

Thermodynamics

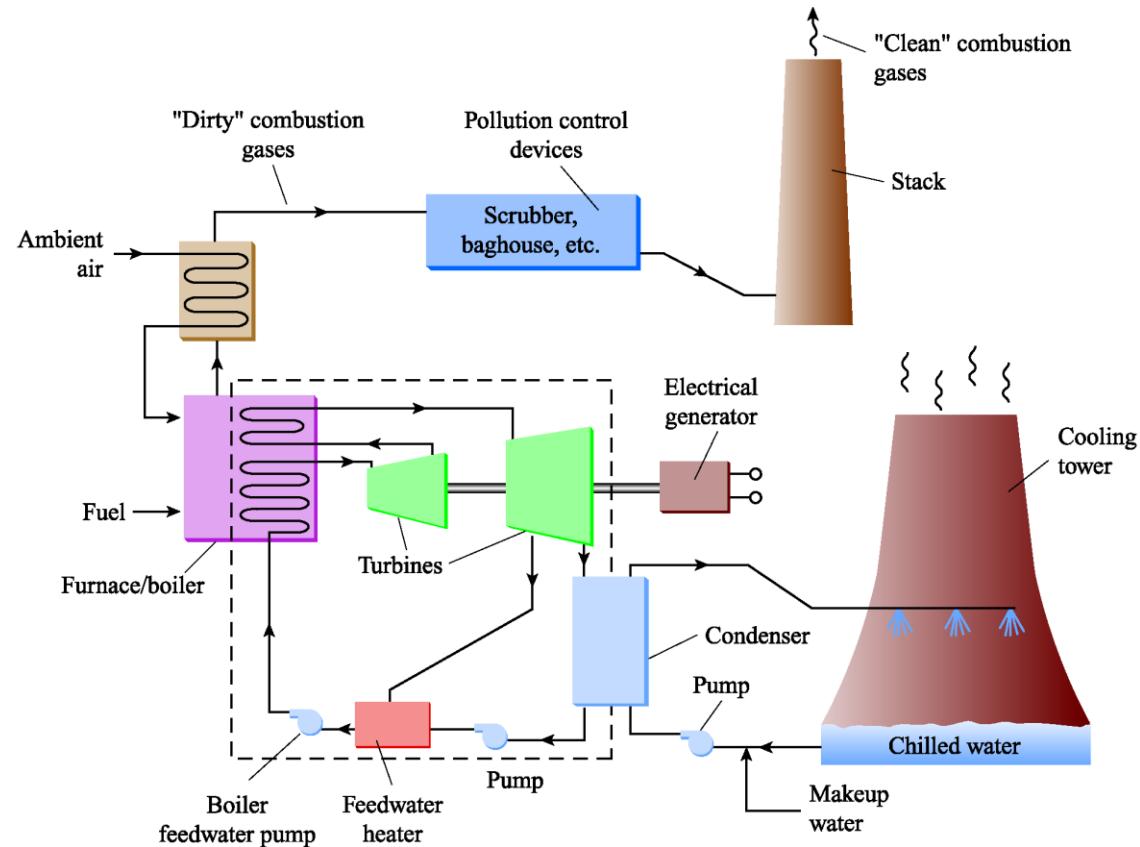
UCC 501

Dr. Mohamed Ibrahim Ali
Fall 2014



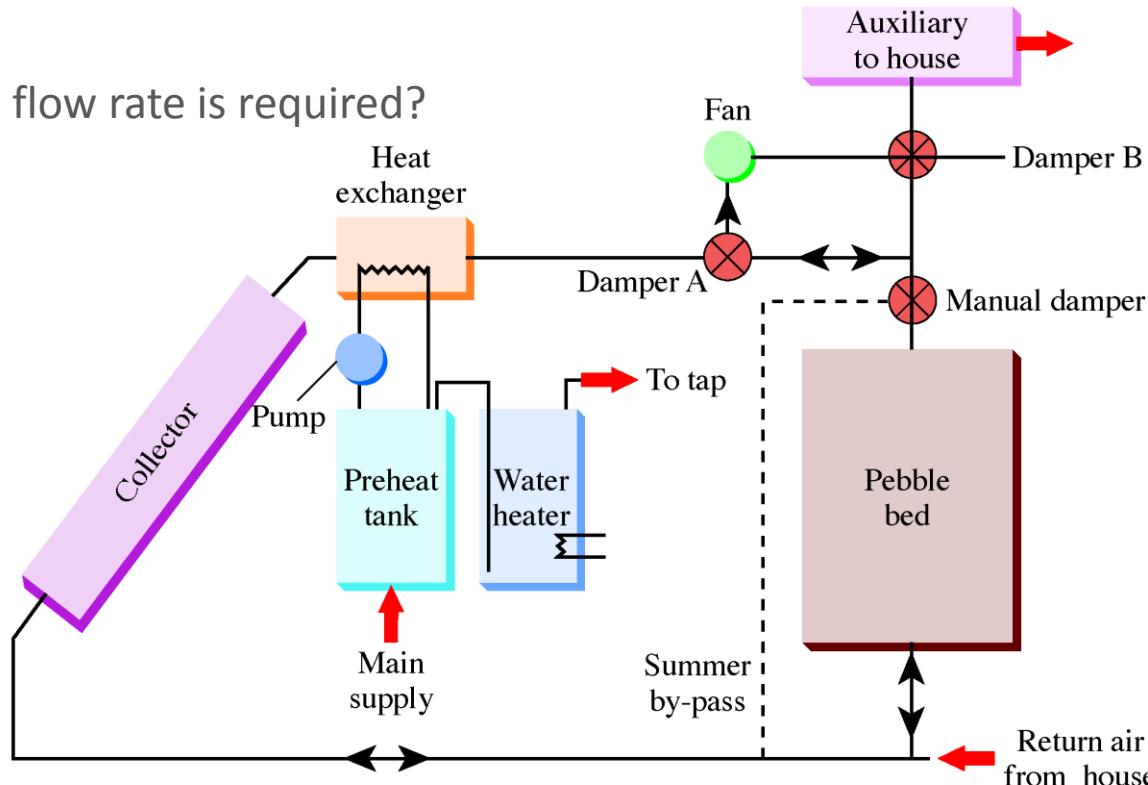
- Introduction
- Outcomes
- Applications
- Basics and definitions
- Thermodynamics system, process, cycle, equilibrium and properties
- Forms of energy
- Heat transfer modes
- Types of work
- Thermodynamics laws, first and second laws
- Entropy and irreversibility
- Exergy (Availability)
- Thermodynamics cycles analysis
- System's devices analysis

- How would energy be converted from one form to another?
- What is the energy conversion efficiency?
- How much fuel is required to produce certain amount of electricity?
- How can we improve the energy system components efficiency?
- What is the impact of the energy system on the environment?
- How can we construct a cycle?
- What is the impact of the working medium (fluid) on the cycle performance?
- What is the most possible cycle efficiency?



Schematic of utility-type fossil-fueled steam power plant showing major components.

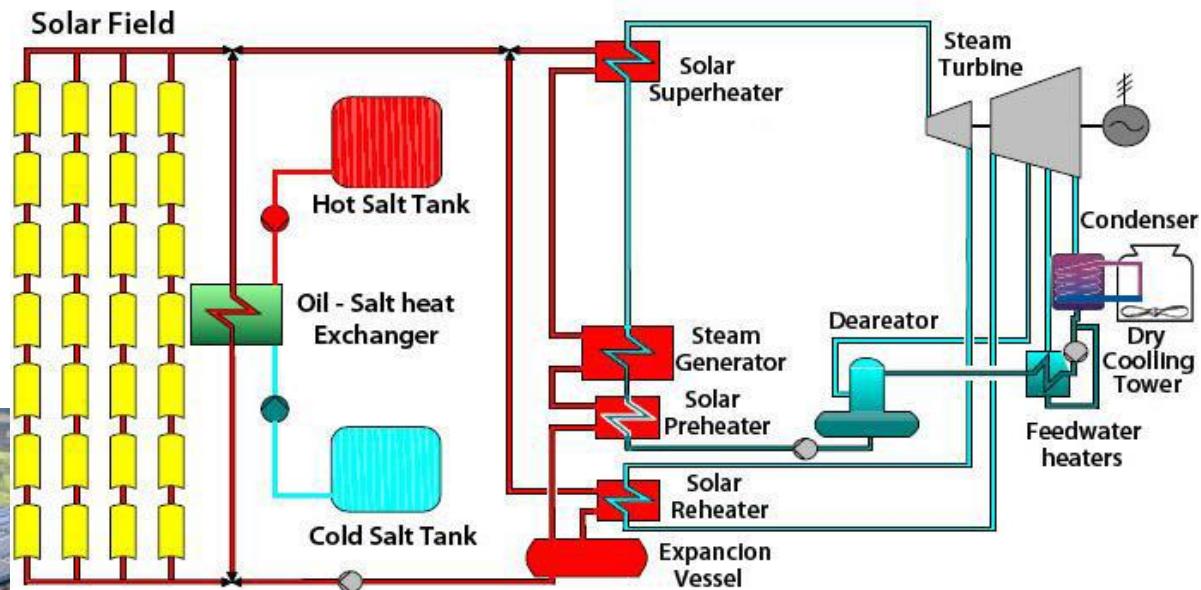
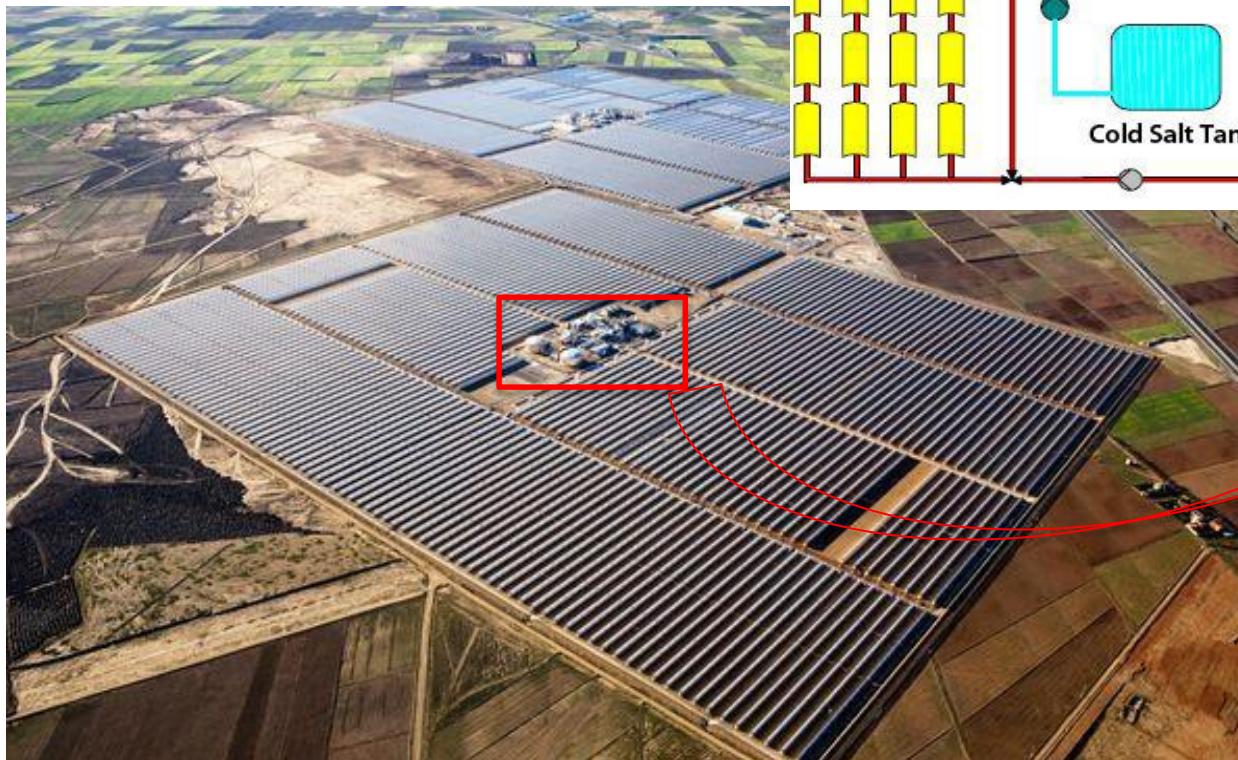
- How much energy would be collected by a solar heater?
- What is the collector area?
- How much working medium flow rate is required?



Schematic diagram of flow paths for a solar-heated house. Energy is used to heat domestic water as well as to heat the house. Energy is stored in a pebble bed to be used as needed. Adapted from Ref. [18] with permission.

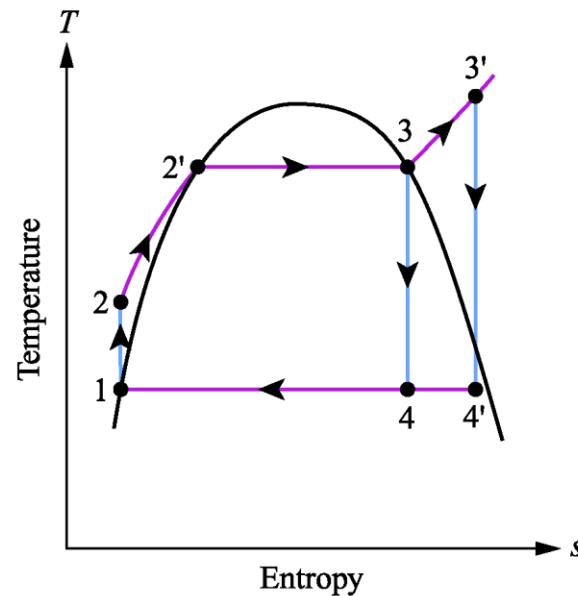
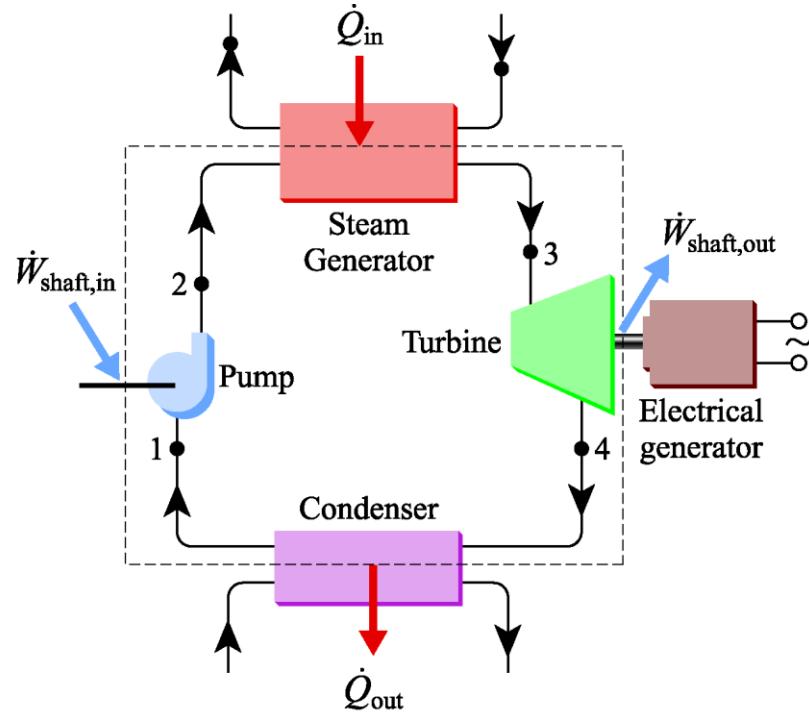
Thermodynamics Answers Questions

- How much power would be produced from solar troughs?
- What is the total area that would replace a gallon of fossil fuel?



