

Seneca College BES 702

(20160831 revision)

1– Principles of Refrigeration

<https://senema.senecac.on.ca/videos/3396/refrigeration-cycle> - Refrigeration Cycle Video

SAQ 1.1: Heat, Temperature and Pressure

1) Can you define the following terms:

- Heat
- Sensible and latent heat
- Joules and British Thermal Units (BTU)

2) Can you explain the relationships between Celsius, Kelvin, Fahrenheit, and Rankine temperature scales?

3) Can you explain the relationship between absolute and gauge pressure, and give appropriate units for this quantity?

4) Do you know what heat of vaporization is?

Solution:

1) Heat is thermal energy moving from one place to another; that is, when we are talking about “heat” we are really talking about an energy flow. Sensible heat is heat that brings about a temperature change, and latent heat is heat that brings about a change in state without any temperature change, as in the latent heat of vaporization.

2) The Kelvin (absolute) temperature = the Celsius temperature + 273.16

Conversion of Celsius to Fahrenheit degrees or vice versa is done with the following formula: $^{\circ}\text{F} = ^{\circ}\text{C} \times \frac{9}{5} + 32$ or $^{\circ}\text{C} = (^{\circ}\text{F} - 32) \times \frac{5}{9}$

The Rankine (absolute) temperature = the Fahrenheit temperature + 459.7

3) Gauge pressure is the difference between the absolute pressure in a system and the prevailing atmospheric pressure = absolute system pressure – atmospheric pressure; of course, the atmospheric pressure varies with location and time, so we cannot say what the absolute pressure is in the system without knowing what the atmospheric pressure is at the time of measurement. There are several units that are used for pressure in general and gauge pressure in particular, but it is always necessary to state clearly that the pressure is a “gauge” pressure, or an absolute pressure. Units in the Imperial system are often pounds/square inch, or psi, specifying psig for the gauge pressure or psia for absolute. The standard unit of pressure in the SI system is the kilopascal, or kPa.

4) Heat of vaporization, or latent heat of vaporization (its full name) is the energy required by a liquid to change in state to vapour, or the energy given up by a vapour when it condenses to a liquid. It is expressed in terms of the quantity of the substance; so, in the Imperial system, we would use Btu/lb and in SI kJ/kg.

SAQ 1.2: Evaporation, Condensation and Energy

Explain how energy interacts with a substance when the process of evaporation occurs. What is the interaction when condensation occurs?

Solution:

In order to evaporate—that is, change from the liquid to the vapour state—the liquid molecules require a certain amount of energy, namely the latent heat of vaporization. That heat is absorbed from the body of the liquid, giving some of the molecules the “launch energy” to escape from the liquid and move into the vapour space, of course carrying that energy with them. The net result is that the energy stored in the remaining liquid has been reduced, and consequently we observe a temperature drop. When vapour condenses, the opposite process occurs; that is, molecules of vapour release energy equivalent to the latent heat of vaporization and they coalesce into the liquid phase. The quantity of energy is the same per unit mass of substance in the two processes, but the direction is opposite.

SAQ 1.3: Latent Heat of Vaporization

Why is the heat of vaporization said to be “latent”?

Solution:

The word “latent” means “concealed, existing but not manifest”; the heat of vaporization is “latent” because we know that it exists but it is not observable by means of a temperature change.

SAQ 1.4: Boiling Point and Pressure

Using the data in Table 1.1, how many atmospheres of pressure would need to be applied to increase the boiling point of water to 200°C? Similarly, what would the applied pressure need to be reduced to in order to allow water to boil at 50°C?

Solution:

For water to boil at 200°C (rather than the normal 100°C) the applied pressure must be 1550 kPa or about 15.3 atm.

For a boiling point of 50°C, we need to “interpolate” the values in the table—that is, estimate the value for 50, given values for 40 and 60 (this is not precisely correct since to do it we are assuming that the relationship is a straight line, which it is not, but provided the interval is not too large, the error involved in doing this is small). Here’s how it works:

We have a pressure of 7.38 kPa at 40, and 19.93 at 60, and we want the value that is exactly half the distance between them for 50 °C; $19.93 - 7.38 = 12.55$ and $12.55/2 = 6.275$; $6.275 + 7.38 = 13.66$ kPa, and this is the pressure corresponding to a boiling point of 50 °C.

