36 Heat: Phase Changes

There is a tendency to believe that any time heat is flowing into ice, the ice is melting. NOT SO. When heat is flowing into ice, the ice will be melting only if the ice is already at the melting temperature. When heat is flowing into the ice that is below the melting temperature, the temperature of the ice is increasing.

As mentioned in the preceding chapter, there are times when you bring a hot object into contact with a cooler sample, that heat flows from the hot object to the cooler sample, but the temperature of the cooler sample does *not* increase, even though no heat flows out of the cooler sample (e.g. into an even colder object). This occurs when the cooler sample undergoes a phase change. For instance, if the cooler sample happens to be H_2O ice or H_2O ice plus liquid water, at 0°C and atmospheric pressure, when heat is flowing into the sample, the ice is melting with no increase in temperature. This will continue until all the ice is melted (assuming enough heat flows into the sample to melt all the ice). Then, after the last bit of ice melts at 0°C, if heat continues to flow into the sample, the temperature of the sample will be increasing [1].

Lets review the question about how it can be that heat flows into the cooler sample without causing the cooler sample to warm up. Energy flows from the hotter object to the cooler sample, but the internal kinetic energy of the cooler sample does not increase. Again, how can that be? What happens is that the energy flow into the cooler sample is accompanied by an increase in the internal *potential* energy of the sample. It is associated with the breaking of electrostatic bonds between molecules where the negative part of one molecule is bonded to the positive part of another. The separating of the molecules corresponds to an increase in the potential energy of the system. This is similar to a book resting on a table. It is gravitationally bound to the earth. If you lift the book and put it on a shelf that is higher than the tabletop, you have added some energy to the earth/book system, but you have increased the potential energy with *no* net increase in the kinetic energy. In the case of melting ice, heat flow into the sample manifests itself as an increase in the potential energy of the molecules without an increase in the *kinetic* energy of the molecules (which would be accompanied by a temperature increase).

The amount of heat that must flow into a single-substance solid sample that is already at its melting temperature in order to melt the whole sample depends on a property of the substance of which the sample consists, and on the mass of the substance. The relevant substance property is called the latent heat of melting. The latent heat of melting is the heat-per-mass needed to melt the substance at the melting temperature. Note that, despite the name, the latent heat is not an amount of heat but rather a ratio of heat to mass. The symbol used to represent latent heat in general is L, and we use the subscript m for melting. In terms of the latent heat of melting, the amount of heat, Q, that must flow into a sample of a single-substance solid that is at the melting temperature, in order to melt the entire sample is given by:

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[1] In this discussion, we are treating the sample as if it had one well-defined temperature. This is an approximation. When the sample is in contact with a hotter object so that heat is flowing from the hotter object to the sample, the part of the sample in direct contact with and in the near vicinity of the hotter object will be at a higher temperature than other parts of the sample. The hotter the object, the greater the variation in the temperature of the local bit of the sample with distance from the object. We neglect this temperature variation so our discussion is only appropriate when the temperature variation is small.

$$Q = mL_{\text{m}}$$

Note the absence of a ΔT in the expression $Q = mL_{\text{m}}$. There is no ΔT in the expression because there is no temperature change in the process. The whole phase change takes place at one temperature.

So far, we have talked about the case of a solid sample, at the melting temperature, which is in contact with a hotter object. Heat flows into the sample, melting it. Now consider a sample of the same substance in *liquid* form at the *same* temperature but in contact with a *colder* object. In this case, heat will flow *from* the sample to the colder object. This heat loss from the sample does not result in a decrease in the temperature. Rather, it results in a phase change of the substance of which the sample consists, from liquid to solid. This phase change is called freezing. It also goes by the name of solidification. The temperature at which freezing takes place is called the freezing temperature, but it is important to remember that the freezing temperature has the same value as the melting temperature. The heat-per-mass that must flow out of the substance to freeze it (assuming the substance to be at the freezing temperature already) is called the latent heat of fusion, or L_{f}. The latent heat of fusion for a given substance has the same value as the latent heat of melting for that substance:

$$L_{\text{f}} = L_{\text{m}}$$

The amount of heat that must flow out of a sample of mass m in order to convert the entire sample from liquid to solid is given by:

$$Q = mL_{\text{f}}$$

Again, there is no temperature change.