Power Cycle: Steam Power Plant

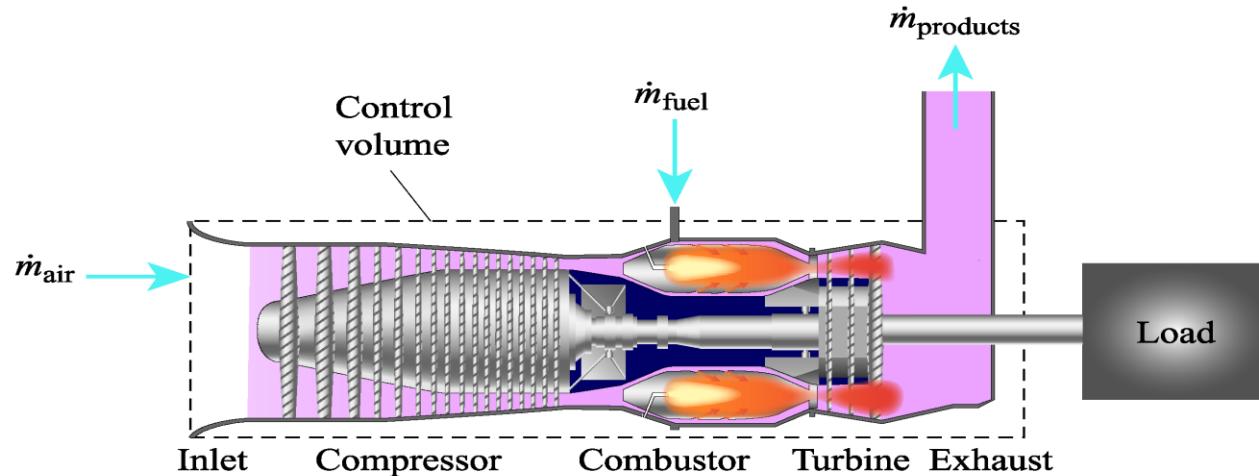
- Simplified cycles for system performance studies
- System improvements stated from the system's cycle



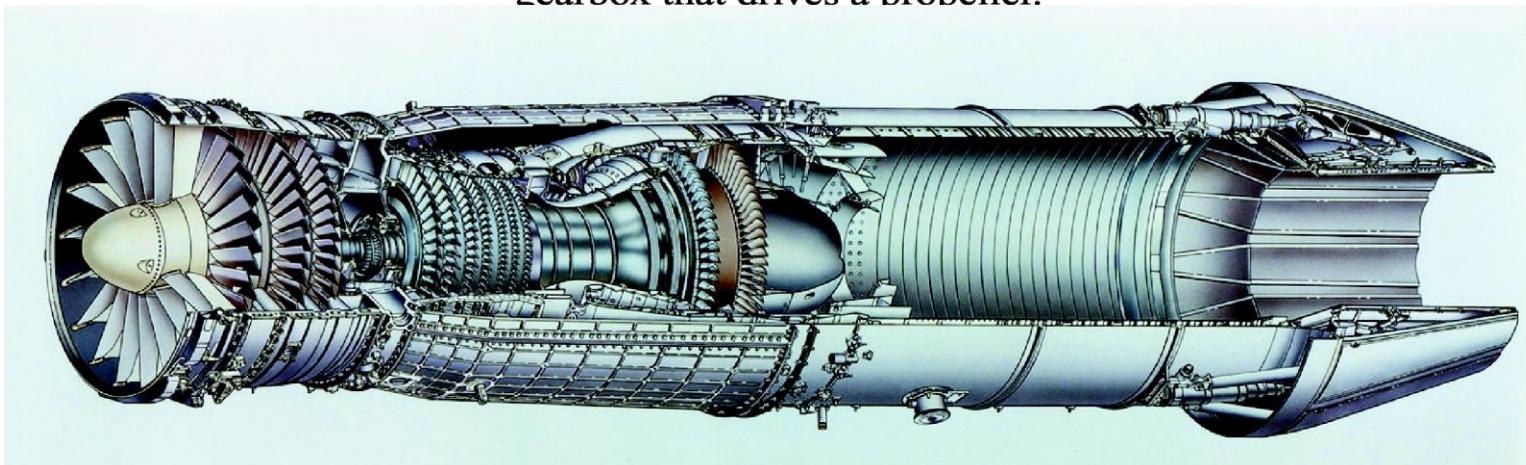
Components associated with a simple Rankine cycle (left) and the corresponding T-s diagram (right) for the cycle: 1–2–3–4–1. Also shown on the T-s diagram is a Rankine cycle with superheat: 1–2–3'–4'–1.

Power Cycle: Gas Turbine and Jet Engines

- Are Gas turbine and Jet engines produces the same power?
- What is the efficiency?

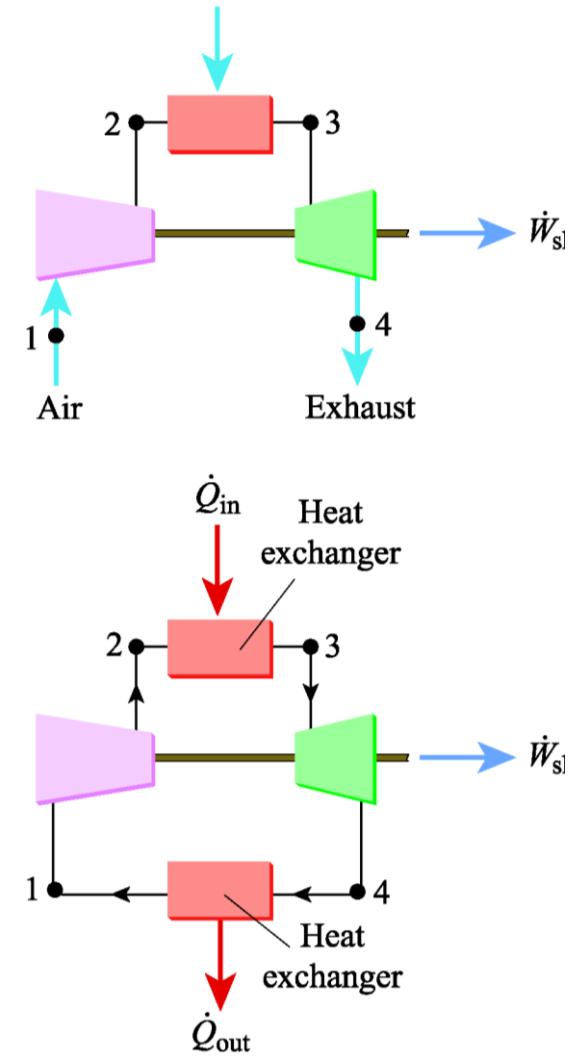
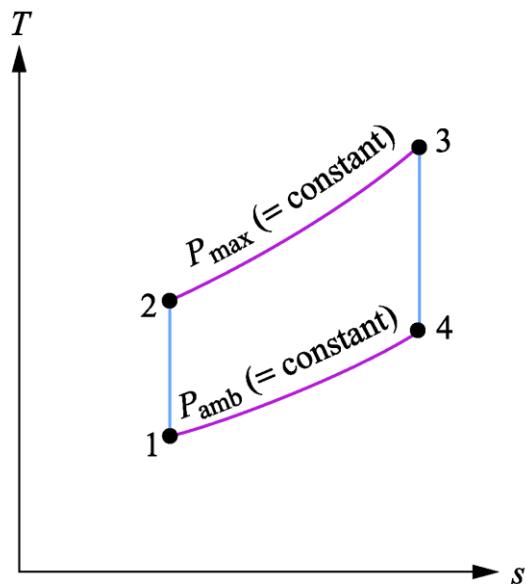
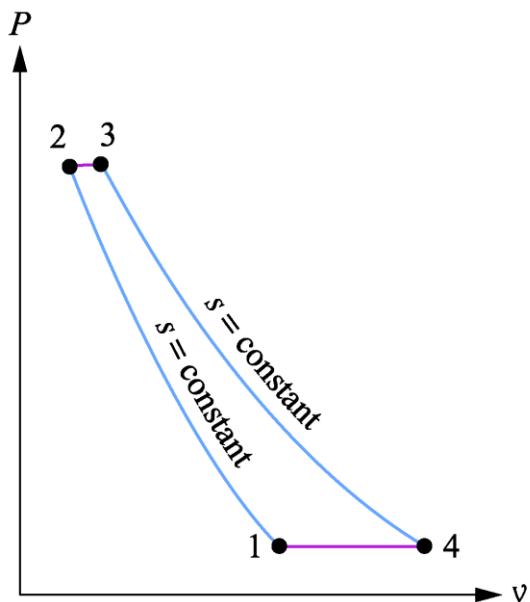


Schematic diagram of a gas-turbine engine. The nature of the load depends on the application. For example, the load is an electrical generator for stationary power generation; whereas for marine propulsion, the load is a gearbox that drives a propeller.



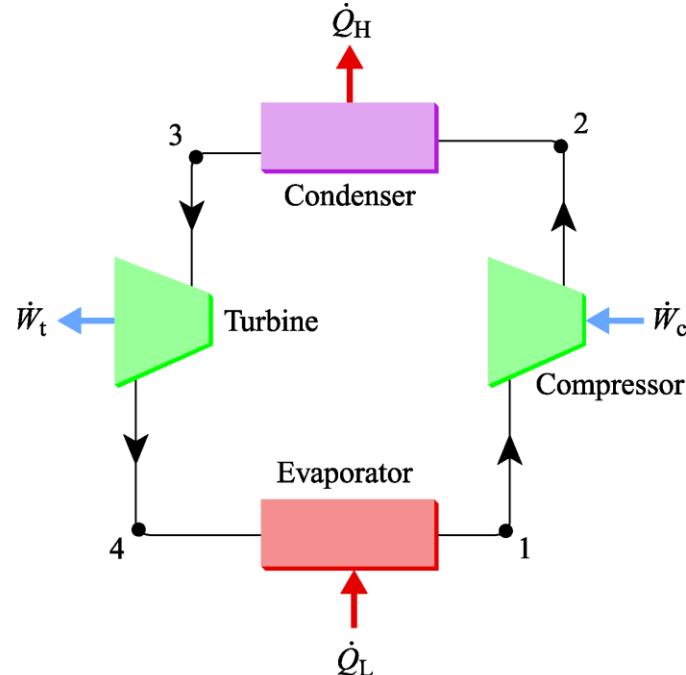
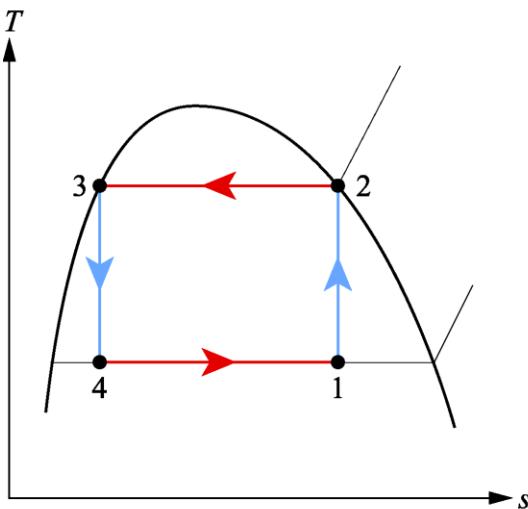
Power Cycle: Gas Turbine Standard Cycle

- Gas power – Air standard cycles



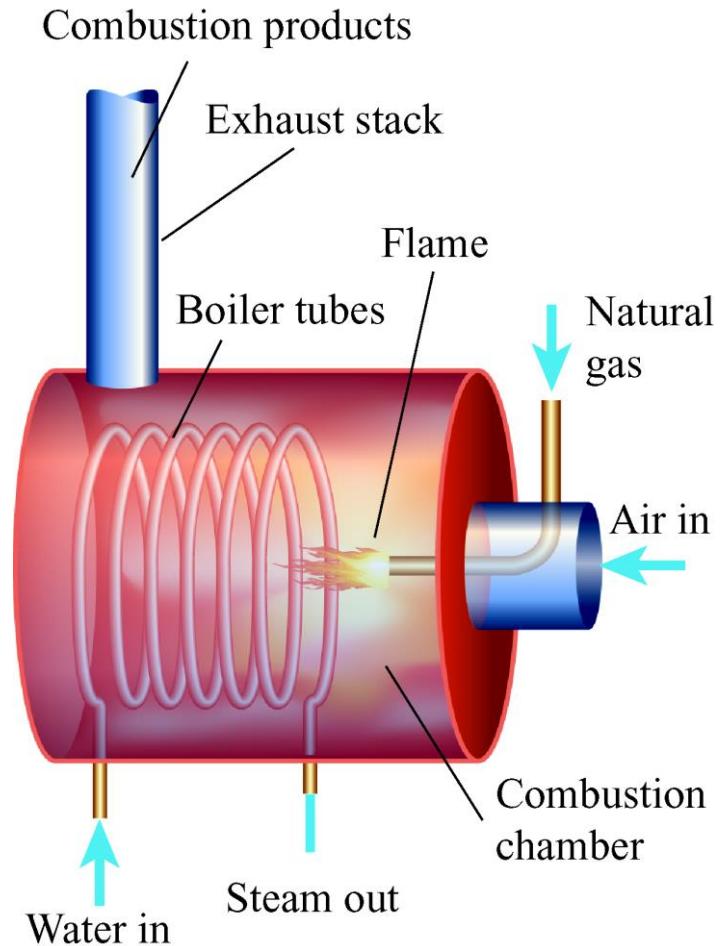
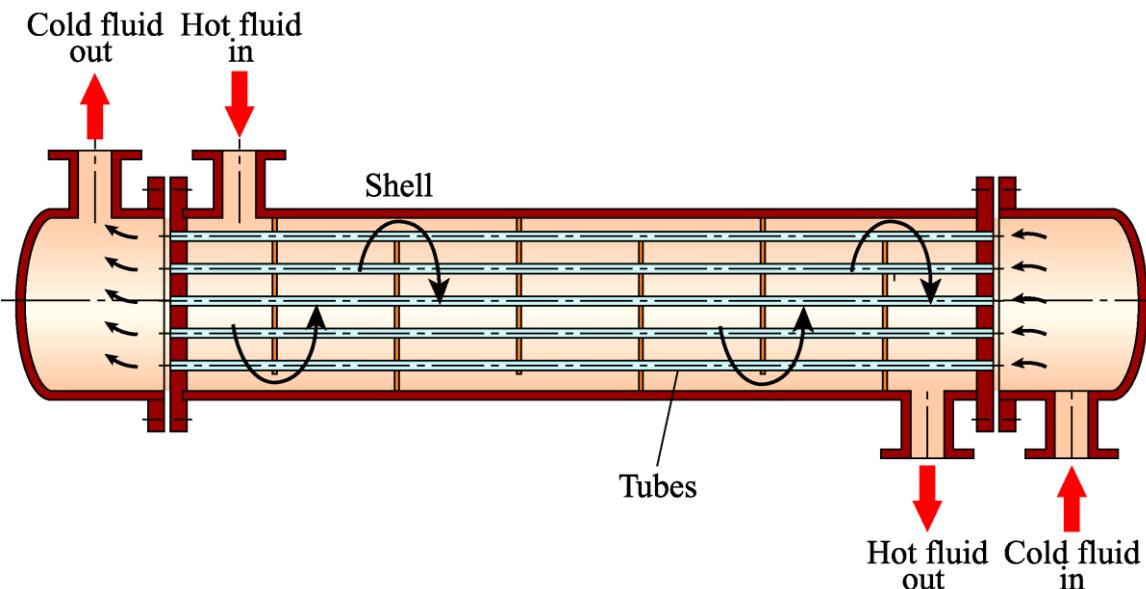
Refrigeration and Heat Pump Cycles

- How is vapor compression cycle work?
- What is the refrigerant?
- What is the cooling load?
- What is the difference between refrigerator and Heat pump?
- Refrigerant and heat pump COP vs. engine efficiency