SAQ 1.5: Wet Bulb Depression and RH

Measurements taken with a sling psychrometer give a dry bulb reading of 22°C and wet bulb 16°C. What are:

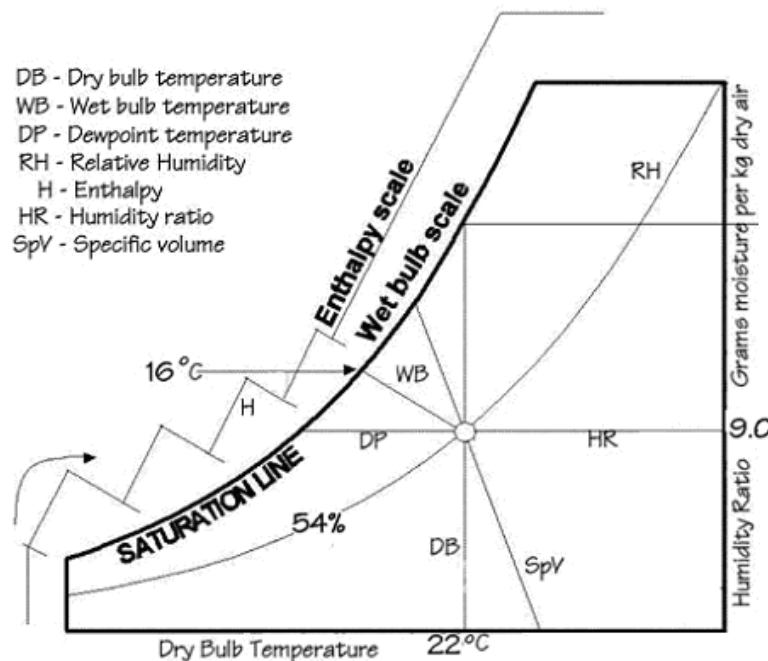
- The wet bulb depression
- The relative humidity of the air
- The absolute humidity of the air?

Hint: to answer b, you can use Table 1.3, but to find c you will need to use the SI psychrometric chart.

Solution:

Refer to the simplified psychrometric chart shown below.

- The wet bulb depression = $22 - 16 = 6^\circ\text{C}$
- The relative humidity of the air from Table 1.3, using dry bulb 22°C and wet bulb depression of 6°C is 54%.
- The absolute humidity of the air? The point on the SI Psychrometric Chart that defines this air is at the intersection of the dry bulb and wet bulb temperature lines; taking a horizontal line from this point to the absolute humidity (or humidity ratio) scale gives us the reading 9.0 g H₂O/kg dry air.



SAQ 1.6: Reading the Psychrometric Chart

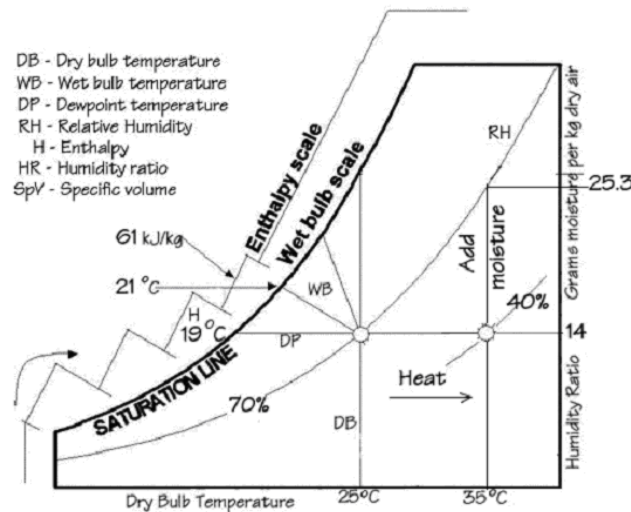
A fresh air supply is measured to be at 25°C dry bulb and 21°C wet bulb. What are:

- The relative humidity
 - Dewpoint
 - Absolute humidity
 - Enthalpy
- for this air?

Solution:

Refer to the simplified psychrometric chart shown below. The point on the Psychrometric Chart that defines this air is at the intersection of the dry and wet bulb temperature lines; reading on the appropriate scale enables us to find these other quantities:

- a. The relative humidity is 70%
- b. Dewpoint is 19°C
- c. Absolute humidity is 14 g H₂O/kg dry air
- d. Enthalpy is 61 kJ/kg dry air.



