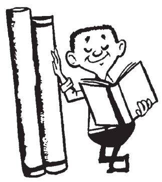
Refrigeration Cycle

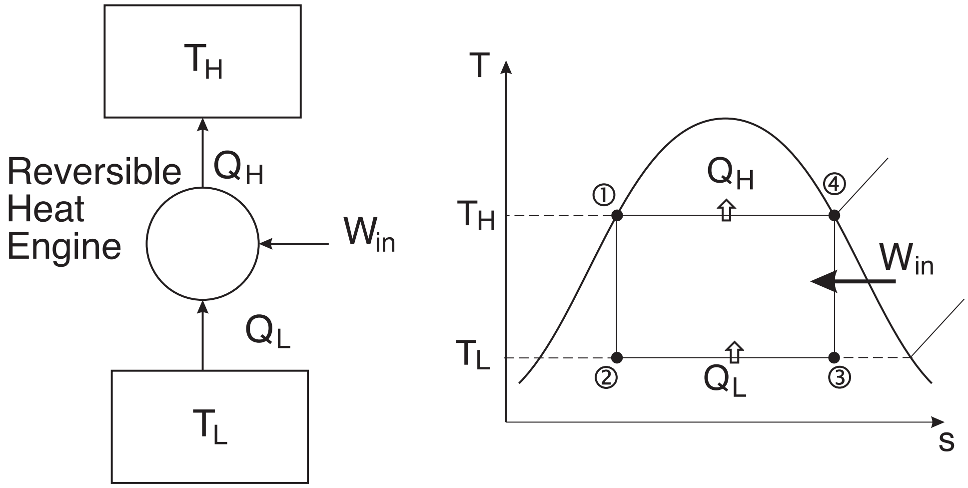


Reading	**Problems**
11-1 → 11-7, 11-9	11-11, 11-44, 11-47, 11-104

Definitions

- a refrigeration system removes thermal energy from a low-temperature region and transfers heat to a high-temperature region.
- the 1st law of thermodynamics tells us that heat flow occurs from a hot source to a cooler sink, therefore, energy in the form of work must be added to the process to get heat to flow from a low temperature region to a hot temperature region.
- refrigeration cycles may be classified as
  - vapour compression
  - gas compression
- we will examine only the vapour compression systems
- refrigerators and heat pumps have a great deal in common. The primary difference is in the manner in which heat is utilized.
  - ***Refrigerator*** $\underbrace{\downarrow C}_{takes\ heat\ from} \rightarrow \underbrace{H}_{transfers\ to}$
  - ***Heat Pump*** $\underbrace{C}_{takes\ heat\ from} \rightarrow \underbrace{H \uparrow}_{transfers\ to}$
- this is simply a change in view point
- the Carnot cycle can serve as the initial model of the ideal refrigeration cycle.
  - operates as a reversed heat engine cycle - transfers a quantity of heat, Q_L, from a cold source at temperature, T_L

$$\begin{aligned} Q_L &= T_L(s_3 - s_2) \\ Q_H &= T_H(s_4 - s_1) \end{aligned}$$



$$W_{in} = Q_{net} = Q_H - Q_L$$
$$= (T_H - T_L)(s_3 - s_2)$$

The coefficient of performance (COP) is given by

$$COP = \frac{benefit}{cost}$$

where the benefit for a refrigeration process is the cooling load given as Q_L. This is the net benefit, i.e. heat is removed from the cold space. For a heat pump, the benefit is the heat added to the hot space, i.e. Q_H.

