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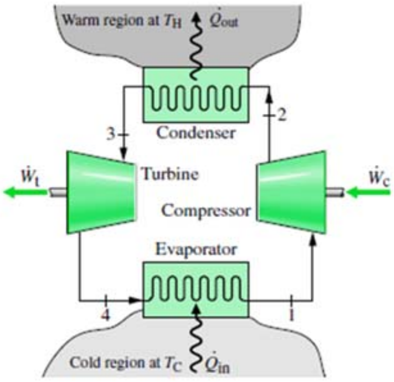
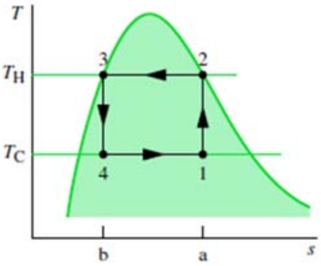


Thermodynamics I

Refrigeration and Heat Pump Cycles



Dr.-Eng. Zayed Al-Hamamre

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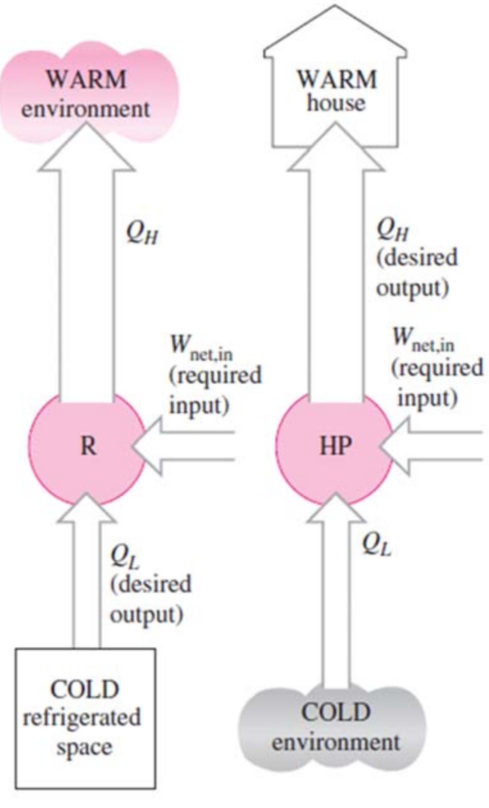
Introduction

- The transfer of heat from a low-temperature region to high-temperature one requires special devices called **refrigerators.**
- The working fluids used in the refrigeration cycles are called **refrigerants.**
- The objective of a refrigerator is to maintain the refrigerated space at a low temperature by removing h from it.
- The objective of a heat pump, however, is to maintain heated space at a high temperature.
- The performance of refrigerators and heat pumps is expressed in terms of the **coefficient of performance** (COP)

$$\mathrm{COP_R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{\mathrm{net,in}}}$$

$$\mathrm{COP_{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{\mathrm{net,in}}}$$



(*a*) Refrigerator (*b*) Heat pump

Introduction

$$\mathrm{COP_{HP}} = \mathrm{COP_R} + 1 \qquad \text{for fixed values of } Q_L \text{ and } Q_H.$$

Since $\mathrm{COP_R}$ is a positive quantity. $\mathrm{COP_{HP}} > 1$

- The *cooling capacity* of a refrigeration system—that is, the rate of heat removal from the refrigerated space—is often expressed in terms of **tons of refrigeration**