SAQ 1.7: Heating the Air

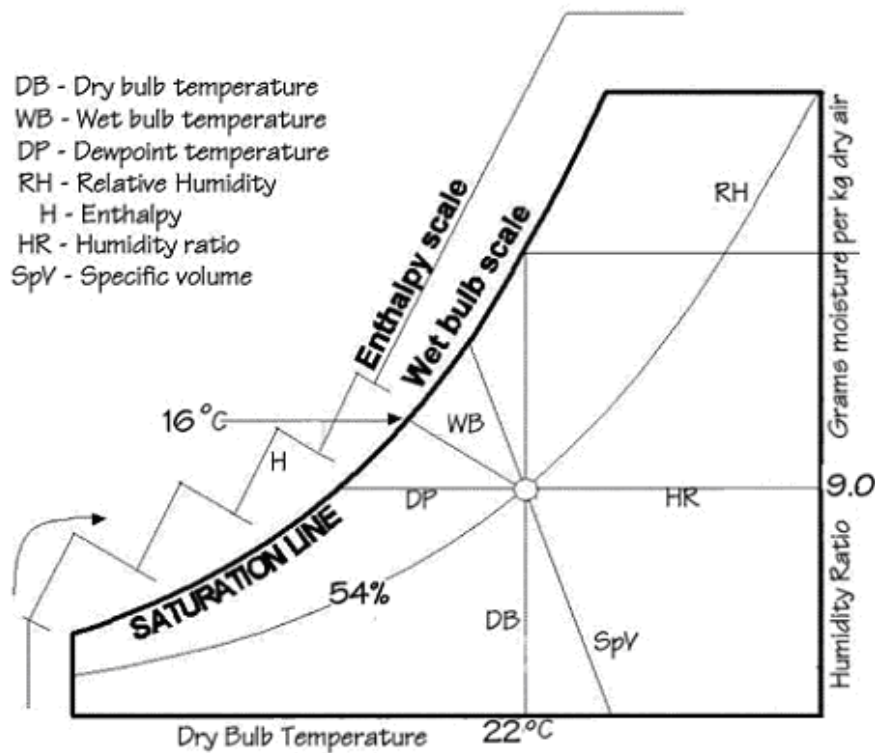
The air supply of SAQ 1.6 is heated to 35°C without adding any moisture.

- a. What is its relative humidity after heating?
- b. How much moisture would need to be added in order to maintain its relative humidity at the same value it was before heating?

Solution:

Refer to the simplified psychrometric chart below from SAQ 1.5.

- a. Since no moisture is added, the absolute humidity remains constant; this corresponds to moving on the Psychrometric Chart horizontally to the right to 35°C and reading the relative humidity at that point: 40%.
- b. To maintain the relative humidity at 70% at a dry bulb temperature of 35°C would correspond to an absolute humidity of about 25.3 g H₂O/kg dry air; that is $25.3 - 14 = 11.3$ g H₂O/kg dry air would have to be added.



SAQ 1.8: Mixing of Air

Outdoor air at 90°F dry bulb and 72°F wet bulb is being brought in through dampers to form 25% of a mixture with return air at 78°F dry bulb and 64°F wet bulb. What would be the dry bulb and wet bulb temperatures of the resulting mixture? As a result, is the total heat content of the mixture higher or lower than the heat content of the return air?

Solution:

Refer to the simplified psychrometric chart below. Locate the outside air on the chart and mark it as point A (note that its RH is 43%). Similarly, locate the return air on the chart and mark it as point B (with RH 51%). Draw a line joining A and B; the mixed air lies somewhere on this line and to locate it, we need to know its temperature, which is found as follows:

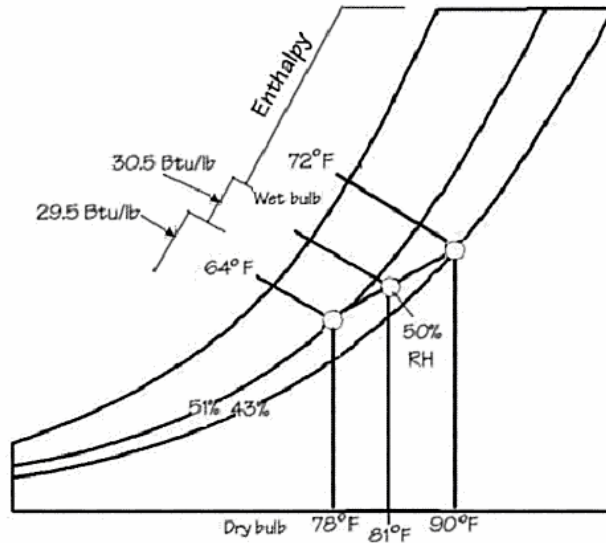
Temperature of mixed air

$$= (\% \text{ outside air} \times \text{outside temperature}) + (\% \text{ return air} \times \text{return temperature})$$

$$= (0.25 \times 90^\circ\text{F})$$

Now locate the mixed air on the chart and read its RH = 50%.

