Innovative Refrigeration Systems

Sameer Khandekar
Sir M. Visvesvaraya Chair Professor
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur (UP) 208016 INDIA
Webpage: home.iitk.ac.in/~samkhan/

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

In this presentation…

- Cascade
- Multi-stage
- Multi-purpose

- Liquefaction of gases
- Gas refrigeration cycle

Sameer Khandekar

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

1 Innovative refrigeration systems

Going beyond simple systems

Sameer Khandekar

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Innovative vapor compression refrigeration systems

- The simple vapor-compression refrigeration cycle is the most widely used refrigeration cycle, and it is adequate for most refrigeration applications.
- The ordinary vapor-compression refrigeration systems are simple, inexpensive, reliable, and practically maintenance-free.
- However, for large industrial applications efficiency, not simplicity, is the major concern.
- Also, for some applications the simple vapor-compression refrigeration cycle is inadequate and needs to be modified.

Sameer Khandekar

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Innovative vapor compression refrigeration systems

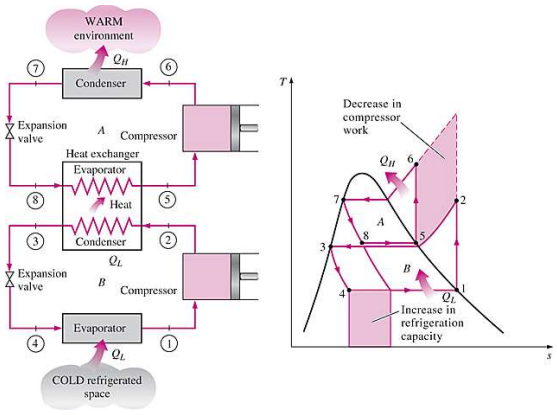
- For moderately and very low temperature applications some innovative refrigeration systems are used.
- Some of these are:
  - Cascade refrigeration systems
  - Multistage compression refrigeration systems
  - Multipurpose refrigeration systems with a single compressor
  - Liquefaction of gases
  - Gas refrigeration systems

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Cascade Refrigeration Systems

- Some industrial applications require moderately low temperatures, and the temperature range they involve may be too large for a single vapor-compression refrigeration cycle to be practical.
- The solution is cascading.



A two-stage cascade refrigeration system with the same refrigerant in both stages.

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

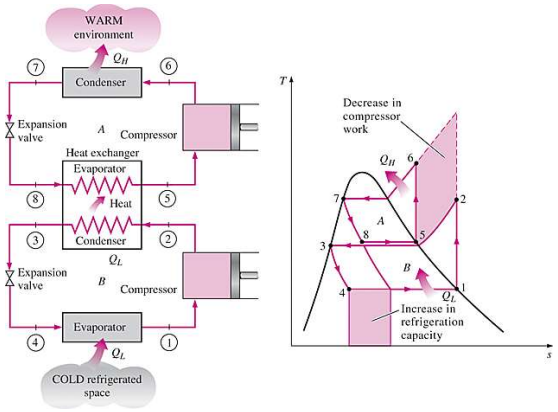
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Cascade Refrigeration Systems

- Cascading improves the COP of a refrigeration system.
- Some systems use three or four stages of cascading.

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

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



A two-stage cascade refrigeration system with the same refrigerant in both stages.

Sameer Khandekar

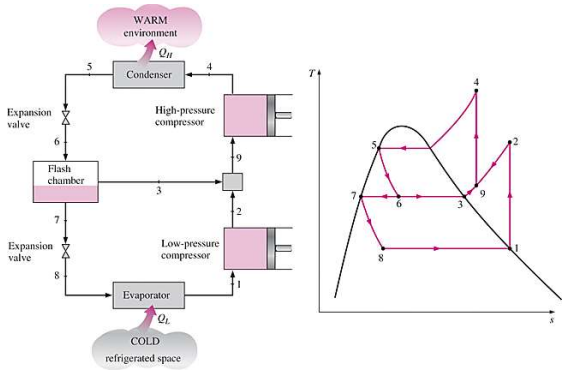
7

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Multistage Compression Refrigeration Systems

- When the fluid used throughout the cascade refrigeration system is the same, the heat exchanger between the stages can be replaced by a mixing chamber (called a *flash chamber*) since it has better heat transfer characteristics.



