Chapter 10
Temperature and Heat

GOALS

When you have mastered the contents of this chapter, you will be able to achieve the following goals:

Definitions
Define each of the following terms, and use it an operational definition:
temperature mechanical equivalent of heat
thermometer heat capacity
heat specific heat
linear expansion latent heat of fusion
volumetric expansion latent heat of vaporization
calorie heat of combustion

Calorimetry
Solve problems in calorimetry.

Gas Laws
Solve problems using the gas laws involving the pressure, volume, and temperature of a confined gas.

PREREQUISITES

Before beginning this chapter you should have achieved the goals of Chapter 5, Energy, and Chapter 9, Transport Phenomena.
Chapter 10
Temperature and Heat

OVERVIEW
Heat is a form of energy. As this energy moves from one object to another, we may detect physical changes in both the object losing heat energy and the object gaining heat energy. This chapter deals with many of these basic changes and the rules used to describe them.

SUGGESTED STUDY PROCEDURE
This chapter places emphasis on three primary Chapter Goals: Definitions, Calorimetry, and Gas Laws. Please read these chapter goals carefully. For an expanded discussion of the terms listed under Definitions, please turn to the next page of this Study Guide Chapter. Next, read text sections 10.1-10.9. Be sure to check the answer to each question in the text readings. You will find these answers in the second section of this chapter.

Now read the Chapter Summary and complete Summary Exercises 1-12. Then do Algorithmic Problems 1-9 and check your answers carefully against the answers given in the text. Now do Problems and Exercises 1, 2, 4, 9, 10, 14, and 18. For additional examples of problems from this text chapter, please see the Examples section of this chapter. Now you should be prepared to attempt the Practice Test over Temperature and Heat. Check your answers with those given. If you have difficulties with any of the problems, refer to the appropriate text section and the suggested study procedure. This study procedure is outlined below.

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DEFINITIONS

TEMPERATURE
The relative hotness or coldness of an object.
The human body contains many temperature sensors to inform you of the
temperature of your body and its environment.

THERMOMETER
A device or transducer which can be used to measure the temperature of a system.
The most common kinds of thermometer are mercury in glass and red-colored
alcohol in glass.

HEAT
Thermal work, a process by which the internal energy of a system is changed.

LINEAR EXPANSION
Change in length accompanied by a change in temperature.
Most materials increase in length when their temperatures are increased.

VOLUMETRIC EXPANSION
The change in volume accompanied by a change in temperature.
Most substances expand when they are heated. Water at 4øC expands if it is heated
and if it is cooled!

CALORIE
The mean amount of heat required to increase the temperature of one gram of water
one degree Celsius.

MECHANICAL EQUIVALENT OF HEAT
The amount of mechanical energy which is equivalent to one unit of heat or thermal
work.
In the SI units 4.186 joules is equivalent to 1 calorie. Your (Fuller)³ textbook weighs
about 13 Newtons. If you lift it about 32 cm you will have done about 4.19 joules
of work. That amount of work would raise the temperature of 1 cubic centimeter
of water one degree Celsius.

HEAT CAPACITY
Product of the mass of a body in grams and specific heat; i.e., amount of heat
required to raise the temperature of the body one degree Celsius.

SPECIFIC HEAT
Heat energy required to raise the temperature of a mass of material one Celsius
degree.
Compared to many other substances, See Table 10.3, water has a large specific heat.
Water is a good substance to use for the storage of thermal energy.

LATENT HEAT OF FUSION
Heat required to change unit mass of material from the solid state to the liquid at the
melting point.
Consider how high you would have to lift your copy of (Fuller)³ to do the amount of
work equivalent to the latent heat of fusion of one cubic centimeter of ice at 0°C.
More than 25 meters!
LATENT HEAT OF VAPORIZATION
Heat required to convert unit mass of material from liquid state to vapor state at the boiling point temperature.
Guess how high you would have to lift your copy of (Fuller) to do an amount of work equivalent to the amount of energy required to convert one cubic centimeter of hot water at 100øC to steam at 100øC. About 173 meters! That’s much higher than the state capitol building in Lincoln, Nebraska (which is about 130 meters tall!)

HEAT OF COMBUSTION
Energy produced per unit measure of quantity of material for complete oxidation. Which would you rather oxidize, spinach or beef steak? You will get about 20 times more energy from the steak as from an equal mass of spinach.

