

# **Refrigeration Cycles**

## **Chapter 10**

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ME 372 Thermodynamics

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**Discussion:**

The objective of this paper is to introduce the topic of refrigeration. In order to understand how refrigeration systems work, it is helpful to know how a refrigeration system operates, the different applications that exist, the components that make up a system, and how to calculate system parameters. These are fundamental underlying principles of refrigeration systems.

Refrigeration is defined as “the transfer of heat from a lower temperature region to a higher temperature one.”<sup>1</sup> Refrigeration devices that produce refrigeration operate using the vapor-compression cycle (reversed Carnot cycle). Some examples of refrigeration devices are heat pumps, refrigerators, automotive air-conditioners, and residential/commercial air-conditioners. All of these devices have one thing in common, to reduce the temperature of an enclosed environment.

The ideal vapor-compression cycle uses refrigerant as the working fluid to absorb and reject heat energy. The energy transfer allows the vapor-compression cycle to reduce or cool a closed environment. The ideal vapor-compression cycles assumes that the system is perfect based on thermodynamic theory, therefore neglecting any losses associated to performance.

In the ideal vapor-compression cycle, refrigerant enters the compressor as a saturated vapor (Figure 1)<sup>3</sup>. As the refrigerant is compressed, it increases in temperature and pressure (points 1-2). After the compressor the refrigerant passes through the condenser. Heat energy ( $Q_H$ ) is exchanged with the surrounding environment causing the refrigerant to cool and become a saturated liquid (points 2-3). Next, the refrigerant passes through the expansion valve causing the temperature and pressure to decrease (points 3-

4). Because of the reduction in temperature and pressure, the refrigerant enters the evaporator as a saturated mixture. As the refrigerant passes through the evaporator, it absorbs heat energy ( $Q_L$ ) from the environment that it is trying to cool. The refrigerant exits the evaporator as a saturated vapor and returns to the compressor to begin the process all over again (points 4-1).

Figure 1.  
Typical vapor compression refrigeration cycle diagram.

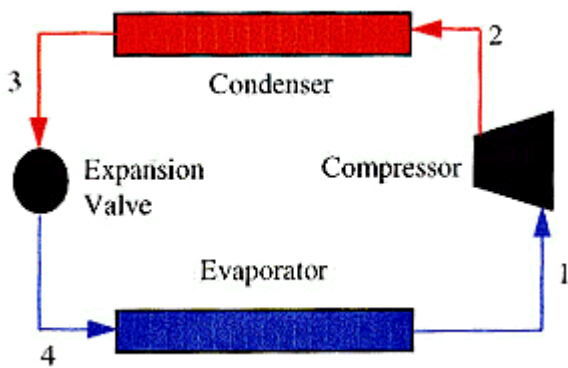
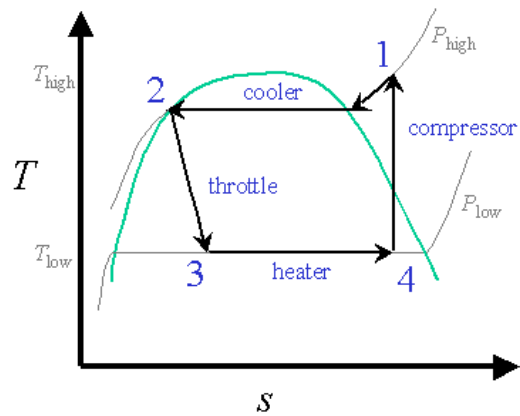


