Please write your name in BLOCK letters. Otherwise Gradescope may not recognize your name.

CIRCLE YOUR LECTURE BELOW:

MWF 10:30 am  MWF 3:30 pm  TR 8:30 am
Prof. Chen  Prof. Meyer  Prof. Jain

EXAM # 2 ME 300 SP2018

INSTRUCTIONS
1. Please place all your electronics, including but not limited to cell phones, computers, watches, tablets, etc., into your bag and store your bag under your seat.
2. The only calculator that is permitted to be used during this exam is the TI-30X IIS basic scientific calculator.
3. This is a closed book and closed notes examination. You are provided with an equation sheet and all the necessary property tables.
4. Do not hesitate to ask the instructor if you do not understand a problem statement.
5. Start each problem on the same page as the problem statement. Write on only the front side of the page. Materials on the back side of the page will not be graded.
6. Put only one problem on a page. Another problem on the same page will not be graded.
7. Identify your system(s), list relevant assumptions, and start with basic equations for Problem 3.
8. If you give multiple solutions, you will receive only a partial credit although one of the solutions might be correct. Cross out any solutions that you do not want to be graded.
9. For your own benefit, please write clearly and legibly. Maximum credit for each problem is indicated below.
10. After you have completed the exam, put your papers in order. This may mean that you have to remove the staple and then re-staple the exam. Do not turn in loose pages.
11. If you use additional blank pages, do not staple on your exam but use clip to hold it together.
12. Once time is called you will have three minutes to turn in your exam. Points will be subtracted for exams turned in after these three minutes.
13. Keep your eyes on your own paper. If you are caught cheating you will get a zero for the exam and your name will be turned over to the Dean of Students.

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Solution Key

Problem 1 (30 points). Each part is 3 points.

Please fill only ONE circle ● for your answer to each problem.

(1) Which is more likely to be found in the products of incomplete combustion of a hydrocarbon fuel, CO or OH?

● CO ○ OH ○ Insufficient Information

*K values of CO equilibrium are greater than K values of OH equilibrium in any temperatures, which means CO is more likely to be found in the products.

(2) The adiabatic flame temperature for a fuel lean combustion reaction is ______ that for the same fuel with 100% theoretical air.

● lower than ○ higher than ○ the same as

The adiabatic flame temperature is the highest at 100% theoretical air.

(3) For a chemical reaction that has reached equilibrium,

○ $dS_{U,V} < 0$ ○ $dS_{U,V} > 0$ ○ $dS_{U,V} = 0$

For equilibrium, $dG = 0 = d(U + TV - TS)_{U,V} = dS_{U,V} = 0$

(4) Consider the stoichiometric reaction $CO_2 \rightleftharpoons CO + 0.5O_2$. What will happen to the moles of $CO_2$ if the pressure doubles under a constant temperature process?

● increases ○ decreases ○ remains the same

Since temperature is constant, $K$ is constant. Therefore, an increase in $P$ will be require an increase in the moles of $CO_2$ based on the equation of reaction equilibrium.

(5) Methane (CH$_4$) burns completely with $x\%$ of theoretical air. The products are subsequently cooled at a pressure of 1 bar. As $x$ increases from 100 to 150, the corresponding dew point temperature

○ increases ○ decreases ○ remains the same

The mole fraction of H$_2$O decreases as the percent of theoretical air increases from 100 to 150. Then, the partial pressure of H$_2$O decreases, which means the dew point temperature decreases.
Problem 1 (Continued)

(6) Consider a two-phase fluid with a positive enthalpy of vaporization \((h_g-h_f)\). The saturation pressure ____________ with increasing temperature.

- Increases
- Decreases
- Remains the same

Consider the Clapeyron equation.

(7) The differential of the Helmholtz function, \(\psi = u - Ts\), is

- \(d\psi = du - s dT\)
- \(d\psi = -p dv - s dT\)
- \(d\psi = du - T ds\)

\(d\psi = du - d(Ts) = du - T ds - s dT = -P dv - s dT\)

(8) Consider a mixture of CO, O\(_2\) and CO\(_2\). Will the equilibrium constant, \(K\), change if the pressure is doubled under a constant temperature process?

