Thermodynamics Qualifying Examination
(Syllabus)

Exam Content: (will be based on material covered in the following courses)
ME 400, Energy Conservation Systems
ME 404, Intermediate Thermodynamics

Exam Topics:
1. Covered in ME 400:
   - Basic property concepts; states (tables, equations of state, charts), processes, cycles, state postulate
   - Work and Heat Transfer Processes
   - First Law of Thermodynamics
   - Entropy concepts and the Second Law of Thermodynamics
   - Component efficiencies and cycle efficiencies
   - Reversible work, availability (exergy), and irreversibility concepts
   - Power and refrigeration cycles
   - Direct energy conversion

2. Covered in ME 404:
   - Maxwell's relations
   - Real gases; equations of state, generalized property charts
   - Gas Mixtures and psychrometrics
   - Chemical potential and partial molal properties
   - Fugacity and ideal solutions
   - Phase equilibrium; Gibbs Phase Rule
   - Dilute solutions
   - Chemical equilibrium and combustion reactions
   - Microstates and macro states
   - Boltzmann relation
   - Statistical models (Maxwell-Boltzmann, Bose-Einstein, Fermi-Dirac)
   - Boltzmann distribution
   - Partition functions and the calculation of thermodynamic properties including contributions from transitional, rotational, vibrational and electronic modes

Reference Textbooks:

QUALIFYING EXAMINATION
FOR
Thermodynamics

Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign

Wednesday, August __, __
9:00 AM – 12:00 PM

IMPORTANT EXAMINATION INFORMATION

1. Identify your examination and work with your University Identification Number (UIN, I-Card number in blue beginning with 65) on each page. **DO NOT ENTER YOUR NAME ANYWHERE IN THE EXAMINATION.**

2. Choose 3 out of the 4 problems.

3. Each problem counts 10 points.

4. Start each problem in a new examination booklet and write on only the right-hand side (front side) of each sheet.

5. Hand in this problem package with your exam booklets.
Problem #1

Calculate the equilibrium ratio $\frac{Y_2}{Y_0}$ at $T = 5000$ K and $P = 100$ kPa for the reaction

$$O_2 \leftrightarrow O$$

where $y_i = N_i/N$ is mole fraction (O-atom weighs 16 amu’s, atomic mass units).

Assume that $O_2$ is a rigid-rotator, harmonic-oscillator, ideal-gas ($PV = NkT$) and use the following molecular/atomic data based on the standard reference state (which takes enthalpy of naturally occurring elements as zero at 25°C).

<table>
<thead>
<tr>
<th>Molecule</th>
<th>$T_{\text{rot}}$</th>
<th>$T_{\text{vib}}$</th>
<th>$D/\text{hc (cm}^3\text{)}$</th>
<th>Term</th>
<th>$\epsilon/\text{hc (cm}^3\text{)}$</th>
<th>$g_{\text{elec}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$O_2$</td>
<td>2.08 K</td>
<td>2274 K</td>
<td>41,260</td>
<td>$^3\Sigma$</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^1\Delta$</td>
<td>7882</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$^1\Sigma$</td>
<td>13,121</td>
<td>1</td>
</tr>
</tbody>
</table>

O-atom

<table>
<thead>
<tr>
<th>Term</th>
<th>$\epsilon/\text{hc (cm}^3\text{)}$</th>
<th>$g_{\text{elec}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3P_2$</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>$^3P_1$</td>
<td>158.5</td>
<td>3</td>
</tr>
<tr>
<td>$^3P_0$</td>
<td>226.5</td>
<td>1</td>
</tr>
<tr>
<td>$^1D_2$</td>
<td>15,867.7</td>
<td>5</td>
</tr>
</tbody>
</table>

Helpful Relations:

**Partition Function**

$$Z = \sum_j g_j \exp(-\epsilon_j/kT)$$

$$Z_{\text{vib}} = \sqrt[3]{\frac{2\pi m k T}{\hbar^2}}$$

$$Z_{\text{rot}} = \frac{1}{\sigma} \left(\frac{T}{T_{\text{rot}}}\right) \quad \text{for } T \gg T_{\text{rot}}.$$  

$$Z_{\text{vib}} = \frac{1}{1 - \exp(-T_{\text{vib}}/T)} \quad \text{[zero-point energy at } v = 0\text{]}$$
For the reaction: \[ v_A A + v_B B \leftrightarrow v_C C + v_D D \]

\[
\frac{N_C^{y_C} N_D^{y_D}}{N_A^{y_A} N_B^{y_B}} = \frac{Z_C^{y_C} Z_D^{y_D}}{Z_A^{y_A} Z_B^{y_B}} \exp(-\epsilon_R/kT)
\]

where the \( Z \)'s are relative to \( v = 0 \) state and

\[
\epsilon_R = v_A D_{0A} + v_B D_{0B} - v_C D_{0C} - v_D D_{0D}
\]