Figure 2.  
T-s Diagram



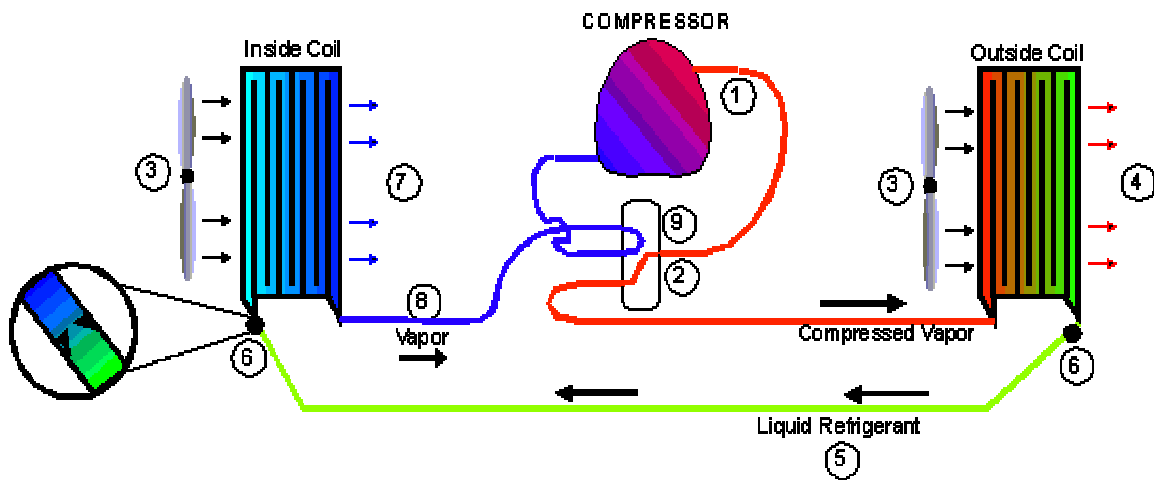
Due to fluid friction, heat transfer losses, and component inefficiency, the refrigeration cycle is unable to achieve complete thermodynamic saturation. The result of the inefficiencies and losses prevent the refrigeration cycle from operating at the optimum performance. This is called the actual vapor-compression refrigeration cycle.

When designing a refrigeration system, it is important to understand how the refrigeration cycle works and the effects of component inefficiency on overall performance. Another important factor when designing a refrigeration system is the working fluid. The working fluid is commonly referred as refrigerant. It is the media used to absorb and reject heat energy. Chlorofluorocarbons (CFCs), ammonia, propane, ethane, ethylene, carbon dioxide, air and water are just some of the refrigerants used in

refrigeration systems. The design of the system should include refrigerant that is nontoxic, noncorrosive, nonflammable, chemically stable, and inexpensive. In order to maintain heat transfer, the refrigerant and the surrounding environment must have a temperature difference of 5°C to 10°C. For a more in depth discussion, please refer to Vollstedt (April 2001), “Selecting the Right Refrigerant.”

Figure 3 – Heat Pump Cooling Mode

A heat pump consists of a compressor (item 1), reversing valve (item 2), fans (item 3), condenser (item 4), metering valves (item 6), and evaporator (item 7)



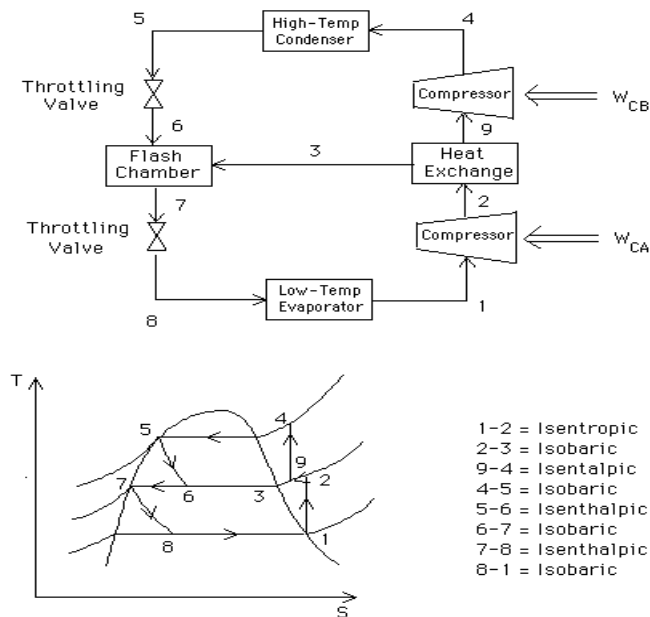
While vapor-compression refrigeration systems are commonly known for residential/commercial refrigeration, this system is also used as a heat pump (Figure 3)<sup>4</sup>. A heat pump is another device used as an air conditioning unit to cool residential houses or commercial buildings.