$$COP_{refrig} = \frac{Q_L}{W_{in}} = \frac{T_L}{T_H - T_L}$$

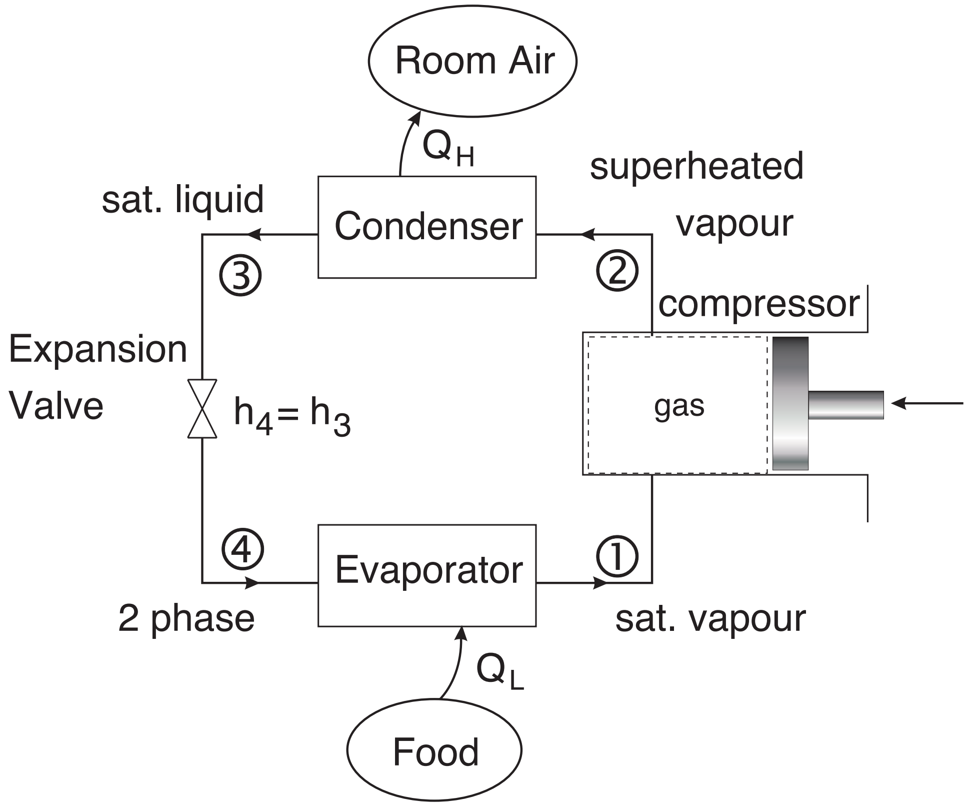
$$COP_{heat\ pump} = \frac{Q_H}{W_{in}} = \frac{T_H}{T_H - T_L}$$

Note:

$$COP_{heat\ pump} = \frac{T_H}{T_H - T_L} = \frac{(T_H - T_L) + T_L}{T_H - T_L} = \frac{T_L}{T_H - T_L} + 1$$
$$= COP_{refrig} + 1$$

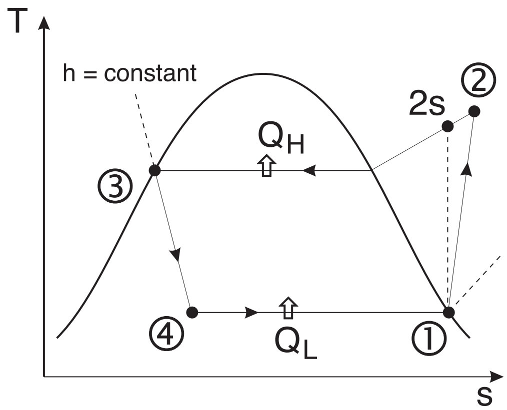
The "1" accounts for the sensible heat addition in going from T_L to T_H.

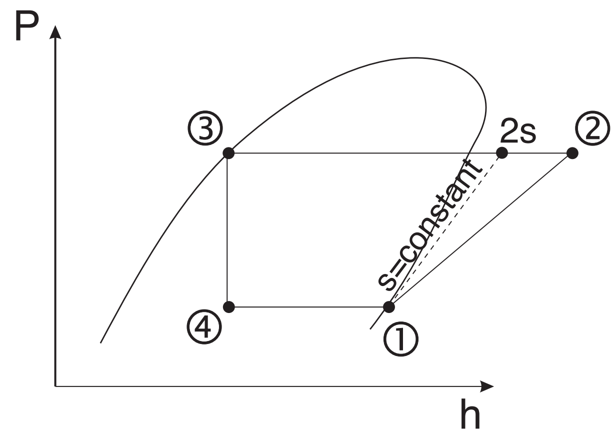
Vapour Compression Refrigeration Cycle



Assumptions for Ideal VCRC

- irreversibilities within the evaporator, condenser and compressor are ignored
- no frictional pressure drops
- refrigerant flows at constant pressure through the two heat exchangers (evaporator and condenser)
- stray heat losses to the surroundings are ignored
- compression process is isentropic





