THERMODYNAMICS

1. The Carnot cycle is a totally reversible thermodynamic cycle, with all processes internally reversible. The Carnot cycle is the most efficient cycle, and operates at the Carnot efficiency given by

\[ \eta = 1 - \frac{T_L}{T_H} \]

CARNOT CYCLE
1-2 Reversible adiabatic compression of the working fluid until it reaches the temperature \( T_H \) of the high-temperature reservoir.
2-3 Reversible isothermal expansion during which heat \( Q_H \) is transferred from the high-temperature reservoir \( T_H \) to the working fluid.
3-4 Reversible adiabatic expansion of the working fluid until it reaches the temperature \( T_L \) at the low-temperature reservoir.
4-1 Reversible isothermal compression during which heat \( Q_L \) is transferred from the working fluid to the low-temperature reservoir at \( T_L \).

2. The Rankine cycle incorporates a phase change, and the wet steam leaving the turbine is condensed to a saturated liquid. The compression of the liquid is handled by a pump which isentropically compresses the liquid leaving the condenser to the pressure desired in the heat addition process.

RANKINE CYCLE
1-2 Adiabatic compression to boiler pressure.
2-3 Isobaric heating to boiling point.
3-4 Isobaric, isothermal vaporization into saturated steam.
4-5 Adiabatic expansion into wet steam.
5-1 Isobaric, isothermal condensation.
3. **1st Law:** When a closed system is altered adiabatically, the total work associated with the change of state is the same for all possible processes between the two given equilibrium states. For a closed system, the 1st law describes the conservation of energy of the system when heat and work are the sole mechanisms by which energy is exchanged between the system and surroundings.

\[ Q + W = \Delta E \]

**2nd Law:** Any system having certain specified constraints and having an upper bound in volume can reach from any initial state a stable equilibrium state with no net effect on the environment. A corollary to the 2nd Law, known as the Kelvin-Plank statement, proposes that it is impossible to construct a heat engine which produces no effects other than the exchange of heat from a single source initially in equilibrium and the production of net work output.

**3rd Law:** The entropy of a pure crystalline substance may be taken to be zero at the absolute zero thermodynamic temperature, that is, 0 K or 0° R.

4. Because the refrigerator door is open, the refrigerator cannot be considered a closed system. For the air in the room,

\[ Q + W = \Delta E \]

No work is done externally on or by the air, \( W = 0 \), and since the hot temperature and low temperature reservoirs are the same, there can be no heat transfer, \( Q = 0 \). However, due to inefficiencies the work done by the pump, produces waste heat which is deposited into the insulated room. This waste heat will cause the temperature of the room to rise very slowly over time.

5. Since the tank is open to the environment, the pressure will remain constant. The water is heated up to the boiling point, after which the water will remain at the saturation temperature. The water at the bottom of the tank will be superheated slightly above the saturation temperature. The increase in temperature over time can be expressed graphically as shown below.

6. Superheating increases the overall cycle performance and produces higher exit steam quality, thereby decreasing the liquid fraction in the turbines. The downside is that the shaft work generated per unit mass is decreased.
7. Heat transfer is energy in transit due to a temperature difference. The different types of heat transfer processes are referred to as modes. Heat is transferred from hot to low temperatures described by different rate equations depending upon the mode.

Conduction heat transfer occurs when a temperature gradient exists in a stationary medium that may be a solid or a fluid. Mathematically it is expressed by Fourier’s Law of heat conduction

$$q_x = -k \frac{dT}{dx}$$

where $k$ is the thermal conductivity of the material and $dT/dx$ is the temperature gradient in the direction of heat transport.

Convection heat transfer will occur between a surface at temperature $T_s$ and a moving fluid at bulk temperature $T_\infty$. Newton’s Law of Cooling expresses the heat transfer as

$$q_x = h(T_\infty - T_s)$$

where $h$ is the convection heat transfer coefficient which depends upon the conditions in the boundary layer of the fluid.

Radiative heat transfer occurs because all surfaces of finite temperature emit energy in the form of electromagnetic waves. The net rate of radiation heat exchange between a surface, $T_s$, and its surroundings, $T_{sur}$, is expressed as

$$q_x = \varepsilon \sigma (T_s^4 - T_{sur}^4)$$

where $\varepsilon$ is the emissivity of the material and $\sigma$ is the Stefan-Boltzmann constant.

