things that it causes is for the temperature of the object to increase. However, it can cause other things to occur that do not involve any change in temperature, such as a change of state (ex. water changing into steam). The fact that one of the most common experiences is that the temperature changes leads to another erroneous definition. Many books also define temperature as "a measure of the speed of motion of a typical atom or molecule in a substance." Again, this is wrong. While it may be true for an ideal gas, it does not apply to all objects. The best definition for temperature is **the property that two objects have in common when no heat is transferred between them when placed in thermal contact**. The observant reader is going to note a certain circuitousness about these definitions for heat and temperature. But, these are the only definitions that truly make sense. The best way to illustrate this is to examine what happens when you measure the temperature of a glass of water with a mercury or alcohol thermometer. Upon entering the water, the thermometer does not instantly register the correct temperature. Instead, it takes several seconds for the liquid in the thermometer to settle to the correct reading. During this time, heat is being exchanged between the water and the liquid in the thermometer.

As it does so, the temperature of the liquid in the thermometer changes, becoming closer to that of the water. This change in temperature of the alcohol or mercury results in its volume changing, which is what changes the level of the fluid in the thermometer. Once the temperature of the fluid has reached that of the water in the glass, heat stops being transferred between them, and the volume of the fluid stops changing.

Thus, the thermometer is not measuring the average speed of the molecules in the water. The only thing that is being measured is the volume of the liquid in the thermometer. Somebody (or some machine) calibrated the volume of the fluid in the thermometer to a temperature scale that is painted onto its side. Because of this, we are able to read a value for the temperature by merely measuring the height of the liquid in the thermometer. The temperature that we read, though, only tells us which way that heat will flow if the object is put into thermal contact with another object.

Conduction

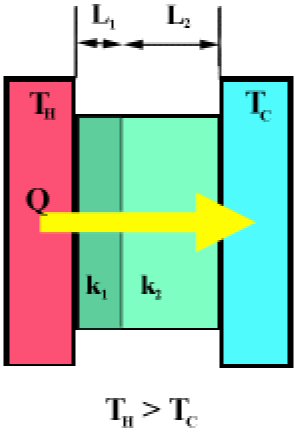
As we have previously stated, homeowners, on average, spend almost 50% of their energy budget for heating and cooling. The reason for this is because heat is constantly transferring through all of the exterior surfaces of the home. The most predominant type of heat transfer for the majority of homes is known as conduction, which occurs when two regions of different temperature are put into direct contact, but are not allowed to mix. As an example, the inside temperature of a home in the winter is hotter than the exterior temperature if the home is being heated. The walls, doors, and windows are all conducting heat to the outside since they are in direct contact with both reservoirs of air.



The rate at which heat gets transferred depends upon (1) the thickness of the material L, (2) the thermal conductivity k (this depends on the composition of the material), (3) surface area of the material A, and 4) the temperature difference between the reservoirs. In particular (see Fig. 2), the rate of heat transfer = A k (T_H-T_C)/L. This equation shows that the thicker the material separating the two reservoirs (L larger), the smaller the surface area that is contact (A larger), or the smaller the temperature difference, the slower the rate of heat transfer through the substance. When it comes to heating and cooling our homes, this is exactly what we will need to strive for in order to reduce our energy bills.

In our homes, the exterior surfaces are usually comprised of more than one type of material. For instance, a wall can be composed of 3 1/2 inches of fiberglass insulation which is covered by 1/2 inches of sheetrock on the inside and plywood and brick on the exterior. When two or more different materials are between the hot and cold reservoirs, the equation on the previous page can become quite messy since there will be various thermal conductivities and thicknesses with which to deal.

The equation is greatly simplified if we consider the R-value of objects instead of their thermal conductivity. This is a measure of how well the material resists the flow of heat through it, and it combines the thermal conductivity and thickness into one term (R-value = thickness/thermal conductivity = L/k). While the common units for the R-value are ft^2 hr ^oF/Btu, these are often not quoted. If you visit any hardware store, you are likely to just see the R-value of a substance to just be quoted as a number, as in "Fiberglass R-value = 13."



