Lecture 5
Refrigeration & Liquefaction (Part 1)

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Goals

- Introduce basic concepts of cryogenic refrigeration & liquefaction
- Describe the Carnot cycle
- Define Coefficient of Performance and Figure of Merit
- Describe practical helium refrigeration/liquefaction cycles

Introduction How do we get things cold?

- In general, cooling is done by using a working fluid (in cryogenics this is almost always helium) and making it under go a closed thermodynamic cycle that removes heat at low temperature and rejects the heat at room temperature.
  - This process requires work
  - There are many thermodynamic cycles – we will only examine a few key ones
- Here we will concentrate of refrigeration systems of ~ 100 W or greater
  - Systems of less than ~ 100 W are known as cryocoolers and tend to use different cycles. These will be covered in a later lecture

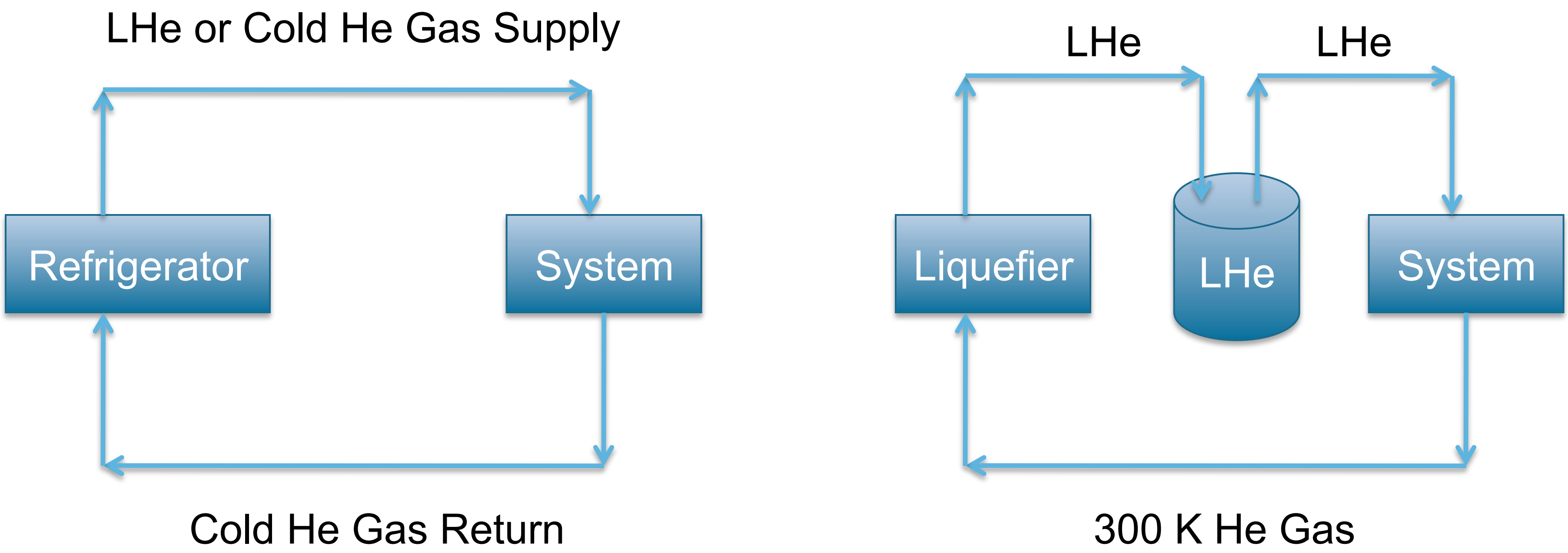
Introduction

- There are other approaches to cooling
  - Non cryogenic refrigeration e.g. home refrigerators, AC etc – not covered here
  - Very low temperature (<1.5 K) approaches : Magnetic refrigerators, adiabatic demagnetization refrigerators, dilution refrigerators etc – will be mentioned (at least) later
- Remember – no matter the technique, the Laws of Thermodynamics apply

Refrigerators vs. Liquefiers

- Refrigerators are closed cycle systems
  - They provide cooling and can create liquids but all the mass flow is returned to the start of the cycle
  - Such systems are said to have "balanced flow"
- Liquefiers are open cycle systems
  - They provide a liquid which is then drawn off and used elsewhere
  - These have "unbalanced flows" the amount of mass returned to the start of the cycle is less than the amount that started by the mass that was converted to liquid.
  - In order to keep the cycle running this mass would have to be added as room temperature gas.