8. In the parallel flow arrangement the hot and cold fluids enter at the same end, flow in the same direction, and leave the same end. In the counterflow arrangement, the fluids enter opposite ends, flow in opposite directions, and leave at opposite ends. For any heat exchanger, the overall heat transfer depends upon the log-mean temperature difference, $\Delta T_{lm}$ given by

$$q = UA \Delta T_{lm}$$

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$$

For the parallel-flow exchanger

$$\Delta T_1 = T_{hi} - T_{co}$$
$$\Delta T_2 = T_{ho} - T_{ci}$$

For the counter-flow exchanger

$$\Delta T_1 = T_{hi} - T_{co}$$
$$\Delta T_2 = T_{ho} - T_{ci}$$

For the same inlet and outlet temperatures, the log mean temperature difference for counterflow exceeds that for parallel flow. Hence, for similar surface area and the same overall heat transfer coefficient, $U$, the counterflow heat exchanger is more efficient.
9. Assume all the heat transferred from the hot leg goes to the cold leg, and the thermal heat capacity of the fluid in both legs is the same. Then

\[
\begin{align*}
q_{\text{h, out}} &= q_{\text{c, in}} \\
\dot{m}_n c_{p,n} (T_{\text{h, in}} - T_{\text{h, out}}) &= \dot{m}_c c_{p,c} (T_{\text{c, out}} - T_{\text{c, in}}) \\
c_{p,h} &= c_{p,c} \\
\therefore \dot{m}_h &= \frac{\dot{m}_n (T_{\text{c, out}} - T_{\text{c, in}})}{(T_{\text{h, in}} - T_{\text{h, out}})}
\end{align*}
\]

10. Assume that \( V_i < V_{\text{cont}} \) and that the air in the containment building has similar fluid properties before and after the helium mixes and that the containment building is insulated. Then from an energy balance, the energy from the mass of helium in the reactor will mix with the containment environment resulting in a final temperature given by

\[
U_{\text{init}} = U_{\text{final}} \\
\dot{m}_n c_{v,n} T_i + \dot{m}_a c_{v,\text{air}} T_{\text{cont}} = (\dot{m}_n + \dot{m}_a) c_{v,\text{air}} T_f \\
\therefore T_f = \frac{(\rho_n V_i) T_i + (\rho_a V_{\text{cont}}) T_{\text{cont}}}{(\rho_n V_i + \rho_a V_{\text{cont}})}
\]

11. From the Ideal Gas Law, in a constant volume tank

\[
\frac{P_1}{T_1} = \frac{P_2}{T_2} \\
\therefore P_2 = \frac{T_2}{T_1} P_1 = \left(\frac{140 \degree F}{70 \degree F}\right)^2 2000 \text{ psig} = 4000 \text{ psig}
\]

12. Assuming steady-state, one-dimensional heat conduction with uniform energy generation per unit volume, the heat diffusion equation becomes

\[
\frac{d^2T}{dx^2} + \frac{q}{k} = 0
\]

with general solution is

\[
T = -\frac{q}{2k} x^2 + C_1 x + C_2
\]

If the boundary conditions are the same and \( T_{\text{s,1}} = T_{\text{s,2}} = T_s \) then the general solution becomes

\[
T(x) = \frac{q L^2}{2k} \left( 1 - \frac{x^2}{L^2} \right) + T_s
\]

and the centerline temperature \((x=0)\) is

\[
T(0) = \frac{q L^2}{2k} + T_s
\]

which is the maximum temperature in the bar.
13. Enthalpy is heat absorbed by a system at constant pressure with the only work being done by expansion

\[ H = U + PV \]

\[ \Delta H = \Delta U + \int P \, dV \]

14. Entropy is the measure of the irreversibility of a process. It indicates the efficiency of the process. Machine "B" would be preferred as its lower entropy change implies less heat lost to the environment and thus greater efficiency.

15. The addition of heat will increase the internal energy of the gas, causing a temperature increase. By the first law, with constant volume, pressure will increase proportionately with temperature (PV=nRT).

16. Yes, it is possible to have different pressures if the number of moles of gas is different. PV=nRT.

17. The heat needed to raise a 100 lbs of water 23° F is given by

\[ Q = mc_\text{w} \Delta T = (100 \text{ lbs})(1 \text{ BTU/°F - lb})(23° \text{ F}) \]

\[ = 2300 \text{ BTU} \]

In metric units, this is equivalent to 5.8 x 10^5 calories of heat.

