Question 2
(9 points)

An 8.55 mol sample of methanol, CH_3OH, is placed in a 15.0 L evacuated rigid tank and heated to 327°C. At that temperature, all of the methanol is vaporized and some of the methanol decomposes to form carbon monoxide gas and hydrogen gas, as represented in the equation below.

$$CH_3OH(g) \rightleftarrows CO(g) + 2\,H_2(g)$$

(a) The reaction mixture contains 6.30 mol of $CO(g)$ at equilibrium at 327°C.

(i) Calculate the number of moles of $H_2(g)$ in the tank.

$6.30 \text{ mol CO} \times \dfrac{2 \text{ mol } H_2}{1 \text{ mol CO}} = 12.6 \text{ mol } H_2$	1 point is earned for the correct number of moles.

(ii) Calculate the number of grams of $CH_3OH(g)$ remaining in the tank.

$6.30 \text{ mol CO} \times \dfrac{1 \text{ mol } CH_3OH}{1 \text{ mol CO}} = 6.30 \text{ mol } CH_3OH \text{ reacted}$ $8.55 \text{ mol } CH_3OH_{\text{initial}} - 6.30 \text{ mol } CH_3OH_{\text{reacted}} = 2.25 \text{ mol } CH_3OH$ $2.25 \text{ mol} \times \dfrac{32.042 \text{ g}}{1 \text{ mol}} = 72.1 \text{ g}$	1 point is earned for the correct number of grams.

(iii) Calculate the mole fraction of $H_2(g)$ in the tank.

$\dfrac{12.6 \text{ mol } H_2}{2.25 \text{ mol } CH_3OH + 6.30 \text{ mol CO} + 12.6 \text{ mol } H_2}$ $= \dfrac{12.6}{21.15} = 0.596$	1 point is earned for the correct setup. 1 point is earned for the correct answer.

(iv) Calculate the total pressure, in atm, in the tank at 327°C.

$PV = nRT \Rightarrow P = \dfrac{nRT}{V}$ $= \dfrac{(21.15 \text{ mol})(0.0821 \frac{\text{L atm}}{\text{mol K}})(600 \text{ K})}{15.0 \text{ L}}$ $= 69.5 \text{ atm}$	1 point is earned for the correct setup. 1 point is earned for the correct answer.

Question 2 (continued)

(b) Consider the three gases in the tank at 327°C: $CH_3OH(g)$, $CO(g)$, and $H_2(g)$.

(i) How do the average kinetic energies of the molecules of the gases compare? Explain.

The average kinetic energies are the same because all three gases are at the same temperature.	1 point is earned for the correct answer and explanation.

(ii) Which gas has the highest average molecular speed? Explain.

$KE = \frac{1}{2}mv^2$, so at a given temperature the molecules with the lowest mass have the highest average speed. Therefore the molecules in H_2 gas have the highest average molecular speed.	1 point is earned for the correct answer and explanation.

(c) The tank is cooled to 25°C, which is well below the boiling point of methanol. It is found that small amounts of $H_2(g)$ and $CO(g)$ have dissolved in the liquid CH_3OH. Which of the two gases would you expect to be more soluble in methanol at 25°C? Justify your answer.

The only attractive forces between molecules of H_2 and CH_3OH would be due to weak London dispersion forces (LDFs). In contrast, the LDFs are stronger between CO molecules and CH_3OH molecules because CO has more electrons than H_2. In addition CO is slightly polar; thus intermolecular dipole-dipole attractions can form between CO molecules and CH_3OH molecules. With stronger intermolecular interactions between molecules of CO and CH_3OH, CO would be expected to be more soluble in CH_3OH than H_2.	1 point is earned for the correct answer and justification.