Refrigeration Process

Process	Description
1-2s:	A reversible, adiabatic (isentropic) compression of the refrigerant. The saturated vapour at state 1 is superheated to state 2. $\Rightarrow \quad w_c = h_{2s} - h_1$
2s-3:	An internally, reversible, constant pressure heat rejection in which the working substance is desuperheated and then condensed to a saturated liquid at 3. During his process, the working substance rejects most of its energy to the condenser cooling water. $\Rightarrow \quad q_H = h_{2s} - h_3$
3-4	An irreversible throttling process in which the temperature and pressure decrease at constant enthalpy. $\Rightarrow \quad h_3 = h_4$
4-1	An internally, reversible, constant pressure heat interaction in which the working fluid is evaporated to a saturated vapour at state point 1. The latent enthalpy necessary for evaporation is supplied by the refrigerated space surrounding the evaporator. The amount of heat transferred to the working fluid in the evaporator is called the refrigeration load. $\Rightarrow \quad q_L = h_1 - h_4$

The thermal efficiency of the cycle can be calculated as

$$\eta = \frac{q_{evap}}{w_{comp}} = \frac{h_1 - h_4}{h_{2s} - h_1}$$

Common Refrigerants

There are several fluorocarbon refrigerants that have been developed for use in VCRC.

R11		
R12	CCl_2F_2	dichlorofluoromethane - used for refrigeration systems at higher temperature levels - typically, water chillers and air conditioning
R22	$CHClF_2$	has less chlorine, a little better for the environment than R12 - used for lower temperature applications
R134a	CFH_2CF3	tetrafluorethane - no chlorine - went into production in 1991 - replacement for R12
R141b	$C_2H_3FCl_2$	dichlorofluoroethane
Ammonia	NH_3	corrosive and toxic - used in absorption systems
R744	CO_2	behaves in the supercritical region - low efficiency
R290	**propane**	combustible

How to Choose a Refrigerant

Many factors need to be considered

- ozone depletion potential
- global warming potential
- combustibility
- thermal factors

Ozone Depletion Potential

- chlorinated and brominated refrigerants
- acts as a catalyst to destroy ozone molecules

- reduces the natural shielding effect from incoming ultra violet B radiation

Global Warming Potential

- gases that absorb infrared energy
- gases with a high number of carbon-fluorine bonds
- generally have a long atmospheric lifetime

Combustibility

- all hydro-carbon fuels, such as propane

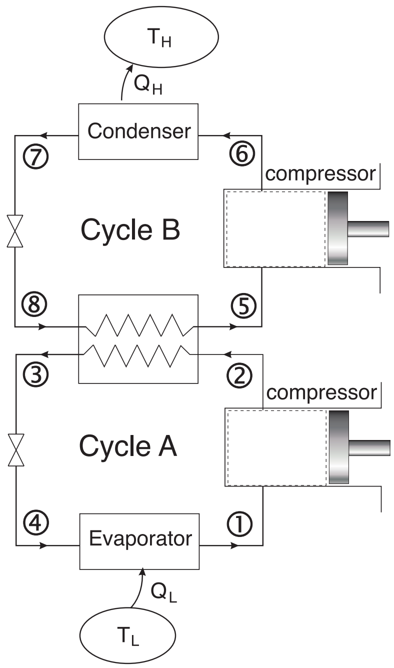
Thermal Factors

- the heat of vaporization of the refrigerant should be high. The higher h_{fg}, the greater the refrigerating effect per kg of fluid circulated
- the specific heat of the refrigerant should be low. The lower the specific heat, the less heat it will pick up for a given change in temperature during the throttling or in flow through the piping, and consequently the greater the refrigerating effect per kg of refrigerant
- the specific volume of the refrigerant should be low to minimize the work required per kg of refrigerant circulated
- since evaporation and condenser temperatures are fixed by the temperatures of the surroundings - selection is based on operating pressures in the evaporator and the condenser
- selection is based on the suitability of the pressure-temperature relationship of the refrigerant
- other factors include:
  - chemical stability
  - toxicity
  - cost
  - environmental friendliness
  - does not result in very low pressures in the evaporator (air leakage)
  - does not result in very high pressures in the condenser (refrigerant leakage)