**Constants and Conversion Factors**

1 amu = \( 1.67 \times 10^{-27} \) kg (proton or neutron mass)

\[
\bar{R} = 8.314 \frac{J}{(\text{mole})(K)}
\]

\[
c = 2.998 \times 10^8 \frac{m}{sec} = 2.998 \times 10^{10} \frac{cm}{sec}
\]

\[
h = 6.626 \times 10^{-34} J - sec
\]

\[
k = 1.38062 \times 10^{-23} J/K
\]

\[
hc/k = 1.4388 \text{ cm-K}
\]
Problem #2

Two rigid tanks (A and B), each of volume 1 m$^3$, are connected by a valve. Initially each tank contains air at ambient temperature (300 K) with 200 kPa in tank-A and 100 kPa in tank-B (state-1). The valve is opened wide, left open long enough for pressure to equilibrate between the two tanks, and then quickly closed again (state-2). The air in the tanks eventually comes to ambient temperature again (state-3) due to heat transfer with the surroundings. Making whatever assumptions you think reasonable, find the following.

(a) State-2: pressure and temperature in each tank.

(b) State-3: pressure and mass in each tank.

(c) Discuss briefly if one tank ends up with more mass than the other and why or why not.

(Properties for air at near ambient temperature: $R = 0.287$ kJ/kg⋅K, $C_p = 1.0$ kJ/kg⋅K, $k = 1.4$)
T.3 An ideal gas of molecular weight \( M \) and constant specific heat \( c_p \) (mass basis) is at absolute pressure \( P_1 \) and absolute temperature \( T_2 \) in a vessel of volume \( V \) as shown below. At time \( t = 0 \), the valve is opened and the gas discharges to the atmosphere until equilibrium is reached. The entire process is adiabatic and frictionless.

(a) Draw the control volume and write the governing equations (First and Second Law of Thermodynamics) for this process. Ignore kinetic and potential energy.

(b) Use the constant-\( c_p \), ideal-gas property model to obtain an algebraic expression for the final temperature \( T_2 \) in the vessel.

Figure T.3 Ideal Gas in Closed Container.
T.4 A simple Rankine-cycle, steam power plant operates with a condenser pressure of 1 psia and a boiler pressure of 800 psia. Water exits the condenser as saturated liquid. Steam exits the boiler as superheated vapor at 800 °F. The pump and turbine both have an isentropic efficiency of 80 % and are well insulated so that heat transfer to the environment is negligible. The total mass flow rate of steam in the cycle is 10^6 lb/hr.

(a) Determine the temperature, pressure, quality, enthalpy and entropy of the flow at the following four flow points (1) inlet to the pump, (2) inlet to the boiler, (3) inlet to the turbine, and (4) inlet to the condenser.

(b) Determine the net power output of the cycle, the rate of heat addition in the boiler, and the cycle efficiency. Neglect kinetic and potential energy.

A table of properties along the 1 psia and 800 psia isobars is given below. Liquid water may be treated as incompressible with ρ = 62 lb/ft^3 and cp = 1 Btu/lb-R. 1 Btu = 778 ft-lb.
### Table T.4  Enthalpy and Entropy of Steam along Two Isobars.