A two-stage compression refrigeration system with a flash chamber.

Sameer Khandekar

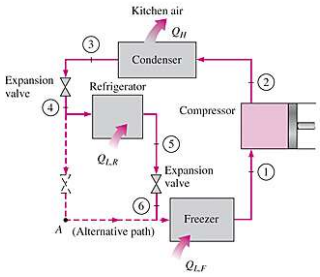
8

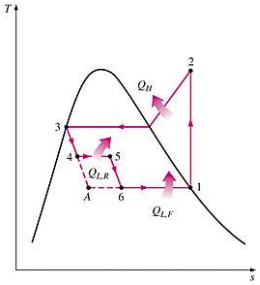
ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Multipurpose Systems with a Single Compressor

- Some applications require refrigeration at more than one temperature.
- A practical and economical approach is to route all the exit streams from the evaporators to a single compressor and let it handle the compression process for the entire system.





Schematic and *T-s* diagram for a refrigerator–freezer unit with one compressor.

Sameer Khandekar

9

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

2 Liquefaction of gases

How gases can be liquified?

Sameer Khandekar

10

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Liquefaction of Gases

- Many scientific and engineering processes at cryogenic temperatures depend on liquefied gases including the separation of O_2 and N_2 from air, preparation of liquid propellants for rockets, study of material properties at low temperatures, and superconductivity.
- The storage (i.e., H_2) and transportation of some gases (i.e., CNG) are done after they are liquefied at very low temperatures.
- Several innovative cycles are used for the liquefaction of gases.

Liquefaction temperatures for some systems

System	CH_4	O_2	Ar	CO_2	N_2	Ne	H_2	He
Liquefaction temperature (K)	111.7	90.1	87.4	81.1	77.3	27.2	20.4	4.2

Sameer Khandekar

11

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Adiabatic expansion of gases

- The adiabatic (no heat exchange) expansion of a gas may be carried out in a number of ways.
- The change in temperature experienced by the gas during expansion depends not only on the initial and final pressure, but also on the manner in which the expansion is carried out.
- Three common methods are
  - dS = 0
  - dU = 0
  - dH = 0

Sameer Khandekar

12

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Adiabatic expansion of gases

- (dS = 0) → If the expansion process is reversible, meaning that the gas is in thermodynamic equilibrium at all times, it is called an isentropic expansion. In this scenario, the gas does positive work during the expansion, and its temperature decreases.
- (dU = 0) → In a free expansion, on the other hand, the gas does no work and absorbs no heat, so the internal energy is conserved. Expanded in this manner, the temperature of an ideal gas would remain constant, but the temperature of a real gas decreases, except at very high temperature.

Sameer Khandekar

13

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Joule-Thomson expansion

- In this method, a gas or liquid at pressure P1 flows into a region of lower pressure P2 without significant change in kinetic energy.
- The expansion is inherently irreversible.
- During this expansion, enthalpy remains unchanged (dH =0).
- Unlike a free expansion, work is done, causing a change in internal energy.
- Whether the internal energy increases or decreases is determined by whether work is done on or by the fluid; that is determined by the initial and final states of the expansion and the properties of the fluid.

Sameer Khandekar

14

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Joule-Thomson coefficient

- The temperature change produced during a Joule–Thomson expansion is quantified by the Joule–Thomson coefficient, μ_{JT}.
- It is defined as the rate of change of temperature T with respect to pressure P, in a Joule-Thomson process (that is, at constant enthalpy H). This coefficient can be expressed in terms of the gas's volume V, its heat capacity at constant pressure Cp., and its coefficient of thermal expansion α.

$$\mu_{\mathrm{JT}} = \left(\frac{\partial T}{\partial P}\right)_H = \frac{V}{C_\mathrm{p}}(\alpha T - 1)$$

- This coefficient may be either positive (corresponding to cooling) or negative (heating).