From the previous page, we can see that the equation for conductive heat transfer through a single substance is given by

rate of heat transfer = A (T_H-T_C) k/L = A (T_H-T_C)/R

If there are multiple materials that comprise the surface (see Fig. 3), then the equation becomes

rate of heat transfer = A (T_H-T_C)/R_T

where R_T = sum of all of the individual R-values. As an example, in the wall that we proposed above, the R-value for the fiberglass is 13, for the plywood and brick is 4, and for the sheetrock is 0.5. Therefore the total R-value for the wall is 17.5, which is what would be placed in the denominator of the heat transfer equation.

R-Factors for Common Materials

The R-factor of a surface determines how quickly heat is conducted across it. The values below are some of the more common R-factors for surfaces found on homes in the U.S.

Exterior Walls with Siding

Concrete block (8")	Factor
(a.) Concrete block (8")	2.0
with foam insulated cores	20
with 4" on unisulated stud wall	4.3

Floor

Over unheated basement or crawl space vented to outside	Factor
Uninsulated floor	4.3
6" fiberglass floor insulation	25
Over sealed, unheated, completely underground basement	

with 4" insulated stud wall	14
Brick (4")	
with 4" uninsulated stud wall	4
with 4" insulated stud wall	14
Wooden Frame	
Uninsulated with 2" x 4" construction	4.6
with 1 1/2" fiberglass	9
with 3 1/2" fiberglass; studs 16" o.c.	12
with 3 1/2" fiberglass and 1" foam	20

Uninsulated floor	8
with 1" foam on basement walls	19
with 3 1/2 fiberglass on basement walls	20
Insulated floor, 6" fiberglass	43
Concrete Slab	
No insulation	11
1" foam perimeter insulation	46
2" foam perimeter insulation	65

Exterior Doors (Excluding sliding glass doors)
Calculate glass area of door as window

Wood Door	Factor
1 1/2" no storm door	2.7
1 1/2" with 1" storm door	4.3
1 2/3" solid core door	3.1
Steel with Foam Core Door	
1 3/4" Pella	13
1 3/4" Therma-Tru	16

Roof/Ceiling

Material	Factor
No insulation	3.3
3 1/2" fiberglass	13
6" fiberglass	20
6" cellulose	23
12" fiberglass	43
12" cellulose	46
14" cellulose	54

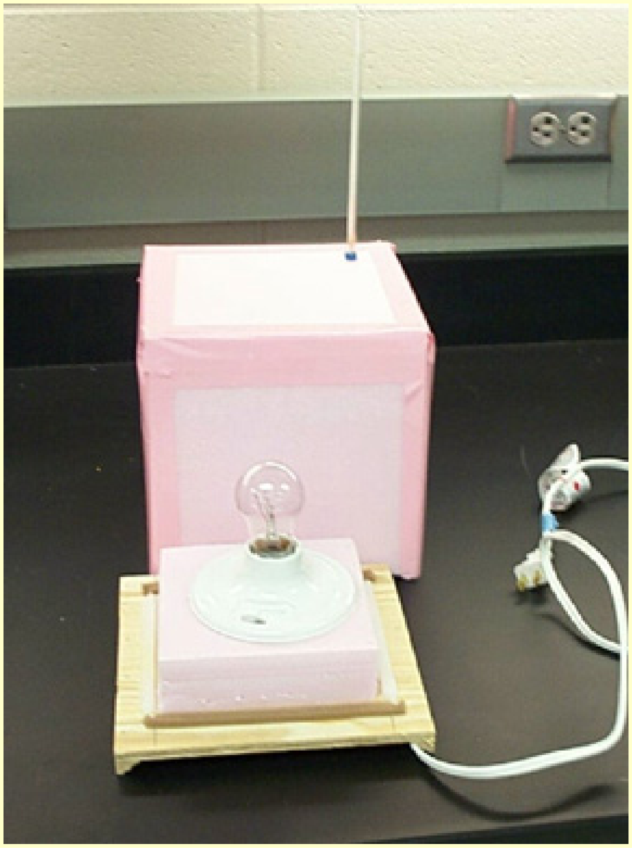
Windows and Sliding Glass Doors:

