Trent University: PHYS 2700H – Thermal Physics 2023 – 2024

Midterm: Monday Feb 12, 2024 **Name:__________________**

Allowed: Formula sheet (given), calculator, 1 hour 50 minutes

PART 1 – answer questions **1-8** in pencil/pen here or in your exam booklet and **then** use your scratch card: one scratch = **100%**; two scratches = **50%**; three scratches = **25%** (part 1 total is 50%)
PART 2 – answer questions **9** & **10** in the exam booklet provided (each question here is worth 25%)

Qu's 1-2) Consider the *isothermal compressibility*, κ_T, of both an ideal gas and a van der Waals gas.

1) Which of the following expressions is the isothermal compressibility of an *ideal gas* in terms of its state variables?

A. nPV/R **B.** $1/nP$ **C.** V/RT **D.** $1/T$ **E.** $1/P$

2) Though derivation, or by employing dimensional analysis and recognizing which state variables scale with the number of moles (called *extensive* variables) and which don't (called *intensive* variables), which of the following expressions might plausibly be κ_T for a van der Waals gas?

A. $\dfrac{nR}{V-nb}$ **B.** $\dfrac{\left(1-\frac{nb}{V}\right)}{P+\frac{2n^2ab}{V^3}}$ **C.** $\dfrac{-nRT}{(V-nb)^2}+\dfrac{2n^2a}{V^3}$ **D.** $\dfrac{\left(1-\frac{nb}{V}\right)}{P-\frac{n^2a}{V^2}+\frac{2n^3ab}{V^3}}$ **E.** $\dfrac{\left(1-\frac{b}{V}\right)}{P-\frac{n^2a}{V^2}+\frac{2n^3ab}{V^3}}$

3) Liquid nitrogen is commonly used in hospitals, and it needs to be kept at $-196\ °\text{C}$. What is the *theoretical maximum* coefficient of performance for a refrigerator that can maintain this temperature if the refrigerator is placed in a room held at $20\ °\text{C}$? [Hint: pick a Carnot refrigerator for this].

A. 0.66 **B.** 0.56 **C.** 0.46 **D.** 0.36 **E.** 0.26

Qu's 4–6: We wish to compare the time taken to boil 1 kg of untreated tap water with the time taken to boil a solution made from 1 kg of tap water with salt *added to it* as per the table below. Assume a heating element with output of $1200\ \text{W}$, that no heat is lost, and there is negligible evaporation. Consider the following values, which we shall assume to remain constant during the heating:

	Untreated tap water	**Tap water with salt added** (concentration $\approx$ that of seawater)
Mass of salt added	0 g salt per kg water	35 g salt per kg water
Density	998 kg/m^3	1025 kg/m^3
Specific heat, c_p	4186 J/kg/°C	3850 J/kg/°C
Boiling point at 1 atm	100 °C	102 °C

4) Based on the table above, what can be concluded about the effect of adding salt to tap water to produce a concentration of approximately that of seawater?

A. The mass *increases* by 3.5% and the total volume *decreases* by $\approx 0.8\%$.
B. The mass stays the same and the total volume *decreases* by $\approx 0.8\%$.
C. The mass *increases* by 3.5% and the total volume *increases* by $\approx 0.8\%$.
D. The mass stays the same and the total volume *decreases* by $\approx 2.7\%$.
E. The mass *increases* by 8% and the total volume *decreases* by $\approx 0.8\%$.

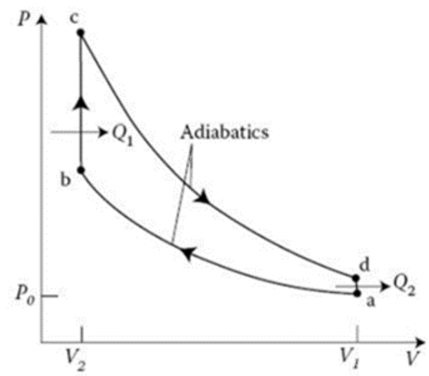
5) How long does it take to bring to a boil 1 kg of *untreated* tap water, starting from a temperature of $22\ ^\circ\text{C}$?

