

# Thermodynamics Review

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# Systems

- ◆ Why?

- ◆ Open vs. Closed systems

# Con-App Principles

## ◆ Conservation of Mass

$$\frac{dm_{\text{sys}}}{dt} = \sum_{\text{in}} \dot{m}_i - \sum_{\text{out}} \dot{m}_o$$

$$m_{\text{sys}} = \rho V_{\text{sys}} = \text{"system mass"}$$

$$\dot{m} = \rho A_c V = \rho \dot{V} = \text{"mass flow rate"}$$

# Con-App Principles

## ◆ Conservation of Energy (First Law of Thermo)

$$\frac{dE_{\text{sys}}}{dt} = \dot{Q}_{\text{in,net}} + \dot{W}_{\text{in,net}} + \sum_{\text{in}} \dot{m}_i \left( h + \frac{V^2}{2} + gz \right)_i - \sum_{\text{out}} \dot{m}_o \left( h + \frac{V^2}{2} + gz \right)_o$$

$$E_{\text{sys}} = U + KE + PE = m_{\text{sys}} \left( u + \frac{V^2}{2} + gz \right)$$

$h = u + Pv$  = "specific enthalpy"       $u$  = "specific internal energy"

$\dot{m}$  = "mass flow rate"

$gz$  = "specific gravitational potential energy"

$V^2/2$  = "specific kinetic energy"

# Con-App Principles

- ◆ Entropy Accounting Principle (or Balance)  
(Second Law of Thermodynamics)

$$\frac{dS_{sys}}{dt} = \sum_j \frac{\dot{Q}_{in,j}}{T_{b,j}} + \sum_{in} \dot{m}_i s_i - \sum_{out} \dot{m}_o s_o + \dot{S}_{gen}$$

$S_{sys} = m_{sys} s$  = "system entropy"

$s$  = "specific entropy"

$T_{b,j}$  = "boundary temperature at surface  $j$ " (R or K)

$\dot{S}_{gen}$  = "entropy production rate"

## WARNING!!!!

- ◆ Sign Convention
- ◆ Work vs Work transfer of energy
- ◆ Heat vs Heat transfer of energy
- ◆ Entropy production.

## Example - Piston

- ◆ A piston-cylinder contains 5 kg of air. During a compression process, 100 kJ of heat is removed while 250 kJ of work is done on the air. Find the change in internal energy in kJ/kg.

## Example - Turbine

- ◆ Heated air enters a turbine at a flow rate of 5 kg/s. The entering and leaving conditions are shown below. The heat loss from the turbine is 50 kW. Find the power produced.

	Inlet	Outlet
Pressure, kPa	1000	100
Temperature, K	800	500
Specific Internal Energy, kJ/kg	137	85
Specific Volume, m <sup>3</sup> /kg	0.23	1.44

# Constitutive Models

## ◆ Ideal Gas Law

$$PV = NR_u T \quad PV = mRT \quad \text{where} \quad R = \frac{R_u}{M}$$
$$Pv = RT$$
$$P = \rho RT$$

## Enthalpy and Internal Energy Changes

Using average or "constant"

heat values -----

$$h_2 - h_1 = c_p (T_2 - T_1)$$

$$u_2 - u_1 = c_v (T_2 - T_1)$$

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{P_2}{P_1}\right)$$

$$c_p = c_v + R$$

$$k = \frac{c_p}{c_v}$$

$$c_p = \frac{kR}{k-1}$$

$$c_v = \frac{R}{k-1}$$

# Property Tables ( $v, u, h, s$ )

## ◆ Saturated tables

- give properties of saturated liquids and saturated vapors (under the vapor dome). Quality is used to get property values of two-phase mixtures

$$x = \frac{u - u_f}{u_{fg}} = \frac{h - h_f}{h_{fg}} = \frac{s - s_f}{s_{fg}}$$

## ◆ Superheated tables

- give properties for superheated substances (right of vapor dome)

## ◆ Subcooled / Compressed Liquid tables

- give properties for subcooled substances (left of vapor dome)

## Example - Property Tables

◆ Fill in the following table for steam (water).