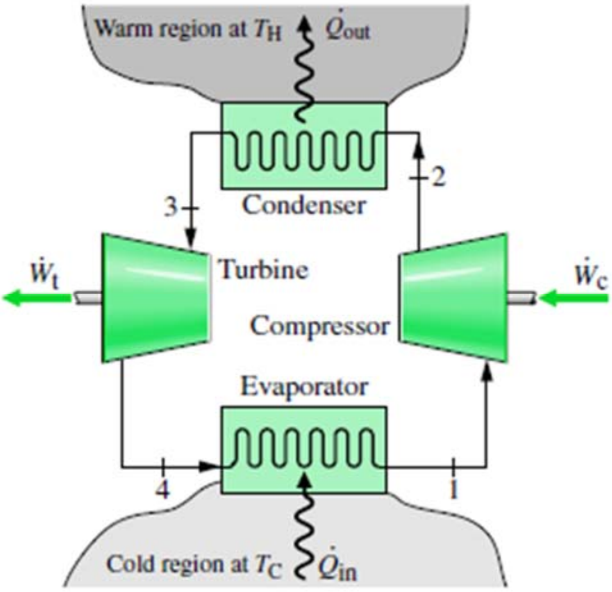
The capacity of a refrigeration system that can freeze 1 ton (2000 lbm) of liquid water at 0°C (32°F) into ice at 0°C in 24 h is said to be 1 ton.

One ton of refrigeration is equivalent to 211 kJ/min or 200 Btu/min.

The cooling load of a typical 200-m^2 residence is in the 3-ton (10-kW) range.

The Reversed Carnot Cycle

- Carnot cycle is a totally reversible cycle that consists of two reversible isothermal and two isentropic processes.
- Reversing the cycle does also reverse the directions of any heat and work interactions.
- The result is a cycle that operates in the counterclockwise direction on a *T-s* diagram, which is called the **reversed Carnot cycle.**
- A refrigerator or heat pump that operates on the reversed Carnot cycle is called a **Carnot refrigerator** or a **Carnot heat pump**



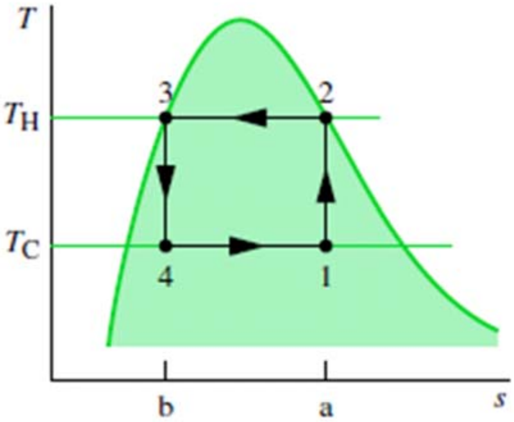
The Reversed Carnot Cycle

The *coefficient of performance* β of *any* refrigeration cycle is the ratio of the refrigeration effect to the net work input required to achieve that effect.

$$\beta_{\max} = \frac{\dot{Q}_{in}/\dot{m}}{\dot{W}_c/\dot{m} - \dot{W}_t/\dot{m}}$$

$$= \frac{\text{area 1–a–b–4–1}}{\text{area 1–2–3–4–1}} = \frac{T_C(s_a - s_b)}{(T_H - T_C)(s_a - s_b)}$$

$$= \frac{T_C}{T_H - T_C}$$



1–a–b–4–1 is the heat added to the refrigerant from the cold region per unit mass of refrigerant flowing.

Area 2–a–b–3–2 is the heat rejected from the refrigerant to the warm region per unit mass of refrigerant flowing.

The Reversed Carnot Cycle

The enclosed area 1–2–3–4–1 is the *net* heat transfer *from* the refrigerant.

The net heat transfer *from* the refrigerant equals the net work done *on* the refrigerant.

$$\mathrm{COP}_{\mathrm{R,Carnot}} = \frac{1}{T_H/T_L - 1} \qquad \mathrm{COP}_{\mathrm{HP,Carnot}} = \frac{1}{1 - T_L/T_H}$$

both COPs increase as the difference between the two temperatures decreases,

- The reversed Carnot cycle is the *most efficient* refrigeration cycle operating between two specified temperature levels.
- Process 1-2 involves the compression of a liquid–vapor mixture, which requires a compressor that will handle two phases, and process 3-4 involves the expansion of high-moisture-content refrigerant in a turbine

