Refrigeration

3: Refrigeration Cycles

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THERMODYNAMICS

THERMODYNAMICS is the study of energy, its transformations, and its relation to states of matter.

A **thermodynamic system** is a region in space or a quantity of matter bounded by a closed surface. The surroundings include everything external to the system, and the system is separated from the surroundings by the system boundaries. These boundaries can be movable or fixed, real or imaginary.

THERMODYNAMICS

A **process** is a change in state that can be defined as **any change in the properties** of a system. A process is described by specifying the **initial** and **final** equilibrium states, the **path** (if identifiable), and the interactions that take place across system boundaries during the process.

A **cycle** is a **process** or a **series** of **processes** wherein the **initial and final states** of the system are **identical**. Therefore, at the **conclusion** of a cycle, all the properties have the same value they had at the **beginning**. **Refrigerant circulating in a closed system undergoes a cycle.**

A **pure substance** has a homogeneous and invariable chemical composition. It can exist in more than one phase, but the chemical composition is the same in all phases.

If a substance is liquid at the saturation temperature and pressure, it is called a **saturated liquid**.

If the **temperature** of the liquid is **lower** than the saturation temperature for the existing pressure, it is called either a **subcooled liquid** (the temperature is lower than the saturation temperature for the given pressure) or a **compressed liquid** (the pressure is greater than the saturation pressure for the given temperature).

When a substance exists as part liquid and part vapor at the saturation temperature, its **quality** is defined as the ratio of the **mass of vapor** to the **total mass**. Quality has meaning only when the substance is **saturated** (i.e., at saturation pressure and temperature).

Pressure and temperature of saturated substances are not independent properties.

If a substance exists as a vapor at saturation temperature and pressure, it is called a **saturated vapor**. (Sometimes the term **dry saturated vapor** is used to emphasize that the quality is 100%.)

When the vapor is at a temperature greater than the saturation temperature, it is a **superheated vapor**.

Pressure and temperature of a superheated vapor are **independent properties**, because the temperature can increase while pressure remains constant.

Gases such as **air at room temperature and pressure are highly superheated vapors.**

FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics is often called the **law of conservation of energy**. Based on the first law or the law of conservation of energy, for any system, open or closed, there is an energy balance as:

$$\left[\begin{array}{c}\text{Net amount of energy}\\ \text{added to system}\end{array}\right] = \left[\begin{array}{c}\text{Net increase of stored}\\ \text{energy in system}\end{array}\right]$$

Or [Energy in] – [Energy out] = [Increase of stored energy in system]

A common application is the **closed stationary system** for which the first law equation reduces to

$$Q - W = [m\,(u_f - u_i)]_{system}\,,$$

where u is the internal energy per unit mass, subscripts i and f refer to the initial and final states, respectively.

SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics differentiates and quantifies processes that only proceed in a certain direction (**irreversible**) from those that are **reversible**. The second law may be described in several ways.

One method uses the **concept of entropy** flow in an open system and the **irreversibility** associated with the process. The concept of irreversibility provides added insight into the operation of cycles. For example, the larger the **irreversibility** in a refrigeration cycle operating with a given refrigeration load between two fixed temperature levels, the **larger** the amount of **work required** to operate the cycle.

Irreversibilities include **pressure drops** in lines and heat exchangers, heat transfer between fluids of different temperature, and **mechanical friction**.

Reducing total irreversibility in a cycle **improves cycle performance**. In the limit of no irreversibilities, a cycle attains its **maximum ideal efficiency**.

THERMODYNAMIC ANALYSIS OF REFRIGERATION CYCLES

Refrigeration cycles transfer thermal energy from a region of low temperature T_R to one of higher temperature. Usually the higher temperature heat sink is the **ambient air** or **cooling water**, at temperature T_0, the temperature of the surroundings.

The first and second laws of thermodynamics can be applied to individual components to determine **mass and energy balances and the irreversibility** of the components.