Sameer Khandekar

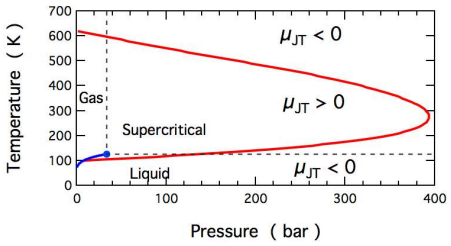
15

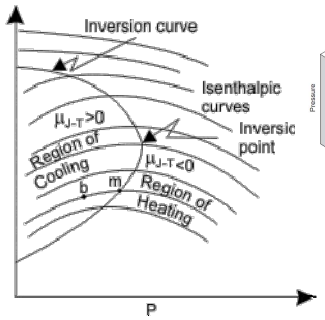
ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

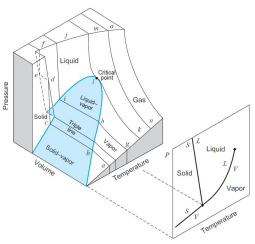
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Example: Nitrogen

- For Nitrogen, the Joule–Thomson coefficient, μ_{JT} is shown in the figure.
- Note that most conditions in the figure correspond to N2 being a supercritical fluid, where it has some properties of a gas and some of a liquid, but can not be really described as being either.
- The coefficient is negative at both very high and very low temperatures; at very high pressure it is negative at all temperatures.







Sameer Khandekar

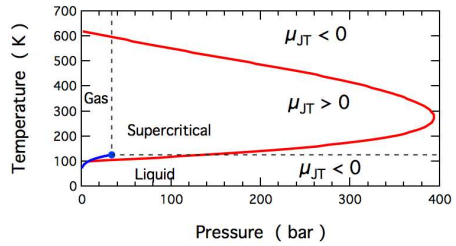
16

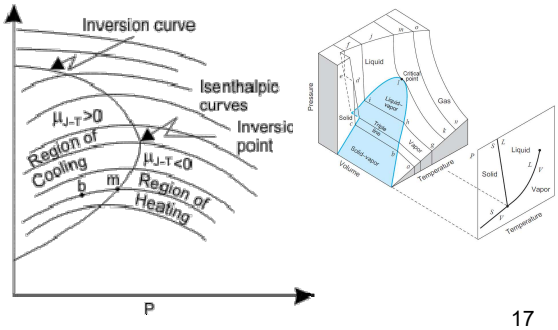
ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Example: Nitrogen

- The maximum inversion temperature (621 K for N_2) occurs as zero pressure is approached. For N_2 gas at low pressures, μ_{JT} is negative at high temperatures and positive at low temperatures.
- At temperatures below the gas-liquid coexistence curve, N_2 condenses to form a liquid and the coefficient again becomes negative. Thus, for N_2 gas below 621 K, a JT expansion can be used to cool N_2 until liquid is formed.



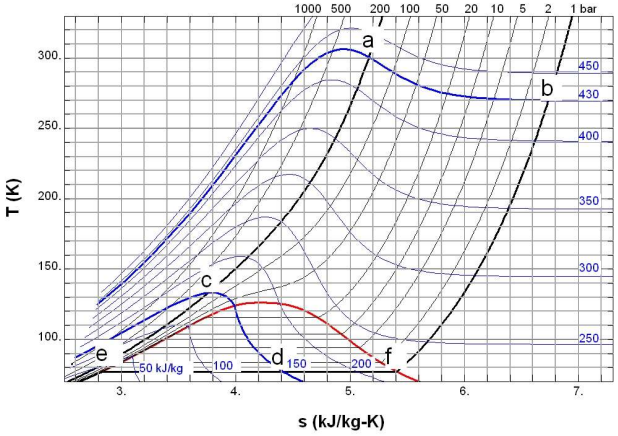


ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Liquefaction of gases (Example: Nitrogen)

- The red dome represents the two-phase region with the low-entropy side (the saturated liquid) and the high-entropy side (the saturated gas). The black curves give the T-s relation along isobars. The pressures are indicated in bar. The blue curves are isenthalps (curves of constant specific enthalpy). The specific enthalpies are indicated in kJ/kg.



T-s diagram of nitrogen.