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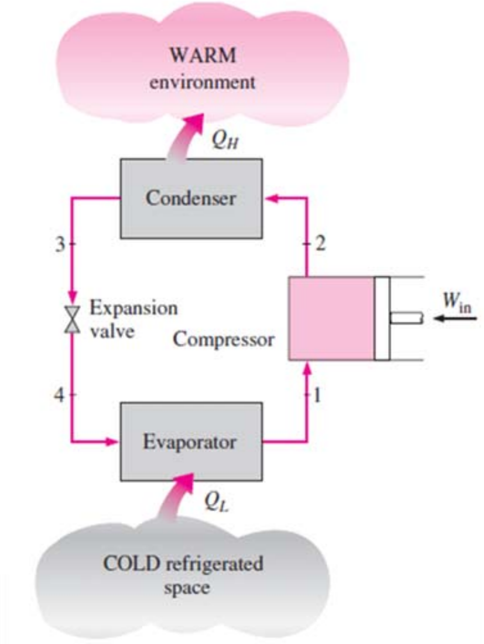
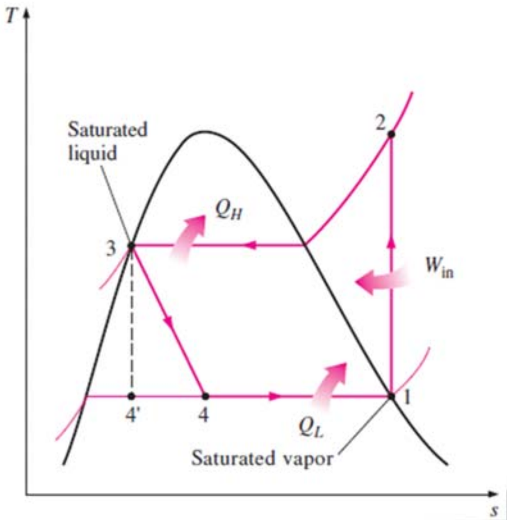
The Ideal Vapor-Compression Refrigeration Systems

- Impracticalities associated with the reversed Carnot cycle can be eliminated by vaporizing the refrigerant completely before it is compressed and by replacing the turbine with a throttling device.
- The cycle that results is called the **ideal vapor-compression refrigeration cycle,**





The Ideal Vapor-Compression Refrigeration Systems

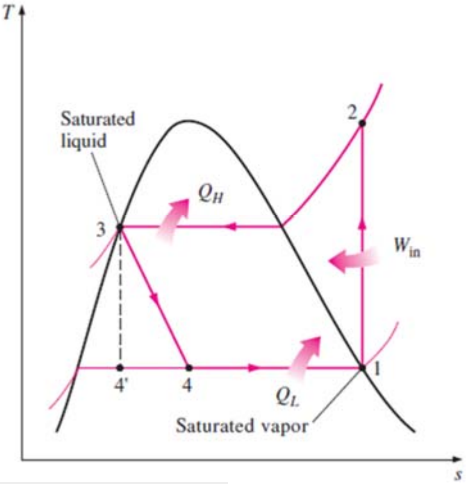
Process 1–2s: *Isentropic* compression of the refrigerant from state 1 to the condenser pressure at state 2s.

Process 2s–3: Heat transfer *from* the refrigerant as it flows at constant pressure through the condenser. The refrigerant exits as a liquid at state 3.

Process 3–4: *Throttling* process from state 3 to a two-phase liquid–vapor mixture at 4.

Process 4–1: Heat transfer *to* the refrigerant as it flows at constant pressure through the evaporator to complete the cycle.

- All of the processes in the above cycle are internally reversible except for the throttling process.