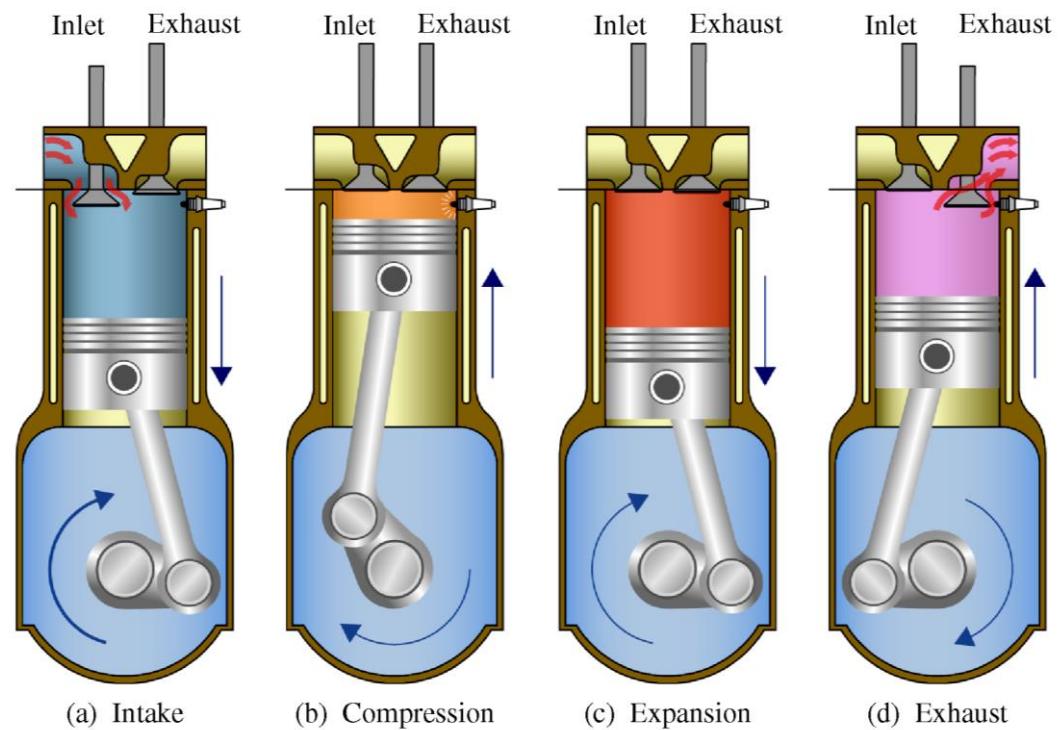
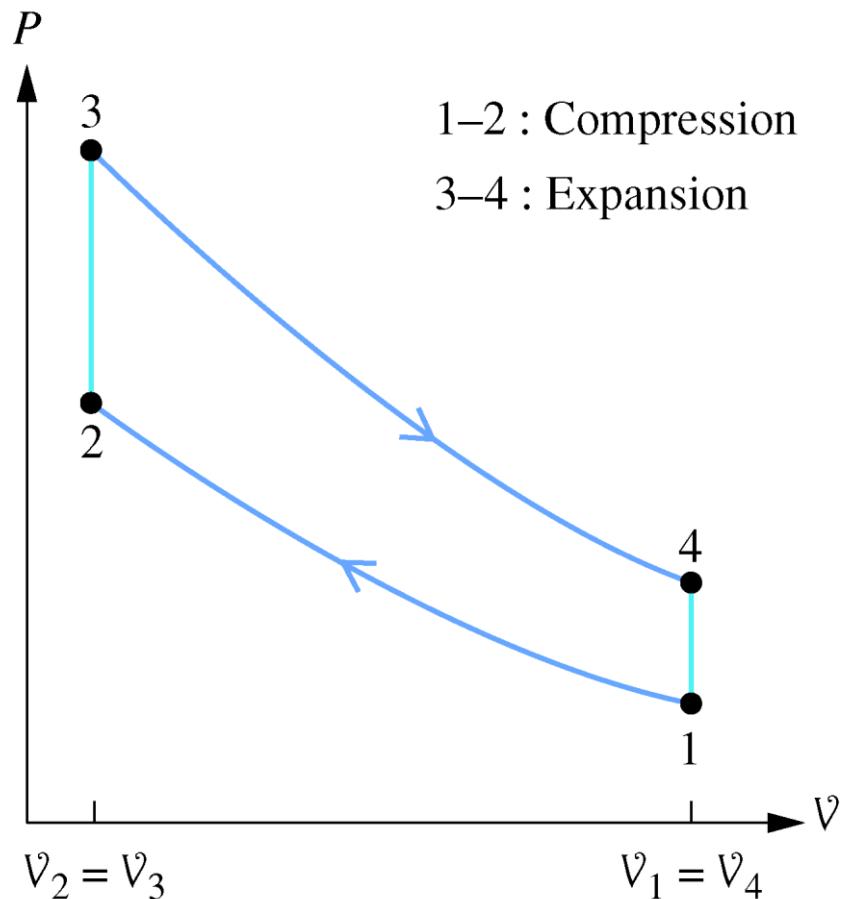
What is the performance of the non-cyclic Devices?

- How would the heat exchanger performance improved?
- Heat Exchange devices effectiveness vs. engine efficiency



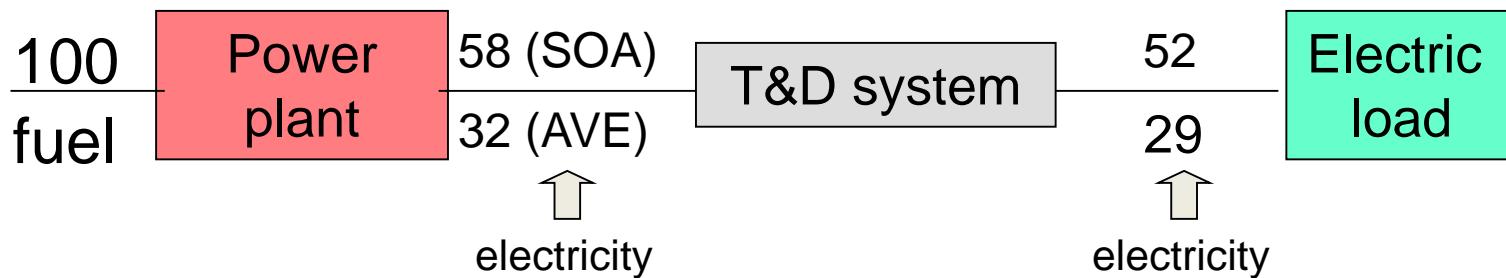
Reciprocating Engine Power Cycle

- Reciprocating engines – gasoline and diesel engines
- Air standard cycle efficiency



- How much electrical work would be earned from fuel's chemical energy work?
- Work conversion to another form of work is associated with losses because of the conversion devices' irreversibility

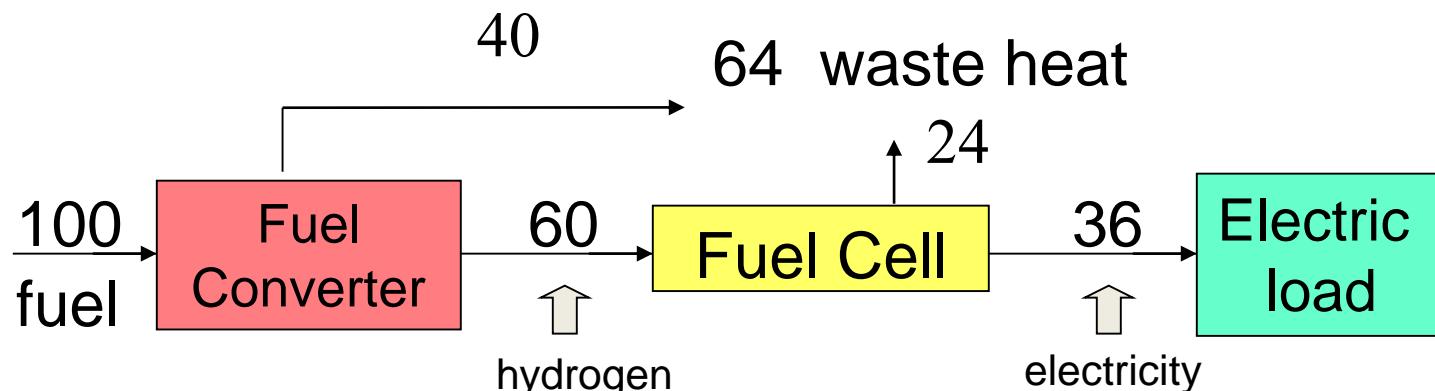
State of the art (SOA) vs system average (AVE) performance



$\eta_{SOA} = 52/100$ or 52% -- state of the art technology
 or $\eta_{AVE} = 29/100$ or 29% -- system average

Why thermodynamics is important

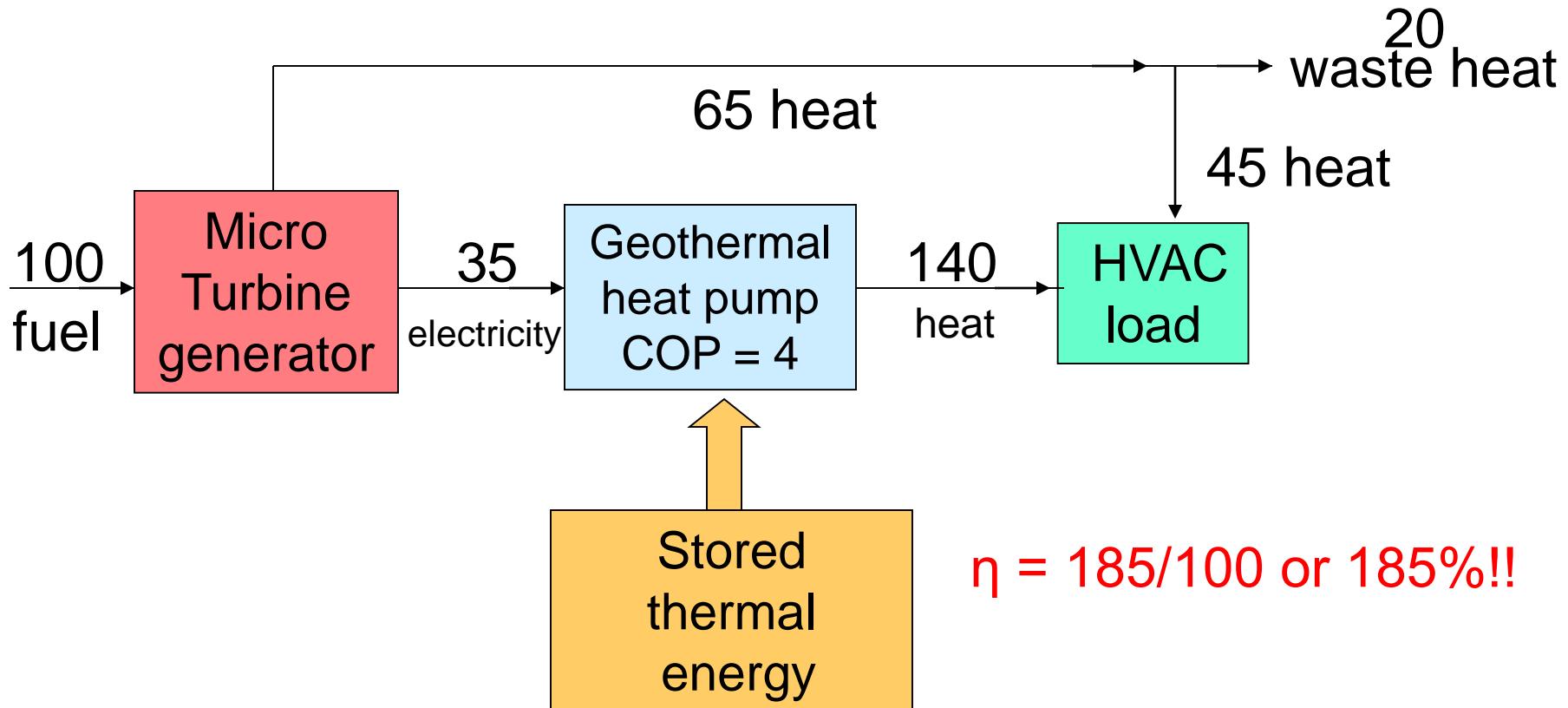
- Distributed energy resources – Fuel cell system
- The system efficiency is the multiplication of the devices' efficiency that has been used to build the system in series.



$$\eta = 36/100 \text{ or } 36\%$$

Why thermodynamics is important

- Distributed energy resources – Combined heat and power Microturbine + Geothermal HP
- Work can easily be converted to heat with high efficiency
- Heat pump, water heater, friction, and exothermic reaction are some of the examples

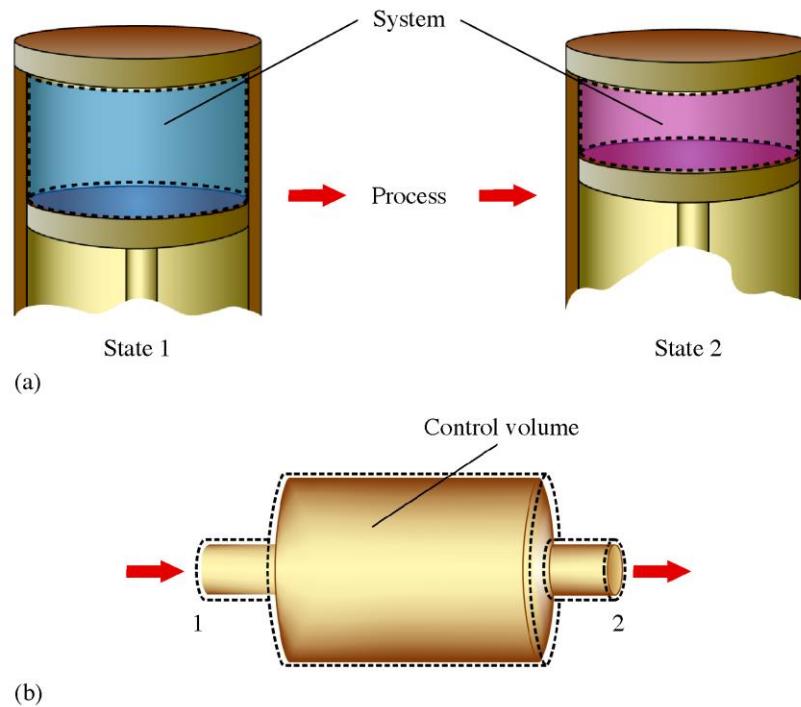


- Calculate the efficiency of energy conversion systems based on thermodynamics laws
- Clearly understand the thermal energy terms: heat, work, forms of energy, exergy
- Understand the effect of irreversibility on system exergy

- Power systems
- Conventional Energy system
- Industrial furnaces
- HVAC systems
- Renewable energy systems
- Biological systems
- Chemical reactions
- All systems that deals with transport phenomena, heat, mass, fluid flow, ...etc.

- **Thermodynamics:** The science of *energy*.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle:** During an interaction, energy can change from one form to another but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics:** An expression of the conservation of energy principle.
- **The second law of thermodynamics:** It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.
- **Classical thermodynamics:** A *macroscopic approach* to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
- **Statistical thermodynamics:** A *microscopic approach*, based on the average behavior of large groups of individual particles.