Performance of a refrigeration cycle is usually described by a **coefficient of performance (COP)**, defined as the benefit of the cycle (amount of heat removed) divided by the required energy input to operate the cycle:

$$\text{COP} \equiv \frac{\text{Useful refrigerating effect}}{\text{Net energy supplied from external sources}}$$

THERMODYNAMIC ANALYSIS OF REFRIGERATION CYCLES

For a **mechanical vapor compression system**, the net energy supplied is usually in the form of work, mechanical or electrical, and may include work to the compressor and fans or pumps. Thus,

$$\text{COP} = \frac{Q_{evap}}{W_{net}}$$

Applying the second law to an entire refrigeration cycle shows that a completely reversible cycle operating under the same conditions has the maximum possible COP.

Departure of the actual cycle from an ideal reversible cycle is given by the **refrigerating efficiency**:

$$\eta_R = \frac{\text{COP}}{(\text{COP})_{rev}}$$

COMPRESSION REFRIGERATION CYCLES

1. CARNOT CYCLE

The Carnot cycle, which is **completely reversible**, is a **perfect model** for a refrigeration cycle operating between two fixed temperatures, or between two fluids at different temperatures and each with infinite heat capacity.

Reversible cycles have **two important properties**:

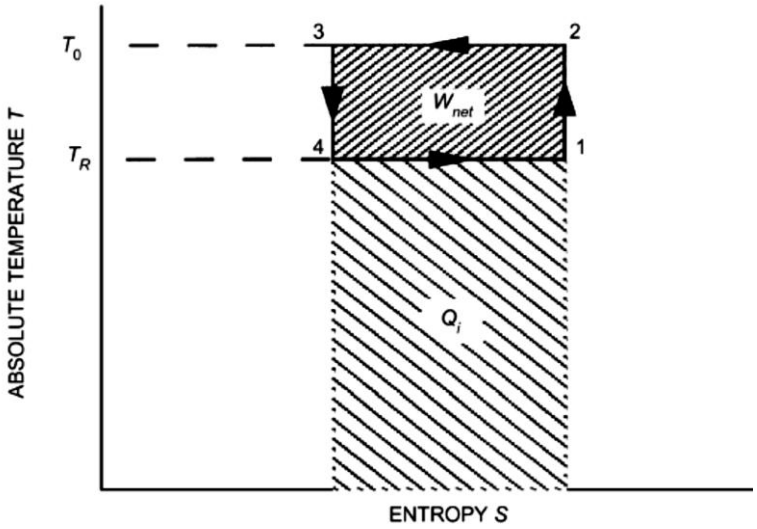
(1) No refrigerating cycle may have a coefficient of performance higher than that for a reversible cycle operated between the same temperature limits.

(2) All reversible cycles, when operated between the same temperature limits, have the same coefficient of performance.

COMPRESSION REFRIGERATION CYCLES

CARNOT CYCLE

Carnot cycle on temperature-entropy coordinates. Heat is withdrawn at constant temperature T_R from the region to be refrigerated. Heat is rejected at constant ambient temperature T_0 . The cycle is completed by an isentropic expansion and an isentropic compression. The energy transfers are given by



$$Q_0 = T_0(S_2 - S_3)$$
$$Q_i = T_R(S_1 - S_4) = T_R(S_2 - S_3)$$
$$W_{net} = Q_o - Q_i$$