Refrigerators vs. Liquefiers



Closed Cycle Refrigerator

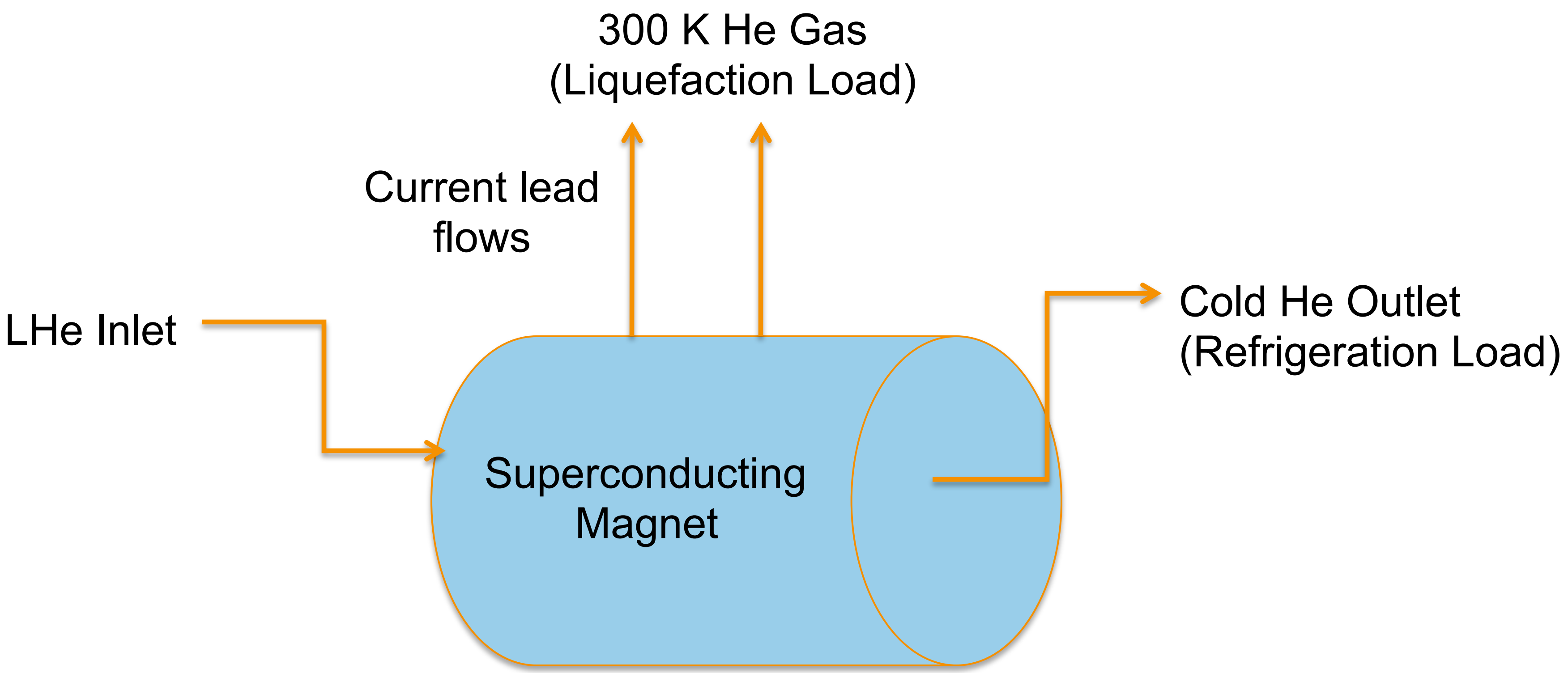
Open Cycle Liquefier

From Helium Cryogenics – Van Sciver

Refrigerators vs. Liquefiers

- In practice, this distinction is less clear cut
  - Modern cryogenic plants can operate either as refrigerators or liquefiers and in fact, generally operate as a mixture of the two.
  - We talk about refrigeration loads & liquefaction loads
  - A key issue is at what temperature is the boil off gas from a cryogenic liquid returned to the cycle?
    - If brought back at a cryogenic temperature and used to cool incoming warmer gas then this is a refrigeration load
    - If brought back warm and not used to cool incoming warmer gas this is a liquefaction load
- The thermodynamic rules are the same for refrigerators and liquefiers