The heat pump consists of the same components as a refrigerator except the evaporator coils are much larger and are buried underground or connected to a water storage tank. Heat energy from the working fluid is dissipated to the soil or water source. The cooled fluid is returned to the compressor to begin the process all over again. There are three types of heat pumps commonly used; air-to-air, air-to-water, and air-to-ground. Each system operates in the same fashion except for the way the heat energy is

transferred to the sink. A sink is defined as a location where heat energy is dissipated. While the air-to-air system uses refrigerant as the working fluid, the air-to-water and air-to-ground use water. For a more in depth discussion, please refer to Cloutier (March 2001), “Heat pumps.”

There are other refrigeration systems used to accomplish refrigeration. Cascade, and absorption refrigeration systems are used for industrial refrigeration applications.

Figure 4. – Cascade Refrigeration Cycle



The cascade refrigeration system is commonly used for industrial application that incorporates two or more refrigeration cycles in series (see Figure 4)<sup>5</sup>. This is done to acquire low temperatures, which cannot be achieved with a single refrigeration cycle. Refrigerant enters the compressor as a saturated vapor (Figure 4). As the refrigerant is compressed, it increases in temperature and pressure (points 1-2). After the compressor the refrigerant passes through the condenser. Heat energy ( $Q_H$ ) is exchanged in the heat exchanger causing the refrigerant to cool and become a saturated liquid (points 2-3). The

heat energy rejected by the first condenser is absorbed by the second systems evaporator located in the heat exchanger (points 2-9). Next, the refrigerant passes through the second compressor, which increases the temperature of the refrigerant even higher (points 4-9). The refrigerant then passes through the second condenser giving off heat energy ( $Q_H$ ) causing the refrigerant to cool (points 4-5). Then the refrigerant is passed though the second throttling valve, which causes the fluid to expand and decrease in temperature (points 5-6). Next, both refrigerants from the first and second stage mix in the flash chamber creating a liquid vapor mixture (points 6-7). The mixture then passes through another throttling valve and reduces the temperature even farther (points 7-6). Finally, the refrigerant passes through the evaporator, it absorbs heat energy ( $Q_L$ ) from the environment that it is trying to cool. The refrigerant exits the evaporator as a saturated vapor and returns to the compressor to begin the process all over again (points 8-1). The cascade refrigeration operates the same as a regular refrigeration unit except for the second stage of operation.

The absorption refrigeration cycle is used as a method of absorbing heat energy with the use of two fluids as the working medium. Ammonia/water, lithium bromide/water, and ammonia/sodium thiocyanate are primarily used for absorption refrigeration systems. The limitation of this system is operating temperature. Because most commercial and industrial refrigeration applications occur at temperatures below 32°F, the required input temperature must be at least 230°F<sup>2</sup>. The source of heat energy required to meet the temperature requirements come from geothermal energy, solar energy, and waste heat from cogeneration plants and process steam plants.

The absorption system contains the same components as a vapor compression cycle except that it has a absorption device that consists of a rectifier, absorber, generator, and pump. The general premise of the absorption system is to transfer heat energy from one medium to another.

Heat pumps systems, cascade refrigeration systems, and absorption systems all operate on the theory of ideal vapor compression cycle. Although there are many different types of refrigeration systems that exist, they all operate with the same objective: To reduce the temperature of a closed environment.