	$T, ^\circ\text{C}$	$P, \text{kPa}$	$x, \%$	$h, \text{kJ/kg}$	$u, \text{kJ/kg}$	$v, \text{m}^3/\text{kg}$
a)	200			852.45		
b)		150			1000	
c)	300	800				
d)	200	5000				
e)		300				0.85
f)	300		80			
g)		1000	90			

# Processes

- ◆ General
- ◆ Constant pressure (isobaric)
- ◆ Constant volume (isochoric)
- ◆ Constant temperature (isothermal)
- ◆ No heat flow (adiabatic)
- ◆ Reversible

## Example - Processes

- ◆ Air at 27 C is heated to 927 C. Find the change in enthalpy and internal energy, using constant specific heats ( $c_p=1.0047$  kJ/(kg-K),  $c_v=0.717$  kJ/(kg-K) and the air tables.

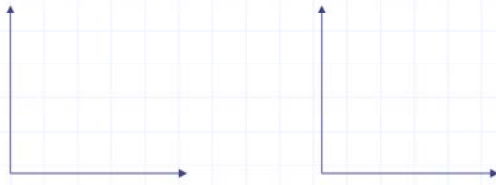
$T, K$	$h, kJ/kg$	$u, kJ/kg$
300	300.19	214.07
1200	1277.79	933.33

## Second Law and Entropy

- ◆ No heat engine (power) cycle is possible without the rejection of some heat.
- ◆ A Carnot cycle exchanges energy by heat transfer at two different temperatures and converts the maximum amount of heat into work; it has the highest thermal efficiency.
- ◆ A Carnot machine's measure of performance (efficiency or COP) is a function only of the two reservoir temperatures
- ◆ Natural processes result in a production of (not increase in) entropy within a system.
- ◆ The entropy of a closed system will always increase when there is a net heat transfer into the system.
- ◆ Entropy of a closed system will remain constant when it undergoes a reversible and adiabatic process.
- ◆ Entropy of a closed system can decrease only when entropy is removed from the system by heat transfer.

# Cycles - Carnot

- ◆ 1-2 Reversible adiabatic compression
- ◆ 2-3 Reversible isothermal heat addition
- ◆ 3-4 Reversible adiabatic expansion
- ◆ 4-1 Reversible isothermal heat rejection



$$\eta = \frac{W_{net,out}}{Q_{in}} = 1 - \frac{T_C}{T_H}$$
$$COP_{ref} = \frac{Q_{in}}{W_{net,in}} = \frac{T_C}{T_H - T_C}$$
$$COP_{hp} = \frac{Q_{out}}{W_{net,in}} = \frac{T_H}{T_H - T_C}$$

## Example - Carnot

- ◆ A Carnot machine operates between a hot reservoir at 200 C and a cold reservoir at 20 C. a) When operated at an engine, it receives 1000 kJ/kg; find the work output. b) Find the COP when operated as a refrigerator and a heat pump.

## Cycles - Otto (Gasoline Engine)

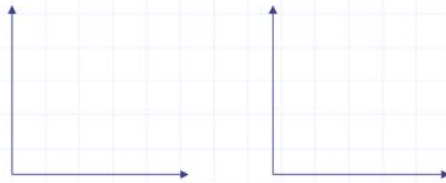
- ◆ 1-2 Isentropic compression
- ◆ 2-3 Isochoric heat addition
- ◆ 3-4 Isentropic expansion
- ◆ 4-1 Isochoric heat rejection

$$W_{in} = u_2 - u_1$$

$$q_{in} = u_3 - u_2$$

$$W_{out} = u_3 - u_4$$

$$q_{out} = u_4 - u_1$$



$$\eta_{th} = \frac{W_{net}}{q_{in}} = \frac{(u_3 - u_4) - (u_2 - u_1)}{u_3 - u_2}$$

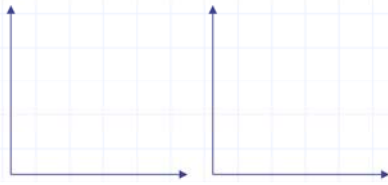
$$r_c = \frac{v_1}{v_2} = \frac{v_4}{v_3}$$

$$\frac{v_2}{v_1} = \frac{v_{r2}}{v_{r1}} ; \quad \frac{v_3}{v_4} = \frac{v_{r3}}{v_{r4}}$$

$$\frac{T_2}{T_1} = \left( \frac{v_1}{v_2} \right)^{k-1} ; \quad \frac{T_3}{T_4} = \left( \frac{v_4}{v_3} \right)^{k-1}$$