Designation	Chemical Formula	Ozone Depletion Potential[1]	Global Warming Potential[2]
Ozone Depleting & Global Warming Chemicals			
CFC-11	CCl_3F	1	3,400
CFC-12	CCl_2F_2	0.89	7,100
CFC-13	$CClF_3$		13,000
CFC-113	$C_2F_3Cl_3$	0.81	4,500
CFC-114	$C_2F_4Cl_2$	0.69	7,000
CFC-115	$C_2F_5Cl_1$	0.32	7,000
Halon-1211	CF_2ClBr	2.2-3.5	
Halon-1301	CF_3Br	8-16	4,900
Halon-2402	$C_2F_4Br_2$	5-6.2	
carbon tetrachloride	CCl_4	1.13	1,300
methyl chloroform	CH_3Ccl_3	0.14	
nitrous oxide	N_2O		270
Ozone Depleting & Global Warming Chemicals - Class 2			
HCFC-22	CHF_2Cl	0.048	1,600
HCFC-123	$C_2HF_3Cl_2$	0.017	90
HCFC-124	C_2HF_4Cl	0.019	440
HCFC-125	C_2HF_5	0.000	3,400
HCFC-141b	$C_2H_3FCl_2$	0.090	580
HCFC-142b	$C_2H_3F_2Cl$	0.054	1800
Global Warming, non-Ozone Depleting Chemicals			
carbon dioxide	CO_2	0	1
methane	CH_4	0	11
HFC-125	CHF_2CF_3	0	90
HFC-134a	CFH_2CF_3	0	1,000
HFC-152a	CH_3CHF_2	0	2,400
perfluorobutane	C_4F_{10}	0	5,500
perfluoropentane	C_5F_{12}	0	5,500
perfluorohexane	C_6F_{14}	0	5,100
perfluorotributylamine	$N(C_4F_9)_3$	0	4,300

1 - relative to R11
2 - relative to CO_2

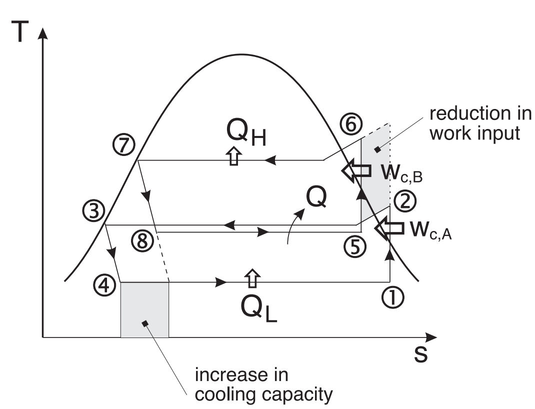
Cascade Refrigeration System



- combined cycle arrangements
- two or more vapour compression refrigeration cycles are combined
- used where a very wide range of temperature between T_L and T_H is required
- the condenser for the low temperature refrigerator is used as the evaporator for the high temperature refrigerator

Advantages

- the refrigerants can be selected to have reasonable evaporator and condenser pressures in the two or more temperature ranges



Absorption Refrigeration System

Differences between an absorption refrigeration system and a VCRC

VCRC	Absorption RS
• vapour is compressed between the evaporator and the condenser • process is driven by work	• the refrigerant is absorbed by an absorbent material to form a liquid solution • heat is added to the process to retrieve the refrigerant vapour from the liquid solution • process is driven by heat

