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# Midterm 1

Please fill in your name and student id There is a total of four sections in this exam:

- Section 1. True or false
- Section 2. Fill in the blank
- Section 3. Multiple choice
- Section 4. Short-to-medium length questions

For Section 1-3, you are only graded based on your final answers. For Section 4, you will be graded based on your final answers and showing your work. The exam is closed book, closed notes, and no electronic devices

## List of Equations

An exact differential for a multi-variable function:

$$df = \left( \frac{\partial f}{\partial x_1} \right)_{x_i \neq 1} dx_1 + \dots + \left( \frac{\partial f}{\partial x_j} \right)_{x_i \neq j} dx_j + \dots + \left( \frac{\partial f}{\partial x_m} \right)_{x_i \neq m} dx_m$$

Gibbs phase rule:

$$F = 2 + N_c - N_{\text{ph}}$$

Ideal gas' molar internal energy and enthalpy (both for constant and temperature-dependent heat capacities):

$$u_{ig} = c_v(T) \cdot T; \quad h_{ig} = c_p(T) \cdot T$$

Total energy balance and the 2nd law in Open Systems:

$$0 = \dot{Q} + \dot{W}_s + \sum_{in} \dot{m} \left( \hat{h} + \frac{1}{2}V^2 + gz \right)_{in} - \sum_{out} \dot{m} \left( \hat{h} + \frac{1}{2}V^2 + gz \right)_{out}$$
$$\left( \frac{dS}{dt} \right)_{\text{sys}} + \sum_{out} (\dot{m}\hat{s})_{out} - \sum_{in} (\dot{m}\hat{s})_{in} - \frac{\dot{Q}}{T_{\text{surr.}}} \geq 0$$

Change of entropy in an ideal gas with temperature-independent heat capacity:

$$\Delta s = c_v \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1} = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1} = c_v \ln \left( \frac{P_2}{P_1} \left( \frac{V_2}{V_1} \right)^\gamma \right)$$

where  $\gamma = c_p/c_v$ .

Efficiency of a power cycle and coefficient of performance in refrigeration cycles:

$$\eta = \frac{|W|}{Q_{\text{in}}}; \quad COP = \frac{Q_{\text{in}}}{|W|}$$

Sackur-Tetrode equation for the entropy of an ideal gas:

$$\frac{S}{k_B N} = \ln \left[ \frac{V}{N} \left( \frac{4\pi m U}{3h^2 N} \right)^{3/2} \right] + \frac{5}{2}$$

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Boltzmann entropy formula

$$S = k_B \ln W$$

Combination formula (choosing  $k$ -many things from  $n$ -many things)

$$\binom{n}{k} = \frac{n(n-1)\cdots(n-k+1)}{k(k-1)\cdots 1} = \frac{n!}{k!(n-k)!}$$

Lost work:

$$-W_{\text{lost}} = T_0 \Delta S_{\text{univ.}} = W_{\text{rev.}} + W_{\text{irrev.}} = |W_{\text{rev.}}| - |W_{\text{irrev.}}|$$

Thermodynamic potentials

$$U = TS - PV + \mu N$$

$$A = -PV + \mu N$$

$$H = TS + \mu N$$

$$G = \mu N$$

Fundamental equations of thermodynamics with their thermodynamic potentials:

$$dU = T dS - P dV + \sum_i \mu_i dN_i$$

$$dA = -S dT - P dV + \sum_i \mu_i dN_i$$

$$dH = T dS + V dP + \sum_i \mu_i dN_i$$

$$dG = -S dT + V dP + \sum_i \mu_i dN_i$$

Homogeneity property of thermodynamic potentials:

