Review for Exam 2
Exam Guidelines

• 50-minutes

• Resources allowed
  – The blue properties booklet
    • You can write anything you want in the white space of this booklet.
    • NO photocopies, no taping, pasting, photocopies, loose papers
  – A handheld calculator
    • No other electronic devices used including cell phones, computers, tablets, music players, etc.
Exam Information

- A table of conversion factors will be provided with the exam 😊
- NO interpolation will be required 😊
- Material covered
  - Everything since the first day of class
    - All in-class lecture material
    - All in-class problem solutions
    - All assigned reading questions
    - All homework assignments
Do you know ...

• How to Identify Transport, Gain, and Production Terms within the Laws of the Universe?
  – Conservation of mass
  – Conservation of energy
  – Entropy Balance

• How to apply the Continuity Equation along with the 1st Law of Thermodynamics in...
  – Closed system problems?
  – Open system problems?
  – Simple transient problems?

• The purpose of the following flow devices?
  – Diffuser, Nozzle
  – Boiler, Condenser, Heat Exchanger
  – Valves, Throttling Devices
  – Turbine, Compressor, Pump

• How to find ideal gas properties with the air tables?
• How to find real fluid properties with tables and with EES?
• How to find properties of incompressible substances?
Do you know ...

- How to use the caloric equation of state? (for ideal gas enthalpy and internal energy)
- How to find the fluid velocity given mass flow, area, and either density or specific volume?
- What is meant by reversibility? What causes irreversibility?
- What is meant by entropy? What are its units?
- How to obtain reversible work and heat transfer from the first and second Gibbs equations?
  \[ \text{dU} = T \text{dS} - p \text{dV} \]
  \[ \text{dH} = T \text{dS} + v \text{dP} \]
- Characteristic shape of isobars, isotherms, isentropes, and isochores on T-s diagrams?
- How to represent reversible work transfer for a closed system on P-v diagrams?
  How to represent reversible heat transfer for a closed system on T-s diagrams?
- How to use array tables in EES to organize state point data and superimpose thermodynamic processes on property diagrams?
Do you know ...

- How to define the **thermal efficiency** for a cycle?
- How to define the **coefficient of performance** for a cycle?
- Kelvin-Planck statement of the 2\textsuperscript{nd} Law?
- Clausius statement of the 2\textsuperscript{nd} Law?
- How to determine the maximum thermal efficiency of a heat engine?
- How to determine the maximum coefficient of performance for a refrigerator?
- How to determine the maximum coefficient of performance for a heat pump?
- How to determine entropy changes for substances using real fluid, ideal gas, and incompressible substance models?
- The **polytropic relationships** for the special case of ideal gases with constant heat capacity undergoing isentropic processes?
The Laws of the Universe

Conservation of Mass – The Continuity Equation

\[ \sum_{i} m_i - \sum_{e} m_e = \frac{dm_{sys}}{dt} \]

Conservation of Energy – The First Law of Thermodynamics

\[ \dot{Q} - \dot{W} + \sum_{i} \dot{m}_i \left( h_i + \frac{V_i^2}{2g_c} + \frac{g}{g_c} z_i \right) - \sum_{e} \dot{m}_e \left( h_e + \frac{V_e^2}{2g_c} + \frac{g}{g_c} z_e \right) = \frac{dE_{sys}}{dt} \]

The Entropy Balance – The Second Law of Thermodynamics

\[ \sum_{k} \frac{\dot{Q}_k}{T_k} + \sum_{i} \dot{m}_i s_i - \sum_{e} \dot{m}_e s_e + \dot{S}_p = \frac{dS_{sys}}{dt} \]
Alternate Forms: 1st Law for Closed Systems

The First Law over a finite period of time is (making a movie),

\[ Q - W = (U_2 - U_1) + \frac{m}{2g_c} (V_2^2 - V_1^2) + \frac{mg}{g_c} (z_2 - z_1) \]

\[ q - w = (u_2 - u_1) + \frac{(V_2^2 - V_1^2)}{2g_c} + \frac{g}{g_c} (z_2 - z_1) \]

The First Law at an instant in time is (taking a picture),

\[ \dot{E}_T = \dot{E}_G = \frac{dE_{sys}}{dt} \]

\[ \dot{Q} - \dot{W} = \frac{dE_{sys}}{dt} = \frac{d}{dt} \left[ U + \frac{mV^2}{2g_c} + \frac{mgz}{g_c} \right] \]
For an ideal gas,

\[ du = c_v dT \]

Since we are dealing with an ideal gas, \( pv = RT \). Therefore,

\[ h = u + pv \rightarrow h = u + RT \rightarrow h = h(T) \]

This leads to the following conclusion (section 3.9.2),

\[ dh = c_p dT \]

It can also be shown that,

\[ c_p - c_v = R \]
The Polytropic Process – Ideal Gas

Definition of a polytropic process:
\[ \frac{p_2}{p_1} = \left( \frac{V_1}{V_2} \right)^n \]