$$\Longrightarrow \quad \text{COP} = \frac{T_R}{T_0 - T_R}$$

1-2. Adiabatic compression

2-3. Isothermal rejection of heat

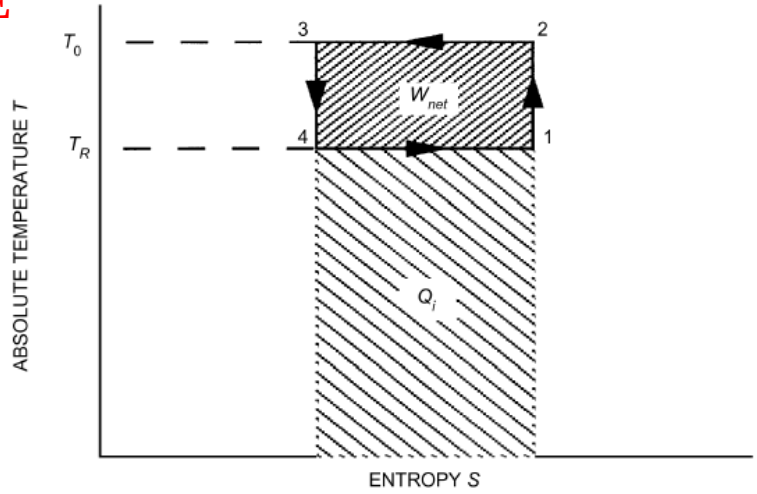
3-4. Adiabatic expansion

4-1. Isothermal addition of heat

All the processes in the Carnot cycle are thermodynamically reversible. Processes 1-2 and 3-4 are consequently **isentropic**.

COMPRESSION REFRIGERATION CYCLES

CARNOT CYCLE



The withdrawal of heat from the low-temperature source in process 4-1 is the **refrigeration step and is the entire purpose of the cycle.**

The Carnot cycle consists of reversible processes which make its efficiency higher than could be achieved in an actual cycle. A reasonable question is: Why discuss the Carnot cycle if it is an unattainable ideal? There are two reasons:

(1) it serves as a standard of comparison

(2) it provides a convenient guide to the temperatures that should be maintained to achieve maximum effectiveness.

Example 1. Determine entropy change, work, and COP for the cycle. Temperature of the refrigerated space T_R is 250 K, and that of the atmosphere T_0 is 300 K. Refrigeration load is 125 kJ.

COMPRESSION REFRIGERATION CYCLES

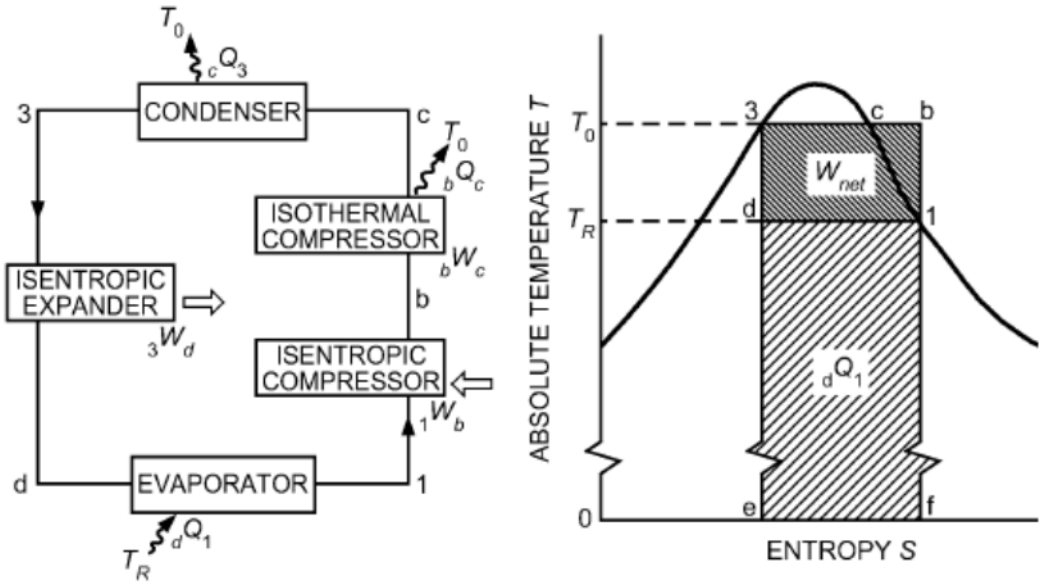
CARNOT CYCLE

The **net change of entropy** of any refrigerant in any cycle is always **zero**. In Example 1, the change in entropy of the refrigerated space is $\Delta S_R = -125/250 = -0.5$ kJ/K and that of the atmosphere is $\Delta S_o = 125/250 = 0.5$ kJ/K. The net change in entropy of the isolated system is $\Delta S_{total} = \Delta S_R + \Delta S_o = 0$.