A. 272 s **B.** 256 s **C.** 280 s **D.** 250 s **E.** 278 s

6) How does the time found in Question 5 compare with the time it takes to bring to a boil the solution of water and added salt described in the table, starting from the same temperature?

A. The water/salt solution boils *more slowly*, by between 4 and 8 sec.
B. The water/salt solution boils *more quickly*, by between 4 and 8 sec.
C. The water/salt solution boils *more slowly*, by between 8 and 12 sec.
D. The water/salt solution boils *more quickly*, by between 8 and 12 sec.
E. The water/salt solution boils *more slowly*, by between 0 and 4 sec.

Qu's 7–8: A simplified description of a gasoline engine, with air as the working substance, is shown. By treating air as an ideal diatomic gas, the theoretical efficiency of the engine can be found to be $\eta_{\text{gas}} = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma-1}$, with V_1/V_2 called the *compression ratio*.



7) What is the efficiency of this engine for a compression ratio of 5?

A. 0.47 **B.** 0.54 **C.** 0.68 **D.** 0.86 **E.** 0.92

8) Suppose you wish to write the theoretical efficiency of this gasoline engine in terms of the *temperature* of the air at various points in the cycle. Which of the following is the correct expression for its efficiency?

A. $\eta_{\text{gas}} = 1 - \frac{T_{\text{d}}}{T_{\text{b}}}$ **B.** $\eta_{\text{gas}} = 1 - \left(\frac{T_{\text{a}}}{T_{\text{b}}}\right)^{\gamma-1}$ **C.** $\eta_{\text{gas}} = 1 - \frac{T_{\text{a}}}{T_c}$ **D.** $\eta_{\text{gas}} = 1 - \left(\frac{T_{\text{a}}}{T_{\text{c}}}\right)^{\gamma-1}$ **E.** $\eta_{\text{gas}} = 1 - \frac{T_{\text{a}}}{T_{\text{b}}}$

PART II –answer <u>both</u> questions in the exam booklet provided

9. a) A hypothetical substance has an isothermal compressibility $\kappa_T = an^2/V^2$ and a volume expansion coefficient $\beta = 3nbT^2/V$. By writing the general expression for dV, given that $V(T,P)$, find the equation of state for this substance in the form $f(V,T,P)=0$.

b) Refrigerators are known to make use of the *Joule-Kelvin effect*.

(i) Explain with the help of a diagram what is meant by the Joule-Kelvin effect, and describe how this enables a region of space to be cooled (you need only focus on the Joule-Kelvin part of a refrigerator).

(ii) A van der Waals gas in the low pressure regime satisfies the following:

$$\mu_{\mathrm{JK}} \approx \frac{1}{c_{\mathrm{p}}}\left(\frac{2a}{RT} - b\right)$$

The van der Waals parameters for argon are $a = 0.1358\ \mathrm{Pa\,m^6/mol^2}$ and $b = 3.2\times10^{-5}\ \mathrm{m^3/mol}$. By approximating argon to be an ideal gas for the purposes of finding c_{p}, find μ_{JK} for argon at 300 K in the low pressure regime, and determine how much its temperature would drop due to a pressure decrease of 0.5 atm.

10. a) An ideal gas with adiabatic exponent γ is compressed adiabatically from an initial state (P_i, V_i) to a final state (P_f, V_f). Show that the work done on the gas in this process is

$$W = \frac{P_i V_i}{\gamma - 1}\left[\left(\frac{V_i}{V_f}\right)^{\gamma-1} - 1\right]$$

b) Find the work done on one mole of nitrogen (N_2), initially at $3\ \mathrm{atm}$ and $350\ \mathrm{K}$, if it is compressed to half its volume, assuming it behaves as an ideal gas.