Consider the cooling of a superconducting magnet and its current leads



Catching Cold

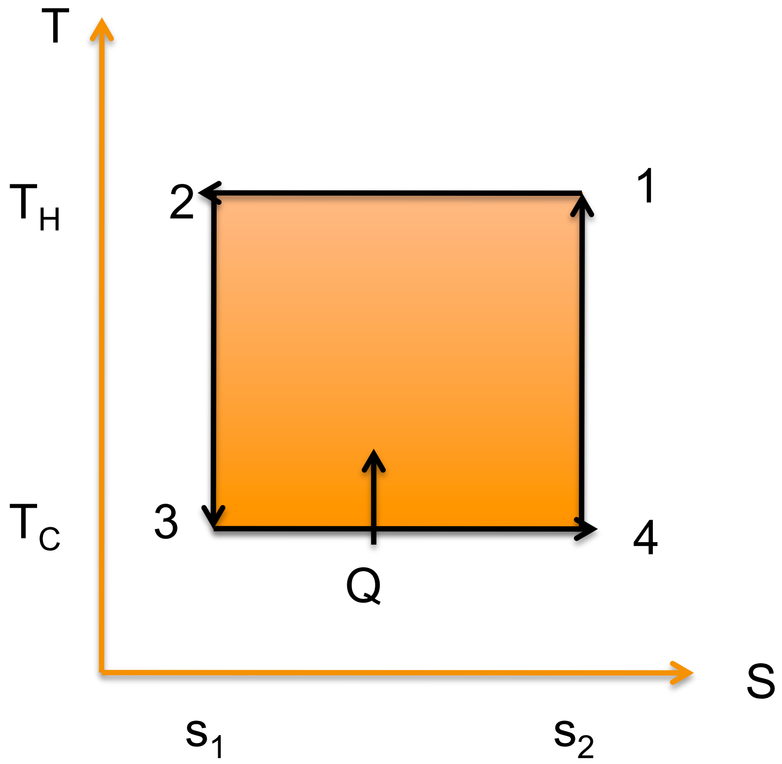
- Before we get involved in thermodynamic cycles, let's go over the basics
- There are really only a few ways in which to make a pure fluid such as helium colder
  - Cause the fluid to do work by making it expand against a piston or turbine while keeping it thermally isolated from the outside environment Isentropic Expansion
  - Transfer heat from the fluid to a colder surface
  - Cause the fluid to do "internal work" by expanding it through a valve while keeping it thermally isolated Isenthalpic Expansion
    - » Joule-Thomson expansion (more later)
  - Once the fluid is a liquid, reduce the pressure above the fluid below atmospheric pressure thus reducing the saturation temperature
- All modern cryogenic plants do the first 3. Ones that provide cooling below 4.2 K also do the last item

Carnot Cycle

- This is an ideal cycle: all processes are reversible
  - Entropy is only changed by absorbing or removing heat at constant temperature
  - 2nd law of Thermodynamics, in a reversible process dQ = -TdS
- The Carnot Consists of 4 steps
  - Compress the working fluid isothermally at T_H (1-2)
  - Expand the working fluid isentropically from T_H to T_C (2-3)
  - Absorb heat into the working fluid isothermally and reversibly at T_C (3-4)
  - Compress the working fluid isentropically from T_C to T_H (4-1)

  - Note isentropically = reversibly and adiabatically

Carnot Cycle



- How do we describe the performance of such a cycle?

Coefficient of Performance & the Carnot Cycle

- Coefficient of Performance: the heat absorbed from the cold sink divided by the net work required to remove this heat

$$\text{COP} = -\frac{Q_a}{W_{net}} = -\frac{\left(Q_a/m\right)}{\left(W_{net}/m\right)}$$

  - Minus sign takes into account that the heat absorbed by the cycle is positive while the work do is negative