- Yes
- No
- Insufficient Information

If temperature is constant, equilibrium constant, \(K\), does not change.

(9) At \(T=3500\) K and \(P=1\) atm, \(\log_{10} K = -7.312\) for \(N_2 \rightleftharpoons 2N\). Then for \(2N \rightleftharpoons N_2\) at the same temperature and pressure, \(\log_{10} K\) is

- \(-1/7.312\)
- \(7.312\)
- \(1/7.312\)

If the direction of equilibrium is switched, \(K\) changes to \(1/K\). Then, it is applied as a negative sign in log scale.

(10) Consider an exothermic equilibrium reaction (i.e. one that releases energy). For this reaction, the equilibrium constant \(K\) ______________ with increasing temperature.

- increases
- decreases
- remains the same

Consider the van’t Hoff equation.
Problem 2 (20 points)

Derive an expression for \( u_2 - u_1 \) for a gas whose equation of state is

\[
(p + \frac{a}{v^2})(v - b) = RT
\]

\[
\Rightarrow P = \frac{RT}{v-b} - \frac{a}{v^2}
\]

\[
\Rightarrow \frac{\partial P}{\partial T} = \frac{R}{v-b}
\]

From the equation sheet,

\[
u_2 - u_1 = \int_1^2 C_v dT + \int_1^2 \left[ T \left( \frac{\partial P}{\partial T} - P \right) \right] dv
\]

\[
u_2 - u_1 = \int_1^2 C_v dT + \int_1^2 \left[ T \left( \frac{R}{v-b} \right) - \left( \frac{RT}{v-b} - \frac{a}{v^2} \right) \right] dv
\]

\[
= \int_1^2 C_v dT + \int_1^2 \left[ \frac{a}{v^2} \right] dv
\]

\[
= \int_1^2 C_v dT + \left[ -\frac{a}{v} \right]_1^2
\]

\[
u_2 - u_1 = \int_1^2 C_v dT - \frac{a}{v_2} + \frac{a}{v_1}
\]

The above should be the final answer, but the following is also acceptable.

By assuming \( C_v \) is constant,

\[
u_2 - u_1 = C_v (T_2 - T_1) - \frac{a}{v_2} + \frac{a}{v_1}
\]
Problem 3 (50 points)

Given:
An inlet stream consisting of 1 kmol/s of H₂, 1 kmol/s of O₂, and 1 kmol/s of N₂ at \( T_1 = 298 \) K and \( P_1 = 10 \) atm enters steadily into a rigid combustor. After combustion and some heat transfer with the surroundings at 298 K, the exhaust stream exits the combustor is at \( T_2 = 1800 \) K and \( P_2 = 10 \) atm. Note that,
\[
\begin{align*}
\bar{h}_{O_2} (1800 \text{ K}, 10 \text{ atm}) &= \bar{h}_{O_2}^o + \bar{h}_O - \bar{h}_{298,O_2} = 51,689 \text{ kJ/kmol} \\
\bar{s}_{O_2} (298 \text{ K}, 10 \text{ atm}) &= 195.020 \text{ kJ/kmol·K} \\
\bar{s}_{O_2} (1800 \text{ K}, 10 \text{ atm}) &= 258.938 \text{ kJ/kmol·K} \\
\bar{h}_{N_2} (1800 \text{ K}, 10 \text{ atm}) &= \bar{h}_{N_2}^o + \bar{h}_N - \bar{h}_{298,N_2} = 48,982 \text{ kJ/kmol} \\
\bar{s}_{N_2} (298 \text{ K}, 10 \text{ atm}) &= 181.492 \text{ kJ/kmol·K} \\
\bar{s}_{N_2} (1800 \text{ K}, 10 \text{ atm}) &= 236.669 \text{ kJ/kmol·K}
\end{align*}
\]