Glass	Factor	Low Emissivity	Drapes	Quilts
Single pane	0.9	1.1	1.4	3.2
Single w/storm window	2.0		2.5	4.2
Double pane, 1/4" air space	1.7		2.2	4.0
1/2" air space	2.0	2.99	2.5	4.3
Triple pane, 1/4" air space	2.6		3.0	4.8
Triple pane, 1/2" air space	3.2	3.7	3.7	5.5

Procedures

Measuring R-Factors for Common Materials

For this week's activity, we are going to measure the R-value of various building materials that are used in the construction of homes and offices. This will be done by placing a heat source inside of a box made of a particular material and monitoring the temperature both inside and outside of it. As the temperature of the inside of the box increases, heat will begin to be conducted through the material at a rate that is proportional to the temperature difference. At some point, the rate of heat that is being conducted out of the box will equal the rate of energy (power) that is being emitted by the heater. When this occurs, the box will have reached equilibrium, and we will be able to measure the R-value from the temperature difference [R-value = $A (T_H - T_C)$/(power of the heater)].

<table>
<tr><th colspan="3">Measuring R-factor</th></tr>
<tr><td>1.</td><td>At your experimental station, you should find three complete box set-ups similar to the picture at the right. Each one should consist of a box base with light bulb and a five-sided box top. You should also have a stopwatch and 4 thermometers.</td><td rowspan="6"></td></tr>
<tr><td>2.</td><td>Before placing the box top over the base, make sure that the light bulbs work by turning them on.</td></tr>
<tr><td>3.</td><td>After checking the flashbulbs, place the box tops over the bases. Place one thermometer on top of the box with the bulb resting on the box. Place another thermometer into the top of each box, about 2 inches deep.</td></tr>
<tr><td>4.</td><td>Record the initial temperature before turning on the bulb, then turn on each light bulb and start the stopwatch. It is most efficient to run all three boxes at the same time.</td></tr>
<tr><td>5.</td><td>Record the room temperature and the temperature of each box every 2 minutes until the temperatures stabilizes.</td></tr>
<tr><td>6.</td><td>Turn off the light bulbs, remove the thermometers from the box tops, and remove the box tops.</td></tr>
</table>

Calculation

Now that we have the temperature differences that can be maintained at equilibrium, we can proceed with calculating the R-values of the various materials. As stated above, the R-value for the material is given by the equation

R-value = A (T_H-T_C)/(power of the heater)

where A is the area of the box (the boxes have been constructed to have A=1.5 ft^2), T_H-T_C is the temperature difference that we just measured, and the power of the heater is the wattage of light bulb. In order to have the correct units for R-values (ft^2 hr ^{o}F/Btu), we need to know A in square feet, T_H-T_C in ^{o}F, and the power of the heater in Btu/hr. In other words, we need the following correction factors:

1 ^{o}C = 1.8 ^{o}F **(NOTE: This is for temperature difference, not for temperature)**
1 W = 3.41 Btu/hr

Using these factors, you should now be able to calculate the R-value for all three materials.

Name: Instructor:

Time (minutes)	½” Plywood Box		½” Insulating Board		1” Insulating Board	
	Inside T	Outside T	Inside T	Outside T	Inside T	Outside T
Temperature Difference						

Using the conversion: Temperature Difference = _____ ^{o}C x 1.8 ^{o}F/^{o}C = _____ ^{o}F

and the equation: $$R-Value = \frac{(1.25\,\text{ft}^2)(\_\_\_\_\ \text{oF})}{(\_\_\_\ \text{Watts})(3.41\,\text{Btu/W}\bullet\text{hr})}$$

	½” Plywood Box	½” Insulating Board	1” Insulating Board
R- Value			