- Since this is a closed cycle, the net work done is equal to the net heat transferred. Since this cycle completely reversible, the 2nd law gives the net heat transferred as:

$$Q_{net} = \oint mTds = 0 + mT_C(s_2 - s_1) + 0 + mT_H(s_1 - s_2)$$

Coefficient of Performance & the Carnot Cycle

- Thus

$$Q_{net}/m = W_{net}/m = -(T_H - T_C)(s_2 - s_1)$$

- Again from the 2nd Law:

$$Q_a/m = T_C(s_2 - s_1)$$

- Thus, for the Carnot cycle the COP may be written as:

$$COP = -Q_a/W_{net} = \frac{T_C}{T_H - T_C}$$

• For the Carnot cycle the COP is dependent only on the temperatures

Coefficient of Performance & the Carnot Cycle

- For a plant operating between room 300 K and 4.2 K, the Carnot COP is 4.2/(300 – 4.2) or 0.0142
- The Carnot cycle is the ideal case. It is the best you can do without violating the laws of thermodynamics
- Note that the form of the Carnot COP shows that you have a better COP (thus a more efficient process or refrigerator) if T_C is large
  - It is always thermodynamically more efficient to intercept heat (provide cooling) at higher temperatures
  - This fact drives a lot of cryogenic design
- In practice, we generally discuss the inverse of the COP because this allows us to describe the number of watts of work required to provide 1 Watt of cooling at a given temperature. For a Carnot cycle providing cooling at 4.2 K. This is **70 W/W**
  - People will frequently and incorrectly refer to this as a COP as well

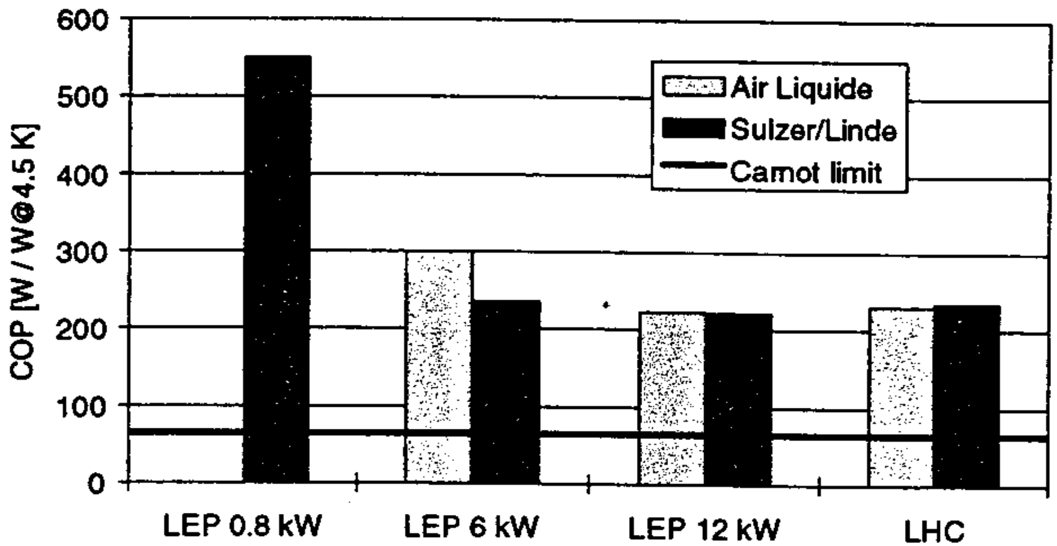
Carnot Cycles & the Real World

- Can we build a real machine using a Carnot cycle?
  - In a word NO
- Why?
  - Compressing a fluid isothermally is very hard to achieve, Normally the fluid is compressed and then cooled back down to 300 K
  - Expanding or compressing fluid isentropically is basically impossible
  - We can absorb heat into a boiling fluid isothermally but not with out irreversible losses
- How close can we get to Carnot? We define the Figure of Merit (FOM) as:

$$FOM = \frac{COP}{COP_{Carnot}}$$

We also speak in terms of "percent Carnot" i.e. FOM of 0.2 is 20% Carnot

The real world is sometimes not kind to cryogenic engineers



- These are state of the art helium refrigerators. Note that the best of them (for LHC) runs at about 220 W/W or a FOM of 0.318 or at 32% Carnot
  - The FRIB refrigerator specification requires that the plant operates at >/= 28% of Carnot

Practical Impact of Plant Performance

- How much power does it take to operate a large cryogenic refrigeration plant?
- AT ESS we expect to have a refrigeration plant capable of removing as much as 9.5 kW at 4.5 K. The FOM of the plant is expected to be 0.26

If the plant operates as expected this means we will need:

(66/0.26) x 9500 = 2.4 MW of mechanical power

- We are adding some additional margin to the electrical power requirements and have asked for at least 2.6 MW available for powering the compressors