### **Evaluating the Parameters:**

When it comes to evaluating refrigeration systems, it is important to know how to calculate system parameters such as power input, system efficiency, and cooling capacity. These parameters apply to a variety of systems from household refrigeration to automotive air-conditioning.

The following sample problems are presented in order to understand how to derive system parameters given predetermined data and operating system. The predetermined data may be found with instrumentation such as pressure gauges or thermometers. System engineers often use the data to perform calculations to design systems with increased efficiency. Technicians who install and repair refrigeration systems also routinely measure and calculate parameters in order to adjust systems in the field.

The problems presented have been solved step by step to show the method of solving each problem. This has simplified the problem and allows an easier understanding of how the solution was derived.

**Sample Problems:**

**Example I.** (Problem 10-18<sup>1</sup>): Refrigerant-134a enters the compressor of a refrigerator at 140 kPa and  $-10^{\circ}\text{C}$  at a rate of  $0.2 \text{ m}^3/\text{min}$  and leaves at 1 MPa. The isentropic efficiency of the compressor is 78 percent. The refrigerant enters the throttling valve at 0.95 MPa and  $30^{\circ}\text{C}$  and leaves the evaporator as saturated vapor at  $-18.5^{\circ}\text{C}$ . Show the cycle on a T-s diagram with respect to saturation lines, and determine (a) the power input to the compressor, (b) the rate of heat removal from the refrigerated space, and (c) the pressure drop and rate of heat gain in the line between the evaporator and the compressor.

**Solution:**

**Step 1.** Write down all given variables from problem statement.

Compressor inlet pressure = 140 KPa

Compressor inlet temperature =  $-10^{\circ}\text{C}$

Compressor outlet pressure = 1 MPa

$\eta_c = 89\%$

$\dot{V} = 0.2 \text{ m}^3/\text{min}$

Throttling inlet pressure = 0.95 MPa

Throttling inlet temperature =  $30^{\circ}\text{C}$

Evaporator outlet temperature =  $-18.5^{\circ}\text{C}$  (saturated vapor)

**Step 2.** Determine what stages the given temperatures and pressures belong to.

P1 = 140 kPa

P2 = 1.0 MPa

P3 = 0.95 MPa

P4 = Unknown

T1 =  $-10^{\circ}\text{C}$

T2 = Unknown

T3 =  $30^{\circ}\text{C}$

T4 = Unknown

P5 = Unknown

T5 =  $-18.5^{\circ}\text{C}$

**Step 3.** Determine what equations will be required.

(a) Mass flow rate ( $m_{\dot{}}$ ).

$$m_{\dot{}} = V_{\dot{}} / v$$

(b) The power input to the compressor.

$$W_{\dot{},in} = [(m_{\dot{}}*(h_{2s} - h_1))/\eta_c]$$

(c) The rate of heat removal.

$$Q_{L,\dot{}} = m_{\dot{}}*(h_5 - h_4)$$

(d) The pressure drop between the evaporator and the compressor.

$$\Delta P = P_5 - P_1$$

(e) The rate of heat gain in the line between the evaporator and the compressor.

$$Q_{gain,\dot{}} = m_{\dot{}}*(h_1 - h_5)$$

**Step 4.** Determine values of entropy and enthalpy for each stage and unknown values of pressure. These values can be determined using Tables A-11, A-12, and A-13 located in the back of the book.

