13.4: Heat Transfer Involving Phase Changes

Learning Objectives

- Apply an equation to quantify the heat transfer that is associated with changing the state of matter of a substance.

The primary objective of this chapter is to quantify the amount of heat that is transferred during physical and chemical changes. As stated previously, heat must be applied in order to overcome the attractive forces between a substance's constituent particles, in order to transform that substance from a solid to a liquid, and then, subsequently, from a liquid to a gas. Heat must also be transferred to a substance in order to raise its temperature. Because these transformations cannot occur simultaneously with one another, the heat transfers that are associated with these physical changes must be calculated separately.

This section will present and apply the equation that can be used to quantify the heat transfer that is associated with changing the state of matter of a substance.

Equation and Variables

In order to quantify the heat transfer, q, that is associated with changing the state of matter of a substance, the mass, m, of that substance must be multiplied by a phase change constant, ΔH, that corresponds to the phase change that is occurring, as shown in the equation below. Each of these quantities can be measured using multiple units. However, in order to be incorporated into this equation, the heat transfer must be recorded in calories (cal) or joules (J) and the mass must be reported in grams (g).

$$q = m(\Delta H)$$

A **phase change constant**, **ΔH**, for a substance is a physical property that quantifies the amount of heat that is required required to change the state of matter of 1 gram that substance. The value of a phase change constant, ΔH, is dependent on the strength of the attractive forces that exist between that substance's constituent particles. By definition, complementary phase changes relate the same states of matter. As a result, the relative attractive forces that are involved in melting and freezing, vaporization and condensation, and sublimation and deposition are *identical*. Therefore, the phase changes *within* each of these complementary pairs share a *common* phase change constant. Finally, the value of a phase change constant *varies between* each pair of complementary phase changes, as each combination involves a transformation between *different* states of matter. Therefore, three unique phase change constants, ΔH_{fusion}, ΔHvaporization, and $\Delta H_{sublimation}$, can be incorporated into the "$q = m(\Delta H)$" equation for a particular substance. Finally, because the variables in this equation are related multiplicatively, the unit for these phase change constants must incorporate the heat and mass units that are indicated in the previous paragraph, in order to achieve unit cancelation. As a result, phase change constants, which consist of both a numerator and a denominator, are reported in either cal/g or J/g. The phase change constants for several compounds and elements are shown below in Table 13.4.1. Because sublimation and its complement, deposition, are rarely studied, the corresponding $\Delta H_{sublimation}$ values for many chemicals have not been determined and, therefore, are not reported in this table.

Table 13.4.1: Selected Phase Change Constant Values

Substance	ΔH_{fusion} (cal/g)	ΔH_{fusion} (J/g)	$\Delta H_{vaporization}$ (cal/g)	$\Delta H_{vaporization}$ (J/g)
Water	79.9	540.	334	2,260
Benzene	30.4	94.1	127	394
Ethanol	25.6	200.3	107	838.1
Sodium Chloride	123.5	691	516.7	2,890
Aluminum	94.0	2,602	393	10,890
Gold	15.3	409	64.0	1,710
Iron	63.2	1,504	264	6,293

Indicator Phrases

Because the equation that is shown above is used to quantify the heat transfer that is associated with changing the state of matter of a substance, the phrases "to freeze," "to melt," "to boil," and "to condense" indicate that this equation should be applied to solve a problem. Additionally, since freezing and melting are complementary phase changes, the presence of the phrases "to freeze" and "to melt" within a given problem both indicate that a ΔH_{fusion} phase change constant should be incorporated into the "q = m(ΔH)" equation. Furthermore, because vaporization and condensation are complementary phase changes, any reference to boiling or condensation denotes that a ΔHvaporization phase change constant should be utilized to solve the given problem. Finally, if heat is *added to* a substance, its state of matter will change from a solid to a liquid or from a liquid to a gas, and the corresponding heat transfer, q, will have a *positive* value. In contrast, the *removal of heat from* a substance will cause its state of matter to change from a gas to a liquid or from a liquid to a solid, and the associated heat transfer, q, will be *negative*.

