

ENGR 352 – THERMODYNAMICS – SPRING 2018 – FINAL EXAM

Recommendation: Solve two out of the three given problems.

- You have **110 minutes** from the moment that the beginning of the exam is announced.
- This exam consists of three problems. Each is worth up to 25 credits, out of 100 credits for the whole course. At most 35 credits can be gained from the present term exam.
You need to **work on two problems** to achieve an optimal outcome.
- If you **choose to work on two problems**, the problem with the best outcome will count normally (i.e., up to 25 credits), and the other problem will be scaled by a factor of 40% (i.e., up to ten credits), yielding an **optimum total of 35 credits**.
- If you choose to work on all three problems, the outcomes will be ordered by the number of credits achieved. **The best problem counts with a factor of 100%**, and **the second best problem is scaled by a factor of 40%**, yielding up to 35 credits for the exam as a whole. The outcome of the remaining problem does not influence your grade.
- There is also a bonus problem, yielding up to seven credits additionally.

Make sure that **every paper** that you submit contains your **name** and **student ID**. Any access to means of communication is a case of cheating irrespective of what is communicated. It is enough to **turn off your cell phones**. *You absolutely do not need to place your cell phones on the front desk.*

Recall that it is sufficient to **solve two out of the three present exam problems**. Feel free to hand in your submission at any time and leave the room without disturbing the other participants.

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[Problem F1] Sulfur hexafluoride (SF_6), with the critical temperature $T_c = 318.7 \text{ K}$, is considered here at a temperature of 240 K . The saturated vapor pressure at 240 K is 444.4 kPa . The saturated liquid at 240 K has a molar volume of $82.87 \text{ ml mol}^{-1}$, a molar enthalpy of $24.75 \text{ kJ mol}^{-1}$, and a molar entropy of $128.6 \text{ J K}^{-1} \text{ mol}^{-1}$.

- What is the chemical potential of the saturated liquid, and what is the chemical potential of the saturated vapor? (*T is always 240 K here.*)
- At what pressure does fluid SF_6 have a chemical potential that is 1.4 kJ mol^{-1} greater than that of the saturated liquid? Approximate the liquid as incompressible. (*T is always 240 K here.*)
- At what pressure does fluid SF_6 have a chemical potential that is 1.4 kJ mol^{-1} less than that of the saturated vapor? Approximate the vapor phase as an ideal gas.¹ (*T is always 240 K here.*)

For a pure fluid, $\mu = g$, which as a function of p and T has the total differential $dg = v dp - s dT$. Therein, g is the molar Gibbs free energy, $g = G/n$, defined by $G = U + pV - TS$.

[Problem F2] The higher heating value (HHV) of liquid ethanol ($\text{C}_2\text{H}_5\text{OH}$) is 29.67 MJ kg^{-1} .

- Give the chemical reaction equation ("reactants \rightarrow products") for the combustion of ethanol.
- Determine the lower heating value (LHV) of liquid ethanol. Recall that the HHV applies to processes where eventually the water is liquid, the LHV to cases where water is formed as a gas.
- A mass $m = 100 \text{ g}$ of an ideal water-ethanol mixture with the mass fractions 0.54 kg kg^{-1} for water and 0.46 kg kg^{-1} for ethanol is combusted in a piston-cylinder device in which, initially and finally, the pressure is 100 kPa and the temperature is $25 \text{ }^\circ\text{C}$. How much heat is released?
(*There is enough oxygen in the device, and a complete combustion occurs until no ethanol is left.*)

Approximate the gas phase as an ideal mixture of ideal gases.¹ At 298 K and 100 kPa , pure water, pure ethanol, and water-ethanol mixtures are liquid. Ethanol has a molar mass of 46.07 g mol^{-1} ; for water, it is 18.02 g mol^{-1} . At $25 \text{ }^\circ\text{C}$, water has an enthalpy of vaporization of 2.442 MJ kg^{-1} .

[Problem F3] In a reversible Carnot power cycle with 100 g of air as working fluid, to be considered here as an ideal gas¹ with the polytropic exponent $\kappa = c_p/c_v = 1.4$, where $c_p = 3.5 R$, the isothermal compression occurs at a temperature of 250 K ; during this transition, 3.4 kJ of heat are transferred from the working fluid to the surroundings. The isothermal expansion occurs at 300 K . Before the isothermal expansion (*i.e., after the adiabatic compression*), the volume of the fluid is 0.01 m^3 .

- Determine the pressure for each of the four states of the cycle (use numbers to identify them).
- Draw a p - V diagram containing the four states (use the same numbers for the states as above) as well as the four transitions between them (use arrows to indicate the direction).
- Determine the thermal efficiency of the cycle.
- Determine the net work **done to (!)** the fluid as it undergoes this cycle once. The value must be positive if more work is done to the fluid than by the fluid, and negative in the obverse case.

Air has a molar mass of $M = 28.97 \text{ g mol}^{-1}$. A Carnot cycle has two isothermal and two adiabatic transitions. In a reversible Carnot cycle, the ratio of the heats can be determined from the ratio of the temperatures. For a reversible adiabatic transition ($a \rightarrow b$) in an ideal gas, $p_b/p_a = (T_b/T_a)^{c_p/R}$. The work for a reversible isothermal transition ($\alpha \rightarrow \beta$), per mole of ideal gas, is $w_{\alpha\beta} = RT \ln(p_\beta/p_\alpha)$.

Bonus problem: What behavior does the specific isobaric heat capacity, defined by $c_p = (\partial h/\partial T)_p$, exhibit in the vapor-liquid coexistence region, *i.e.*, for thermodynamic states with a quality x greater than 0 and less than 1? **Give a proof.**

(*It is essential to substantiate your claim with a theoretical argument or deduction.*)

¹ Note: $R = 8.3145 \text{ J K}^{-1} \text{ mol}^{-1}$.

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