Find:
(a) Each product in the exit stream for complete combustion, in kmol/s
(b) The heat transfer for the complete combustion, in kJ/s
(c) Exergy destroyed for the complete combustion and heat transfer processes, in kJ/s
(d) In reality, NO is also found in the exit stream. Which of the following two sets of chemical compound coefficients in kmol for 1 kmol of H₂ would fit better for the actual reaction? (Please circle one answer you think it is correct. You must show your work to receive credit for this part of problem.)
\[
\begin{align*}
n_{H_2O} &= 1 \quad n_{O_2} = 0.4965 \quad n_{N_2} = 0.9965 \quad n_{NO} = 0.007 \\
n_{H_2O} &= 1 \quad n_{O_2} = 0.4835 \quad n_{N_2} = 0.9835 \quad n_{NO} = 0.033
\end{align*}
\]

Sketch of System/Process:

![Combustion Diagram]

Assumptions:
- Ideal gas
- KE=0
- Open system
- PE=0
- Steady state, steady flow
- No work

Basic equations:
\[
\begin{align*}
\frac{dm_{cv}}{dt} &= \sum \dot{m}_i - \sum \dot{m}_e \\
\frac{dE_{cv}}{dt} &= \dot{Q}_{cv} - \dot{W}_{cv} + \sum \dot{m}_i \left( h + \frac{V^2}{2} + gz \right)_i - \sum \dot{m}_e \left( h + \frac{V^2}{2} + gz \right)_e \\
\frac{dS_{cv}}{dt} &= \frac{\dot{Q}_{cv}}{T_b} + \sum \dot{m}_i S_i - \sum \dot{m}_e S_e + \dot{\sigma}_{CV}
\end{align*}
\]
Problem 3 (Continued)

Solution:
(a) Complete combustion reaction: \( H_2 + O_2 + N_2 \rightarrow n_{H_2O} H_2O + n_{O_2} O_2 + n_{N_2} N_2 \)

Atom balance:
- H: \( 2 = 2n_{H_2O} \) \( \Rightarrow n_{H_2O} = 1 \) or 1 kmol/s for steady flow
- N: \( 2 = 2n_{N_2} \) \( \Rightarrow n_{N_2} = 1 \) or 1 kmol/s for steady flow
- O: \( 2 = n_{H_2O} + 2n_{O_2} \) \( \Rightarrow n_{O_2} = 1 - \frac{n_{H_2O}}{2} = 0.5 \) or 0.5 kmol/s for steady flow

Rewrite complete combustion reaction: \( H_2 + O_2 + N_2 \rightarrow H_2O + 0.5O_2 + N_2 \)

(b) Energy balance:
\[
0 = \dot{Q}_{cv} + \sum \dot{n}_l \bar{h}_l - \sum \dot{n}_e \bar{h}_e
\]
\[
\sum \dot{n}_l \bar{h}_l \bigg|_{298K} = \left[ \frac{1 \text{ kmol}}{s} \times \left( \frac{0 \text{ kJ}}{\text{kmol}} \right) \right]_{H_2} + \left[ \frac{1 \text{ kmol}}{s} \times \left( \frac{0 \text{ kJ}}{\text{kmol}} \right) \right]_{O_2} + \left[ \frac{1 \text{ kmol}}{s} \times \left( \frac{0 \text{ kJ}}{\text{kmol}} \right) \right]_{N_2}
\]
\[
\sum \dot{n}_e \bar{h}_e \bigg|_{1800K} = \left[ \frac{1 \text{ kmol}}{s} \times \left( -241,820 + 72,513 - 9,904 \text{ kJ/kmol} \right) \right]_{H_2O}
+ \left( 0.5 \frac{\text{ kmol}}{s} \times 51,689 \text{ kJ/kmol} \right)_{O_2} + \left( \frac{1 \text{ kmol}}{s} \times 48,982 \text{ kJ/kmol} \right)_{N_2}
\]
\[
= -104,384.5 \frac{\text{kJ}}{s}
\]

Thus, \( \dot{Q}_{cv} = \sum \dot{n}_e \bar{h}_e - \sum \dot{n}_l \bar{h}_l = -104,384.5 \frac{\text{kJ}}{s} \)