(a) Stage 1

$$P_1 = 140 \text{ kPa}$$

$$T_1 = -10^\circ\text{C}$$

$$h_1 = 243.40 \text{ kJ/kg (Table A-13, pg. 918)}$$

$$s_1 = 0.9606 \text{ kJ/(kg}\cdot\text{K) (Table A-13, pg. 918)}$$

$$v = 0.14549 \text{ m}^3/\text{kg (Table A-13, pg. 918)}$$

(b) Stage 2

$$P_2 = 1.0 \text{ MPa}$$

$$T_2 = \text{Unknown}$$

$$s_2 = s_1 = 0.9606 \text{ kJ/(kg}\cdot\text{K)}$$

$$h_{2s} = 286.04 \text{ kJ/kg (Table A-13, pg. 919)}$$

(c) Stage 3

$$P_3 = 0.95 \text{ MPa}$$

$$T_3 = 30^\circ\text{C}$$

$$h_3 \cong h_f @ 30^\circ\text{C} = 91.49 \text{ kJ/kg (Table A-11, pg. 916)}$$

(d) Stage 4

$$\begin{aligned}P_4 &= \text{Unknown} \\T_4 &= \text{Unknown} \\h_4 &\cong h_3 = 91.49 \text{ kJ/kg}\end{aligned}$$

(e) Stage 5

$$\begin{aligned}T_5 &= -18.5^\circ\text{C} \\&\text{Saturated vapor} \\P_5 &= 0.14287 \text{ MPa (Table A-11, pg. 916)} \\h_5 &= 236.23 \text{ kJ/kg (Table A-11, pg. 916)}\end{aligned}$$

**Step 5.** Plug variables into equations and solve.

$$\begin{aligned}m_{\dot{}} &= V_{\dot{}} / v \\m_{\dot{}} &= [(0.2 \text{ m}^3/\text{min}) * (1\text{min}/60\text{sec})] / 0.14549 \text{ m}^3/\text{kg} \\m_{\dot{}} &= 0.0229 \text{ kg/s}\end{aligned}$$

(A) The power input to the compressor.

$$\begin{aligned}W_{\dot{},in} &= [(m_{\dot{}} * (h_{2s} - h_1)) / \eta_c] \\W_{\dot{},in} &= [0.0229 \text{ kg/s} * (286.04 \text{ kJ/kg} - 243.40 \text{ kJ/kg})] / 0.89 \\W_{\dot{},in} &= \mathbf{1.25 \text{ kW}}\end{aligned}$$

(B) The rate of heat removal.

$$\begin{aligned}Q_{L,\dot{}} &= m_{\dot{}} * (h_5 - h_4) \\Q_{L,\dot{}} &= 0.0229 \text{ kg/s} * (236.23 \text{ kJ/kg} - 91.49 \text{ kJ/kg}) \\Q_{L,\dot{}} &= \mathbf{3.31 \text{ kW}}\end{aligned}$$

(C) The pressure drop between the evaporator and the compressor.

$$\begin{aligned}\Delta P &= P_5 - P_1 \\ \Delta P &= 0.14287 \text{ MPa} - 140 \text{ kPa} \\ \Delta P &= \mathbf{2.87 \text{ kPa}}\end{aligned}$$

(D) The rate of heat gain in the line between the evaporator and the compressor.

$$\begin{aligned}Q_{\text{gain},\dot{}} &= m_{\dot{}} * (h_1 - h_5) \\Q_{\text{gain},\dot{}} &= 0.0229 \text{ kg/s} * (243.40 \text{ kJ/kg} - 236.23 \text{ kJ/kg})\end{aligned}$$

$$Q_{\text{gain\_dot}} = 0.164 \text{ kW}$$

**Example II** (Problem 10-29<sup>1</sup>): A heat pump using refrigerant-134a heats a house by using underground water at 8°C as the heat source. The house is losing heat at a rate of 60,000 kJ/h. The refrigerant enters the compressor at 280 kPa and 0°C, and it leaves at 1 MPa and 60°C. The refrigerant exits the condenser at 30°C. Determine (a) the power input to the heat pump, (b) the rate of heat absorption from the water, and (c) the increase in electric power input if an electric resistance heater is used instead of a heat pump.