Calculations

For example, calculate how many calories of heat are required to melt a 6,387 milligram block of iron. The phase change constants for iron are given in Table $13.4.1$.

The phrase "to melt" indicates that a ΔH_{fusion} phase change constant should be incorporated into the "q = m(ΔH)" equation to solve this problem. Before this equation can be applied, each numerical quantity that is given in the problem must be assigned to a variable. Finally, in order to be incorporated into this equation, the validity of the units that are associated with the given numerical values must be confirmed. As stated above, the heat transfer must be recorded in calories (cal) or joules (J), the mass must be provided in grams (g), and the phase change constant must be expressed in either cal/g or J/g.

The numerical values that are given in the problem, the variables to which these quantities are assigned, and an indication of the validity of their corresponding units are shown in the following table.

Numerical Quantity	Variable	Unit Validity
q	q	
6,387 mg	m	✗
63.2 cal/g	ΔH_{fusion}	✓

Because q is the only variable that cannot be assigned to a numerical value in the given problem, heat transfer is the unknown quantity that will be calculated upon solving the "q = m(ΔH)" equation. The problem specifies that the final answer must be expressed in calories. Therefore, while Table $13.4.1$ lists two values for the ΔH_{fusion} of iron, 63.2 cal/g and 1,504 J/g, the first value must be incorporated into the equation that is indicated above, because its associated unit, cal/g, is consistent with the unit that is specified for the unknown quantity, q. Of the remaining variables, only mass, m, is not reported in an acceptable unit. Therefore, as shown below, this quantity must be converted to grams before it can be incorporated into the "q = m(ΔH)" equation.

$$6{,}387\ \cancel{\text{mg}} \times \frac{\text{g}}{1{,}000\ \cancel{\text{mg}}} = 6.387\ \text{g}$$

The updated numerical values that are summarized in the following table are all expressed in the appropriate units and, therefore, can be utilized to solve the given problem.

Numerical Quantity	Variable	Unit Validity
q	q	
6.387 g	m	✓
63.2 cal/g	ΔH_{fusion}	✓

The quantities that are shown in the table above can now be incorporated into the "q = m(ΔH)" equation. When solving for q, the mass and phase change constant are multiplied, resulting in the cancelation of the mass unit, "g," which is present in a numerator and a denominator in the second equation that is shown below. The unit that remains after these cancelations is "cal," which, per the information in the given problem, is the unit in which the unknown quantity, heat transfer, q, must be expressed. Applying the correct number of significant figures to the calculated quantity results in the final answer that is shown below.

$$q = m\left(\Delta H_{fusion}\right)$$

$$q = (6.387\ \cancel{g})\left(63.2\ \frac{cal}{\cancel{g}}\right)$$

$$q = 403.6584\ cal \approx 404\ cal$$

Example 13.4.1

8,432 joules of heat are required to boil 21.4 grams of an unknown substance. Calculate the phase change constant for this chemical and compare its value the entries in Table 13.4.1 to identify the substance.

Solution

The phrase "to boil" indicates that a $\Delta H_{vaporization}$ phase change constant should be incorporated into the "$q = m(\Delta H)$" equation to solve this problem. Before this equation can be applied, each numerical quantity that is given in the problem must be assigned to a variable. Finally, in order to be incorporated into this equation, the validity of the units that are associated with the given numerical values must be confirmed. As stated above, the heat transfer must be recorded in calories (cal) or joules (J), the mass must be provided in grams (g), and the phase change constant must be expressed in either cal/g or J/g.

The numerical values that are given in the problem, the variables to which these quantities are assigned, and an indication of the validity of their corresponding units are shown in the following table.

Numerical Quantity	Variable	Unit Validity
8,432 J	q	✓
21.4 g	m	✓
$\Delta H_{vaporization}$	$\Delta H_{vaporization}$	

Because $\Delta H_{vaporization}$ is the only variable that cannot be assigned to a numerical value in the given problem, the phase change constant, $\Delta H_{vaporization}$, is the unknown quantity that will be calculated upon solving the "$q = m(\Delta H)$" equation. Since the problem does not specify whether the final answer should be expressed in cal/g or J/g, the given unit for heat, "joules," is acceptable for this problem. Finally, the numerical values that are summarized in the table that is shown above are all expressed in the appropriate units and, therefore, can be utilized to solve the given problem.