ANSWERS TO QUESTIONS FOUND IN THE TEXT
SECTION 10.2 Temperature
Absolute zero in Celsius is -273.16°C. In Fahrenheit, absolute zero is -459.69°F.

SECTION 10.4 Volumetric Expansion
Let us consider a cube of side \( L_0 \) then its volume is \( V_0 \) at a temperature \( T_0 \). Now let us heat the cube to a new temperature \( \Delta T \) degrees hotter than \( T_0 \). Now we calculate the new volume \( V \) in terms of the volumetric coefficient of expansion \( \beta \),
\[
V = V_0 + \Delta V = V_0 + \beta V_0 \Delta T = V_0 (1 + \beta \Delta T)
\]
But we can use the linear measurement to calculate this same volume.
\[
V = L^3 = (L_0 + \alpha L_0 \Delta T)^3 = L_0^3 (1 + \alpha \Delta T)^3 = V_0 (1 + \alpha \Delta T)^3
\]
\[
= V_0 (1 + 3\alpha \Delta T + 3\alpha^2 \Delta T^2 + \alpha^3 \Delta T^3)
\]
If \( \alpha \) is much smaller than 1; then \( \alpha^2 \ll \alpha \); so neglect the \( \alpha^2 \) and \( \alpha^3 \) terms:
\[
V \approx V_0 (1 + 3\alpha \Delta T)
\]
By comparing equations (1) and (2) we see
\[
\beta = 3\alpha
\]

SECTION 10.8 Heat of Combustion
At this date the cost of butter is about $.80 per pound and gasoline costs about $.65 per gallon.
Energy from butter = 716 kcal/100gm x 454 gm/1 lb. x 1 lb./$.80
= 4060 kcal per dollar
Energy from gasoline = 1150 kcal/100 gm x 4546 cm³/gallon x 1 gallon/$0.65 x 0.68 gm/1 cm³
= 54700 kcal per dollar
Butter costs 13 times as much as gasoline per unit of energy.

EXAMPLES
CALORIMETRY
1. A nurse withdraws 50 cc’s of blood from the arm of a patient. He wants to keep the sample for a while, so he puts it in a refrigerator and cools the sample to 2°C. How much heat in calories must be removed from the blood to do this? Assume for this problem that 50 cc’s of blood has a mass of 52 gm; assume that the specific heat of blood is the same as the specific heat of water; assume that the body temperature of the patient is 98.6°F or 37°C. Be sure to give the correct units.
What Data Are Given?
Mass of blood = 52 gm; initial temperature of blood = 37°C; final temperature of blood = 2°C, specific heat of blood = $10^3$ calories per kg.

What Data Are Implied?
None, it is all given.

What Physics Principles Are Involved?
The basic Calorimetry equation (10.9) is all that is needed.

What Equations Are to Be Used?
$\Delta Q = mc\Delta T$ (10.9)

Algebraic Solution
Heat Removed = $\Delta Q = mc\Delta T$

Numerical Solution
$\Delta Q = (52 \text{ gm})(1 \text{ cal/gm})(2^\circ \text{C} - 37^\circ \text{C}) = -1.8 \times 10^3 \text{ calories}$

Thinking About the Answer
The change in heat, $\Delta Q$, is negative because heat is lost from the system of blood.

2. Heat is required to change ice (solid) to water (liquid) without changing its temperature. In fact, it requires 80 calories of heat to change 1 gram of ice at 0°C to 1 gm of water at 0°C. Furthermore, heat is required to change water (liquid) to steam (gas) without changing its temperature. In fact, under standard conditions it requires 540 calories of heat to change 1 gm. of water at 100°C to 1 gm. of steam at 100°C.

(a) How much total heat is required to warm and convert a 1 gm piece of ice at 0°C to steam at 100°C under standard conditions?
(b) What percentage of the total heat is used to change the 100°C water to 100°C steam?

What Data Are Given?
1 gram of ice exists at 0°C.

What Data Are Implied?
During the heating process, no heat will be lost from the ice - water - steam system to its surroundings.

What Physics Principles Are Involved?
The basic concepts of Calorimetry (Equation 10.9) and changes in state (Section 10.7) are needed.