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Joule-Thomson Effect

- The Joule–Thomson effect (also known as the Joule–Kelvin effect or Kelvin–Joule effect) describes the temperature change of a real gas or liquid (as differentiated from an ideal gas) when it is forced through a valve or porous plug, while keeping it insulated so that no heat is exchanged with the environment.
- At room temperature, all gases except hydrogen, helium, and neon cool upon expansion by the Joule–Thomson process when being throttled through an orifice; these three gases experience the same effect but only at lower temperatures.
- Most liquids such as hydraulic oils will be warmed by the Joule–Thomson throttling process.

Sameer Khandekar

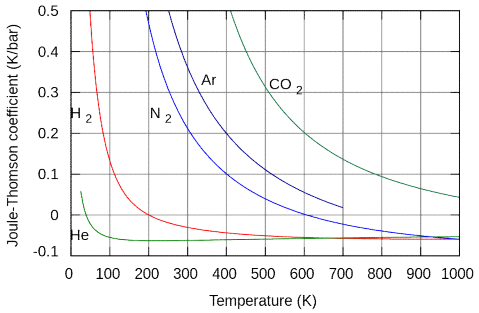
19

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

J-T coefficient of common gases (at atm pressure)

- All real gases have an inversion point at which the value of μJT changes sign.
- The temperature of this point, the Joule–Thomson inversion temperature, depends on the pressure of the gas before expansion.
- In a gas expansion, pressure decreases, so the sign of dP is negative by definition.



If the gas temperature is	then μ_{JT} is	since ∂P is	thus ∂T must be	so the gas
below the inversion temperature	positive	always negative	negative	cools
above the inversion temperature	negative	always negative	positive	warms

Sameer Khandekar

20

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

J-T coefficient of common gases (at atm pressure)

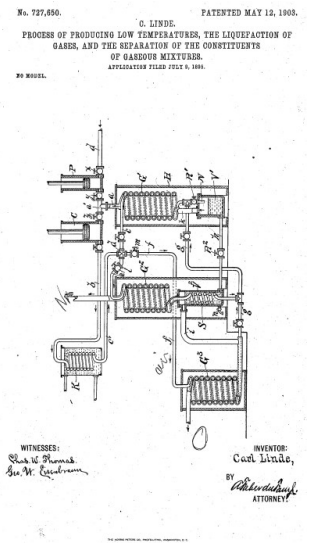
- Helium and hydrogen are two gases whose Joule–Thomson inversion temperatures at a pressure of one atmosphere are very low (e.g., about 45 K (−228 °C) for helium).
- Thus, helium and hydrogen get warm when expanded at constant enthalpy at typical room temperatures.
- On the other hand, nitrogen and oxygen, the two most abundant gases in air, have inversion temperatures of 621 K (348 °C) and 764 K (491 °C) respectively: these gases can be cooled from room temperature by the Joule–Thomson effect.
- For an ideal gas, JT-coefficient is always equal to zero: ideal gases neither warm nor cool upon being expanded at constant enthalpy.

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Linde-Hampson liquefaction system

- The Hampson–Linde cycle is used in the liquefaction of gases, especially for air separation.
- William Hampson and Carl von Linde independently filed for patents of the cycle in 1895: Hampson on May 23, 1895 and Linde on June 05, 1895.
- A gas must be below its inversion temperature to be liquefied by this cycle. For this reason, simple Linde cycle liquefiers, starting from ambient temperature, cannot be used to liquefy helium, hydrogen, or neon.
- However, the J-Teffect can be used to liquefy even helium, provided that the helium gas is first cooled below its inversion temperature of 40 K.

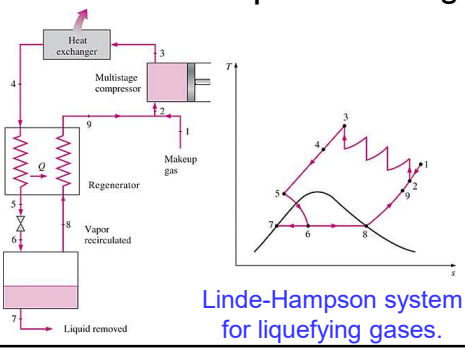

No. 727,650. PATENTED MAY 12, 1903.
C. LINDE.
PROCESS OF PRODUCING LOW TEMPERATURES, THE LIQUEFACTION OF GASES, AND THE SEPARATION OF THE CONSTITUENTS OF GASEOUS MIXTURES.
APPLICATION FILED JULY 9, 1894.
NO MODEL.
WITNESSES:
INVENTOR:
Carl Linde,
BY
ATTORNEY