COMPRESSION REFRIGERATION CYCLES

CARNOT CYCLE

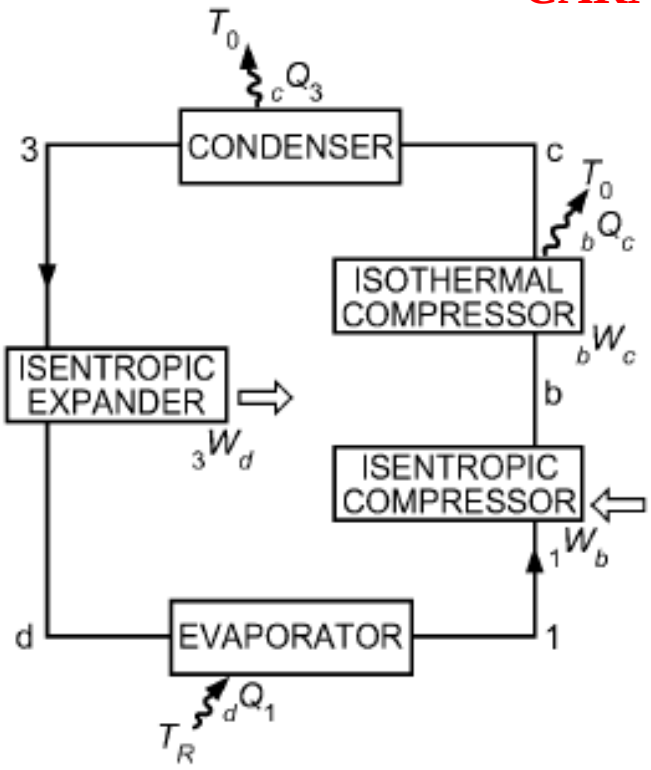
The Carnot cycle in Figure shows a process in which heat is added and rejected at constant pressure in the two-phase region of a refrigerant. Saturated liquid at state 3 expands isentropically to the low temperature and pressure of the cycle at state d. Heat is added **isothermally** and **isobarically** by evaporating the liquid-phase refrigerant from state d to state 1.

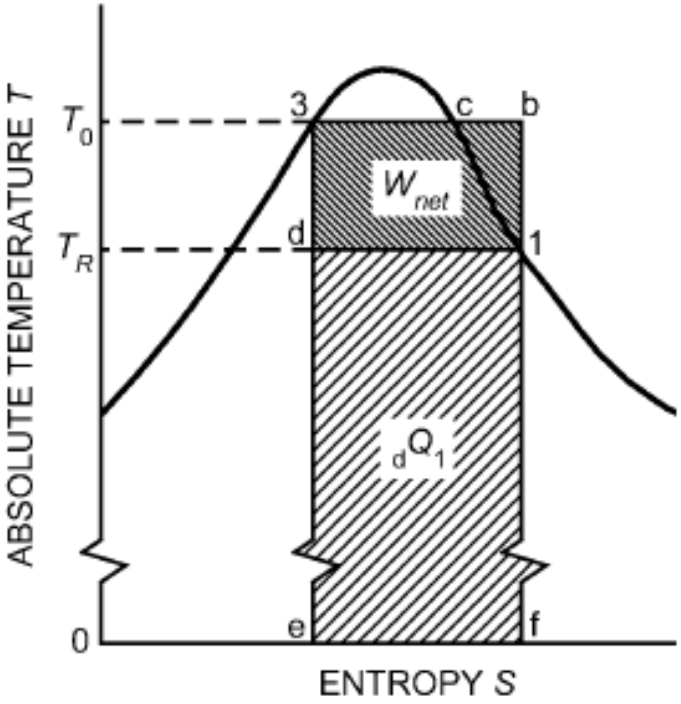


The cold saturated vapor at state 1 is compressed **isentropically** to the high temperature in the cycle at state b. However, the pressure at state b is below the saturation pressure corresponding to the high temperature in the cycle. The compression process is completed by an **isothermal** compression process from state b to state c. The cycle is completed by an **isothermal and isobaric** heat rejection or condensing process from state c to state 3. Applying the energy equation for a mass of refrigerant m yields (all work and heat transfer are positive)