- Thermodynamics system
 - Surroundings
 - System boundaries
 - Closed system (control mass)
 - Open system (control volume)
 - System state
- System processes
 - Isothermal ($T=C$, $PV=C$)
 - Isobaric ($P=C$, $\frac{V}{T} = C$)
 - Isometric ($V=C$, $\frac{P}{T} = C$)
 - Isentropic ($S=C$, $PV^k=C$)
 - Polytropic ($PV^n=C$, $k>n>1$)

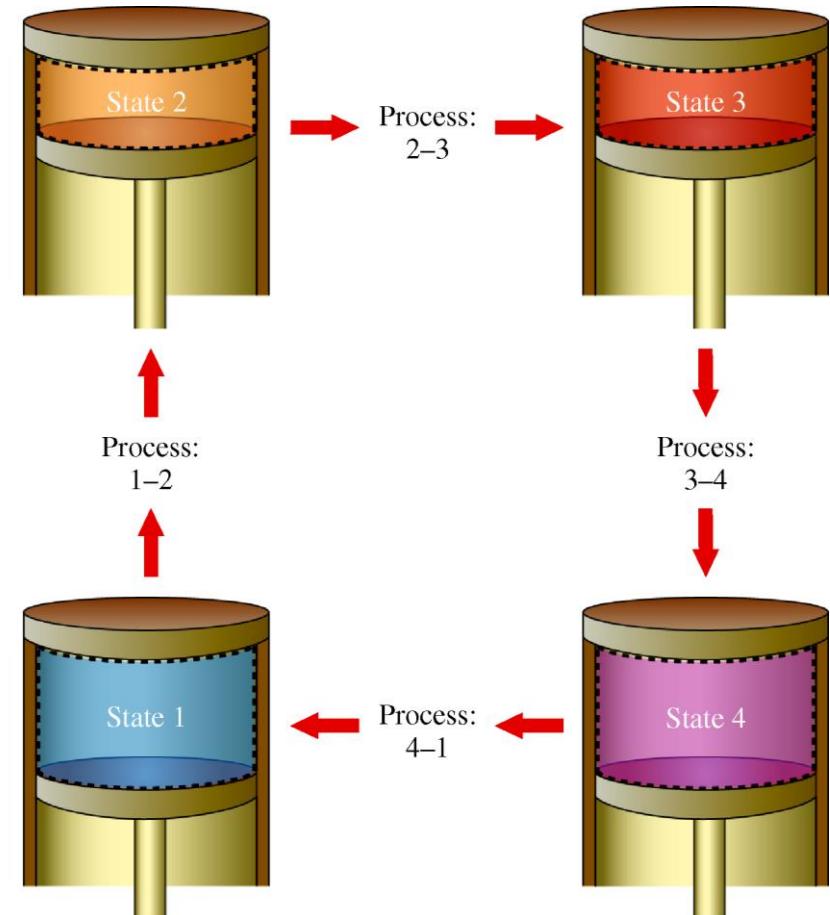
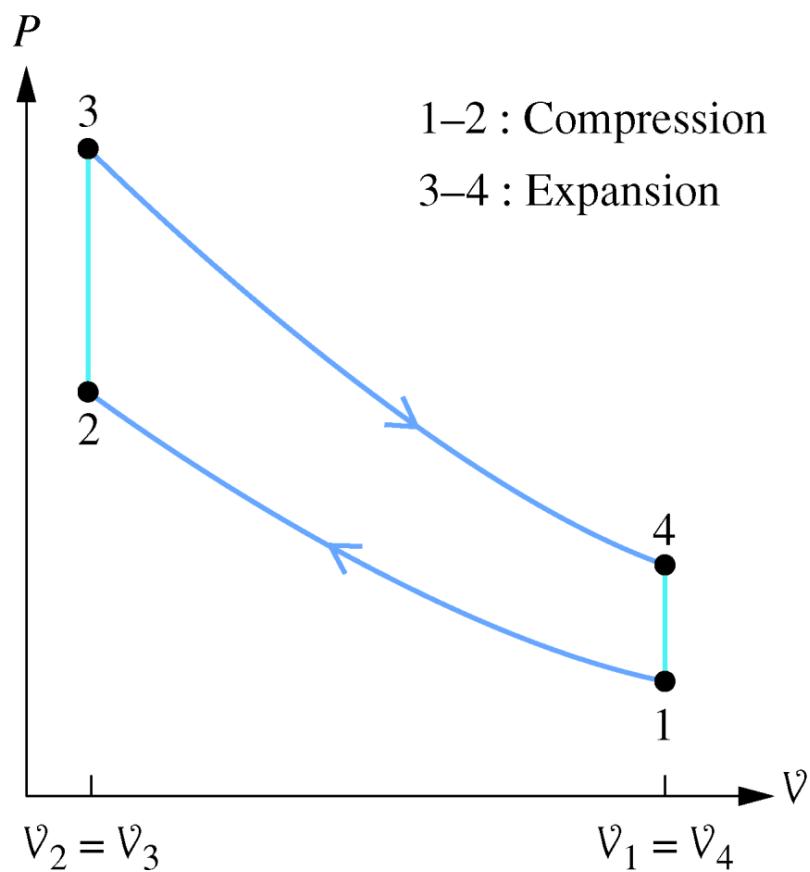


To describe a process completely, one should specify the initial and final states, as well as the path it follows, and the interactions with the surroundings.

Quasistatic or quasi-equilibrium process: When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times.

Thermodynamics cycle

- A system undergoes a cycle when a series of process returns the system to its original state.
 - Air standard cycles
 - Vapor cycles
 - Gas cycles



- Thermodynamics deals with *equilibrium* states.
- **Equilibrium:** A state of balance.
- In an equilibrium state there are no unbalanced potentials (or driving forces) within the system.
- **Thermal equilibrium:** If the temperature is the same throughout the entire system,

$$\frac{dT}{d(x,y,z)} = 0.$$

- **Mechanical equilibrium:** If there is no change in pressure at any point of the system with time.

$$\frac{dP}{d(x, y, z)} = 0.$$

- **Phase equilibrium:** If a system involves two phases and when the mass of each phase reaches an equilibrium level and stays there.
- **Chemical equilibrium:** If the chemical composition of a system does not change with time, that is, no chemical reactions occur (fixed chemical composition and species concentration).

- **Property:** Any characteristic of a system.
- Some familiar properties are pressure P , temperature T , volume V , and mass m .
- Properties are considered to be either *intensive* or *extensive*.
- **Intensive properties:** Are independent of the mass of a system, such as temperature, pressure, and density.
- **Extensive properties:** Those whose values depend on the size (V) and the mass of the system (m). E.g, H , U , E , Q , W ,etc.
- **Specific properties:** Extensive properties per unit mass, e.g. v (specific volume), h , u , e , q , w , ...etc.

2 measurable properties are needed to characterize the system state

- When the vapor of a substance has **relatively low density**, the pressure, specific volume, and temperature are related by an **equation of state**:

$$Pv = RT$$

$$PV = mRT$$

$$PV = NR_u T$$

- A gas for which this equation is valid is called an **ideal gas** or sometimes a **perfect gas**. The gas constant R is related to a **universal gas constant R_u** , which has the same value for all gases, by the relationship:

$$R = \frac{R_u}{M}$$

- Other equation of state for real gas- Van der Waals

$$\left(P + \frac{a}{V^2}\right)(V - b) = RT$$

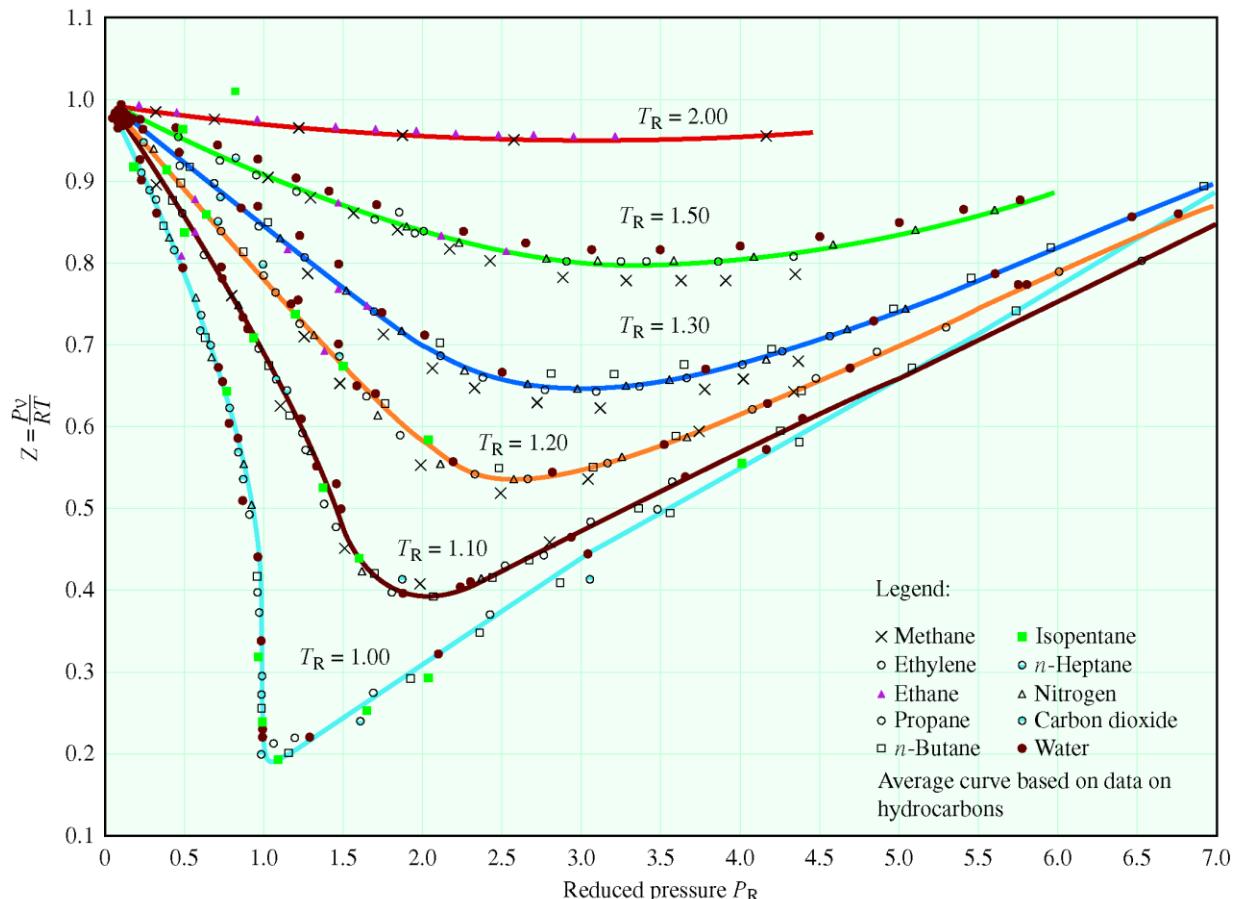
- The *compressibility factor Z* helps us in determining whether or not the *ideal-gas* equation can be used.

$$Pv = ZRT$$

- If $Z = 1$, or very close to 1, the *ideal-gas* equation can be used.

$$T_R = \frac{T}{T_{cr}}$$

$$P_R = \frac{P}{P_{cr}}$$



Thermodynamics Property: Specific Heats

- Constant volume specific heat, C_v
- Constant pressure specific heat, C_p

$$C_v = \left(\frac{\partial u}{\partial T} \right)_{v=c}$$

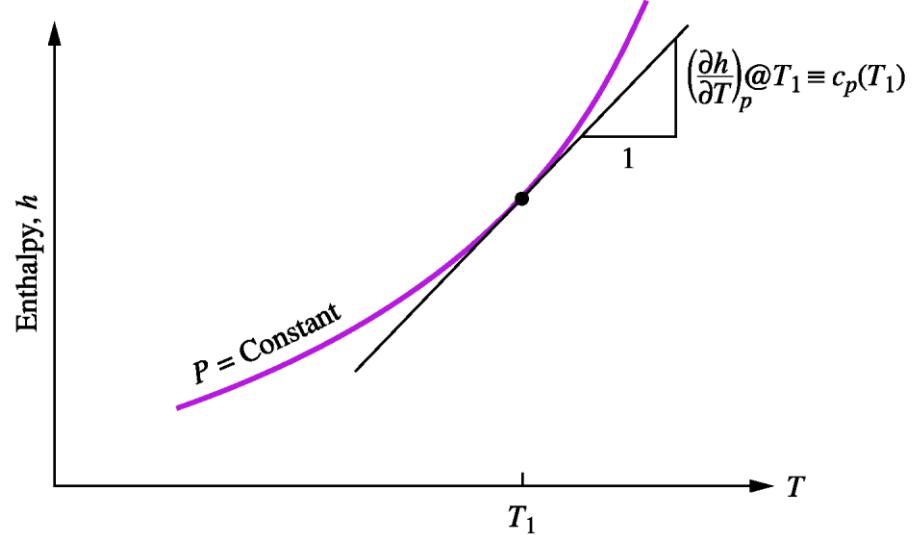
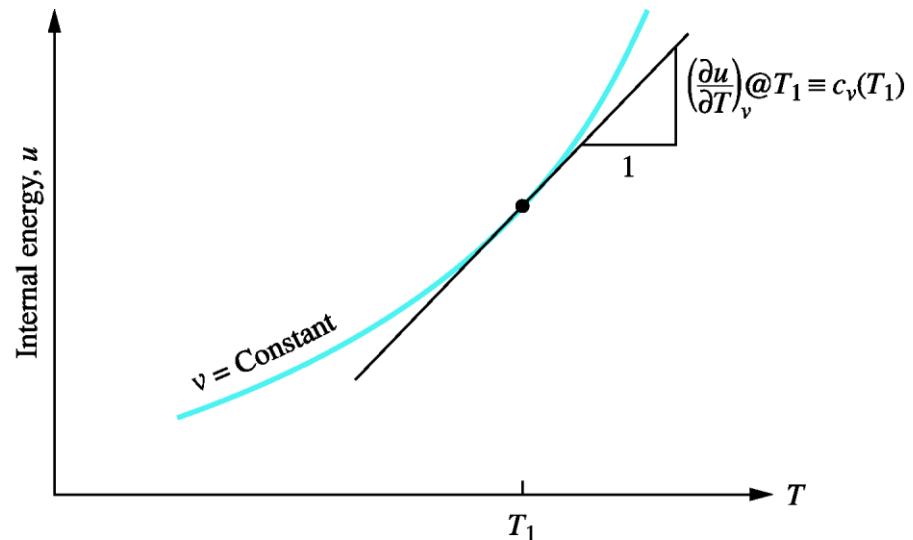
$$C_p = \left(\frac{\partial h}{\partial T} \right)_{p=c}$$

$$du = C_v dT$$

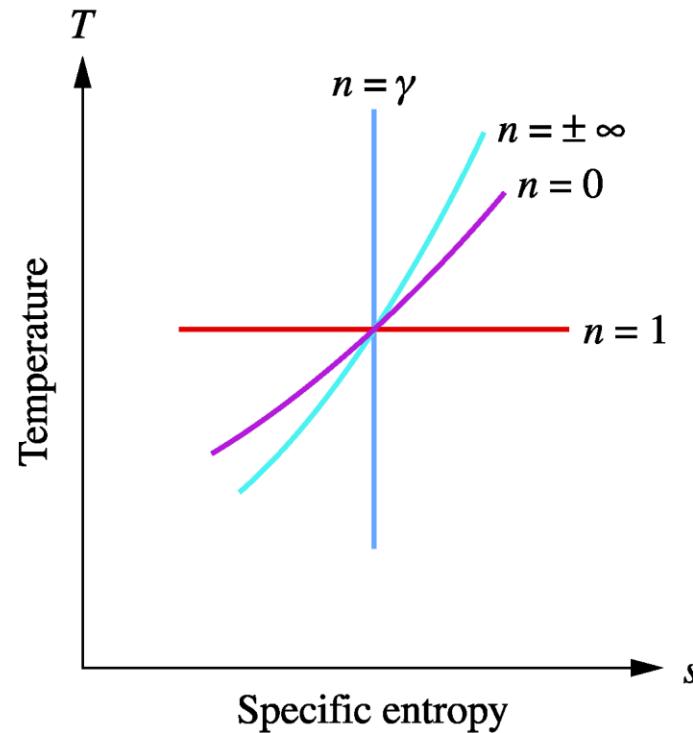
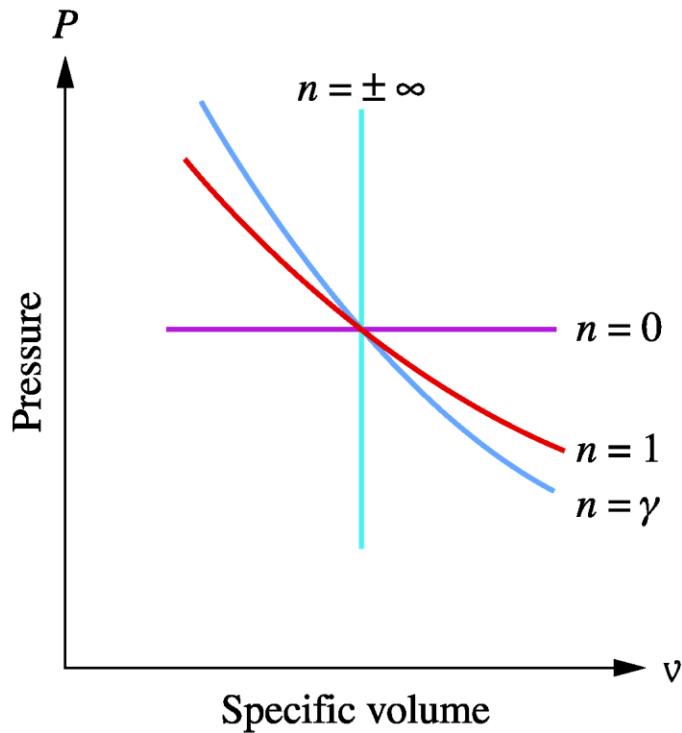
$$dh = C_p dT$$