The quantities that are shown in the table above can be incorporated into the "$q = m(\Delta H)$" equation. To solve for $\Delta H_{vaporization}$, the heat transfer value on the left side of the equal sign must be divided by the mass of the substance. No unit cancelation occurs, because the unit in the numerator, "J" does not match the unit that is shown in the denominator, "g," in the resultant fraction. Therefore, unit that results from this division is "J/g," which is a valid unit for expressing the unknown quantity, $\Delta H_{vaporization}$. Applying the correct number of significant figures to the calculated quantity results in the final answer that is shown below.

$$q = m\left(\Delta H_{vaporization}\right)$$

$$8,432\ J = (21.4\ g)\left(\Delta H_{vaporization}\right)$$

$$\Delta H_{vaporization} = 394.01869...\ \frac{J}{g} \approx 394\ \frac{J}{g}$$

This value corresponds to the ΔHvaporization phase change constant that is shown for **benzene** in Table 13.4.1.

Exercise 13.4.1

739 calories of heat are required to melt an unknown amount of mercury. Calculate the mass of the mercury, which has a ΔHfusion of 11.8 J/g and a ΔHvaporization of 272 J/g.

Answer

The phrase "to melt" indicates that a ΔH_{fusion} phase change constant should be incorporated into the "q = m(ΔH)" equation to solve this problem. Before this equation can be applied, each numerical quantity that is given in the problem must be assigned to a variable. Finally, in order to be incorporated into this equation, the validity of the units that are associated with the given numerical values must be confirmed. As stated above, the heat transfer must be recorded in calories (cal) or joules (J), the mass must be provided in grams (g), and the phase change constant must be expressed in either cal/g or J/g.

The numerical values that are given in the problem, the variables to which these quantities are assigned, and an indication of the validity of their corresponding units are shown in the following table.

Numerical Quantity	Variable	Unit Validity
739 cal	q	✗
m	m	
11.8 J/g	ΔH_{fusion}	✓

Because m is the only variable that cannot be assigned to a numerical value in the given problem, the mass of the substance is the unknown quantity that will be calculated upon solving the "q = m(ΔH)" equation. While the problem does not specify a unit for the final answer, masses that are determined using this equation must be expressed in grams, as stated above. All of the remaining variables are reported in acceptable units. However, the units that are associated with the given values for heat transfer, q, and the phase change constant, ΔH_{fusion}, are not consistent with one another and, therefore, will not cancel when incorporated into the "q = m(ΔH)" equation. In order to remedy this discrepancy, one of these units must be converted to match the other. While altering either unit is acceptable, modifying the unit for heat transfer, q, is more straight-forward and, therefore, is shown below.

$$739\ \cancel{\text{cal}} \times \frac{4.184\ \text{J}}{1\ \cancel{\text{cal}}} = 3{,}091.976\ \text{J} \approx 3{,}090\ \text{J}$$

The updated numerical values that are summarized in the following table are all expressed in the appropriate units and, therefore, can be utilized to solve the given problem.

Numerical Quantity	Variable	Unit Validity
3,090 J	q	✓
m	m	
11.8 J/g	ΔH_{fusion}	✓

The quantities that are shown in the table above can now be incorporated into the "q = m(ΔH)" equation. When solving for m, the heat transfer value on the left side of the equal sign must be divided by the phase change constant, ΔH_{fusion}. This division causes the cancelation of the heat unit, "J," which appears in both the numerator and the denominator of the resultant fraction. Applying the correct number of significant figures to the calculated quantity results in the final answer that is shown below.

$$q = m\left(\Delta H_{vaporization}\right)$$

$$3,090\ \cancel{J} = m\left(11.8\ \frac{\cancel{J}}{g}\right)$$

$$m = 261.8644...\ g \approx 262\ g$$