COMPRESSION REFRIGERATION CYCLES

CARNOT CYCLE





$$_3W_d = m(h_3 - h_d)$$

$$_1W_b = m(h_b - h_1)$$

$$_bW_c = T_0(S_b - S_c) - m(h_b - h_c)$$

$$_dQ_1 = m(h_1 - h_d) = \text{Area def1d}$$

The net work for the cycle is

$$W_{net} = {}_1W_b + {}_bW_c - {}_3W_d = \text{Area d1bc3d}$$

and

$$\text{COP} = \frac{{}_dQ_1}{W_{net}} = \frac{T_R}{T_0 - T_R}$$

COMPRESSION REFRIGERATION CYCLES

CARNOT CYCLE- Heat Pump

A heat pump uses the same equipment as a refrigeration system but operates for the purpose of delivering **heat at a high level of temperature**.

Even though the equipment used in a refrigeration cycle and in a heat pump may be identical, the **objectives are different**.

The purpose of a refrigeration cycle is to absorb heat at a **low temperature**; that of a heat pump is **to reject heat at a high temperature**.

An example of heat-pump operation is to **take heat at a low temperature** from outside air, the earth, or well water and **reject it to heat a building**. In some industrial situations, cooling may be required in one part of the plant and heating in another. Both these functions might be served by a heat-pump system.

A plant can be constructed to operate alternately as a heat pump and a refrigeration system. Units of this type are available for air-conditioning applications of cooling a building during summer and heating it during winter.

The performance of a heat pump is expressed by the **performance factor**. In keeping with the practice of defining the performance index as the amount of the desired commodity divided by the amount of expenditure, the performance factor is

$$\text{Performance factor} = \frac{\text{heat rejected from cycle}}{\text{work required}}$$

COMPRESSION REFRIGERATION CYCLES

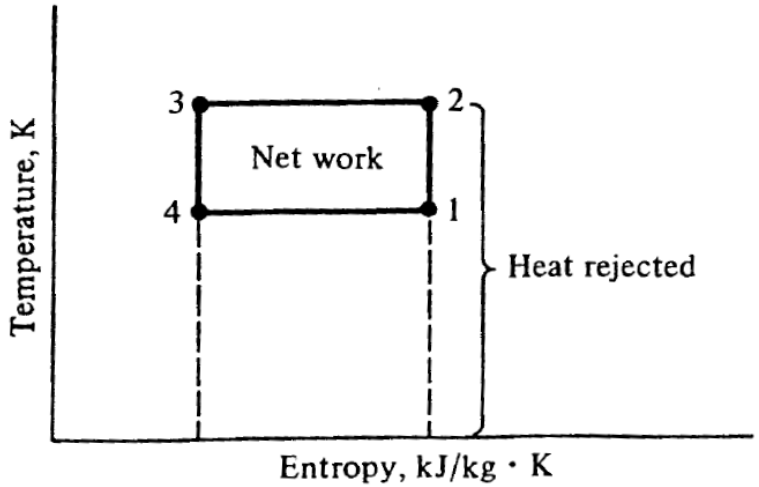
CARNOT CYCLE- Heat Pump

$$\text{Performance factor} = \frac{T_2(s_1 - s_4)}{(T_2 - T_1)(s_1 - s_4)} = \frac{T_2}{T_2 - T_1}$$