$$\lambda U(S, V, N) = U(\lambda S, \lambda V, \lambda N)$$

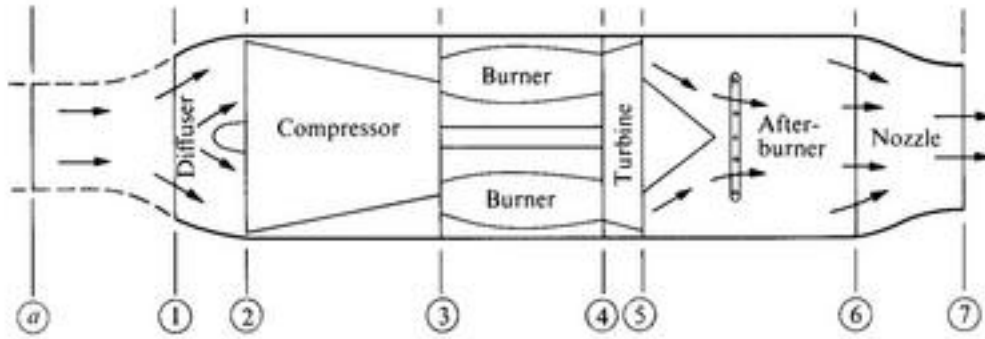
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For grading purposes

Section	Score
1	
2	
3	
4	

## Section 1. 18 questions. 1 point each (True/False)

1. A heat exchanger is an example of a system in equilibrium. **T** **F**
2. In a system at steady state, the pressure must be constant throughout. **T** **F**
3. The Joule expansion process can be represented by a continuous line on the  $P$ - $V$  plane.  
**T** **F**
4. The area inside a cycle traversed counterclockwise in the  $T$ - $S$  plane is net heat out of the system. **T** **F**
5. Any reversible cycle where heat is exchanged only at two temperatures is a Carnot cycle.  
**T** **F**
6. In an irreversible cycle, the entropy of the system (working fluid) increases. **T** **F**
7. In a Joule expansion process (free adiabatic expansion),  $\Delta S_{\text{surr}} = 0$ . **T** **F**
8. A statement of the 2nd law of thermodynamics asserts that it is impossible to transfer heat from a colder body to a warmer one. **T** **F**
9.  $S(U, V, N)$  can always be inverted to solve for  $U(S, V, N)$  **T** **F**
10. The maximum amount of work that can be extracted from a system in a process that takes it from state A to state B is calculated by setting  $S(B) - S(A) = 0$ . **T** **F**
11. As a disordered alloy is cooled to near  $T = 0$ , its entropy approaches 0. **T** **F**
12. If an isolated system is at thermodynamic equilibrium, then its Gibbs free energy must be minimum. **T** **F**
13.  $\left. \frac{\partial T}{\partial V} \right|_S = \left. \frac{\partial P}{\partial S} \right|_V$  **T** **F**
14. In the Joule expansion of a real gas, the internal energy does not change. **T** **F**
15. In the Joule expansion of a real gas, the temperature does not change. **T** **F**



You may refer to this schematic drawing of a turbojet engine for questions 16-22

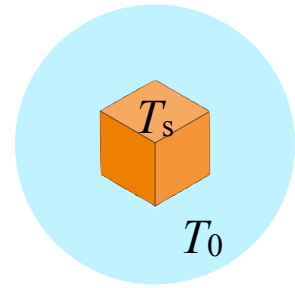
- 16. A sensible engine design could result from switching the position of the compressor and the diffuser. T F
- 17. A sensible engine design could result from switching the position of the turbine and the nozzle. T F
- 18. The only purpose of the turbine in the jet engine drawn in the figure is to power the compressor. T F

Section 2. 12 questions. 1 point each. Please answer in the space provided.

- 19. What design criterion determines the maximum  $T$  of the gas entering the turbine of the jet engine? \_\_\_\_\_
- 20. The jet engine represented in the figure is a practical realization of what cycle?  
\_\_\_\_\_
- 21. If an engine based on the same cycle were used in an electric power generation plant, which two components would be superfluous? \_\_\_\_\_, \_\_\_\_\_
- 22. If an engine based on the same cycle were used in an electric power generation plant, which component would need to be added (that is missing from the design above)?  
\_\_\_\_\_
- 23. How many macroscopic degrees of freedom in an unsaturated solution of  $\text{CaCl}_2$ ? \_\_\_\_\_

24. A power cycle is made up of two isothermal processes (at  $T_H$  and  $T_C$ ) and two isochoric processes. At what temperature(s) is heat rejected in such cycle?  
\_\_\_\_\_