The Ideal Vapor-Compression Refrigeration Systems

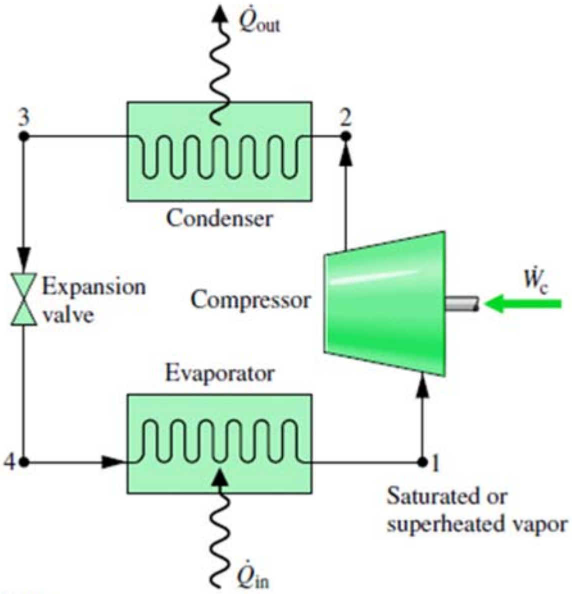
$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4 \qquad \frac{\dot{W}_c}{\dot{m}} = h_2 - h_1$$

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_2 - h_3 \qquad h_4 = h_3$$

$$\text{COP}_R = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

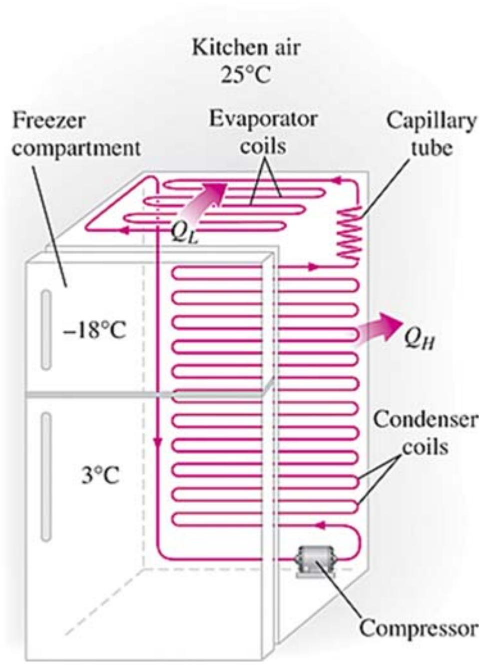
$$\text{COP}_{HP} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

where $h_1 = h_{g\,@\,P_1}$ and $h_3 = h_{f\,@\,P_3}$ for the ideal case.

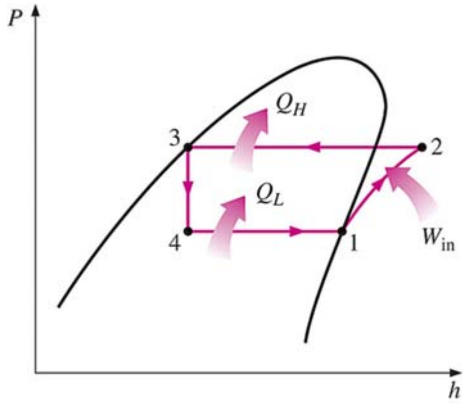


The Ideal Vapor-Compression Refrigeration Systems

$$(q_{\text{in}} - q_{\text{out}}) + (w_{\text{in}} - w_{\text{out}}) = h_e - h_i$$



An ordinary household refrigerator.



The *P-h* diagram of an ideal vapor-compression refrigeration cycle.