The refrigeration cycle with the same temperatures as in Fig. 10-5 would have a coefficient of performance of $T_1/(T_2 - T_1)$. Therefore

$$\text{Performance factor} = \frac{T_2}{T_2 - T_1} = \frac{T_2}{T_2 - T_1} - \frac{T_2 - T_1}{T_2 - T_1} + 1$$

$$= \frac{T_1}{T_2 - T_1} + 1 = \text{coefficient of performance} + 1$$

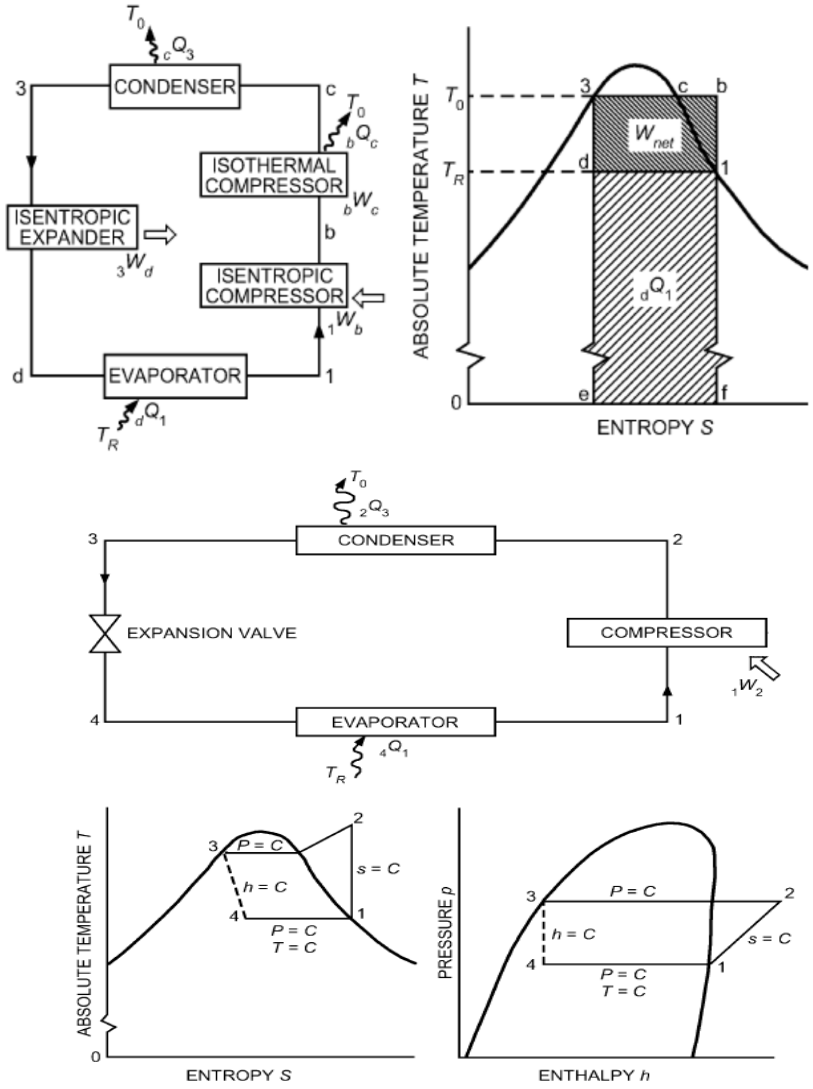


COMPRESSION REFRIGERATION CYCLES

THEORETICAL SINGLE-STAGE CYCLE USING A PURE REFRIGERANT OR AZEOTROPIC MIXTURE

A system designed to approach the ideal model shown in previous Figure is desirable. A pure refrigerant or azeotropic mixture can be used to maintain constant temperature during phase changes by maintaining constant pressure. Because of concerns such as high initial cost and increased maintenance requirements, a practical machine has one compressor instead of two and the expander (engine or turbine) is replaced by a simple expansion valve, which throttles refrigerant from high to low pressure.

This Figure shows the theoretical single-stage cycle used as a model for actual systems.