If the fluid is an ideal gas,
\[ \frac{p_2}{p_1} = \left( \frac{V_1}{V_2} \right)^n = \left( \frac{mRT_1 / p_1}{mRT_2 / p_2} \right) \]

This leads to two additional relationships for ideal gases,
\[ \frac{T_2}{T_1} = \left( \frac{p_2}{p_1} \right)^{(n-1)/n} \quad \text{and} \quad \frac{T_2}{T_1} = \left( \frac{V_2}{V_1} \right)^{1-n} \]
The Polytropic Process – Ideal Gas

The work done during a polytropic process is,

\[ W_{12} = \int_{V_1}^{V_2} \frac{p_1 V_1^n}{V^n} \, dV = \frac{p_2 V_2 - p_1 V_1}{1 - n} \quad \text{for} \quad n \neq 1 \]

If the fluid is an ideal gas,

\[ W_{12} = \frac{mR(T_2 - T_1)}{1 - n} \quad \text{for} \quad n \neq 1 \]

For the case where \( n = 1 \),

\[ W_{12} = \int_{V_1}^{V_2} \frac{p_1 V_1}{V} \, dV = p_1 V_1 \ln \frac{V_2}{V_1} \]
Ideal Gas Entropy \( \rightarrow f(T,V) \)

For the ideal gas, recall that

\[
Pv = RT, \quad du = c_v \, dT, \quad \text{and} \quad dh = c_p \, dT
\]

Then from the first Gibbs equation,

\[
s_2 - s_1 = \int_{u_1}^{u_2} \frac{du}{T} + \int_{v_1}^{v_2} \frac{P}{T} \, dv = \int_{T_1}^{T_2} \frac{c_v}{T} \, dT + \int_{v_1}^{v_2} \frac{RT}{v} \, dv = \int_{T_1}^{T_2} \frac{c_v}{T} \, dT + R \ln \left( \frac{v_2}{v_1} \right)
\]

Furthermore, if the heat capacity can be assumed constant,

\[
s_2 - s_1 = c_v \ln \left( \frac{T_2}{T_1} \right) + R \ln \left( \frac{v_2}{v_1} \right)
\]

Notice that the entropy of an ideal gas is a function of \textit{both} temperature and specific volume (or pressure).
Ideal Gas Entropy $\Rightarrow f(T,P)$

For the ideal gas, recall that

\[ P_v = RT, \quad du = c_v dT, \quad \text{and} \quad dh = c_p dT \]

Then from the second Gibbs equation,

\[
s_2 - s_1 = \int_{h_1}^{h_2} \frac{dh}{T} - \int_{P_1}^{P_2} \frac{\nu}{T} dP = \int_{T_1}^{T_2} c_p \frac{dT}{T} - \int_{P_1}^{P_2} \frac{RT}{P} dP = \int_{T_1}^{T_2} c_p \frac{dT}{T} - R \ln \frac{P_2}{P_1}
\]

Furthermore, if the heat capacity can be assumed constant,

\[
s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}
\]

Notice that the entropy of an ideal gas is a function of both temperature and pressure.
Carnot Heat Engine

\[ \eta_{th} = \frac{W_{cycle}}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \frac{|Q_{out}|}{Q_{in}} \]

\[ \eta_{th, Carnot} = \frac{W_{cycle}}{Q_{in}} = \frac{Q_{in} - |Q_{out}|}{Q_{in}} = 1 - \left( \frac{|Q_{out}|}{Q_{in}} \right)_{rev} \]

Kelvin and Rankine suggested that,

\[ \left( \frac{|Q_{out}|}{Q_{in}} \right)_{rev} = \frac{T_{L}}{T_{H}} \]

Temperatures must be on the absolute scale!

Therefore, the thermal efficiency of a Carnot Heat Engine is,

\[ \eta_{th, Carnot} = 1 - \frac{T_{L}}{T_{H}} \]

This is the maximum efficiency of a heat engine!
Carnot Refrigerator & Heat Pump

For the Refrigeration cycle …

\[ \eta_{th} = \text{COP}_R = \frac{Q_{in}}{|W_{cycle}|} = \frac{Q_{in}}{|Q_{out} - Q_{in}|} = \frac{1}{|Q_{out}|/|Q_{in}| - 1} \]

\[ \text{COP}_{R,\text{Carnot}} = \frac{1}{(|Q_{out}|/|Q_{in}|)_{rev}} - 1 = \frac{1}{T_H / T_L - 1} \]

\[ \text{COP}_{R,\text{Carnot}} = \frac{T_L}{T_H - T_L} \]

For the Heat Pump cycle …

\[ \eta_{th} = \text{COP}_H = \frac{|Q_{out}|}{|W_{cycle}|} = \frac{|Q_{out}|}{|Q_{out} - Q_{in}|} = \frac{1}{1 - Q_{in} / |Q_{out}|} \]

\[ \text{COP}_{H,\text{Carnot}} = \frac{1}{1 - (Q_{in} / |Q_{out}|)_{rev}} = \frac{1}{1 - T_L / T_H} \]

\[ \text{COP}_{H,\text{Carnot}} = \frac{T_H}{T_H - T_L} \]