<table>
<thead>
<tr>
<th></th>
<th>P = 1 psia isobar</th>
<th></th>
<th>P = 800 psia isobar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T [°F]</td>
<td>h [Btu-lb\text{m}]</td>
<td>s [Btu-lb\text{m}-R]</td>
</tr>
<tr>
<td>101.71</td>
<td>69.72</td>
<td>0.03291</td>
<td>0 (sat)</td>
</tr>
<tr>
<td>110</td>
<td>1105.36</td>
<td>1.97739</td>
<td>1 (sat)</td>
</tr>
<tr>
<td>120</td>
<td>1113.67</td>
<td>1.99196</td>
<td>1</td>
</tr>
<tr>
<td>130</td>
<td>1118.20</td>
<td>1.99970</td>
<td>1</td>
</tr>
<tr>
<td>140</td>
<td>1122.73</td>
<td>2.00731</td>
<td>1</td>
</tr>
<tr>
<td>150</td>
<td>1127.25</td>
<td>2.01408</td>
<td>1</td>
</tr>
<tr>
<td>160</td>
<td>1131.78</td>
<td>2.02217</td>
<td>1</td>
</tr>
<tr>
<td>170</td>
<td>1136.31</td>
<td>2.02941</td>
<td>1</td>
</tr>
<tr>
<td>180</td>
<td>1140.84</td>
<td>2.03655</td>
<td>1</td>
</tr>
<tr>
<td>190</td>
<td>1145.37</td>
<td>2.04357</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>1149.90</td>
<td>2.05050</td>
<td>1</td>
</tr>
<tr>
<td>210</td>
<td>1154.43</td>
<td>2.05732</td>
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<tr>
<td>220</td>
<td>1158.97</td>
<td>2.06405</td>
<td>1</td>
</tr>
<tr>
<td>230</td>
<td>1163.51</td>
<td>2.07068</td>
<td>1</td>
</tr>
<tr>
<td>240</td>
<td>1168.06</td>
<td>2.07722</td>
<td>1</td>
</tr>
<tr>
<td>250</td>
<td>1172.61</td>
<td>2.08368</td>
<td>1</td>
</tr>
<tr>
<td>260</td>
<td>1177.16</td>
<td>2.09005</td>
<td>1</td>
</tr>
<tr>
<td>270</td>
<td>1181.72</td>
<td>2.09635</td>
<td>1</td>
</tr>
<tr>
<td>280</td>
<td>1186.29</td>
<td>2.10256</td>
<td>1</td>
</tr>
<tr>
<td>290</td>
<td>1190.86</td>
<td>2.10870</td>
<td>1</td>
</tr>
<tr>
<td>300</td>
<td>1195.43</td>
<td>2.11476</td>
<td>1</td>
</tr>
</tbody>
</table>
\[
\begin{align*}
K(T) &= \text{equilibrium constant} = \exp\left(-\frac{\Delta G}{RT}\right) = \frac{P_{eq}}{P} \frac{\sum_{i=0}^{n} v_{i} \gamma_{i}}{n_{A} v_{A}} \\
\text{phase equilibrium:} \quad \Delta_{p} = \Delta_{g}
\end{align*}
\]

\[
g = 9.80665 \text{ m/s}^2, \quad R = 8.31441 \text{ kJ/K mol}, \quad R = 8.31441 \text{ kPa m}^3/\text{K mol K}, \quad R_{\text{Btu}} = 1.98546 \text{ Btu/K mol K}
\]

\[
\text{MWs (kg/kmol) = lbm/mol):} \quad H = 1.00704 \quad C = 12.011 \quad N = 14.0067 \quad O = 15.9994 \quad S = 32.06 \quad \text{H}_2\text{O} = 18.01529 \quad \text{CO}_2 = 44.0098 \quad \text{Air = 28.9645}
\]

\[
\gamma_{a} = 3.76 \text{ kmol N}_2 / \text{kmol O}_2 \quad M_{\text{Btu}} / M_{\text{H}_2\text{O}} = 0.6521998 \text{ kg H}_2\text{O} / \text{kg air} \quad M_{\text{Btu}} / M_{\text{CO}_2} = 1.6078 \text{ kg H}_2\text{O} / \text{kg air}
\]

**UNIT CONVERSIONS**

1 in. = 25.4 mm 
1 ft = 12 in. = 0.3048 m 
1 yd = 36 in. = 0.9144 m 
1 mile = 5280 ft = 1609.344 m 
1 nautical mile = 1852 m

1 ft³ = 144 in³ 
1 cm³ = 439.56 ft³ 
1 ft³ = 1728 in³ = 7.4805 gal 
1 liter = 0.001 m³ = 63.8233 lbs 
1 gal = 231 in³ = 128 fl. oz 
1 cm³/gm = 0.001 m³/kg 
1 gm/cm³ = 1000 kg/m³ = 62.4209 lbs 
1 lb = 453.60 ft³ 
1 m³ = 35.31 ft³ 
1 lb/hr = 453.60 ft³