**Solution:**

**Step 1.** Write down all given variables from problem statement.

Compressor inlet pressure = 280 kPa

Compressor inlet temperature = 0°C

Compressor outlet pressure = 1 MPa

Compressor outlet temperature = 60°C

Water source temperature = 8°C

$Q_{\text{H\_dot}} = 60,000 \text{ kJ/h}$

Condenser outlet temperature = 30°C

**Step 2.** Determine what stages the given temperatures and pressures belong to.

P1 = 280 kPa

P2 = 1.0 MPa

P3 = 1.0 MPa

P4 = Unknown

T1 = 0°C

T2 = 60°C

T3 = 30°C

T4 = Unknown

**Step 3.** Determine what equations will be required.

(a) Mass flow rate ( $m_{\text{dot}}$ ).

$$m_{\text{dot}} = Q_{\text{H\_dot}} / (h_2 - h_3)$$

(b) The power input to the compressor.

$$W_{\dot{in}} = [m_{\dot{}}(h_2 - h_1)]$$

(c) The rate of heat removal.

$$Q_{L_{\dot{}}} = m_{\dot{}}(h_1 - h_4)$$

(d) The electrical power required without the heat pump.

$$W_{\dot{elect}} = Q_{H_{\dot{}}}$$

**Step 4.** Determine values of enthalpy for each stage. These values can be determined using Tables A-11, A-12, and A-13 located in the back of the book.

(b) Stage 1

$$P_1 = 280 \text{ kPa}$$

$$T_1 = 0^\circ\text{C}$$

$$h_1 = 247.64 \text{ kJ/kg (Table A-13, pg. 918)}$$

(c) Stage 2

$$P_2 = 1.0 \text{ MPa}$$

$$T_2 = 60^\circ\text{C}$$

$$h_2 = 291.36 \text{ kJ/kg (Table A-13, pg. 919)}$$

(d) Stage 3

$$P_3 = 1.0 \text{ MPa}$$

$$T_3 = 30^\circ\text{C}$$

$$h_3 \cong h_{f@30^\circ\text{C}} = 91.49 \text{ kJ/kg (Table A-11, pg. 916)}$$

(e) Stage 4

$$h_4 \cong h_3 = 91.49 \text{ kJ/kg}$$

**Step 5.** Plug variables into equations and solve.

$$m_{\dot{}} = Q_{H_{\dot{}}} / (h_2 - h_3)$$

$$m_{\dot{}} = [(60,000 \text{ kJ/hr}) * (1\text{hr}/3600\text{sec})] / [(291.36 \text{ kJ/kg} - 91.49 \text{ kJ/kg})]$$

$$m_{\dot{}} = \mathbf{0.0834 \text{ kg/s}}$$

(A) The power input to the compressor.

$$W_{\dot{in}} = [m_{\dot{}}(h_2 - h_1)]$$

$$W_{\dot{in}} = [0.0834 \text{ kg/s} \cdot (291.36 \text{ kJ/kg} - 247.64 \text{ kJ/kg})]$$

$$W_{\dot{in}} = \mathbf{3.65 \text{ kW}}$$

(B) The rate of heat removal.

$$Q_{L\dot{}} = m_{\dot{}}(h_1 - h_4)$$

$$Q_{L\dot{}} = 0.0834 \text{ kg/s} \cdot (247.64 \text{ kJ/kg} - 91.49 \text{ kJ/kg})$$

$$Q_{L\dot{}} = \mathbf{13.02 \text{ kW}}$$

(C) The electrical power required without the heat pump.

$$W_{\dot{elect}} = Q_{H\dot{}}$$

$$W_{\dot{elect}} = [(60,000 \text{ kJ/hr}) \cdot (1 \text{ hr}/3600 \text{ sec})]$$

$$W_{\dot{elect}} = \mathbf{16.67 \text{ kW}}$$

$$W_{\dot{increase}} = W_{\dot{elect}} - W_{\dot{in}}$$

$$W_{\dot{increase}} = 16.67 \text{ kW} - 3.65 \text{ kW}$$

$$W_{\dot{increase}} = \mathbf{13.02 \text{ kW}}$$

**Example III** (Problem 10-61<sup>1</sup>): An absorption refrigeration system receives heat from a source at 110°C and maintains the refrigerated space at -20°C. If the temperature of the environment is 25°C, what is the maximum COP this absorption refrigeration system can have?