2A1

2. An 8.55 mol sample of methanol, CH_3OH, is placed in a 15.0 L evacuated rigid tank and heated to 327°C. At that temperature, all of the methanol is vaporized and some of the methanol decomposes to form carbon monoxide gas and hydrogen gas, as represented in the equation below.

$$CH_3OH(g) \rightleftarrows CO(g) + 2\,H_2(g)$$

(a) The reaction mixture contains 6.30 mol of $CO(g)$ at equilibrium at 327°C.

(i) Calculate the number of moles of $H_2(g)$ in the tank.

(ii) Calculate the number of grams of $CH_3OH(g)$ remaining in the tank.

(iii) Calculate the mole fraction of $H_2(g)$ in the tank.

(iv) Calculate the total pressure, in atm, in the tank at 327°C.

(b) Consider the three gases in the tank at 327°C: $CH_3OH(g)$, $CO(g)$, and $H_2(g)$.

(i) How do the average kinetic energies of the molecules of the gases compare? Explain.

(ii) Which gas has the highest average molecular speed? Explain.

(c) The tank is cooled to 25°C, which is well below the boiling point of methanol. It is found that small amounts of $H_2(g)$ and $CO(g)$ have dissolved in the liquid CH_3OH. Which of the two gases would you expect to be more soluble in methanol at 25°C ? Justify your answer.

a)(i) No. of moles of H_2 = 6.30(2)
= 12.6 mols

(ii) No. of moles of CH_3OH = 8.55 - 6.30
= 2.25 mols

Mass of CH_3OH = 2.25(12.01 + 1.008(4) + 16.00)
= 72.1 g

(iii) Total no. of moles = 6.30 + 12.6 + 2.25
= 21.15

Mole fraction of H_2 = $\frac{12.6}{21.15}$
= 0.596

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ADDITIONAL PAGE FOR ANSWERING QUESTION 2

(iv) $P = \frac{nRT}{V}$

$= \frac{21.15(0.0821)(327+273)}{15.0}$

$= 69.5$ atm

b) (i) The average kinetic energies of the three gases are equal, as they are all at the same temperature and would hence have equal amounts of energy.

(ii) H_2 would have the highest molecular speed. As all three gases have equal kinetic energies, and kinetic energy $= \frac{1}{2}(\text{mass})(\text{velocity})^2$, the gas with the lowest mass would have the highest speed, which is H_2.

c) Carbon monoxide.

H_2 molecules can only have dipole-induced dipole interactions with the polar methanol molecules. CO on the other hand is a polar molecule and is able to form stronger hydrogen bonds with the methanol molecules. Hence, carbon monoxide would have higher solubility than hydrogen.

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2B1

2. An 8.55 mol sample of methanol, CH_3OH, is p[...]d to 327°C. At that temperature, all of the methanol is vapo[...]rm carbon monoxide gas and hydrogen gas, as represented

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(a) The reaction mixture contains 6.30 mol of $CO(g)$ at equilibrium at 327°C.

(i) Calculate the number of moles of $H_2(g)$ in the tank.

(ii) Calculate the number of grams of $CH_3OH(g)$ remaining in the tank.

(iii) Calculate the mole fraction of $H_2(g)$ in the tank.

(iv) Calculate the total pressure, in atm, in the tank at 327°C.

(b) Consider the three gases in the tank at 327°C: $CH_3OH(g)$, $CO(g)$, and $H_2(g)$.

(i) How do the average kinetic energies of the molecules of the gases compare? Explain.

(ii) Which gas has the highest average molecular speed? Explain.

(c) The tank is cooled to 25°C, which is well below the boiling point of methanol. It is found that small amounts of $H_2(g)$ and $CO(g)$ have dissolved in the liquid CH_3OH. Which of the two gases would you expect to be more soluble in methanol at 25°C ? Justify your answer.

