PHY695: Cryogenic systems and their design

Homework Set 1

Date handed out

- Aug 26, 2021

Submission due on

- Sept 9, 2021 before 4:30 PM Central Time

Submission procedure

- Prepare homework solutions as a single pdf file named **FirstName_LastName_HW1**
- Email the pdf file to casephy695@gmail.com

Problems

1. Bogolomov-Mayer expansion is commonly used to fit experimental data for constructing virial equation of state for gases. Using Bogolomov-Mayer expansion:
   a. Calculate specific enthalpy, specific entropy, constant pressure specific heat capacity for
      i. Nitrogen, in the temperature range of 150 – 300 K and density of 1.25 kg/m^3
      ii. Argon, in the temperature range of 200 – 300 K and density of 1.75 kg/m^3
      iii. Helium, in the temperature range of 100 – 300 K and density of 0.18 kg/m^3
   b. Obtain all of the above properties from NIST Chemistry Webbook: https://webbook.nist.gov/chemistry/fluid/
   c. Graphically compare the two calculation procedures by plotting the properties as a function of temperature.

2. Normal hydrogen is rapidly liquefied without using a catalyst. Determine the mole fraction of para-hydrogen in the liquid after 24 hours.

3. A Stainless Steel rod with a circular cross section of 15 mm diameter and a length of 3 meters connects room temperature of 300 K to a 5 K heat sink.
   a. Considering only conduction, what is the heat leak from 300 K to 5 K?
   b. What would be the heat leak if the rod is made of OFHC copper?

4. You are required to cool down 1 kg mass of copper starting from room temperature of 300 K. For this purpose, you are given a cryogenic refrigerator with a constant, temperature independent refrigeration capacity of 5 W.
    a. Applying first law of thermodynamics, derive an equation for the cooldown rate of this copper mass
    b. How long will the copper take to cool down from 300 K to 80 K? From 80 K to 5 K? (Hint: Use temperature dependent heat capacity of copper given at https://trc.nist.gov/cryogenics/materials/OFHC%20Copper/OFHC_Copper_rev1.htm)
    c. Plot the specific heat capacity of copper in the temperature range of 5 – 300 K. Based on the shape of this curve, comment on the calculated cooldown times.

5. Consider a stainless steel (SS304) circular rod of diameter 10 mm and length 1 m, rigidly anchored at both its ends. The rod is cooled from 300 K to 30 K, which causes the rod to shrink from thermal contraction.
    a. Estimate the thermal stress in the rod due to this shrinkage. (Hint: Young's modulus and thermal expansion rate of SS304 is available at https://trc.nist.gov/cryogenics/materials/304Stainless/304Stainless_rev.htm)
    b. Suggest a method to mitigate this thermal stress.

6. A helium compressor consumes 600 kW mechanical power to compress 200 g/sec gas from 2.6 bar to 15 bar at 300 K. Assuming helium behaves as an ideal gas, calculate isothermal efficiency of the compressor.

7. Incompressible liquid nitrogen is pumped using a reversible adiabatic process from saturation conditions at 1 bar to 18 bar. Using first law of thermodynamics and the appropriate differential fundamental relation (aka TdS equation), calculate the work input needed for the pumping process. Assume saturated liquid nitrogen density of 807 kg/m^3.

8. Determine Joule-Thompson coefficient for the following:
    a. Helium, 1 atm, 300 K
    b. Helium, 100 atm, 300 K
    c. Helium, 3 atm, 20 K
    d. Helium, 3 atm, 6 K
    e. Nitrogen, 1 atm, 300 K
    f. Which of the above starting conditions will produce cooling *via* an isenthalpic expansion process?