What Equations Are to Be Used?
Heating the water = $\Delta Q = mc\Delta T$ (10.9)
Melting the ice = $\Delta Q_i = L_i m$ (3)
Vaporizing the water = $\Delta Q_v = L_v m$ (4)

Algebraic Solution
(a) total heat = $\Delta Q_i + \Delta Q + \Delta Q_v = mL_i + mL\Delta T + mL_v$ (5)
(b) percentage for vaporization = $mL_v / \text{total heat}$ (6)

Numerical Solutions
(a) $Q_{total} = (1)(80) + (1)(100 - 0) + (1)(540) = 720 \text{ calories}$
(b) Percentage = $540 / 720 = 75\%$

Thinking About the Answer
Notice how much energy is required to convert the liquid water to the gaseous water, 75% of all the energy!
3. About how many hamburgers would a 91 kg (200 lb) man have to eat to enable him to climb to the top of the Nebraska capitol building, about 131 meters high? An average hamburger has a fuel value of about 250 kilocalories. The human body has a 10% efficiency; i.e., 90% of the fuel value of food is used to maintain the body, only 10% is available for work.

**What Data Are Given?**
- Mass = 91 kg; height to be lifted = 131 meters, efficiency = 10%, heat of combustion = 250 kcal/hamburger.

**What Data Are Implied?**
- The energy intake must be 10 times the amount used because the useful work is only 1/10 of the total energy input. Assume $g = 9.8 \, \text{m/s}^2$. It is assumed that the total fuel value of the hamburgers is used by the human body.

**What Physics Principles Are Involved?**
- The mechanical equivalent of heat is what is needed for this problem. The potential energy needed or the work done, to climb to the top of the Nebraska capitol building.

**What Equations Are to be Used?**
- Work done in climbing = $\Delta P.E. = mgh$
- Number of hamburgers = work done in kilocalories / $(\text{efficiency})250\,\text{kcal/hamburger}$

**Algebraic Solution**
- $N = \frac{W}{\text{efficiency}} \left( \frac{\text{W}[1 \, \text{kcal/4186 J}]/250 \, \text{kcal/lb.]}{(\text{efficiency})} \right)$

**Numerical Solution**
- $W = (91 \, \text{kg})(9.8 \, \text{m/s}^2)(131 \, \text{m}) = 1.2 \times 10^5 \, \text{J}$
- $W = 28 \, \text{kcal}$
- Energy needed = $\frac{W}{\text{efficiency}} = \frac{28}{.1} = 280 \, \text{kcal}$.
- $N = \frac{280 \, \text{kcal}}{250 \, \text{kcal/lb.}} = 1.1 \, \text{hamburgers}$.
- During his climb up to the top he would use up about the energy of one hamburger for climbing and for maintaining his body conditions.

**Thinking About the Answer**
- If you assume his other food is used to maintain his body conditions and he ate an extra hamburger, in order to keep from gaining weight he would have had to climb to the top of the capitol building 9 times. This shows why dieting rather than exercise is the easiest way to maintain, or reduce, body weight.

**GAS LAWS**

4. A weather balloon contains 280 m$^3$ of helium gas at sea level where the atmospheric pressure is $1.01 \times 10^5 \, \text{N/m}^2$ and the temperature is $27^\circ \text{C}$. Calculate the volume of the balloon when it reaches an altitude of 16 km where the pressure is $1.00 \times 10^4 \, \text{N/m}^2$ and the temperature is $-55^\circ \text{C}$.

**What Data Are Given?**
- $V_1 = 280 \, \text{m}^3; P_1 = 1.01 \times 10^5 \, \text{N/m}^2; T_1 = 27^\circ \text{C} \text{ or } 300^\circ \text{K}; P_2 = 1.00 \times 10^4 \, \text{N/m}^2, \text{ and } T_2 = -55^\circ \text{C} \text{ or } 218^\circ \text{K}$.

**What Data Are Implied?**
- That the balloon skin applies no extra pressure to the gas on the inside of the balloon, so the gas laws can be applied directly using the given data. It is assumed helium is an ideal gas.

