ES 202 Fluid and Thermal Systems
Exam 2 Review Session (2/8/03)

- Fundamental laws of thermodynamics
    - Zeroth law
    - First law
    - Second law

- Energy balance
    - mass transfer
    - heat transfer
    - work transfer
    - no generation

- Entropy balance
    - heat transfer
    - mass transfer
    - entropy generation

- Phases of a fluid
    - compressed (subcooled) liquid
    - two-phase (liquid-vapor) mixture
    - superheated vapor

- State Principle of a simple substance

- *P-v-T* surface of a general substance and its two-dimensional projections
    - *P-v* diagram
    - *T-v* diagram
    - *P-T* diagram

- Features of two-dimensional phase diagrams
    - relative position of compressed liquid, two-phase and superheated vapor regions
    - slopes of constant property lines
    - direction of property variation

- Properties in two-phase region
    - dependency between temperature and pressure in two-phase region
    - concept and definition of quality (absolutely crucial)
        - mass fraction of vapor in a liquid-vapor mixture

$$x = \frac{m_g}{m_f + m_g}$$

    - intensive (specific) properties can be expressed as a <u>mass-weighted average</u> of its saturated liquid and saturated vapor values

$$f = (1 - x)f_f + xf_g$$

    where *f* can be specific volume, specific enthalpy, specific internal energy or specific entropy

- Phase and state determination of a substance:
    - always look up the two-phase saturation table first (it serves as a reference)
    - then look up corresponding tables

- - finally interpolate between "sandwiched" interval
    - linear
    - bi-linear

- Compressed liquid approximation:
  - key point: dependency on pressure is weak for most properties
  - approximate most properties by their <u>saturated liquid</u> values evaluated at the <u>specified temperature</u>

$$u(T,P) = u_f(T)$$

$$v(T,P) = v_f(T)$$

$$s(T,P) = s_f(T)$$

$$h(T,P) = h_f(T) + \left(P - P_{sat}(T)\right)v_f(T)$$

- Constant property processes
  - they serve as models or idealizations of complex processes
  - constant pressure process (piston-cylinder model)
  - constant volume process (rigid tank model)
  - constant temperature process (slow compression/expansion with significant heat transfer)
  - constant entropy process (reversible, adiabatic)
  - their process paths on phase diagrams are simple (they help tremendously in problem solving!)

- Models versus general substances
  - models: ideal gas, incompressible substance
  - ideal gas model good for gases at low pressures and high temperatures
  - incompressible substance model good for liquids and solids
  - property tables bridge the gaps between models and represent the real behavior
  - basic principles stay the same (energy balance and entropy balance) regardless you use models or general substances

- Gibbs equation holds for any general substance (fundamental in finding entropy change)

$$Tds = du + Pdv$$
$$Tds = dh - vdP$$

- Ideal gas model
  - definition of reduced pressure and reduced temperature
  - compressibility chart

$$Z = \frac{Pv}{RT}$$

  - justification of ideal gas model (Z within 10% of unity)
  - extend the applicability of ideal gas equation with known Z values
  - property changes
    - definition of c_p and c_v
    - specific internal energy and specific enthalpy only depend on temperature

$$\Delta u = \int du = \int c_v dT$$

$$\Delta h = \int dh = \int c_p dT$$

- specific entropy depends on temperature <u>AND</u> pressure (or specific volume)

$$\Delta s = \int ds = \underbrace{\int \frac{c_p}{T} dT}_{s_2^0 - s_1^0} - R \ln\left(\frac{P_2}{P_1}\right)$$

- o solution method for <u>constant</u> specific heats
  - simplification of integral evaluation for <u>constant</u> specific heats

$$\Delta u = c_v \Delta T$$

$$\Delta h = c_p \Delta T$$

$$\Delta s = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) \quad \text{or} \quad \Delta s = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2}{v_1}\right)$$

- o solution methods for <u>variable</u> specific heats
  - needs a way to evaluate (exact) or approximate the above integrals
  - <u>exact method:</u> tabulated values for u, h, s^0 (functions of temperature only) at various temperatures for <u>variable</u> specific heats
  - <u>approximate method:</u> "average" specific heats

$$\Delta u = c_{v,avg} \Delta T$$

$$\Delta h = c_{p,avg} \Delta T$$

$$\Delta s = c_{p,avg} \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right) \quad \text{or} \quad \Delta s = c_{v,avg} \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2}{v_1}\right)$$

    where the "average" specific heats are evaluated at the average temperature

- Isentropic processes
  - o general substance
    - entropy remains constant from one state to another one
    - only needs one more thermodynamic property to fix the state (State Principle)
    - table look-up $(s_2 = s_1)$
  - o ideal gas
    - Gibbs equation is greatly simplified and leads to analytical solution
    - pressure, temperature and specific volume varies in a specific manner
    - <u>constant</u> specific heats:

$$Pv^k = \text{constant}$$

$$Tv^{k-1} = \text{constant}$$

$$TP^{(1-k)/k} = \text{constant}$$

    - <u>variable</u> specific heats:

$$\underbrace{s_2^0(T_2) - s_1^0(T_1)}_{\text{temperature dependency}} = \underbrace{R \ln\left(\frac{P_2}{P_1}\right)}_{\text{pressure dependency}}$$

- Significance of isentropic process:
  - set the limit of (best) performance of certain types of steady-state devices (compressor, turbine, nozzle, diffuser)
  - definition of isentropic efficiency for compressor/pump and turbine
  - representation of process paths on a *T-s* diagram
    - slope of constant pressure line and its direction of variation

- Energy and entropy analysis for ideal and non-ideal compressor and turbine
  - representation of process path of steady state, adiabatic process on *h-s* diagram
    - difference in specific enthalpy represents the amount of work per unit mass flow
    - difference in specific entropy represents the amount of entropy generation (irreversibility) per unit mass flow
    - difference in location of actual and ideal states

- Applications
  - power cycle (Rankine cycle as an example)
  - refrigeration cycle (reverse process direction)
  - analysis follows a "divide and conquer" approach
    - tackle each individual component
    - use thermodynamic conditions for a closed loop to link them together
  - effects of irreversibility on cycle performance (isentropic efficiency)