$$R = C_p - C_v$$

$$k = \frac{C_p}{C_v}$$

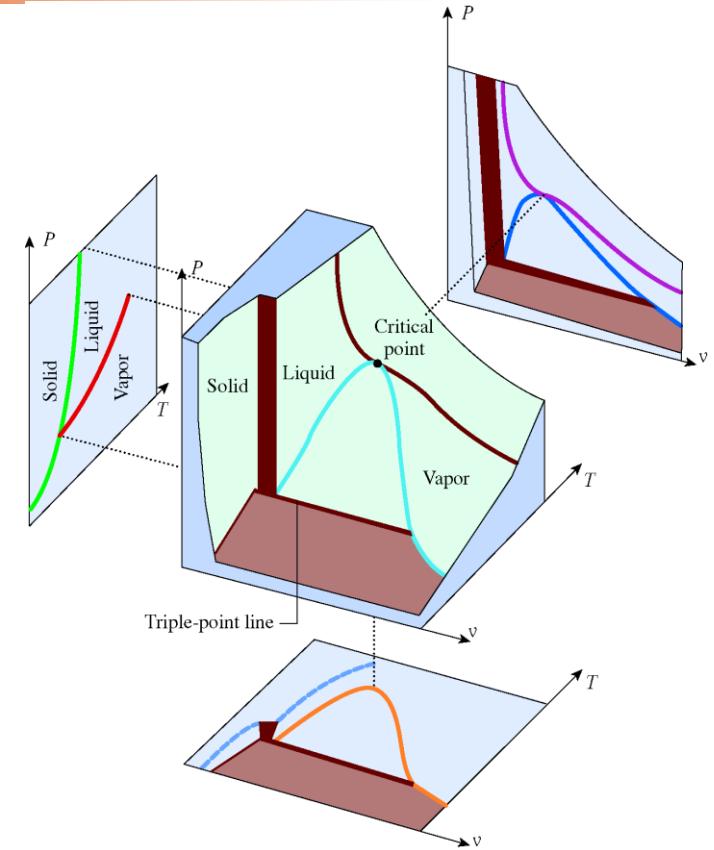
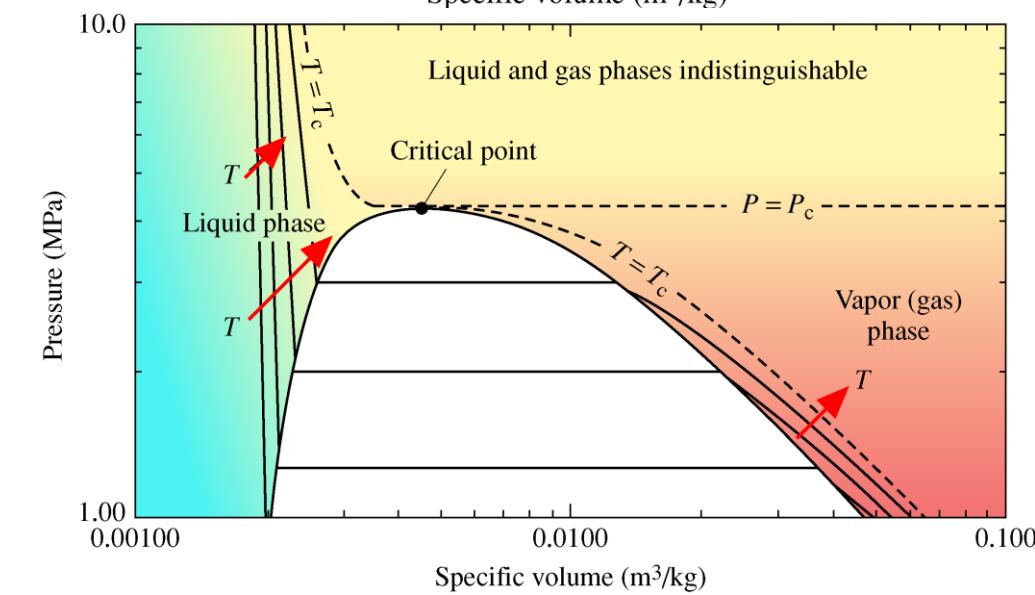
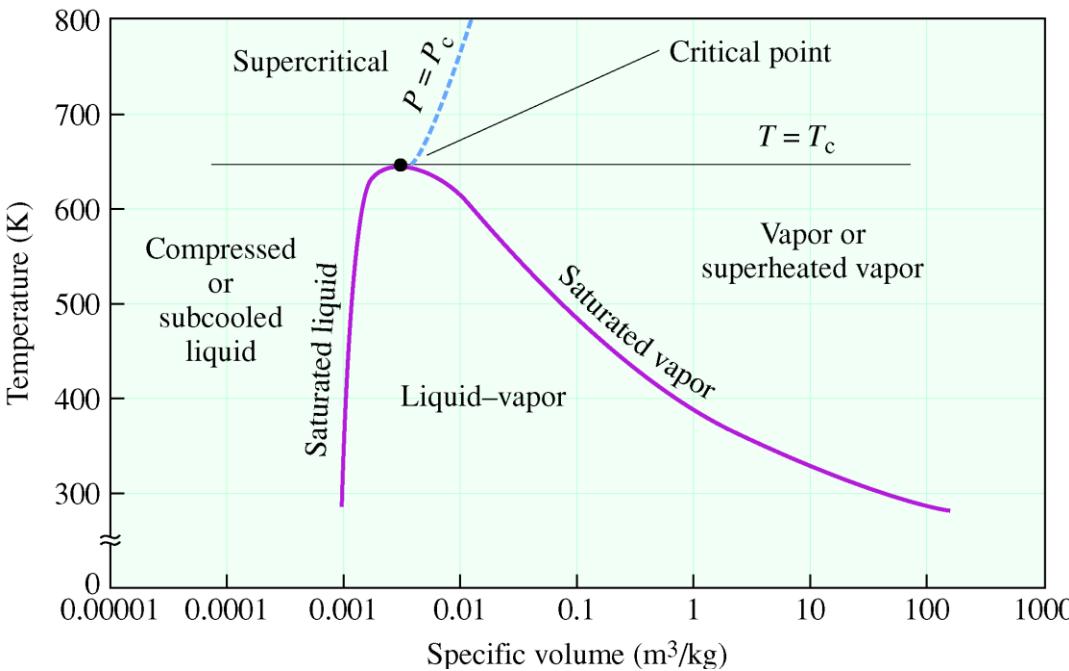


$$PV^n=C$$



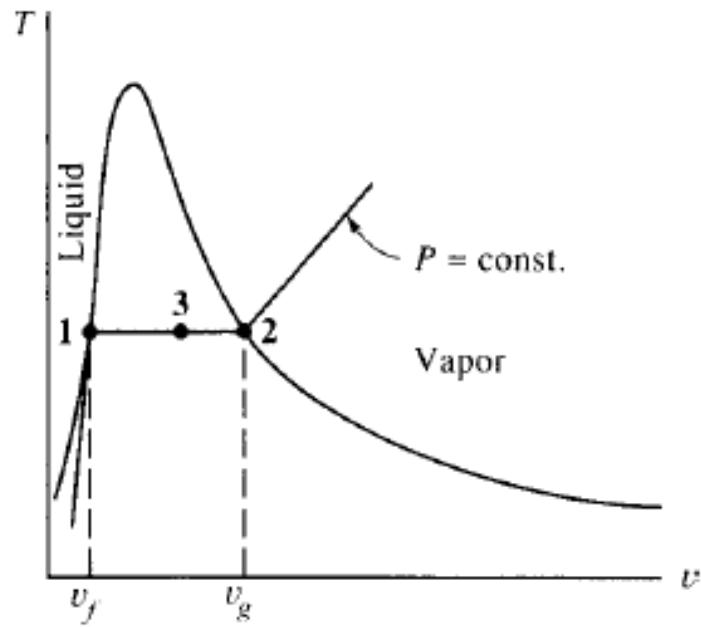
P-v and T-s diagrams illustrating polytropic process paths for special cases of constant pressure ($n = 0$), constant temperature ($n = 1$), constant entropy ($n = \gamma$), and constant volume ($n = \pm\infty$).

Thermodynamics Property: Pure Substance



- Chemically consistent regardless the phase
- A **supercritical state** is encountered when the pressure and temperature are greater than the critical values.

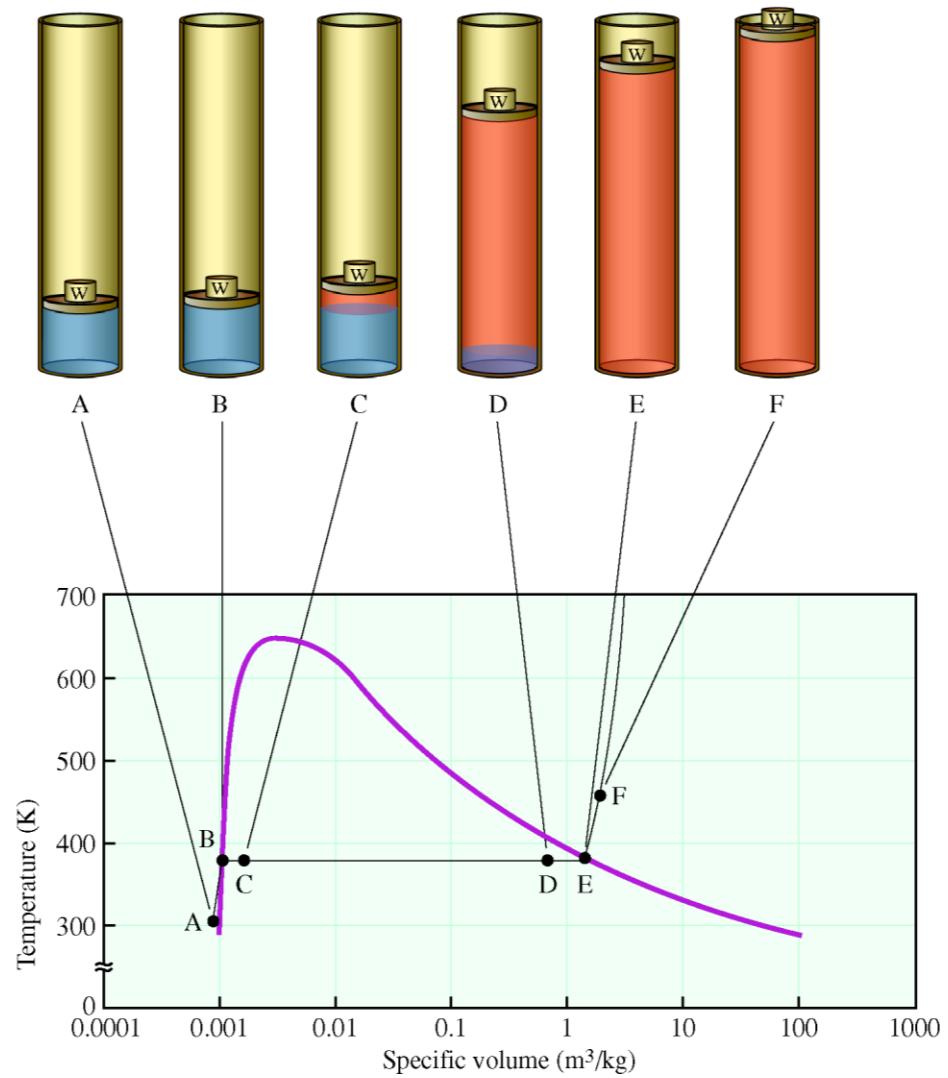
Thermodynamics Property: Pure Substance



$$V = V_f + V_g \quad \text{or} \quad mV = m_f v_f + m_g v_g$$

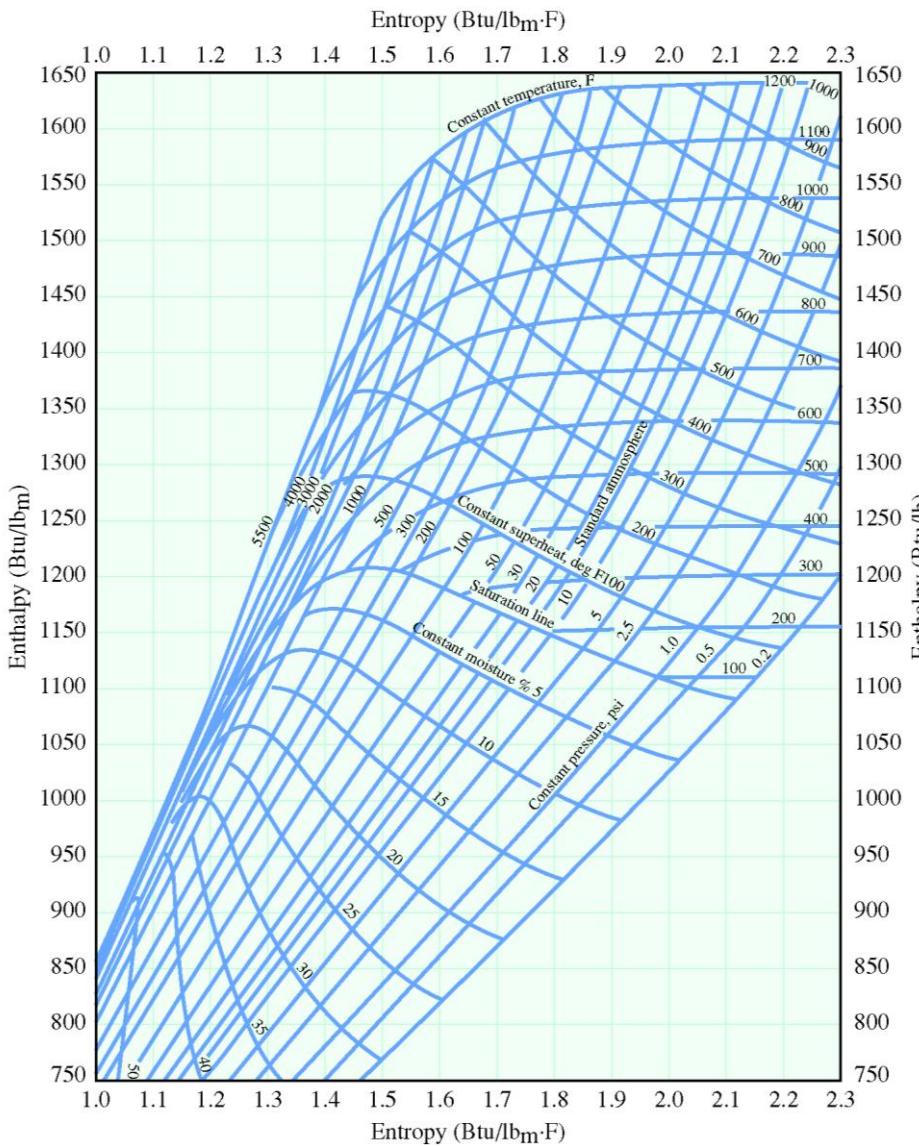
$$x = \frac{m_g}{m}$$

$$v = v_f + x(v_g - v_f)$$



Thermodynamics Property: Pure Substance

- Vapor tables
- Mollier charts
- Properties calculators



- Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electric, magnetic, chemical, and nuclear, and their sum constitutes the **total energy, E** of a system.
- Thermodynamics deals only with the **change** of the total energy.
- **Macroscopic forms of energy:** Those a system possesses as a whole with respect to some outside reference frame, such as kinetic and potential energies.
- **Microscopic forms of energy:** Those related to the molecular structure of a system and the degree of the molecular activity.
- **Internal energy, U :** The sum of all the microscopic forms of energy.
- **Kinetic energy, KE :** The energy that a system possesses as a result of its motion relative to some reference frame.
- **Potential energy, PE :** The energy that a system possesses as a result of its elevation in a gravitational field.
- **Heat And Work:** An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise it is work.

$$E = U + KE + PE = U + m \frac{V^2}{2} + mgz \quad (\text{kJ})$$

$$e = u + ke + pe = u + \frac{V^2}{2} + gz \quad (\text{kJ/kg})$$

- **Heat:** The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.
 - **Conduction:** Solid or fluid at rest (conductivity)
 - **Convection:** Fluid flow and surface (convection coefficient)
 - **Radiation:** surface to surface without medium (emissivity)
- **Work:** The energy transfer associated with a force acting through a distance.
 - **A rising piston, a rotating shaft, and an electric wire crossing the system boundaries** are all associated with work interactions

Heat vs. Work

- Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are *boundary* phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a *process*, not a state.
- Unlike properties, heat or work has no meaning at a state.
- Both are *path functions* (i.e., their magnitudes depend on the path followed during a process as well as the end states).