1 atm = 101.325 kPa 
1 psi = 6894.76 Pa 
1 bar = 101.325 kPa 
1 bar = 0.986923 lb/in² 
1 m/s = 3.2808 ft/s 
1 ft/s = 0.3048 m/s

\[
T [\text{K}] = 1.8 \times [\text{°C}] + 32 \\
T [\text{°F}] = 32 + \frac{9}{5} T [\text{°C}] \\
T [\text{°R}] = 5 \times [\text{°F}] - 459.67
\]

\[
\frac{dP}{dV} = \frac{P_{\text{vap}}}{P_{\text{cond}}} = \frac{P_{\text{cond}}}{P_{\text{vap}}} = \frac{P_{\text{cond}}}{P_{\text{vap}}}
\]

**PROPERTY MODELS**

**Incompressible Substance Model (liquids)**

\[\mathbf{K} = 0 \quad \mathbf{\alpha = 0} \quad \mathbf{\zeta = c_{p}} \quad \mathbf{\kappa = 1}\]

**Isentropic Process:**

\[\mathbf{\gamma = 0} \Rightarrow \mathbf{T} = \mathbf{v} = \mathbf{u} = \mathbf{p} \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Volume</th>
<th>Internal Energy</th>
<th>Entropy</th>
<th>Entropy</th>
</tr>
</thead>
</table>
| Saturated Liquid Table | \(v(T, P) = v(T)\) | \(u(T, P) = u(T)\) | \(h(T, P) = h(T) + p v(T)\) | \(s(T, P) = s(T)\)

**Saturated Mixture Model (liquid/vapor mixtures)**

\[P = P_{\text{sat}}(T) \quad T = T_{\text{sat}}(P) \quad s(T) = s(T) - s(T_{\text{sat}}) = \frac{h(T) - h(T_{\text{sat}})}{T} = \frac{\Delta_{h}}{\Delta_{v}} = \frac{s(T) - s(T_{\text{sat}})}{v'(T)} = \frac{m_{v}}{m_{T} + m_{g}}
\]

**Ideal Gas Model (vapors and gases)**

\[\mathbf{K = \alpha = \beta = 1} \quad \mathbf{c = \sqrt{\mathbf{RT}}}
\]

**Ideal Gas Law:**

\[\mathbf{P = \frac{RT}{V}} \quad \mathbf{V = \frac{RT}{P}} \quad \mathbf{V_{\text{cond}} = \frac{RT}{P_{\text{vap}}}} \quad \mathbf{T_{\text{cond}} = \frac{RT}{P_{\text{cond}}}} \quad \mathbf{V_{\text{vap}} = \frac{RT}{P_{\text{vap}}}}
\]

**Absolute Values:**

\[\mathbf{u = u_{\text{kinetic}} + T u_{\text{thermal}}} \quad \mathbf{h = h_{\text{kinetic}} + T h_{\text{thermal}}} \quad \mathbf{u_{\text{kinetic}} = h_{\text{kinetic}} - T_{\text{sat}}} \quad \mathbf{T_{\text{sat}} = 288 K}
\]
<table>
<thead>
<tr>
<th>Model</th>
<th>Internal Energy</th>
<th>Enthalpy</th>
<th>Entropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Specific Heat</td>
<td>( u = c_p T )</td>
<td>( h = c_p T )</td>
<td>( s = c_p \ln(T_2/T_1) + R \ln(v_2/v_1) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( = c_p \ln(T_2/T_1) - R \ln(P_2/P_1) )</td>
</tr>
<tr>
<td>Ideal Gas Tables</td>
<td>( u = u(T) = \int c_p(T) , dT )</td>
<td>( h = h(T) = \int c_p(T) , dT )</td>
<td>( s^* = s^*(T) - R \ln(P/P_w) )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( s^*(T) = \int \frac{S_p(T)}{T} , dT )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isentropic Process</th>
<th>( s = 0 )</th>
<th>( CR = \frac{v_1}{v_2} )</th>
<th>( PR = P_2 / P_1 )</th>
<th>( TR = T_2 / T_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Compression Ratio Known</td>
<td>Pressure Ratio Known</td>
<td>Temperature Ratio Known</td>
<td></td>
</tr>
<tr>
<td>Constant Specific Heat</td>
<td>( PR = CR^k )</td>
<td>( TR = CR^{\frac{k-1}{k}} )</td>
<td>( PR = TR^{\frac{k}{k-1}} )</td>
<td>( CR = TR^{\frac{k-1}{k}} )</td>
</tr>
<tr>
<td>Ideal Gas Tables</td>
<td>( v_1(T_2) = v_2(T_2) / CR )</td>
<td>( p_r(T_2) = p_r(T_1) , PR )</td>
<td>( T_2 = (T_1) , TR )</td>
<td>( CR = v_1(T_2) / v_2(T_2) )</td>
</tr>
<tr>
<td></td>
<td>( s_u(T_2) - R \ln(T_2) )</td>
<td>( s_u(T_2) = s_u(T_1) + R \ln(PR) )</td>
<td>( CR = PR / TR )</td>
<td>( PR = p_r(T_2) / p_r(T_1) )</td>
</tr>
<tr>
<td></td>
<td>( PR = TR \times CR )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CONSERVATION EQUATIONS