H–C–O–H H–H CO

(a) $CH_3OH(g) \rightleftarrows CO(g) + 2H_2(g)$

6.30 mol at 327°C = 600K

(i) 6.30 mol $CO(g)$ × $\frac{2 \text{mol } H_2(g)}{1 \text{mol } CO(g)}$ = $\boxed{\therefore 12.6 \text{ mol } H_2}$

(ii) 6.30 mol $CO(g)$ × $\frac{1 \text{mol } CH_3OH}{1 \text{mol } CO}$ = 6.30 mol CH_3OH → remaining CH_3OH = 8.55 mol − 6.30 mol = 2.25 mol.

CH_3OH molar mass = 32.042 g/mol

∴ 2.25 mol × $\frac{32.042 g}{mol}$ = 72.0945

∴ 72.1 g CH_3OH remaining

(iii) $CH_3OH(g) \rightleftarrows CO(g) + 2H_2(g)$

2.25 mol 6.30 mol 12.6 mol

total mole = 2.25 + 6.30 + 12.6 = 21.15

mole f of H_2 = $\frac{H_2 \text{ mol}}{\text{total mol}}$ = $\frac{12.6}{21.15}$ = 0.5957… = 0.596

$\boxed{\therefore 0.596}$

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ADDITIONAL PAGE FOR ANSWERING QUESTION 2

(iv) total pressure = $P_{CH_3OH} + P_{CO} + P_{H_2}$
partial pressure.

$PV = nRT$
$P = \frac{nRT}{V} = \frac{n \cdot 0.0821 \cdot 600}{15.0L} = 3.284n$

3.284 atm

$3.284\left(\frac{2.25}{21.15}\right) + 3.284$

(b) (i) All three molecules have the same average kinetic energies because they are at the same temperature. According to the Kinetic Molecular theory, the average kinetic energy is directly proportional only to the temperature only. it

(ii) H_2 has the highest molecular speed. Molecular speed depends on the mass of the molecule. According to the Graham's Law, lighter the molecule faster its speed. ~~The~~ In this question $H_2 \doteqdot 2g/mol$ $CH_3OH_{(g)} \doteqdot 32g/mol$ $CO_{(g)} \doteqdot 28g/mol$.

(C). I expect $CO_{(g)}$ to be more soluble in methanol at 25°C because CO is polar while H_2 is nonpolar. Since methanol, CH_3OH is polar it is more likely to dissolve another polar substance.

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2C1

$$CH_3OH(g) \rightleftarrows CO(g) + 2\,H_2(g)$$

(a) The reaction mixture contains 6.30 mol of $CO(g)$ at equilibrium at 327°C.

(i) Calculate the number of moles of $H_2(g)$ in the tank.

(ii) Calculate the number of grams of $CH_3OH(g)$ remaining in the tank.

(iii) Calculate the mole fraction of $H_2(g)$ in the tank.

(iv) Calculate the total pressure, in atm, in the tank at 327°C.

(b) Consider the three gases in the tank at 327°C: $CH_3OH(g)$, $CO(g)$, and $H_2(g)$.

(i) How do the average kinetic energies of the molecules of the gases compare? Explain.

(ii) Which gas has the highest average molecular speed? Explain.

(c) The tank is cooled to 25°C, which is well below the boiling point of methanol. It is found that small amounts of $H_2(g)$ and $CO(g)$ have dissolved in the liquid CH_3OH. Which of the two gases would you expect to be more soluble in methanol at 25°C ? Justify your answer.

2. $CH_3OH \rightleftharpoons CO + 2H_2$

(a) 6.30 mol of CO at 327°C

(i) ~~the~~ ratio of produced CO and H_2 is 1 to 2.
Thus, if there are 6.30 mol of CO at equilibrium, there must be 2 x 6.30 mol of H_2. ∴ 12.60 mol

(ii) All the carbon in the product comes from CH_3OH.
This means if there are 6.30 mol of CO, 6.30 mol of CH_3OH were consumed.