- Electric Work

- Mechanical Work

$$W = \int_1^2 F \, ds \quad (\text{kJ})$$

- Rotating Shaft

$$T = Fr \quad \rightarrow \quad F = \frac{T}{r}$$

- Spring work

$$F = kx \quad (\text{kN}) \quad \delta W_{\text{spring}} = F \, dx$$

- Chemical work

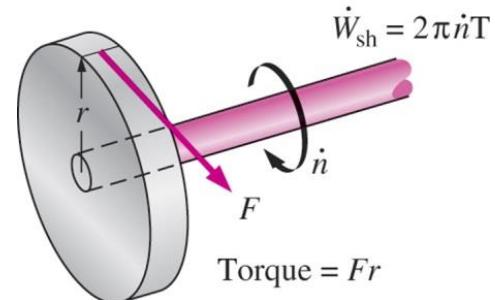
$$W_f = m_f C \cdot V_f$$

$$\dot{W}_e = \mathbf{V}I \quad (\text{W})$$

$$W_e = \mathbf{V}I \Delta t \quad (\text{kJ})$$

$$W_{\text{sh}} = Fs = \left(\frac{T}{r} \right) (2\pi rn) = 2\pi nT \quad (\text{kJ})$$

$$W_{\text{spring}} = \frac{1}{2}k(x_2^2 - x_1^2) \quad (\text{kJ})$$



- Energy is conservation

$$\underbrace{E_{in} - E_{out}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc., energies}} \quad (\text{kJ})$$

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{\text{system}}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}} \quad (\text{kW})$$

$$e_{in} - e_{out} = \Delta e_{\text{system}} \quad (\text{kJ/kg})$$

$$\dot{W}_{\text{net,out}} = \dot{Q}_{\text{net,in}} \quad (\text{for a cycle})$$

$$Q = \dot{Q} \Delta t$$

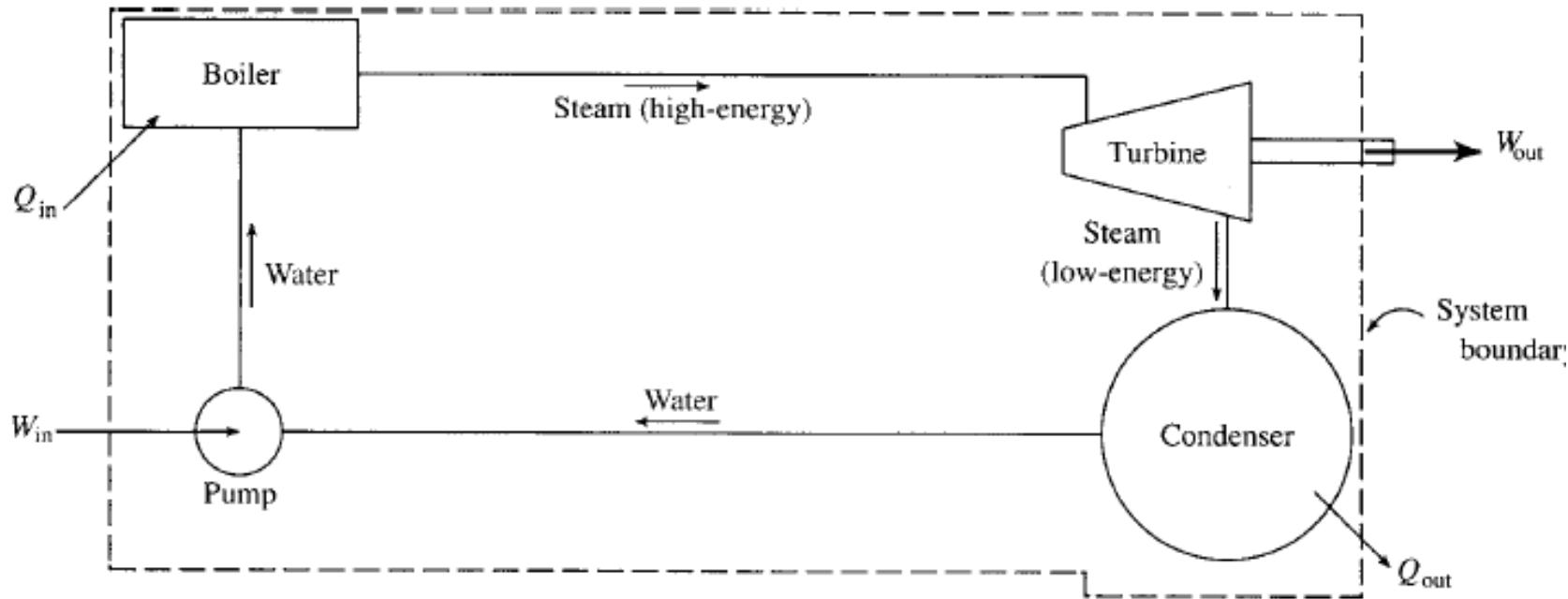
$$W = \dot{W} \Delta t$$

$$\Delta E = (dE/dt) \Delta t$$

- **The zeroth law of thermodynamics:** If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- **First Law of Thermodynamics:** Energy conservation, internal energy and enthalpy are properties of the first law

$$Q-W=\Delta U \text{ for closed system}$$

- **Second Law of thermodynamics:** Energy quality and direction, entropy and exergy (availability) are properties of the second law



- The first law is applied on the system, and its components.
- For a more complete analysis we must relate W_{in} , Q_{in} , W_{out} , and Q_{out} to the pressure and temperature changes for the pump, boiler, turbine, and condenser, respectively.
- Second law will determine the direction of each device process, the device entropy, irreversibility and work destruction

Conservation of Mass and energy

- Mass is conserved as well as the energy

$$\frac{dm_{CV}}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m}$$

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (\text{kg/s}) \quad \dot{m}_1 = \dot{m}_2$$

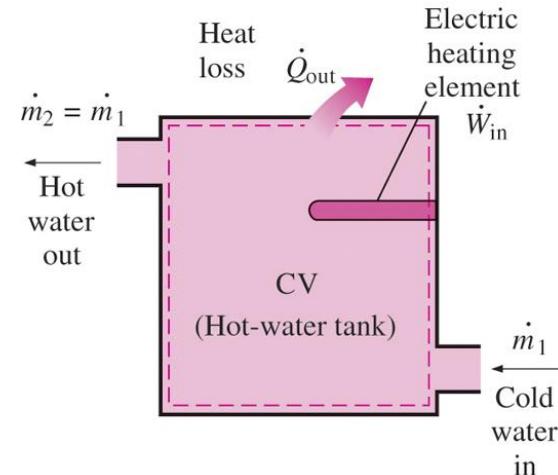
$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{\frac{dE_{\text{system}}}{dt}}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} \xrightarrow{0 \text{ (steady)}} = 0$$

$$\underbrace{\dot{E}_{in}}_{\text{Rate of net energy transfer in by heat, work, and mass}} = \underbrace{\dot{E}_{out}}_{\text{Rate of net energy transfer out by heat, work, and mass}} \quad (\text{kW})$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m} \left(h + \frac{V^2}{2} + gz \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m} \left(h + \frac{V^2}{2} + gz \right)$$

for each inlet

for each exit



- The 1st law stems from the energy conservation law (for steady state steady flow, SSSF)

$$\dot{Q}_{in} + \dot{W}_{in} + \underbrace{\sum_{in} \dot{m} \left(h + \frac{V^2}{2} + gz \right)}_{\text{for each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \underbrace{\sum_{out} \dot{m} \left(h + \frac{V^2}{2} + gz \right)}_{\text{for each exit}}$$

- In open systems, the mass flow across the system' s boundary is carrying the **enthalpy** (internal energy + flow work), **kinetic energy** and **potential energy**. Heat and work are crossing the system's boundary. With E_{b_in} , Q_{in} , W_{in} + and E_{b_out} , Q_{out} , W_{out} -

$$\sum_{i=1}^n \dot{Q}_{bi} + \sum_{i=1}^n \dot{W}_{bi} + \sum_{i=1}^n \dot{E}_{bi} = \left(\frac{dE_s}{dt} \right), \text{ where } E = m \left(h + \frac{V^2}{2} + gz \right)$$

- In closed systems (**control mass**), Internal energy of the system is vary from state to state with system's temperature. Heat and work are crossing the system's boundaries.

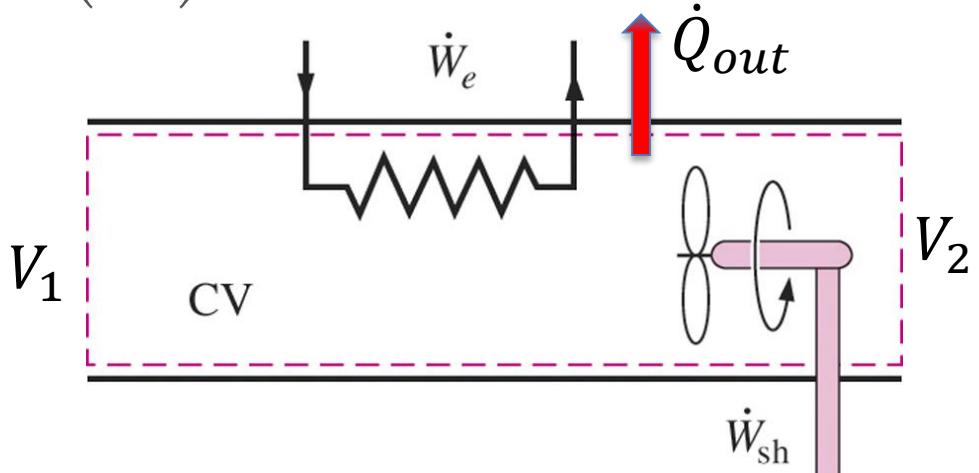
$$\sum_{i=1}^n \dot{Q}_{bi} + \sum_{i=1}^n \dot{W}_{bi} = \frac{dU_s}{dt}$$

- Uniform flow in charging and/or discharging systems (mix), mass flow is carrying energies to the system, accordingly the system's mass and energy will change. Heat and work are crossing the system's boundaries

- With E_{b_in} , Q_{in} , W_{in} + and E_{b_out} , Q_{out} , W_{out} –

$$\sum_{i=1}^n \dot{Q}_{bi} + \sum_{i=1}^n \dot{W}_{bi} + \sum_{i=1}^n \dot{E}_{bi} = \left(\frac{dE_s}{dt} \right) = 0 \text{ Also, } \frac{dm_{CV}}{dt} = 0$$

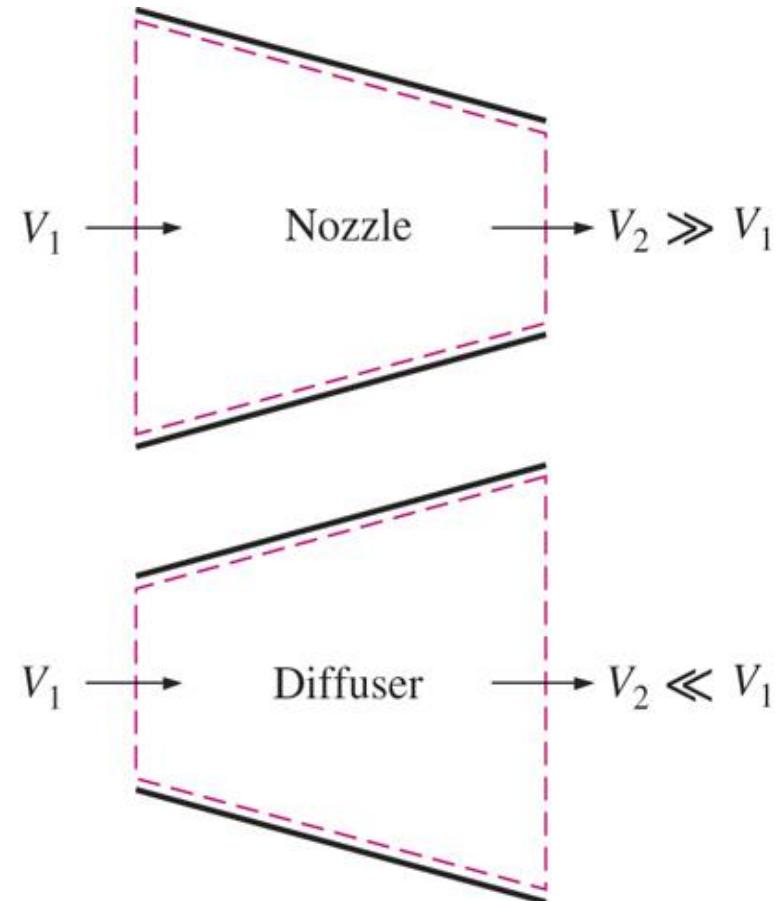
- Air heating system



$$\dot{W}_e + \dot{W}_{sh} - \dot{Q}_{out} + \dot{m}(h_1 - h_2) + \dot{m} \left(\frac{V_1^2 - V_2^2}{2} \right) = 0$$

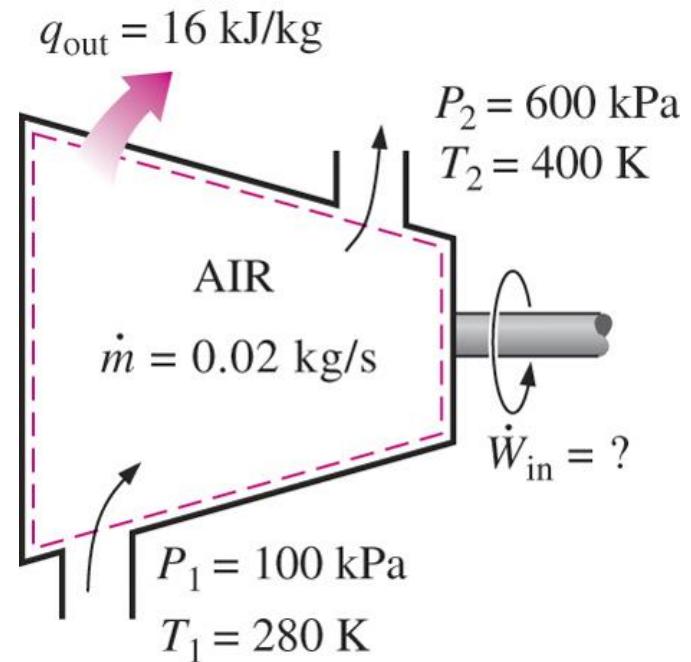
- Nozzle and diffuser

$$\dot{m}(h_1 - h_2) + \dot{m} \left(\frac{V_1^2 - V_2^2}{2} \right) = 0$$



- Compressor and Turbine

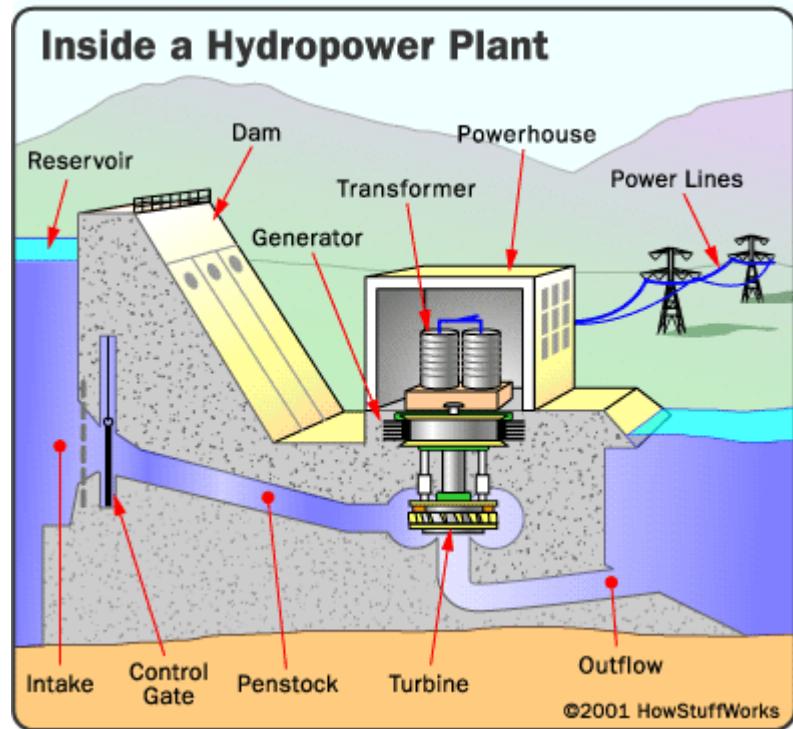
$$\dot{W}_{in} - \dot{Q}_{out} + \dot{m}(h_1 - h_2) = 0$$