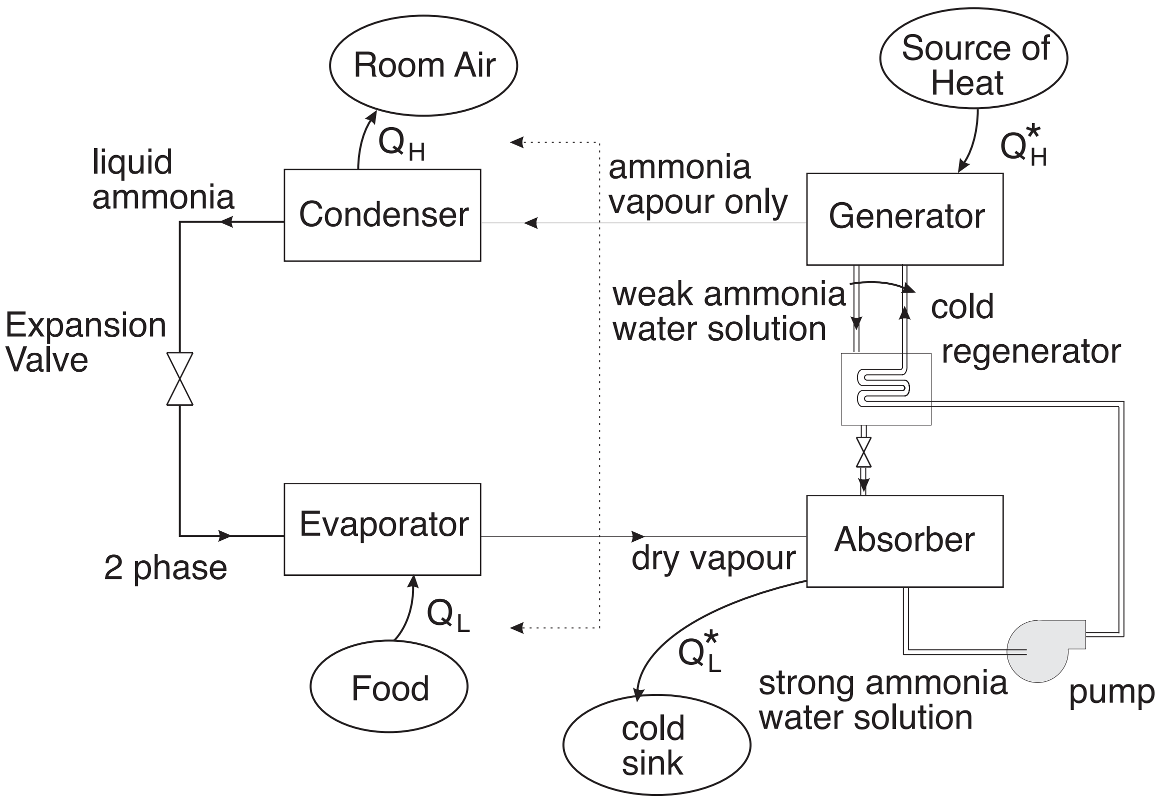
Advantages

- since the working fluid is pumped as a liquid the specific volume is less than that of a gas (as in the VCRC compressor), hence the work input is much less.
- there are considerable savings in power input because a pump is used instead of a compressor.
- this is weighed off against the cost of extra hardware in an absorption system

Common Refrigerant/Absorber Combinations

	Refrigerant	Absorber
1.	ammonia	water
2.	water	lithium bromide lithium chloride

Process



- ammonia circulates through the condenser, expansion valve and evaporator (same as in the VCRC)
- the compressor is replaced by an absorber, pump, generator, regenerator and a valve
- in the absorber, ammonia vapour is absorbed by liquid water
  - the process is exothermic (gives off heat)
  - ammonia vapour is absorbed into the water at low T and P maintained by means of Q^*_L
  - absorption is proportional to $1/T \Rightarrow$ the cooler the better
- the pump raises the solution to the pressure of the generator
- in the generator, ammonia is driven out of the solution by the addition of Q^*_H, (endothermic reaction)
- ammonia vapour is passed back to the condenser
- a regenerator is used to recoup some of the energy from the weak ammonia water solution passed back to the absorber. This energy is transferred to the solution pumped to the generator. This reduces the Q^*_H required to vapourize the solution in the generator. It also reduces the amount of Q^*_L that needs to be removed from the solution in the absorber.