	CH_3OH	$\rightleftharpoons$ CO	$+ 2H_2$
Initial	8.55 mol		
Change	−6.30 mol	+6.30mol	+12.60mol
Equilibrium	2.25mol	+6.30mol	+12.60mol

mass of CH_3OH per mole = (4+12+16) g/mol = 32 g/mol

∴ 32 g/mol x 2.25 mol = 72 g

∴ 72g

(iii) mole fraction of H_2 = $\frac{\text{number of moles of } H_2}{\text{total number of moles}}$

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2C2

$= \frac{12.60 \text{ mol}}{(2.25+12.60+6.30) \text{ mol}} = 0.596$ $\therefore 0.596$

(iv) total number of moles (n) = 21.15 mol

Volume = 15.0L

$R = 0.082 \frac{\text{atm}\cdot\text{L}}{\text{mol}\cdot\text{K}}$

$T = (273 + 327)\text{ K} = 600\text{K}$

$PV = nRT$

$P = \frac{21.15 \text{mol} \times 0.082 \frac{\text{atm}\cdot\text{L}}{\text{mol}\cdot\text{K}} \times 600\text{K}}{15\text{L}} = 69.372 \text{ atm}$

$\therefore 69.372$ atm

(b) (i) All three gases are at the same temperature, 327°C.
In this case, by comparing the mass of these three gases, we can also compare the kinetic energies of the molecules. The heavier the molecule, the smaller its kinetic energy. The lighter the molecules, the greater its kinetic energy.

CH_3OH : 72g

CO : 6.30 mol × 28 g/mol = 176.4 g

H_2 : 12.60 mol × 2 g/mol = 25.2 g

$\therefore H_2 > CH_3OH > CO$

(ii)

CH_3OH	:	CO	:	H_2
72g		176.4g		25.2g
~~2.857~~	:	~~7~~	:	~~1~~
1.69	:	2.646	:	1

⇒ the ratio of average molecular speed (the larger the number, the slower it is)

$\therefore H_2$

(c) Polar molecules dissolve well in polar solutions.
Since CH_3OH, methanol, is a polar solution, the polar one of the two gases will be more soluble in methanol.

$:C{=}\ddot{O}:$ vs H−H $\therefore$ CO

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Question 2

Sample: 2A
Score: 9

This response earned all 9 possible points. Part (a) earned 6 points: 1 point in part (a)(i) for determining the correct number of moles of H_2(*g*), 1 point in part (a)(ii) for correctly determining the grams of CH_3OH(*g*) remaining in the tank, 2 points in part (a)(iii) for the correct mole fraction, and 2 points in part (a)(iv) for correctly using all the moles of gas in the tank in the Ideal Gas Law to calculate the final pressure. Part (b) earned 3 points: 1 point in part (b)(i) for appropriately connecting the average kinetic energy of the particles to the temperature, 1 point in part (b)(ii) for discussing of the inverse relationship between a particle's mass and its speed, and 1 point in part (b)(iii) for discussing the types of intermolecular interactions that could occur between the solvent (CH_3OH) and each of the solutes (CO and H_2).

Sample: 2B
Score: 7

Part (a)(iv) earned 1 point for correctly calculating the pressure using the Ideal Gas Law (where *n* represents the moles of gas in the tank) but did not earn the point because of the incorrect calculation of the final pressure. Part (b)(iii) did not earn the point as the response merely paraphrases the adage that *like dissolves like*; although sometimes an appropriate rule-of-thumb, this is neither a justification nor an explanation.

Sample: 2C
Score: 5

Part (a)(iv) earned the setup point, but by expressing the answer with five significant digits the response did not earn the point. Part (b)(i) did not earn the point because the response incorrectly connects the mass of a gaseous particle to its kinetic energy. Part (b)(ii) did not earn the point, even though the answer is correct (H_2), because the explanation suggests that the ordering of the speed of gaseous molecules is inversely proportional to the amount of that material in the sample. Part (b)(iii) did not earn the point because the paraphrase of *like dissolves like* is not an acceptable justification.