COMPRESSION REFRIGERATION CYCLES

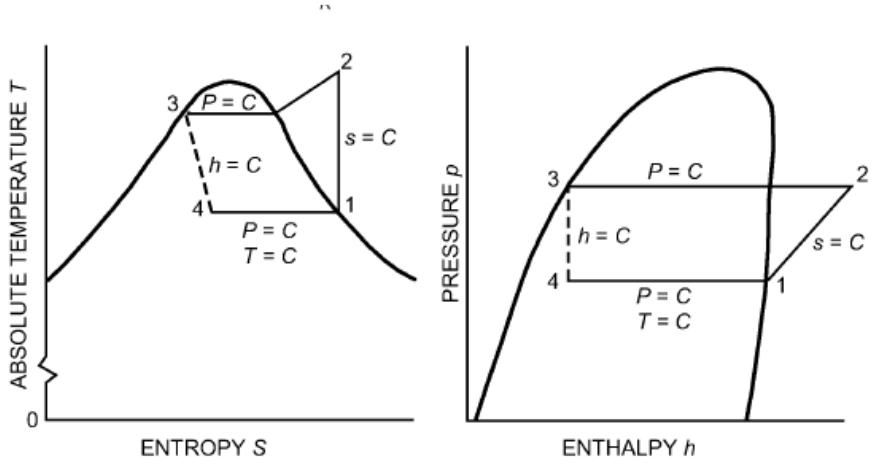
THEORETICAL SINGLE-STAGE CYCLE USING A PURE REFRIGERANT OR AZEOTROPIC MIXTURE

1-2 **Reversible and adiabatic** compression from saturated vapor to the condenser pressure

2-3 **Reversible** rejection of heat at constant pressure, causing condensation of the refrigerant.

3-4 **Irreversible** expansion at constant enthalpy from saturated liquid to the evaporator pressure.

4-1 **Reversible** addition of heat at constant pressure causing evaporation to saturated vapor. Applying the energy equation for a mass m of refrigerant yields



$$ {}_4Q_1 = m(h_1 - h_4) $$

$$ {}_1W_2 = m(h_2 - h_1) $$

$$ {}_2Q_3 = m(h_2 - h_3) $$

$$ h_3 = h_4 $$

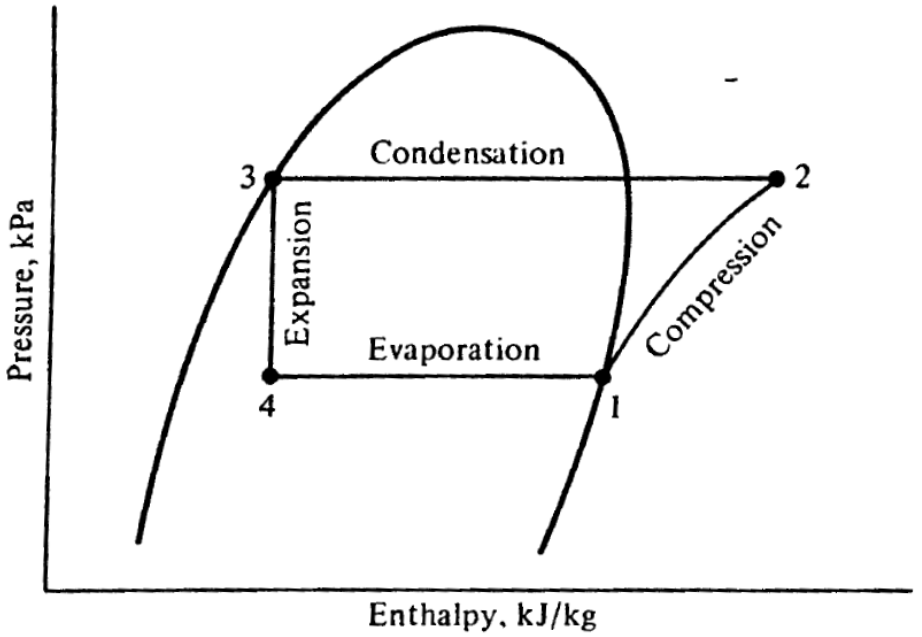
$$ \text{COP} = \frac{{}_4Q_1}{{}_1W_2} = \frac{h_1 - h_4}{h_2 - h_1} $$

COMPRESSION REFRIGERATION CYCLES

Performance of the standard vapor-compression cycle

With the help of the pressure-enthalpy diagram, the significant quantities of the standard vapor-compression cycle will be determined.