The other two phase changes we need to consider are vaporization and condensation. Vaporization is also known as boiling. It is the phase change in which liquid turns into gas. It too (as in the case of freezing and melting), occurs at a single temperature, but for a given substance, the boiling temperature is higher than the freezing temperature. The heat-per-mass that must flow into a liquid to convert it to gas is called the latent heat of vaporization L_{v}. The heat that must flow *into* mass m of a liquid that is already at its boiling temperature (a.k.a. its vaporization temperature) to convert it entirely into gas is given by:

$$Q = mL_{\text{v}}$$

Condensation is the phase change in which gas turns into liquid. In order for condensation to occur, the gas must be at the condensation temperature, the same temperature as the boiling temperature (a.k.a. the vaporization temperature). Furthermore, heat must flow *out* of the gas, as it does when the gas is in contact with a *colder* object. Condensation takes place at a fixed temperature known as the condensation temperature. (The melting temperature, the freezing temperature, the boiling temperature, and the condensation temperature are also referred to as the melting point, the freezing point, the boiling point, and the condensation point, respectively.) The heat-per-mass that must be extracted from a particular kind of gas that is already at the condensation temperature, to convert that gas to liquid at the same temperature, is called the latent heat of condensation L_c. For a given substance, the latent heat of condensation has the same value as the latent heat of vaporization. For a sample of mass m of a gas at its condensation temperature, the amount of heat that must flow *out* of the sample to convert the entire sample to liquid is given by:

$$Q = mL_c$$

It is important to note that the actual values of the freezing temperature, the boiling temperature, the latent heat of melting, and the latent heat of vaporization are different for different substances. For *water* we have:

Phase Change	Temperature	Latent Heat
Melting Freezing	0°C	$0.334\,\frac{\text{MJ}}{\text{kg}}$
Boiling or Vaporization Condensation	100°C	$2.26\,\frac{\text{MJ}}{\text{kg}}$

Example 36-1

How much heat does it take to convert 444 grams of H_2O ice at –9.0°C to steam (H_2O gas) at 128.0 °C ?

Discussion of Solution

Rather than solve this one for you, we simply explain how to solve it.

To convert the ice at –9.0 °C to steam at 128.0 °C, we first have to cause enough heat to flow into the ice to warm it up to the melting temperature, 0 °C. This step is a specific heat capacity problem. We use

$$Q_1 = mc_{\text{ice}}\,\Delta T$$

where ΔT is [0 °C – (–9.0 °C)] = 9.0 C° .

Now that we have the ice at the melting temperature, we have to add enough heat to melt it. This step is a latent heat problem.

$$Q_2 = mL_{\text{m}}$$

After $Q_1 + Q_2$ flows into the H_2O, we have liquid water at 0 °C. Next, we have to find how much heat must flow into the liquid water to warm it up to the boiling point, 100 °C.

$$Q_3 = mc_{\text{liquid water}} \Delta T'$$

where $\Delta T' = (100\,°\text{C} - 0\,°\text{C}) = 100\,°\text{C}$.

After $Q_1 + Q_2 + Q_3$ flows into the H_2O, we have liquid water at 100 °C. Next, we have to find how much heat must flow into the liquid water at 100 °C to convert it to steam at 100 °C.

$$Q_4 = mL_{\text{v}}$$

After $Q_1 + Q_2 + Q_3 + Q_4$ flows into the H_20, we have water vapor (gas) at 100 °C. Now, all we need to do is to find out how much heat must flow into the water gas at 100 °C to warm it up to 128 °C.

$$Q_5 = mc_{\text{steam}} \Delta T''$$

where $\Delta T'' = 128\,°\text{C} - 100\,°\text{C} = 28\,°\text{C}$.

So the amount of heat that must flow into the sample of solid ice at –9.0 °C in order for sample to become steam at 128 °C (the answer to the question) is:

$$Q_{\text{total}} = Q_1 + Q_2 + Q_3 + Q_4 + Q_5$$