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

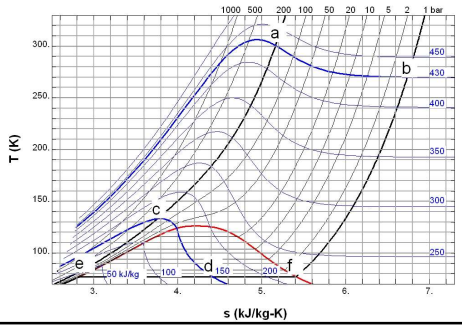
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Linde-Hampson system

- The gas is compressed, which adds external energy into the gas, to give it what is needed for running through the cycle.
- Linde's US patent gives an example with the low side pressure of 25 standard atmospheres and high side pressure of 75 standard atmospheres.



Linde-Hampson system for liquefying gases.

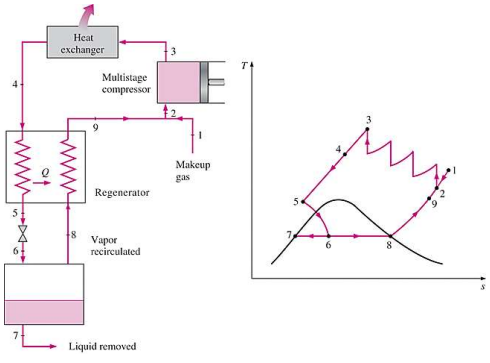


ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Linde-Hampson system

- The high pressure gas is then cooled by immersing the gas in a cooler environment; the gas loses some of its energy (heat). Linde's patent example gives an example of brine at 10°C.
- The high pressure gas is further cooled with a countercurrent heat exchanger; the cooler gas leaving the last stage cools the gas going to the last stage.



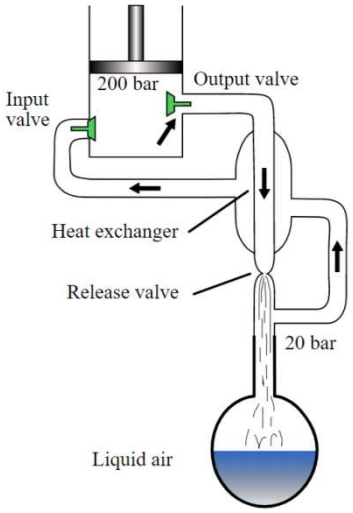
Linde-Hampson system for liquefying gases.

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Linde-Hampson system

- The gas is further cooled by passing the gas through a Joule–Thomson orifice (expansion valve); the gas is now at the lower pressure.
- The low pressure gas is now at its coolest in the current cycle.
- Some of the gas may condense and become output product. (Some method is needed to inject more gas at the compressor to restore the lost mass.)
- The low pressure gas is directed back to the countercurrent heat exchanger to cool the warmer, incoming, high-pressure gas.

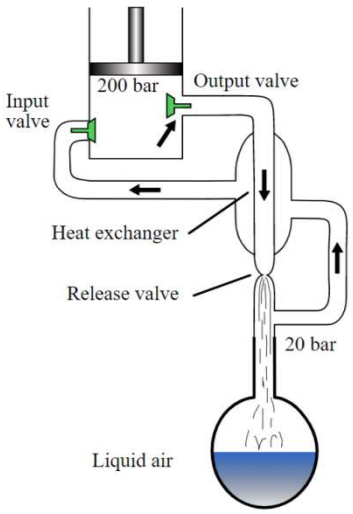


ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Linde-Hampson system

- After leaving the counter-current heat exchanger, the gas is warmer than it was at its coldest, but cooler than it started out at step 1.
- The gas is sent back to the compressor to make another trip through the cycle (and become still colder).
- In each cycle the net cooling is more than the heat added at the beginning of the cycle. As the gas passes more cycles and becomes cooler, reaching lower temperatures at the expansion valve becomes more difficult.



ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

3 Gas Refreigeration Cycle

Refrigeration without phase-change

Sameer Khandekar

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

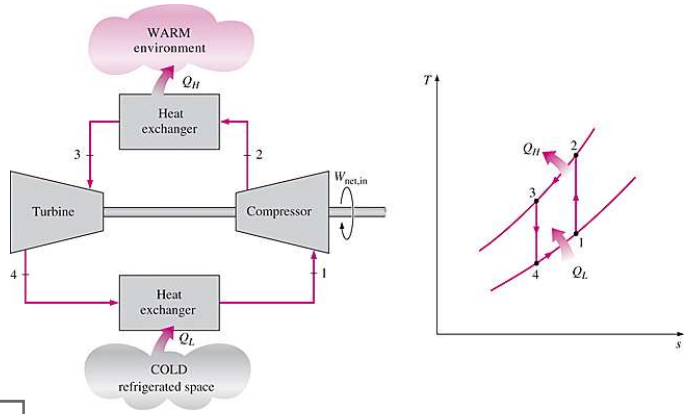
Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Gas refrigeration cycles

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

$$q_L = h_1 - h_4$$
$$w_{\text{turb,out}} = h_3 - h_4$$
$$w_{\text{comp,in}} = h_2 - h_1$$

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



Simple gas refrigeration cycle.

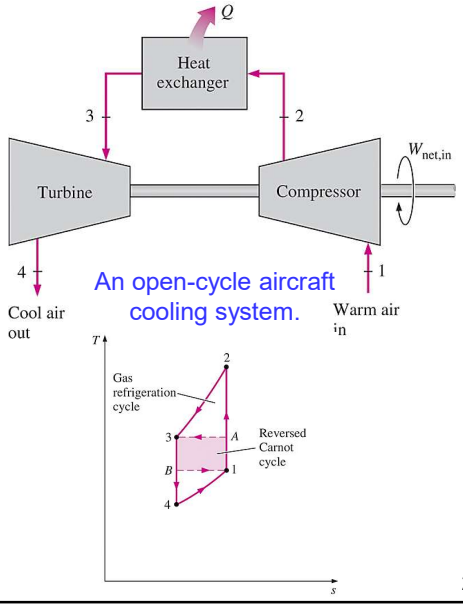
Sameer Khandekar

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Gas refrigeration cycles

- The gas refrigeration cycles have lower COPs relative to the vapor-compression cycles or the reversed Carnot cycle.
- The reversed Carnot cycle consumes a fraction of the net work (area 1*A*3*B*) but produces a greater amount of refrigeration (triangular area under *B*1).
- 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



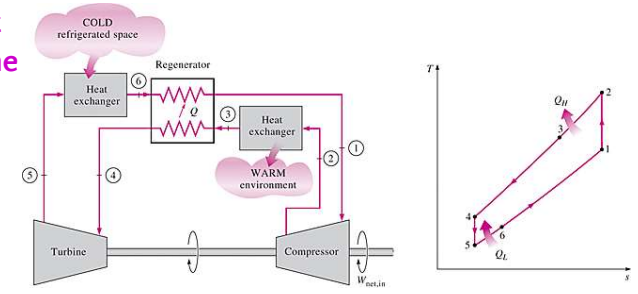
An open-cycle aircraft cooling system.

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Gas refrigeration cycles

- Without regeneration, the lowest turbine inlet temperature is T_0, the temperature of the surroundings or any other cooling medium.
- With regeneration, the high-pressure gas is further cooled to T_4 before expanding in the turbine.
- Lowering the turbine T_{inlet} automatically lowers the turbine T_{exit}, which is the minimum temperature in the cycle.



Gas refrigeration cycle with regeneration.

Extremely low temperatures can be achieved by repeating regeneration process.

ME340A: Refrigeration and Air Conditioning
Instructor: Prof. Sameer Khandekar
Tel: 7038; e-mail: samkhan@iitk.ac.in

Department of Mechanical Engineering
Indian Institute of Technology Kanpur
Kanpur 208016 India

Thanks!

Any questions ?

You can find me at

- samkhan@iitk.ac.in