The enthalpy (or heat content) of the return air is 29.5 Btu/lb. dry air, and the enthalpy of the mixed air is 30.5 Btu/lb. dry air; that is, the heat content of the mixed air is higher than the return air.



2 – Refrigerants

There are no web materials for this chapter

3 – The Compressor

<https://senema.senecac.on.ca/videos/3397/cooling-plant> - Cooling Plant Video

SAQ 3.1: Compression Ration

Refrigerant R-134a has an evaporating pressure of 49.7 psia and a condensing pressure of 138.8 psia. What is the compression ratio for this refrigerant?

Solution:

Compression ratio is defined as condensing pressure (absolute)/evaporating pressure (absolute). In this case, we are given the absolute pressures, rather than gauge pressures, so:

$$\text{Compression ratio} = 138.8/49.7 = 2.79.$$

4 – Condensers and Cooling Towers

<https://senema.senecac.on.ca/videos/3412/cooling-towers-video> - Cooling Towers Video

SAQ 4.1: Superheat

We have met this term “superheat” previously. What does it mean in terms of the condition of the refrigerant?

Solution:

A vapour at its boiling point is said to be “saturated”. A vapour is said to be “superheated” when it has been heated to a temperature above its boiling point, and the number of degrees above the boiling point is the number of degrees of superheat.

SAQ 4.2: Condenser Heat Balance

For the condenser described above, using R-134a, suppose that the inlet temperature of the water is 17°C with the outlet temperature controlled to remain at 30°C. For every 10 kg of refrigerant at the same conditions as in Figure 4.2, how many kg of water would be required?

Solution:

The principle of the heat balance is that the heat lost by the refrigerant = the heat gained by the water. In this case, as in the example,
the heat lost by the refrigerant = $10 (431.5 - 236.6) \text{ kJ} = 1949 \text{ kJ}$

If the quantity of the water is $W \text{ kg}$, the heat gained = $W \text{ kg} \times 4.19 \text{ kJ/kg } ^\circ\text{C} \times (30 - 17) ^\circ\text{C}$
= $54.47 W \text{ kJ}$

So, $54.47 W \text{ kJ} = 1949 \text{ kJ}$, or $W = 1949/54.47 = 35.8 \text{ kg}$

Therefore, 35.8 kg of water is required per 10 kg of refrigerant.

SAQ 4.3: Heat Exchangers

As we have seen, vapour compression refrigeration systems involve two key heat transfer processes between the refrigerant and air or water. For heat transfer to take place efficiently, heat exchangers are required, and one type that is often used for water cooling is the tube and shell heat exchanger.

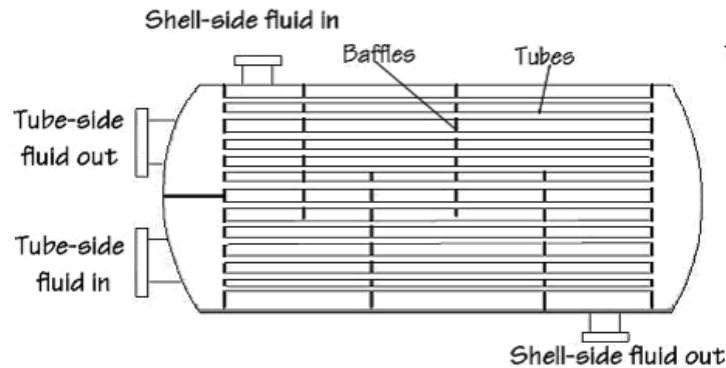
- 1) what is the basic configuration of a tube and shell heat exchanger?
- 2) what are the mechanisms by which heat is transferred in these devices?

Solution:

Refer to the schematic diagram of a tube-and-shell heat exchanger below.

1) A tube and shell heat exchanger consists of a bundle of tubes placed within a cylindrical vessel. The open tube ends are held in an end sheet that creates a manifold into which the “tube-side” fluid flows and enters the tubes, and at the other end exits the tubes and leaves the heat exchanger. The tubes may be configured to have one or more “passes” through the length of the cylinder or shell, with baffles placed in the manifolds to direct the flow back and forth through the tube bundle. The shell-side fluid flows over the exterior surfaces of the tubes, and baffles may be used to direct this flow as well and induce turbulence in the fluid.