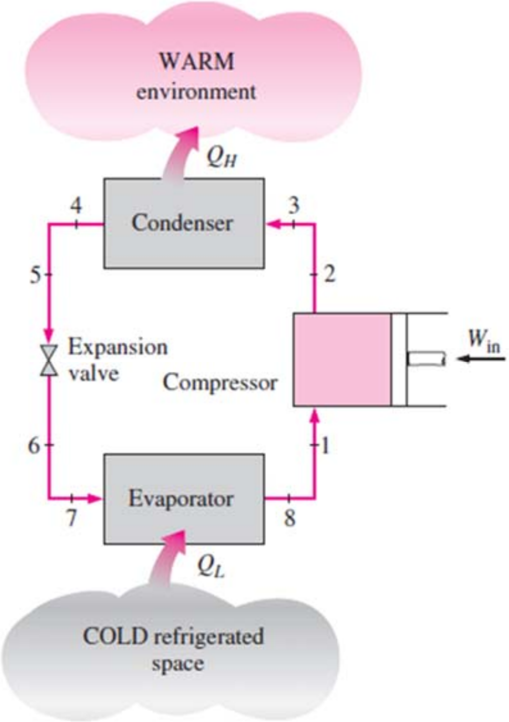
Example

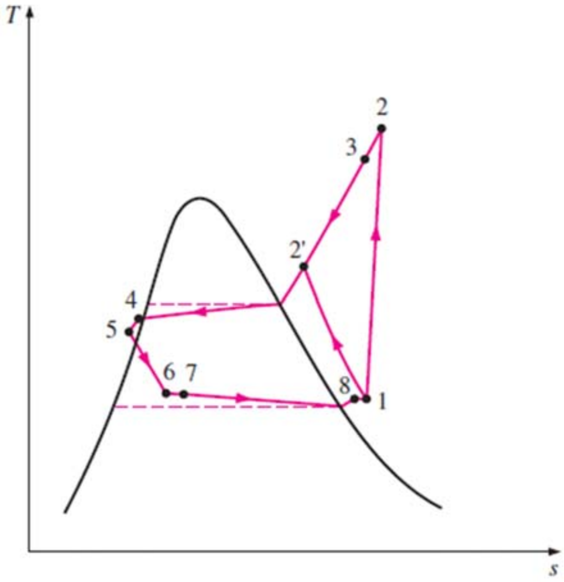
A refrigerator uses refrigerant-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.14 and 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, determine (*a*) the rate of heat removal from the refrigerated space and the power input to the compressor, (*b*) the rate of heat rejection to the environment, and (*c*) the COP of the refrigerator.

Example Cont.

Example Cont.

Deviation from Vapor-Compression Refrigeration Systems





$$\eta_c = \frac{(\dot{W}_c/\dot{m})_s}{(\dot{W}_c/\dot{m})} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