- Pumps and Hydrolic turbine

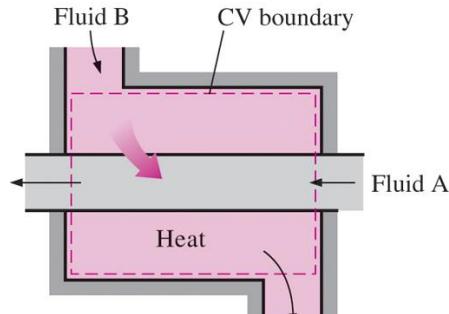
$$\dot{W}_{in} - \dot{Q}_{out} + \dot{m}(h_1 - h_2) + \dot{m}(z_1 - z_2) = 0$$

$$Power_{pump} = \dot{m} \cdot g \cdot head = \Delta p \cdot \dot{V}$$

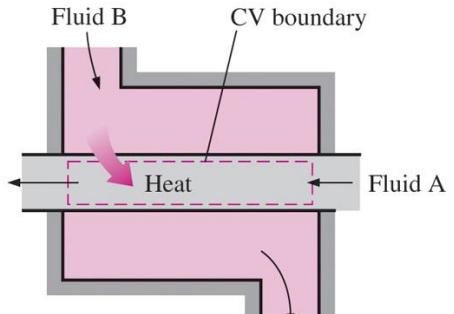


1st Law: SSSF Open Systems Examples

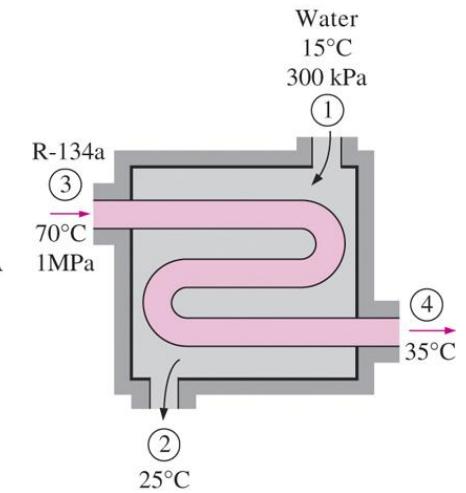
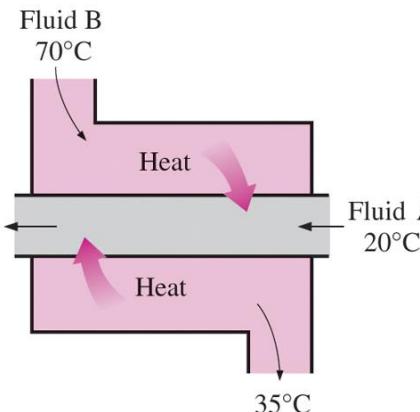
- Heat Exchanger



(a) System: Entire heat exchanger ($Q_{CV} = 0$)



(b) System: Fluid A ($Q_{CV} \neq 0$)

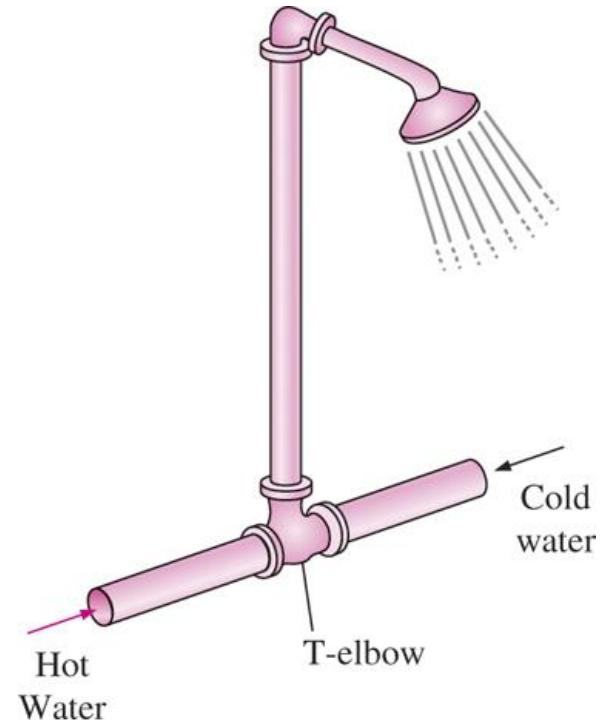


$$\dot{Q}_{out} + \dot{m}(h_{1A} - h_{2A}) = 0$$

$$\dot{m}_A(h_{1A} - h_{2A}) + \dot{m}_B(h_{1B} - h_{2B}) = 0$$

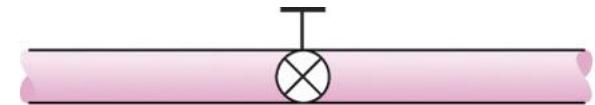
- Heat Exchanger

$$\dot{m}_c h_c + \dot{m}_h h_h - (\dot{m}_c + \dot{m}_h) h_{shower} = 0$$



- Throttling

During a throttling process, the enthalpy of a fluid remains constant. But internal and flow energies may be converted to each other.



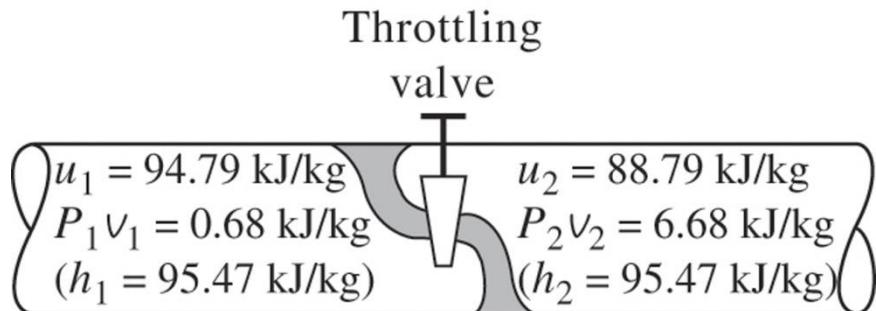
(a) An adjustable valve



(b) A porous plug



(c) A capillary tube

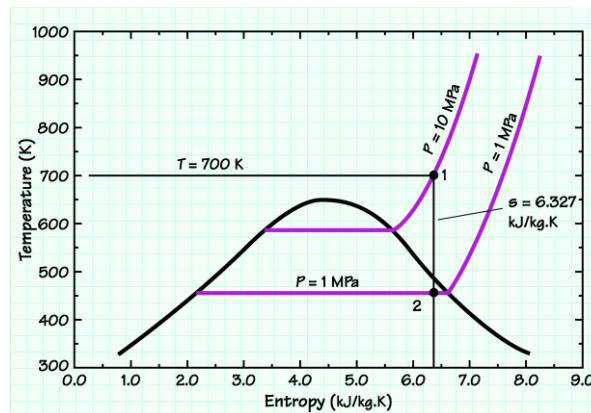
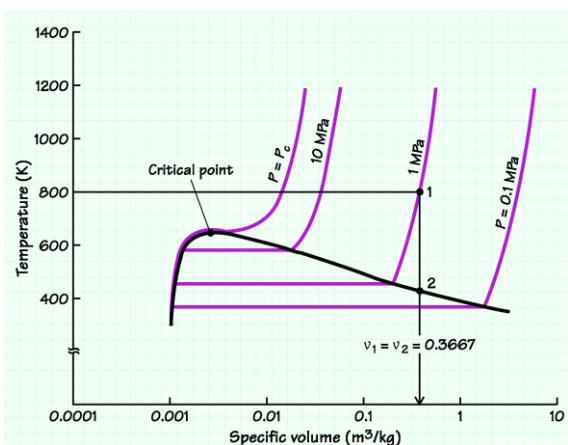
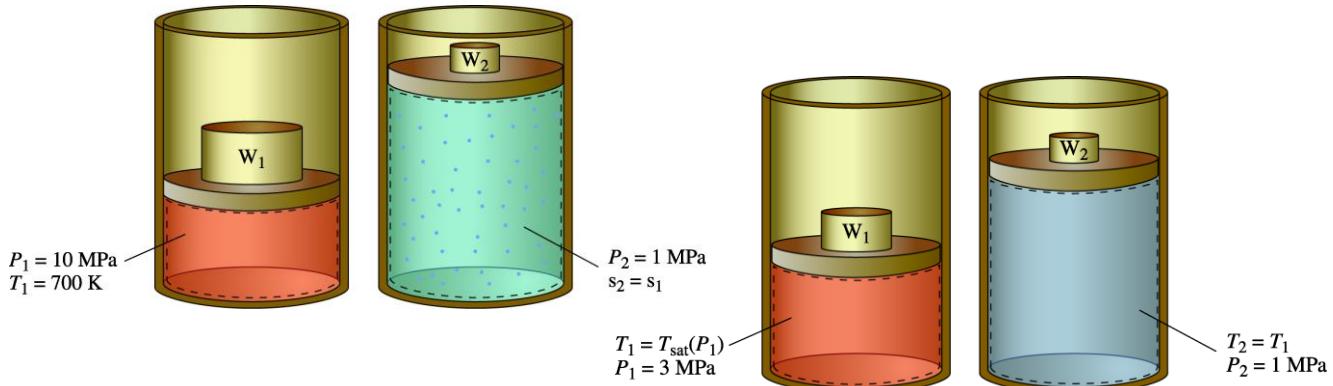
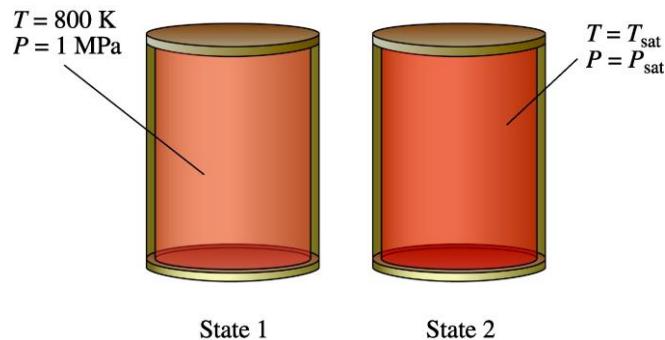


$$\dot{m}(h_1 - h_2) = 0$$

$$u_1 + P_1 v_1 = u_2 + P_2 v_2$$

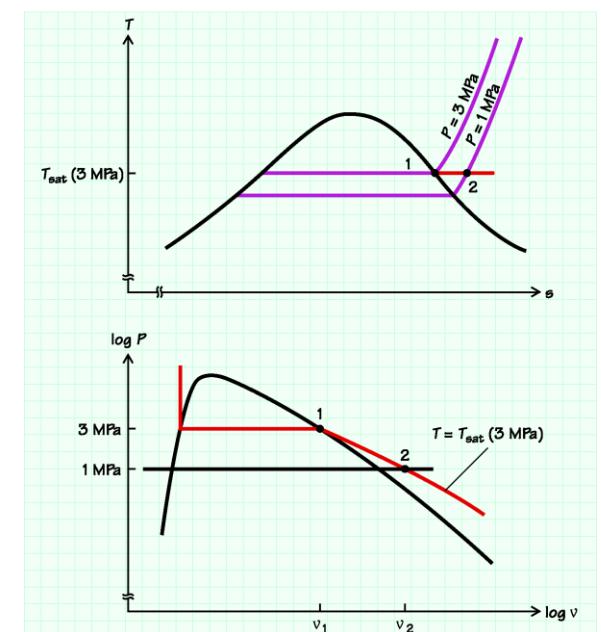
1st Law: Closed Systems Examples

- Piston cylinder and tanks



$$\sum_{i=1}^n \dot{Q}_{bi} + \sum_{i=1}^n \dot{W}_{bi} = \frac{dU_S}{dt}$$

$$\sum_{i=1}^n Q_{bi} + \sum_{i=1}^n W_{bi} = dU_S$$

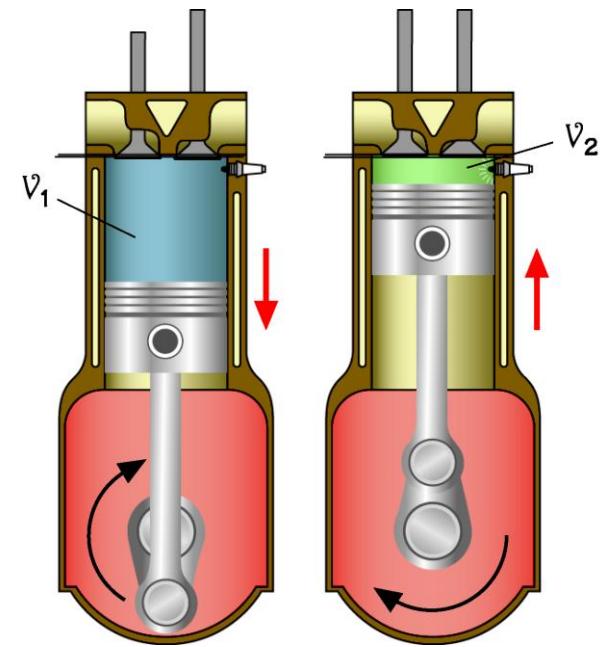
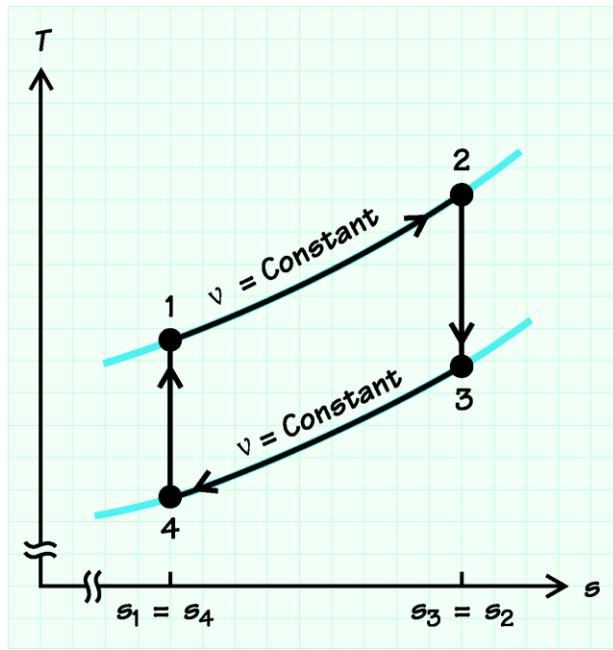
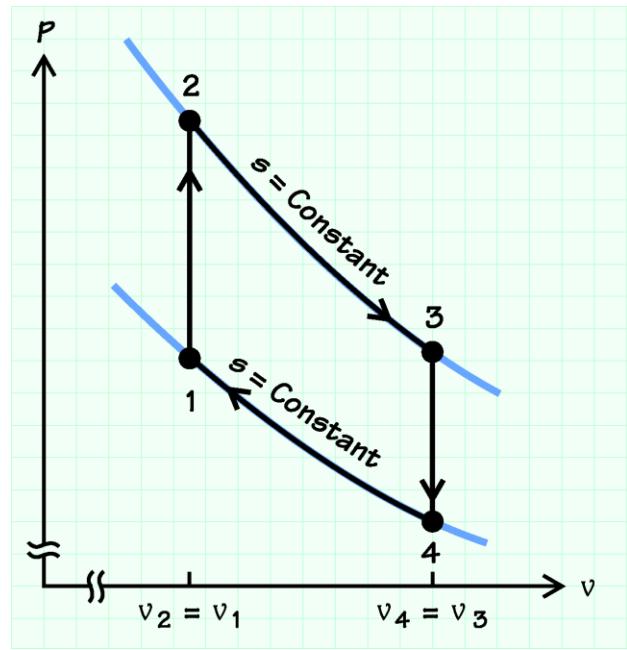