25. In the figure,  $T_s < T_0$ . Can you extract work from the system, and if so, how? \_\_\_\_\_



26. Name a device that lets you transfer heat reversibly across a temperature gradient. \_\_\_\_\_

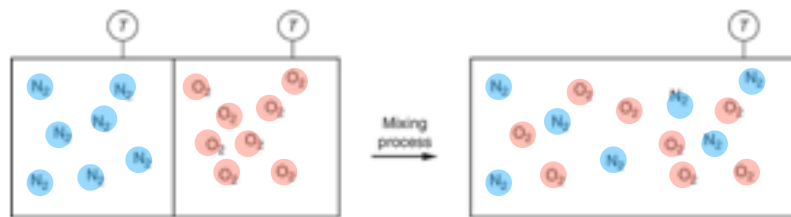
Section 3. 4 questions. 1 point each. Please circle the correct answer.

27. An insulated, empty tank is filled by opening a valve to let in room air. How is the temperature of the air inside the tank after filling? (same, hotter, colder)

28. Given that two cycles have the same areas on the  $T$ - $S$  plane, can you conclude that they have the same efficiency? (yes, no)

29. One liter of  $^{38}\text{Ar}$  at STP is mixed with one liter of  $^{40}\text{Ar}$  also at STP, to produce two liters of Ar at STP. Has entropy increased? (yes, no, depends on  $T$ )

30. One mole of oxygen and one mole of nitrogen are mixed in an isothermal and isobaric process — see figure, where the partition on the left splits the volume in two). What amount of useful work has being missed in the process? ( $2R\ln 2$ ,  $R\ln 2$ ,  $0$ ,  $RT\ln 2$ ,  $2RT\ln 2$ )



**Section 4. Show work and indicate your final answer clearly!***Diffuser Problem* [6 pt]

During a ground-testing of some jet engine, you are responsible for inspecting the diffuser. Air passes through the diffuser with some velocity  $V_1$  and mass flow rate  $\dot{m}$  from the inlet with known pressure and temperature ( $P_1$  and  $T_1$ ) and comes out with some pressure  $P_2$  and velocity  $V_2$ .

(a) Starting from the energy balance equation, derive an equation for the final temperature  $T_2$  coming out of the diffuser. Assume that the air can be treated as an ideal gas with constant heat capacity and that the diffuser is adiabatic. Neglect potential energy effects. Now, relative to the inlet temperature  $T_1$ , will the final temperature  $T_2$  stay the same, decrease, or increase? [3 pt]

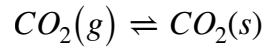
(b) From a molecular perspective, why does the final temperature  $T_2$  stay the same, decrease, or increase [1 pt]?

(c) Starting from the 2<sup>nd</sup> law for an open system, derive an expression for the rate of entropy generation in the universe  $\left(\frac{dS}{dt}\right)_{univ}$  appropriate for the process described in part (a). [1 pt]

(d) Suppose that the air's constant pressure specific heat capacity is linear in temperature, where  $\hat{c}_p = A + BT$ , obtain an equation that will allow you to solve for the final temperature  $T_2$ . Don't solve for it! Just give us the equation in the most compact form. [1 pt]

*Dry Ice Formation* [4 pt]

Dry ice is the solid form of  $\text{CO}_2$ . At atmospheric pressure  $P_{atm}$ , dry ice forms directly from its gas phase at a cold temperature of  $T_s = -78.5^\circ\text{C}$ . The phase change can be written schematically as:



You are interested in forming the dry ice in the lab under isothermal-isobaric conditions (at  $P_{atm}$  and  $T = T_s$ ).

- (a) Assume that the phase change occurred slowly and reversibly. Let the entropy of sublimation be  $\Delta S_{\text{sub}}$ . Write an expression of the latent heat due to sublimation in terms of  $\Delta S_{\text{sub}}$ ; then, state which thermodynamic potential (other than entropy) the latent heat is related to. [2 pt]
- (b) From a molecular perspective, between the gas phase and the crystalline phase, which one has higher entropy? Given the assumption in part (a), what is then the change of entropy in the surroundings? [1 pt]
- (c) Based on your answer in part (a) and/or (b), is dry ice formation an exothermic or endothermic process [1 pt]?