2) Heat transfer from one fluid to the other occurs by two primary mechanisms: convection from the bulk of the hot fluid to the tube wall, conduction through the metal of the tube wall, and convection again away from the tube wall into the bulk of the cold fluid. A third heat transfer mechanism may also be involved, that being radiation of heat from the heat exchanger exterior into the surrounding environment—this, of course, is a heat loss.



SAQ 4.4: Water Treatment Issues

Why is water treatment required in regard to the water used in water-cooled condensers and water towers? What are the consequences of inadequate or improper treatment of water?

Solution:

Water must be treated to modify its properties to prevent

- Scale formation
- Corrosion
- Biological growth.

Scale and biological deposits foul heat transfer surfaces and create additional resistance to heat transfer. In cooling towers, the fouling can also restrict water flow, again reducing the efficiency of heat transfer. Corrosion in a water environment is influenced by the presence of dissolved oxygen and other substances that can increase the corrosivity of the water; water treatment reduces this behaviour.

SAQ 4.5: Evaporative Cooling

How is it that the evaporation of a liquid has a cooling effect? What energy quantity is it that determines the effectiveness of cooling by a given liquid?

Solution:

In order to evaporate, molecules of the liquid must acquire sufficient energy to escape from the liquid phase into the vapour phase; this energy is the latent heat of vaporization. In absorbing this heat from the surroundings or from the remaining liquid, there is a cooling effect. Substances differ in terms of their latent heat of vaporization; the higher the heat of vaporization, the greater is the cooling effect.

5 – Evaporators and Cooling Coils

SAQ 5.1: Heat Balance

Suppose in the example above that the incoming air was at 25°C and at the same mass flow rate; to what temperature would the air be cooled under the same evaporator conditions?

Solution:

The principle that applies to this heat balance is that the heat removed from the air = the heat gained by the refrigerant.

The heat removed from the air = $243.9 \text{ kg} \times 1.005 \text{ kJ/kg } ^\circ\text{C} \times (25 - T) ^\circ\text{C}$

From the example in the text, the heat gained by the refrigerant is still 1471 kJ.

Therefore, $243.9 \text{ kg} \times 1.005 \text{ kJ/kg } ^\circ\text{C} \times (25 - T) ^\circ\text{C} = 1471 \text{ kJ}$

Or $245.12 \times (25 - T) = 1471$

And $T = (245.12 \times 25 - 1471)/245.12 = 19 ^\circ\text{C}$.

6 – Metering Devices

SAQ 6.1: Refrigerant Cooling across the Metering Device

Explain how a metering device decreases the temperature of a refrigerant that flows through it.

Solution:

The metering device separates the high-pressure from the low-pressure side of the system. High pressure liquid passing through the device into the low-pressure side immediately vaporizes or “flashes” to some extent. The change of state from liquid to vapour absorbs energy from the remaining liquid equivalent to the latent heat of vaporization for the amount that vaporizes, with the result that the temperature drops.

7 – Heat Pumps

Why is it more appropriate to use the terms “primary” and “secondary”, than “evaporator” and “condenser”, when referring to the heat exchangers in a heat pump system?

Solution:

Heat pumps are designed to operate in both the “forward” and the “reverse” directions. Consequently, the two processes that occur in a mechanical refrigeration system, evaporation and condensation, occur in either the “evaporator” or the “condenser”, depending on the direction of flow. In the cooling season, the evaporator is the heat exchanger located inside the conditioned space—where energy is being absorbed from the room air—and the condenser is outside—where energy is being discharged to the environment. However, in the heating season, the interior heat exchanger is functioning as the condenser—delivering heat to the room—while the outside heat exchanger is functioning as the evaporator—absorbing heat from the surroundings. Since the heat exchangers are, therefore, each functioning as the evaporator and the condenser, depending on the direction of flow, they are more appropriately named primary and secondary.

8 – Centrifugal Chiller Systems

<https://senema.senecac.on.ca/videos/3412/cooling-towers-video> - Chiller Video

SAQ 8.1: Chiller Capacity

Just a reminder: what rate of heat transfer is a 75 ton chiller capable of delivering? Express your answer in Btu/hr and kW.

Solution:

One ton of cooling capacity is defined as 12,000 Btu/hr. So, a 75 ton chiller has a capacity of $75 \times 12,000 = 900,000$ Btu/hr.