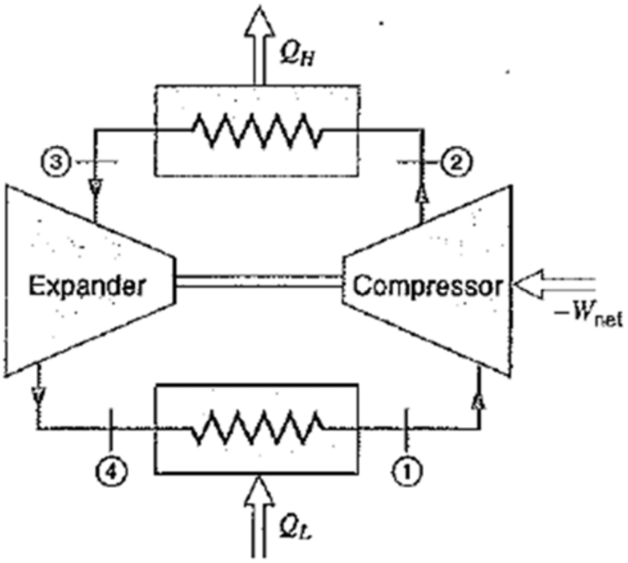
Selection of a Refrigerant

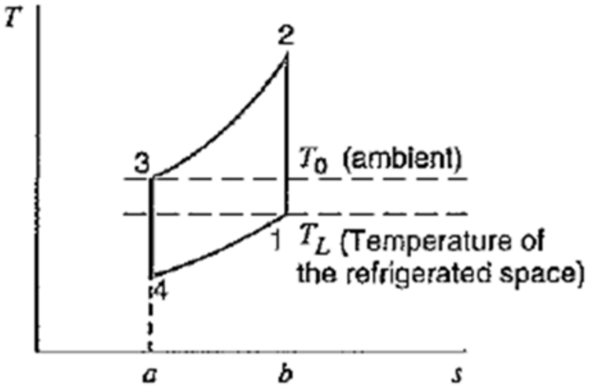
- Several refrigerants may be used in refrigeration systems such as chlorofluorocarbons (CFCs), ammonia, hydrocarbons (propane, ethane, ethylene, etc.), carbon dioxide, air (in the air-conditioning of aircraft), and even water (in applications above the freezing point).
- R-11, R-12, R-22, R-134a, and R-502 account for over 90 percent of the market.
- The industrial and heavy-commercial sectors use *ammonia* (it is toxic).
- R-11 is used in large-capacity water chillers serving A-C systems in buildings.
- R-134a (replaced R-12, which damages ozone layer) is used in domestic refrigerators and freezers, as well as automotive air conditioners.
- R-22 is used in window air conditioners, heat pumps, air conditioners of commercial buildings, and large industrial refrigeration systems, and offers strong competition to ammonia.
- R-502 (a blend of R-115 and R-22) is the dominant refrigerant used in commercial refrigeration systems such as those in supermarkets.
- CFCs allow more ultraviolet radiation into the earth's atmosphere by destroying the protective ozone layer and thus contributing to the greenhouse effect that causes global warming. Fully halogenated CFCs (such as R-11, R-12, and R-115) do the most damage to the ozone layer. Refrigerants that are friendly to the ozone layer have been developed.

Selection of a Refrigerant

- Two important parameters that need to be considered in the selection of a refrigerant are the temperatures of the two media (the refrigerated space and the environment) with which the refrigerant exchanges heat.
- i.e. the selection of a refrigerant is based partly on the suitability of its pressure–temperature relationship in the range of the particular application
- It is generally desirable to avoid excessively low pressures in the evaporator and excessively high pressures in the condenser.
- Other considerations in refrigerant selection include chemical stability, toxicity, corrosiveness, and cost.
- The type of compressor also affects the choice of refrigerant. Centrifugal compressors are best suited for low evaporator pressures and refrigerants with large specific volumes at low pressure. Reciprocating compressors perform better over large pressure ranges and are better able to handle low specific volume refrigerants.

Air Standard Refrigeration Cycle





$$\dot{Q}_{in}/\dot{m} = q_L = h_1 - h_4$$

$$w_{turb,out} = h_3 - h_4$$

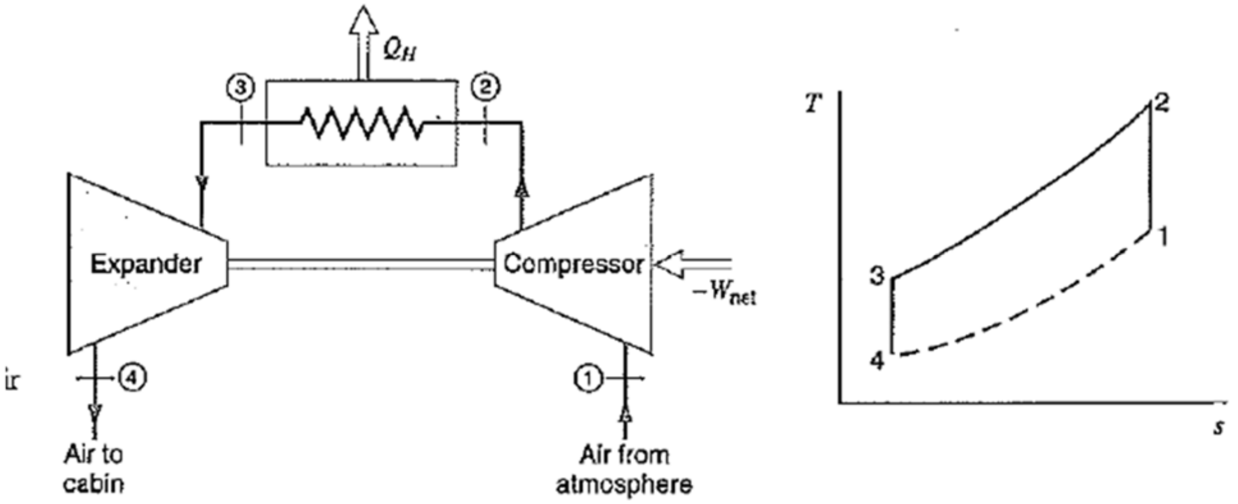
$$w_{comp,in} = h_2 - h_1$$

$$\text{COP}_R = \frac{q_L}{w_{net,in}} = \frac{q_L}{w_{comp,in} - w_{turb,out}}$$