18. Temperature is the physical property that determines if two systems are in thermal equilibrium. Heat content is a function of the quantity of heat transferred and depends on internal energy and work done.

19. Assume that temperature is constant throughout each procedure, the gases are inert to each other and behave as ideal gases. The relation between PT and the partial pressures of each gas can be shown using either the Ideal Gas Law or Dalton’s Law of Partial Pressures.

**Ideal Gas Law**

\[ PV = nRT \]

\[ n_T = n_A + n_B + n_C \]

\[ \frac{P_AV_A}{RT} = \frac{P_BV_B}{RT} + \frac{P_CV_C}{RT} \]

\[ V_T = V_A + V_B + V_C \]

\[ \therefore P_T = P_A + P_B + P_C \]

**Dalton’s Law of Partial Pressures**

\[ P_A = x_AP_T, \quad P_B = x_BP_T, \quad P_C = x_CP_T \]

where x is the molar fraction

\[ x_A + x_B + x_C = 1 \]

\[ \frac{P_A}{P_T} + \frac{P_B}{P_T} + \frac{P_C}{P_T} = 1 \]

\[ \therefore P_T = P_A + P_B + P_C \]

20. The triple point is the pressure and temperature at which ice, liquid and water vapor coexist in equilibrium (273.16 K). The region of five ices is to the left and above the triple point in the solid area. C is the critical point, to the right of which the solid and liquid change phase to a vapor only.
21. Work is the product of a force applied over a distance. Thus
\[ W = \int F \cdot dh = W_L \Delta h \]

22. \( ds = 0 \): adiabatic internally reversible process
\( ds < 0 \): is not possible for a closed adiabatic system, or for a composite of systems which interact amongst themselves. Irreversible effects create entropy, however, if there is heat transfer in one subsystem, \( ds < 0 \) may be permissible as long as
\[ \sum ds_{\text{system}} > 0 \]
\( ds_1 < ds_2 \): The entropy is related to the heat transfer and thermal environment by
\[ ds = \int \frac{\delta Q}{T} \]
There is less heat loss if \( T_1 = T_2 \) in the first system, thus the first process is more efficient.

23. From a heat balance across the fluid and material from \( t_1 \) to \( t_2 \)
\[ q_{1i} = q_{2o} = q_{2a} \]
\[ h_i A (T_1 - T_a) = \frac{kA}{L} (T_a - T_b) = h_o A (T_b - T_2) \]
Then the temperature profile across the wall is given by
\[ T(x) = \frac{(T_b - T_a)}{L} x + T_a \]

24. Assume the pressure stays constant at 1 atm.
\[ \Delta H_{\text{ fus}} = 6.02 \text{ kJ/mol} \]
\[ \Delta H_{\text{ vap}} = 40.7 \text{ kJ/mol} \]
\[ c_{p,i} = 4.18 \text{ (J/ } ^\circ \text{ C g)} \]
\[ c_{p,s} = 2.03 \text{ (J/ } ^\circ \text{ C g)} \]

25. Since the ice is frozen, the energy needed to heat the water is the heat of fusion, \( \Delta H_f \), plus the amount of 200° F water necessary to change to water temperature from 32° F to 50° F.
\[ Q = m \Delta H_f + m c_p \Delta T \]
\[ \Delta H_f = 143.16 \text{ BTU/lb}_m \]
\[ c_p = 1 \text{ BTU/lb} \cdot ^\circ \text{ F} \]
\[ Q = (1 \text{ lb})(143.16 \text{ BTU/lb}_m) + (1 \text{ BTU/lb} \cdot ^\circ \text{ F})(50 - 32) \]
\[ Q = 161.16 \text{ BTU} \]
The mass of 200°F water needed to supply this amount of energy is

\[
Q = mc_p \Delta T
\]

\[
161.16 \text{ BTU} = m(1 \text{ BTU/lb } ^\circ\text{F})(200 - 50)
\]

\[
\therefore m = 1.07 \text{ lb}
\]

26. A Mollier diagram is a plot of enthalpy as a function of entropy. Its primary purpose is to facilitate the determination of enthalpy at a specific state. Given two independent variables, the enthalpy can be located on the diagram.