To convert from Btu/hr to kW, we need to know the following:

1 kW = 1 kJ/s

1 Btu = 1.055 kJ

and, of course, 1 hr = 3600 s

$$900,000 \text{ Btu/hr} = 900,000 \frac{\text{Btu}}{\text{hr}} \times \frac{1.055 \text{ kJ}}{1 \text{ Btu}} \times \frac{1 \text{ hr}}{3600 \text{ s}} = 263.75 \text{ kW}$$

SAQ 8.2: Economizers

“Economizer” is a term used not only in regard to chillers, as in this case, but also in boilers. In general, what is the purpose of an economizer?

Solution:

An economizer is a heat exchanger that is designed to recover what would otherwise be waste heat. In the case of boilers, it is the waste heat in the flue gas that is recovered, and usually used to preheat the boiler feed water.

9 – Absorption Chillers

SAQ 9.1: Lithium Bromide

What kind of substance is lithium bromide? What are its key properties? Can you think of another more common substance that is similar to lithium bromide?

Solution:

Lithium bromide, LiBr, is an inorganic ionic compound. It is highly soluble in water, and is a white crystalline solid. It is similar to “common salt”, sodium chloride NaCl; the metal component, lithium is similar in properties to the metal sodium, while the bromide is similar to chloride. Of importance in chiller applications, solutions of LiBr are hygroscopic; that is, they have a high affinity for water and, therefore, tend to absorb water to cause dilution of the solution.

SAQ 9.2: Ammonia

What kind of substance is Ammonia? What are its key properties?

Solution:

Ammonia, NH₃, is a covalent inorganic compound. It is a gas under normal conditions that is highly soluble in water with which it produces an alkaline or basic solution referred to as aqueous ammonium hydroxide, NH₄OH. As a consequence of its solubility in water it is a hazardous substance that is toxic to humans in higher concentrations and irritating and damaging to respiratory tissues in lower concentrations. The gas has a very strong odour that is immediately recognizable. Ammonia can be liquified when cooled under high pressures.

10 – Efficient Operation and Maintenance

11 – Electrical Controls

SAQ 11.1: Transformers

What do transformers, such as the one discussed here, do? How do they do it?

Solution:

Transformers increase or decrease line voltage, using the principle of electrical induction. Two coils, a primary input voltage coil and a secondary output voltage coil are wound around the two sides of a metal core capable of carrying a magnetic field. The magnetic field induces a voltage in the secondary coil, the magnitude of which is related to the number of windings in the coils as follows:

$$\frac{\text{Primary Voltage}}{\text{Secondary Voltage}} = \frac{\text{No. of turns in Primary Coil}}{\text{No. of turns in Secondary Coil}}$$

12 – Alternative Refrigeration Systems

There are no web materials for this chapter.

S1 – Physics of Refrigeration

SAQ S1.1: Temperature Conversations

“Room temperature” is often taken to be 20°C; what is this in °F?; in °K?; in °R?

Solution:

Conversion to °F: $^{\circ}\text{F} = ^{\circ}\text{C} \times 9/5 + 32 = 20 \times 9/5 + 32 = 36 + 32 = 68 ^{\circ}\text{F}$

Conversion to K (note that the degree symbol is not used when we are talking about the Kelvin temperature scale): $\text{K} = ^{\circ}\text{C} + 273.16 = 20 + 273.16 = 293.16 \text{ K}$ (which reads “293.2 Kelvin”)

Conversion to °R (in the Rankine absolute temperature scale the degree symbol is used): $^{\circ}\text{R} = ^{\circ}\text{F} + 459.7 = 68 + 459.7 = 527.7 ^{\circ}\text{R}$

SAQ S1.2: Latent heat of Vaporization

It is a well-known phenomenon that the evaporation of a liquid—water, for example, or perspiration from our skin—has a cooling effect. Explain this phenomenon.

Solution:

In order to evaporate—that is, change from the liquid to the vapour state—the liquid molecules require a certain amount of energy, namely the latent heat of vaporization. That heat is absorbed from the body of the liquid, giving some of the molecules the “launch energy” to escape from the liquid and move into the vapour space, of course carrying that energy with them. The net result is that the energy stored in the remaining liquid has been reduced, and consequently we observe a temperature drop. In the case of perspiration evaporating from our skin—and this is the body’s way of reducing its temperature when necessary—the heat is absorbed from the skin, and we sense this as a cooling effect.

S2 – Heat Exchangers

There are no web materials for this chapter.

S3 – Chemistry

There are no web materials for this chapter.

S4 – Circuit Diagrams

There are no web materials for this chapter.