Mass Equation (Discrete Flows, Unsteady Form)

\[
\frac{dm_{sys}}{dt} = \sum_{\text{inflows}} \dot{m}_i - \sum_{\text{outflows}} \dot{m}_e
\]

Energy Equation (Discrete Flows, Unsteady Form)

\[
\frac{dE_{sys}}{dt} = \sum_{\text{inflows}} \left( \dot{h}_i (\dot{m}_i + P_i \dot{V}_i) \right) - \sum_{\text{outflows}} \left( \dot{h}_e (\dot{m}_e + P_e \dot{V}_e) \right) \\
= \sum_{\text{inflows}} \dot{h}_i \left( \frac{\dot{h}_i u_i^k u_i^k}{2} + g z_i \right) - \sum_{\text{outflows}} \dot{h}_e \left( \frac{\dot{h}_e u_e^k u_e^k}{2} + g z_e \right)
\]

plus Rate of Heat Transfer into the System

\[
\dot{Q}_i
\]

plus Rate of Work Done on the System

\[
\dot{W}_{in}
\]

minus Rate of Heat Transfer out of the System

\[
\dot{Q}_o ut
\]

minus Rate of Work Done by the System

\[
\dot{W}_{by}
\]

Notes:

1. Time derivatives are zero for steady-state systems.
2. Sign convention: (a) heat transfer into the system and (b) work done by the system are positive; heat transfer out of the system and work done by the system are omitted when the sign convention is used.
3. Work done by gravity is treated using potential energy.
4. The work done by inflow (\( \dot{m}_i P_i \dot{V}_i \)) and outflow (\( \dot{m}_e P_e \dot{V}_e \)) pressures (flow work) is treated using enthalpy \( h = u + P v \).
5. The entropy equation is a reformulation of the energy equation in terms of entropy \( s \); entropy is a thermodynamic property defined by the differential relationship \( T dS = dU + P dV \).
6. The First Law of Thermodynamics states that energy is conserved; the Second Law of Thermodynamics requires that \( \dot{S} \geq 0 \).
CONSERVATION EQUATIONS

Entropy Equation (Discrete Flows, Unsteady Form)

\[
\frac{dS_{sys}}{dt} = \frac{d}{dt} (m_{sys} s_{sys})
\]

equals

\[
\sum_{inflows} \hat{n}_i s_i
\]

minus

\[
\sum_{outflows} \hat{n}_e s_e
\]

plus

Rate of Entropy Increase due to Heat Transfer into the System

\[
\frac{Q_{in}}{T_b}
\]

minus

Rate of Entropy Decrease due to Heat Transfer out of the System

\[
\frac{Q_{out}}{T_b}
\]

plus

Rate of Entropy Generation by System

Second Law \(\Rightarrow S_{sys} \geq 0\)

\[
\dot{S}_{sys} = \int \left( \frac{\dot{S}}{T} - \frac{a^2 - T}{T^2} \right) dV
\]

Momentum Equation (Discrete Flows, Unsteady Form)

\[
\frac{d}{dt} P_{sys}
\]

equals

\[
\sum_{inflows} \hat{n}_i P_i
\]

minus

\[
\sum_{outflows} \hat{n}_e P_e
\]

plus

Sum of Surface Forces Acting on System

\[
\sum_{a_j} F_j
\]