**Solution:**

**Step 1.** Write down all given variables from problem statement.

$$\text{Outside temperature } (T_o) = 25^\circ\text{C} = 298.15 \text{ K}$$

$$\text{Source temperature } (T_s) = 110^\circ\text{C} = 383.15 \text{ K}$$

$$\text{Refrigeration temperature } (T_L) = -20^\circ\text{C} = 253.15 \text{ K}$$

**Step 3.** Determine what equations will be required.

$$\text{COP}_R = (1 - (T_o/T_s)) \cdot (T_L/(T_o - T_L))$$

**Step 5.** Plug variables into equation and solve.

$$\text{COP}_R = (1 - (T_o/T_s)) \cdot (T_L/(T_o - T_L))$$

$$\text{COP}_R = (1 - (298.15 \text{ K}/383.15 \text{ K})) \cdot (253.15 \text{ K}/(298.15 \text{ K} - 253.15 \text{ K}))$$

$$\text{COP}_R = 1.25$$

**Definitions:**

**Coefficient of Performance (COP)** – the ratio of desired output divided by the required input. It is the rate of how well the heat pump or refrigerator is performing.

**Compressor** – pump used to push refrigerant through the system.

**Condenser** – heat exchanger used to reject heat energy.

**Cooling capacity** – the rate of heat removal from the refrigerated space, which is expressed in terms of tons of refrigeration.

**Evaporator** – heat exchanger used to absorb heat energy.

**Expansion valve** – controls the flow of refrigerant and allows for phase change from a liquid to vapor.

**Flash chamber** – mixing chamber where both liquid and vapor are stored.

**Refrigerant** – the working fluids used in the refrigeration cycles.

**Refrigeration** – the heat transfer of heat from a lower temperature region to a higher temperature one. A device called a refrigerator or heat pump accomplishes refrigeration.

**Refrigerator** – the device used to produce refrigeration.

**Thermocouple** – Temperature sensor consisting of the junction of two dissimilar metals. The output voltage produced is a function of the difference in the temperature between the hot and cold junction.

**Turbine** – device used to extract heat energy to produce mechanical energy.

**T-s diagram** – schematic or graphical representation of the temperature versus entropy for refrigeration cycles.

**Symbols:**

$Q_L$  – the magnitude of the heat removed the refrigerated environment.

$T_L$  – desired temperature of the refrigerated environment.

$Q_H$  – the magnitude of the heat rejected to the warm environment.

$T_H$  – temperature of environment that the warm air is rejected to.

$W_{\text{net,in}}$  – required input done an electrically or mechanical driven device.

R – refrigerator  
HP – heat pump

**Equations:**

$$\text{COP}_R = Q_L / W_{\text{net,in}}$$
$$\text{COP}_{\text{HP}} = Q_H / W_{\text{net,in}}$$

$$\text{COP}_{R, \text{Carnot}} = 1 / [(T_H/T_L)-1]$$
$$\text{COP}_{\text{HP}, \text{Carnot}} = 1 / [1-(T_L/T_H)]$$

$$\text{COP}_R = (h1 - h4)/(h2 - h1)$$
$$\text{COP}_{\text{HP}} = (h2 - h3)/(h2 - h1)$$

$$\text{COP}_R = q_L / (W_{\text{comp,in}} - W_{\text{turb,out}})$$

$$\text{COP}_R = Q_L / (Q_{\text{gen}} + W_{\text{pump,in}})$$

$$\text{COP}_R = \eta_{\text{th,rev}} * \text{COP}_R = (1 - (T_o/T_s)) * (T_L/(T_o-T_L))$$

$$m_{\text{dot}} = V_{\text{dot}} / v$$

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