(c) Entropy balance:
\[
0 = \frac{\dot{Q}_{cv}}{T_b} + \sum \dot{n}_l \tilde{s}_l - \sum \dot{n}_e \tilde{s}_e + \dot{\sigma}_{CV} \quad \text{where} \quad \tilde{s}_l = \tilde{s}_e - R \ln \left( \frac{P_{yi}}{P_{ref}} \right)
\]
\[
\sum \dot{Q}_{cv} \frac{T_b}{\text{kmol} \cdot K} = -350.284 \frac{\text{kJ}}{s \cdot K}
\]
\[
\sum \dot{n}_l \tilde{s}_l \bigg|_{298K, 10atm} = \left[ \frac{1 \text{ kmol}}{s} \times \left( 130.57 - 8.314 \ln \left( \frac{10 \times 1/3}{1} \right) \frac{\text{kJ}}{\text{kmol} \cdot K} \right) \right]_{H_2}
+ \left( \frac{1 \text{ kmol}}{s} \times 195.020 \frac{\text{kJ}}{\text{kmol} \cdot K} \right)_{O_2} + \left( \frac{1 \text{ kmol}}{s} \times 181.492 \frac{\text{kJ}}{\text{kmol} \cdot K} \right)_{N_2}
\]
\[
= 497.073 \frac{\text{kJ}}{s \cdot K}
\]
Problem 3 (Continued)

\[ \sum \dot{n}_e \delta_e \bigg|_{1800K,10\ atm} = \left[ \frac{1}{s} \times \left( 259.262 - 8.314 \ln \left( \frac{10 \times \frac{1}{2.5}}{1 \ kmol \cdot K} \right) \right) \right]_{H_2O} \\
+ \left( 0.5 \frac{kmol}{s} \times 258.938 \ \frac{kJ}{kmol \cdot K} \right)_{O_2} + \left( 1 \frac{kmol}{s} \times 236.669 \ \frac{kJ}{kmol \cdot K} \right)_{N_2} \\
= 631.875 \ \frac{kJ}{s \cdot K} \]

Thus,

\[ \dot{\bar{\sigma}}_e = - \sum \frac{\dot{Q}_CV}{T_b} - \sum \dot{n}_I \delta_I + \sum \dot{n}_e \delta_e \]

\[ = - \left( -350.284 \ \frac{kJ}{s \cdot K} \right) - 497.073 \ \frac{kJ}{s \cdot K} + 631.875 \ \frac{kJ}{s \cdot K} \]

\[ = 467.086 \ \frac{kJ}{s \cdot K} \]

Therefore,

\[ \vec{E}_d = T_0 \dot{\bar{\sigma}}_e = 298K \times 467.086 \ \frac{kJ}{s \cdot K} \]

\[ \vec{E}_d = 139,192 \ \frac{kJ}{s} \]

(d)

Actual equilibrium combustion reaction:

\[ H_2O + 0.5O_2 + N_2 \rightarrow n_{H_2O}H_2O + n_{O_2}O_2 + n_{N_2}N_2 + n_{NO}NO \]

or \[ 1H_2 + 1O_2 + 1N_2 \rightarrow n_{H_2O}H_2O + n_{O_2}O_2 + n_{N_2}N_2 + n_{NO}NO \]

Equation of reaction equilibrium: \[ 0.5O_2 + 0.5N_2 \Rightarrow NO \]

\[ K = \frac{n_{NO}^{v_{NO}}}{n_{N_2}^{v_{N_2}}n_{O_2}^{v_{O_2}}} \left( \frac{P}{n_T P_{ref}} \right)^{v_{NO}-v_{N_2}-v_{O_2}} \]

\[ = \frac{n_{NO}^{1}}{n_{N_2}^{0.5}n_{O_2}^{0.5}} \left( \frac{10}{n_{H_2O}+n_{NO}+n_{N_2}+n_{O_2}} \right)^{1-0.5-0.5} = \frac{n_{NO}^{1}}{n_{N_2}^{0.5}n_{O_2}^{0.5}} \]

From Table A-27, \( K = 0.01 \)

The first set of chemical composition would satisfy the equation.
Problem 3 (Continued)