plus

Body Force Acting on System

\[
m_{sys} g
\]
### Momentum Equation

<table>
<thead>
<tr>
<th>Form</th>
<th>Time Rate of Change in System Momentum</th>
<th>equals</th>
<th>Sum of Momentum Inflow Rates</th>
<th>minus</th>
<th>Sum of Momentum Outflow Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discrete Flows</strong></td>
<td>( \frac{d}{dt} P_{\text{sys}} )</td>
<td>=</td>
<td>( \sum_{\text{inflows}} \hat{m}_i P_i )</td>
<td>(-)</td>
<td>( \sum_{\text{outflows}} \hat{m}_e P_e )</td>
</tr>
<tr>
<td><strong>Transient</strong></td>
<td>( \frac{d}{dt} (m_{\text{sys}} u_{\text{sys}}) )</td>
<td></td>
<td>( \sum_{\text{inflows}} \hat{m}_i u_i )</td>
<td>(-)</td>
<td>( \sum_{\text{outflows}} \hat{m}_e u_e )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plus</td>
<td>Sum of Surface Forces</td>
<td>plus</td>
<td>Body Force Acting on System</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Acting on System</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \sum_{S_j} F_j ) dS</td>
<td></td>
<td>( m_{\text{sys}} g )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Form</th>
<th>Change in System Momentum</th>
<th>equals</th>
<th>Sum of Momentum Inflows</th>
<th>minus</th>
<th>Sum of Momentum Outflows</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Discrete Flows</strong></td>
<td>( \Delta P_{\text{sys}} )</td>
<td>=</td>
<td>( \sum_{\text{inflows}} m_i P_i )</td>
<td>(-)</td>
<td>( \sum_{\text{outflows}} m_e P_e )</td>
</tr>
<tr>
<td><strong>Transition</strong></td>
<td>( m_2 u_2 - m_1 u_1 )</td>
<td></td>
<td>( \sum_{\text{inflows}} m_i u_i )</td>
<td>(-)</td>
<td>( \sum_{\text{outflows}} m_e u_e )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plus</td>
<td>Surface Impulse Acting on System</td>
<td>plus</td>
<td>Body Impulse Acting on System</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \int \sum_{S_j} F_j ) dS dt</td>
<td></td>
<td>( \int m_{\text{sys}} g ) dt</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Form</th>
<th>Time Rate of Change in System Momentum</th>
<th>equals</th>
<th>Integrated Momentum Inflow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Integral</strong></td>
<td>( \frac{d}{dt} \int_V \rho u ) dV</td>
<td>=</td>
<td>(- \int_S u (\rho u \cdot n) ) dS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plus</td>
<td>Integrated Surface Force Acting on System</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( \int_S (-P n + D \cdot n) ) dS</td>
</tr>
</tbody>
</table>

### Entropy Equation

<table>
<thead>
<tr>
<th>Form</th>
<th>Time Rate of Change in System Entropy(^1)</th>
<th>equals</th>
<th>Sum of Energy Inflow Rates</th>
<th>minus</th>
<th>Sum of Energy Outflow Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete Flows</td>
<td>(\frac{dS_{sys}}{dt} = \frac{d}{dt} (m_{sys} s_{sys}))</td>
<td>= (\sum m_{in} s_{i})</td>
<td>- (\sum m_{out} s_{o})</td>
<td>(\frac{\dot{Q}_{in}}{T_B})</td>
<td>(\frac{\dot{Q}_{out}}{T_B})</td>
</tr>
<tr>
<td>Transient</td>
<td></td>
<td>plus Rate of Entropy Increase due to Heat Transfer into the System</td>
<td>minus Rate of Heat Transfer out of the System(^2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>plus Rate of Entropy Generation by System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ (\dot{S}_{sys})</td>
<td>(\dot{S}_{sys} \geq 0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Second Law \(\Rightarrow \dot{S}_{sys} \geq 0\)

<table>
<thead>
<tr>
<th>Form</th>
<th>Change in System Entropy(^1)</th>
<th>equals</th>
<th>Sum of Entropy Inflows(^3)</th>
<th>minus</th>
<th>Sum of Entropy Outflows(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discrete Flows</td>
<td>(\Delta S_{sys} = m_{s_2} s_2 - m_1 s_1)</td>
<td>= (\sum m_{in} s_{i})</td>
<td>- (\sum m_{out} s_{o})</td>
<td>(\frac{\dot{Q}_{in}}{T_B})</td>
<td>(\frac{\dot{Q}_{out}}{T_B})</td>
</tr>
<tr>
<td>Transition</td>
<td></td>
<td>plus Rate of Entropy Increase due to Heat Transfer into the System(^5)</td>
<td>minus Rate of Entropy Increase Due to Heat Transfer out of the System(^2,5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ (\dot{S}_{sys})</td>
<td>(\dot{S}_{sys} \geq 0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>