$$= \frac{\dot{Q}_{in}/\dot{m}}{\dot{W}_c/\dot{m} - \dot{W}_t/\dot{m}} = \frac{(h_1 - h_4)}{(h_2 - h_1) - (h_3 - h_4)}$$

Air Standard Refrigeration Cycle

- The reversed Brayton cycle (the gas refrigeration cycle) can be used for refrigeration.



- Despite their relatively low COPs, the gas refrigeration cycles involve simple, lighter components, which make them suitable for aircraft cooling, and they can incorporate regeneration

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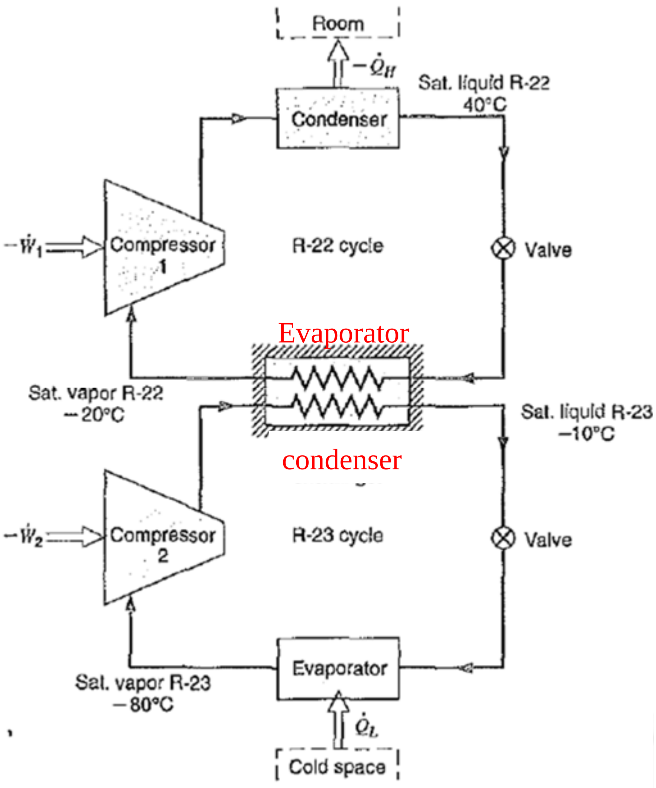
Combined Cycles

- Combined cycles are used in refrigeration systems in cases in which there is a very large temperature difference between the ambient surroundings and the refrigerated space.
- Such a refrigeration system is often called a cascade system.
- The two cycles are connected through the heat exchanger in the middle, which serves as the evaporator for the topping cycle (R-22 cycle) and the condenser for the bottoming cycle (R-23 cycle)
- Refrigerant R-22 is used in the refrigeration system rejecting heat to the ambient surroundings, while its evaporator picks up the heat rejected in the low temperature system condenser, the low temperature working fluid in this case being R-23



Combined Cycles

$$\dot{m}_A(h_5 - h_8) = \dot{m}_B(h_2 - h_3) \longrightarrow \frac{\dot{m}_A}{\dot{m}_B} = \frac{h_2 - h_3}{h_5 - h_8}$$

$$\mathrm{COP}_{\mathrm{R,cascade}} = \frac{\dot{Q}_L}{\dot{W}_{\mathrm{net,in}}} = \frac{\dot{m}_B(h_1 - h_4)}{\dot{m}_A(h_6 - h_5) + \dot{m}_B(h_2 - h_1)}$$

$$= \frac{\dot{Q}_{\mathrm{in}}}{\dot{W}_{\mathrm{cA}} + \dot{W}_{\mathrm{cB}}}$$