## Cycles - Diesel (Diesel Engine)

- ◆ 1-2 Isentropic compression
- ◆ 2-3 Isobaric heat addition
- ◆ 3-4 Isentropic expansion
- ◆ 4-1 Isochoric heat rejection



$$w_{in} = u_2 - u_1$$

$$q_{in} = h_3 - h_2$$

$$w_{out} = p_3 v_3 - p_2 v_2 = R(T_3 - T_2)$$

$$w_{out} = u_3 - u_4$$

$$q_{out} = u_4 - u_1$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{R(T_3 - T_2) + (u_3 - u_4) - (u_2 - u_1)}{h_3 - h_2}$$

$$\frac{v_2}{v_1} = \frac{v_{r2}}{v_{r1}}; \quad \frac{v_3}{v_4} = \frac{v_{r3}}{v_{r4}} \quad \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}; \quad \frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{k-1} \quad r_c = \frac{v_1}{v_2}; \quad r_{co} = \frac{v_3}{v_2}$$

## Cycles - Brayton (Gas Turbine)

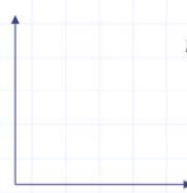
- ◆ 1-2 Isentropic compression (compressor)
- ◆ 2-3 Isobaric heat addition (combustor)
- ◆ 3-4 Isentropic expansion (turbine)
- ◆ 4-1 Isobaric heat rejection (heat dump)

$$w_{in} = h_2 - h_1$$

$$q_{in} = h_3 - h_2$$

$$w_{out} = h_3 - h_4$$

$$q_{out} = h_4 - h_1$$



$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

$$r_p = \frac{p_2}{p_1} = \frac{p_3}{p_4}$$

$$\frac{p_2}{p_1} = \frac{p_{r2}}{p_{r1}} ; \quad \frac{p_3}{p_4} = \frac{p_{r3}}{p_{r4}}$$

$$\frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} ; \quad \frac{T_3}{T_4} = \left( \frac{P_3}{P_4} \right)^{\frac{k-1}{k}}$$

## Example - Brayton

- ◆ An air standard Brayton cycle has air entering the compressor at 27 C and 100 kPa. The pressure ratio is 10 and the maximum temperature is 1350 K. Find all state properties and the thermal efficiency. The value of  $k$  for air is 1.4

State	$T$ , K	$P$ , kPa	$v$ , m <sup>3</sup> /kg
1			
2			
3			
4			

## Cycles - Rankine (Steam)

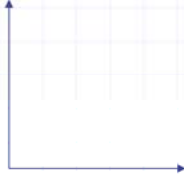
- ◆ 1-2 Isentropic compression (pump)
- ◆ 2-3 Isobaric heat addition (boiler/superheater)
- ◆ 3-4 Isentropic expansion (turbine)
- ◆ 4-1 Isobaric heat rejection (condenser)

$$w_{in} = h_2 - h_1$$
$$\approx v_1(P_2 - P_1)$$

$$q_{in} = h_3 - h_2$$

$$w_{out} = h_3 - h_4$$

$$q_{out} = h_4 - h_1$$


$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

## Cycles - Vapor Compression (Refrigeration)

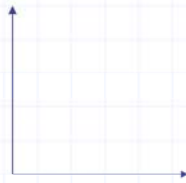
- ◆ 1-2 Isentropic compression (compressor)
- ◆ 2-3 Isobaric heat rejection (condenser)
- ◆ 3-4 Isenthalpic expansion (throttle)
- ◆ 4-1 Isobaric heat addition (evaporator)

$$w_{in} = h_2 - h_1$$

$$q_{out} = h_2 - h_3$$

$$h_3 = h_4$$

$$q_{in} = h_1 - h_4$$



$$COP_{ref} = \frac{q_{in}}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{hp} = \frac{q_{out}}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$