These quantities are the **work of compression**, the **heat rejection rate**, the **refrigerating effect**, the **coefficient of performance,** the **volume rate of flow** per **kilowatt of refrigeration**, and the **power per kilowatt of refrigeration.**



The work of compression in Kj/Kg is the change in enthalpy in process 1-2 or h1 – h2 . This relation derives from the steady-flow energy equation

$h_1 + q = h_2 + w$

Because in the adiabatic compression the heat transfer q is zero, the work w equals $h_1 - h_2$. The difference in enthalpy is a **negative** quantity, indicating that work is done **on the system**.

COMPRESSION REFRIGERATION CYCLES

Performance of the standard vapor-compression cycle

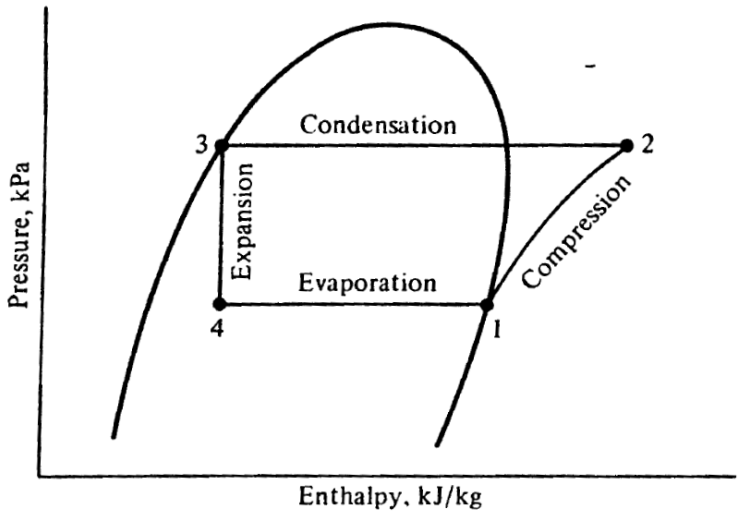
The heat rejection in Kj/Kg is the heat transferred from the refrigerant in process 2-3, which is $h_3 - h_2$. This knowledge also comes from the steady-flow energy equation, in which the kinetic energy~ potential energy, and work terms drop out.

The value of $h_3 - h_2$ is **negative**, indicating that heat is transferred from the refrigerant.

The **refrigerating effect** in Kj/Kg is the heat transferred in process 4-1, or h_1-h_4.

Knowledge of the magnitude of the term is necessary because performing **this process is the ultimate purpose of the entire system.**

The coefficient of performance of the standard vapor-compression cycle is the refrigerating effect divided by the work of compression:



$$\text{Coefficient of performance} = \frac{h_1 - h_4}{h_2 - h_1}.$$

COMPRESSION REFRIGERATION CYCLES

Example 2. A theoretical single-stage cycle using R-134a as the refrigerant operates with a condensing temperature of 30°C and an evaporating temperature of –20°C. The system produces 50 kW of refrigeration. Determine

(a) thermodynamic property values at the four main state points of the cycle,
(b) COP,
(c) cycle refrigerating efficiency
(d) rate of refrigerant flow.

Example 3. A standard vapor-compression cycle developing 50 kW of refrigeration using refrigerant 22 operates with a condensing temperature of 35°C and an evaporating temperature of -10°C. Calculate (a) the refrigerating effect in kilojoules per kilogram, (b) the circulation rate of refrigerant in kilograms per second, (c) the power required by the compressor in kilowatts, (d) the coefficient of performance, (e) the volume flow rate measured at the compressor suction, (f) the power per kilowatt of refrigeration, and (g) the compressor discharge temperature.

Next: Refrigeration Processes and cycles II

References:

-2021 ASHRAE Handbook -- Fundamentals (SI)
- REFRIGERATION & AIR CONDITIONING BY W.F. STOECKER & J.W JHONES

Thank you