**What Physics Principles Are Involved?**
- The combined laws of Boyle’s and Charles’ for ideal gases can be used.
What Equations Are to be Used?
\[ P_1 V_1 / T_1 = P_2 V_2 / T_2 \]  
(10.15)

Algebraic Solution
\[ V_2 = (T_2 / T_1)(P_2 / P_1) \cdot V_1 \]

Numerical Solution
\[ V_2 = (218^\circ K / 300^\circ K) \times (1.01 \times 10^5 / 1.00 \times 10^4) \times (280 \text{ m}^3) \]
\[ V_2 = 2060 \text{ m}^3 \]

Thinking About the Answer
The effect of the greatly reduced pressure to allow the balloon to expand is much more important than the reduced temperature that causes the gas in the balloon to have a reduced volume. The reason for this, of course, is the fact that absolute zero is many degrees below the range of temperatures occurring in this problem. Suppose absolute zero were only -60\(^\circ\)C instead of -273\(^\circ\)C. How would the results of this problem be changed?
SPECIAL PRACTICE PROBLEM FOR FUN

4. A well-known secret fact about Robinson Crusoe is that he was an amateur entomologist. While shipwrecked on his island every day at noon (sun directly overhead) he counted the number of ants coming out of the largest anthill in about one minute (70 beats of his heart). He noticed that on hot days the ants were more active than on cold days, so he constructed his own Robinson Crusoe temperature scale. He assumed there was a linear relationship between the number of ants he counted and the temperature. He made his own simple temperature scale, zero ants was 0°RC and 100 ants was 100°RC. After he was rescued he desired to calibrate his ant hill from known meteorological data and to fill in the missing numbers in his daily log.

Fill in the missing numbers in the table below:

<table>
<thead>
<tr>
<th>Number of days since shipwreck</th>
<th>No. of ants at noon per minute</th>
<th>Temp. in degrees Robinson Crusoe</th>
<th>Meteorological Data for the temperature of his island at noon.</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>100</td>
<td>100°</td>
<td>100°F</td>
</tr>
<tr>
<td>143</td>
<td>0</td>
<td>0°</td>
<td>60°F</td>
</tr>
<tr>
<td>215</td>
<td>20</td>
<td>20°</td>
<td>68°F</td>
</tr>
<tr>
<td>353-I am ill</td>
<td></td>
<td></td>
<td>86°F</td>
</tr>
<tr>
<td>354-I am ill</td>
<td></td>
<td></td>
<td>92°F</td>
</tr>
<tr>
<td>1034-I sighted a ship at noon</td>
<td></td>
<td></td>
<td>72°F</td>
</tr>
</tbody>
</table>

ANSWERS:
The relationship between the two temperature scales is given by
T(°RC) = 2.5 T(°F) - 150.
So 86°F = 65°RC; 92°F = 80°RC; 72°F = 30°RC.
Do you think this is a creepy problem?
PRACTICE TEST

1. Find the Celsius temperatures corresponding to the following common Fahrenheit temperatures.
   a. Room temperature (68°F)
   b. Human body temperature (98.6°F)
   c. Cold winter temperature (-4°F)
   d. Ice melts (32°F)
   e. Water boils (212°F)

2. An automobile tire at 32°F has a gauge pressure of 24 lb/in² (then its absolute pressure is 2.6 x 10⁵ N/m²). Immediately after running at high speed on the interstate highway, the tire pressure is measured to be 32 lb/in² (its absolute pressure is 3.2 x 10⁵ N/m²). What is the temperature of the tire, assuming the volume of the tire remained constant?

3. On a hot summer day (40°C) a physics student fills the 72 liter gasoline tank of her car with cool gasoline (10°C) from a self-service pump. Why will the gasoline overflow the tank? How much gasoline will flow out of the tank? (Coefficient of volumetric expansion of gasoline = 0.90 x 10⁻³/°C)

4. A 5 kilogram lead sphere falls from a 100 meter high building and lands on a hard concrete sidewalk. If all the heat energy created at impact is assumed to be retained by the sphere, answer the following questions.
   ______ a. How much heat is generated at the impact?
   ______ b. What is the final temperature of the lead if its initial temperature was 22°C? (Specific heat of lead = .13 J/gm°C).

ANSWERS:
1.  a. 20°C  b. 37°C  c. -20°C  d. 0°C  e. 100°C
2.  60°C
3. Increase in the temperature of the gasoline causes volumetric expansion; 1.9 liters
4.  a. 5,000 J  b. 29.7°C