1st Law: Closed Systems Examples

- Piston Engines

$$\sum_{i=1}^n \dot{Q}_{bi} + \sum_{i=1}^n \dot{W}_{bi} = \frac{dU_s}{dt}$$

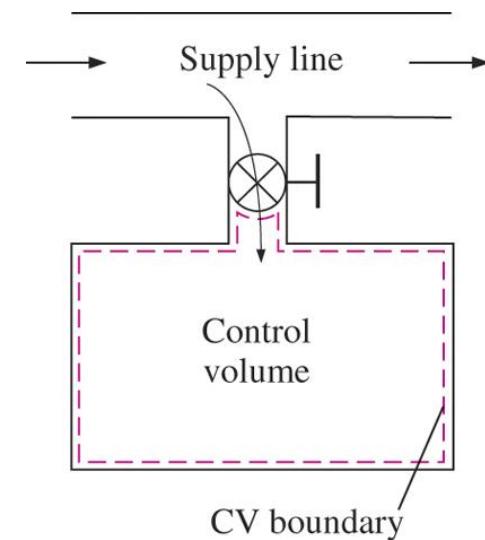
$$\sum_{i=1}^n Q_{bi} + \sum_{i=1}^n W_{bi} = dU_s$$



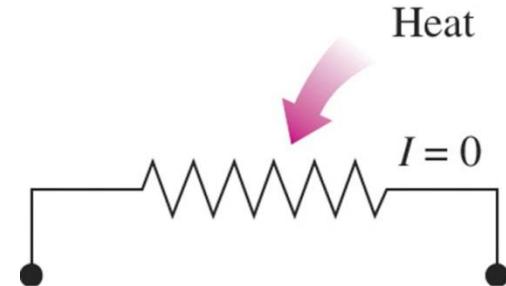
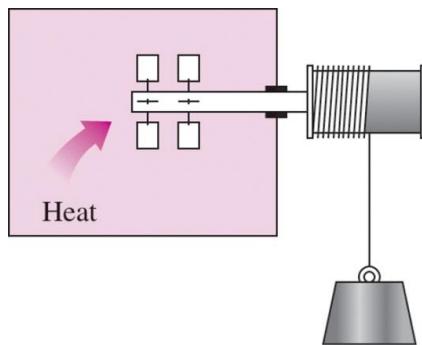
- Piston Engines

$$\sum_{i=1}^n \dot{Q}_{bi} + \sum_{i=1}^n \dot{W}_{bi} + \sum_{i=1}^n \dot{E}_{bi} = \left(\frac{dE_s}{dt} \right) \text{ And,}$$

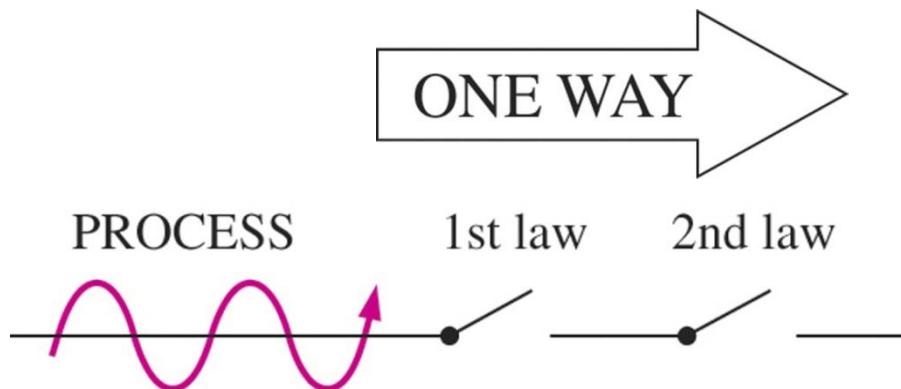
$$\frac{dm_{CV}}{dt} = \dot{m}_{in} - \dot{m}_{out}$$



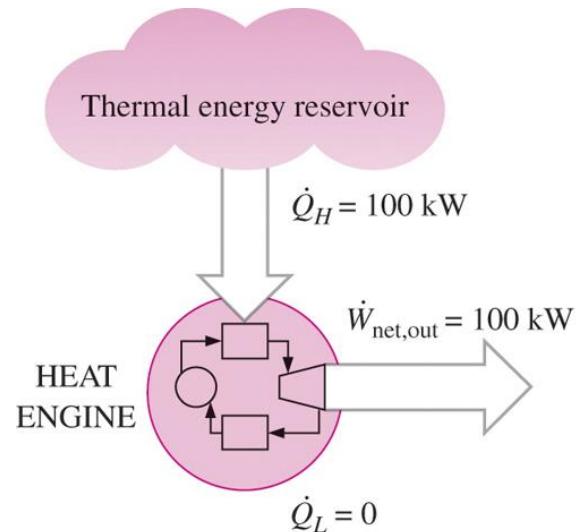
2nd Law of Thermodynamics: Introduction



- A cup of hot coffee does not get hotter in a cooler room.
- Transferring heat to a paddle wheel will not cause it to rotate.
- Processes occur in a certain direction, and not in the reverse direction.
- Transferring heat to a wire will not generate electricity.

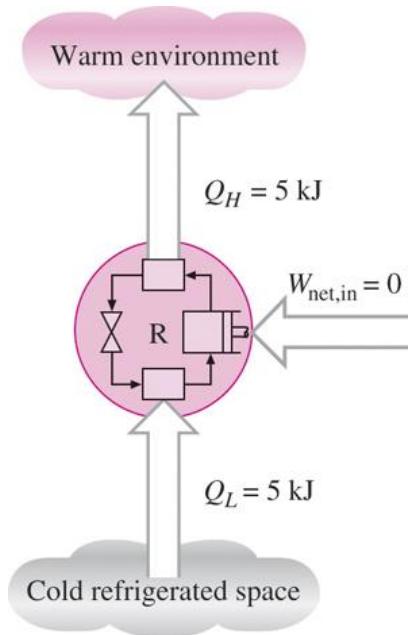


- It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.



- No heat engine can have a thermal efficiency of 100 percent, or as for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace.*
- The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects. It is a limitation that applies to both the idealized and the actual heat engines.

- It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.



- It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor.*
- This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.
- To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.

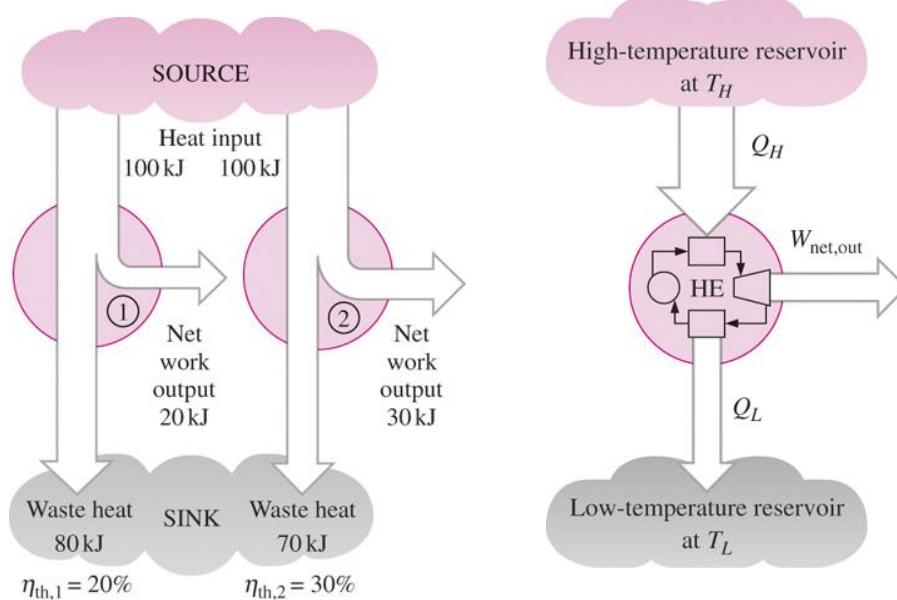
2nd Law: Heat Engine Thermal Efficiency

- Some heat engines perform better than others (convert more of the heat they receive to work).

$$W_{\text{net,out}} = Q_{\text{in}} - Q_{\text{out}}$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_{\text{in}}}$$

$$\eta_{\text{th}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}}$$



$$W_{\text{net,out}} = Q_H - Q_L$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_H}$$

$$\eta_{\text{th}} = 1 - \frac{Q_L}{Q_H}$$

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

Can the value of η_{th} be greater than unity?

- The *efficiency* of a refrigerator is expressed in terms of the **coefficient of performance (COP)**.
- The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.

$$\text{COP}_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\text{net,in}}}$$

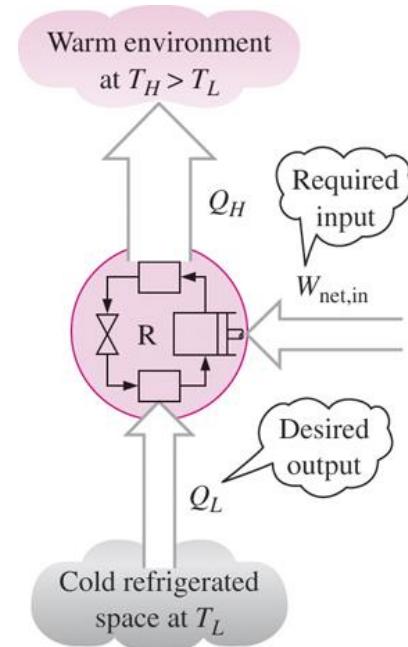
$$W_{\text{net,in}} = Q_H - Q_L \quad (\text{kJ})$$

$$\text{COP}_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

$$\text{COP}_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\text{net,in}}}$$

$$\text{COP}_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H}$$

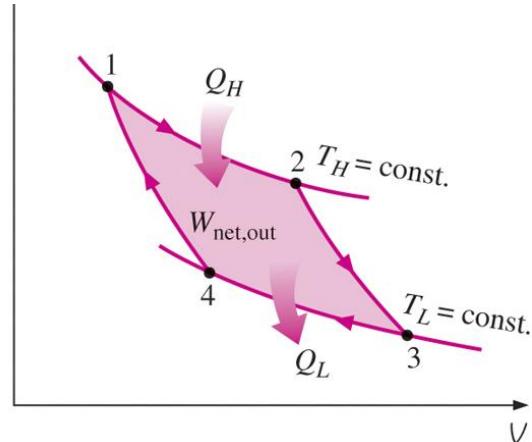
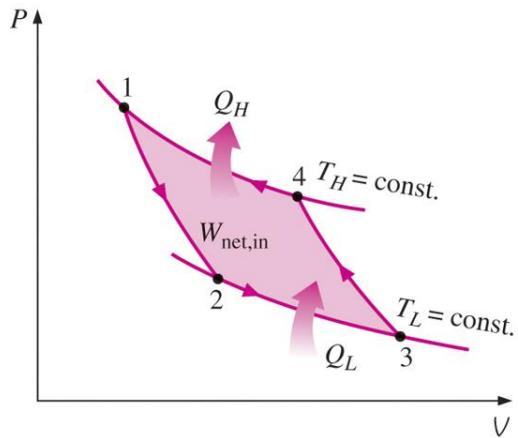
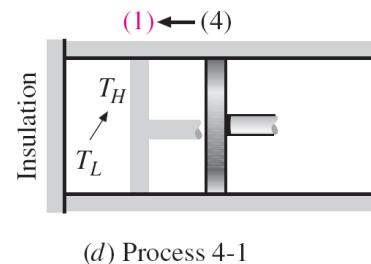
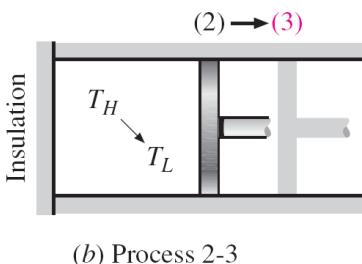
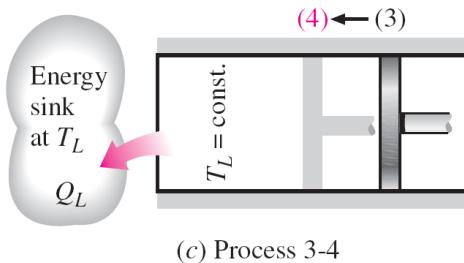
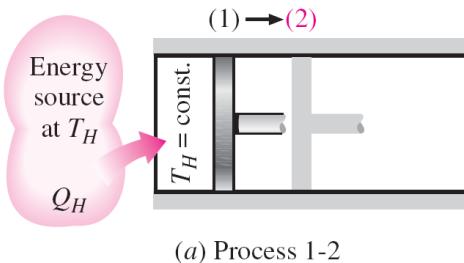
$$\text{COP}_{HP} = \text{COP}_R + 1$$



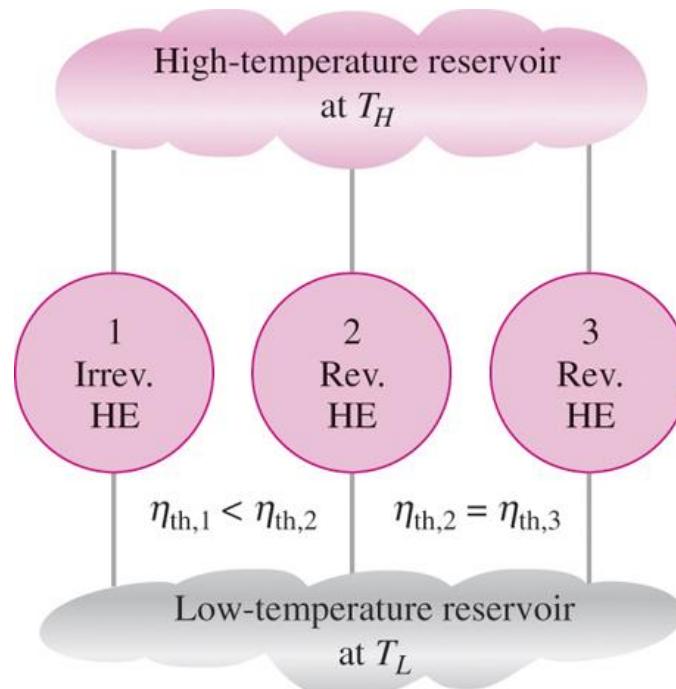
Can the value of COP_R be greater than unity?

2nd Law: Carnot Cycle

- Reversible Isothermal Expansion (process 1-2, $T_H = \text{constant}$)
- Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to T_L)
- Reversible Isothermal Compression (process 3-4, $T_L = \text{constant}$)
- Reversible Adiabatic Compression (process 4-1, temperature rises from T_L to T_H)



1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.



- Clausius inequality

$$\oint \frac{Q}{T} \leq 0, \quad \text{or} \quad \frac{Q_H}{T_H} - \frac{Q_L}{T_L} \leq 0 \quad \left(\frac{Q_H}{Q_L} \right)_{\text{rev}} = \frac{T_H}{T_L}$$

- Carnot Heat Engine

$$\eta_{\text{th}} = 1 - \frac{Q_L}{Q_H}$$

Any heat engine

$$\eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H}$$

Carnot heat engine

$$\eta_{\text{th}} \begin{cases} < & \eta_{\text{th,rev}} \\ = & \eta_{\text{th,rev}} \\ > & \eta_{\text{th,rev}} \end{cases}$$

irreversible heat engine

reversible heat engine

impossible heat engine

- Carnot Refrigerator and Heat Pump

$$\text{COP}_{\text{R}} = \frac{1}{Q_H/Q_L - 1}$$

$$\text{COP}_{\text{HP,rev}} = \frac{1}{1 - T_L/T_H}$$

$$\text{COP}_{\text{HP}} = \frac{1}{1 - Q_L/Q_H}$$

$$\text{COP}_{\text{R,rev}} = \frac{1}{T_H/T_L - 1}$$

$$\left(\frac{Q_H}{Q_L}\right)_{\text{rev}} = \frac{T_H}{T_L}$$

$$\oint \left(\frac{\delta Q}{T}\right)_{\text{int rev}} = 0$$

$$dS = \left(\frac{\delta Q}{T}\right)_{\text{int rev}} \quad (\text{kJ/K})$$

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T}\right)_{\text{int rev}}$$

THE INCREASE OF ENTROPY PRINCIPLE

$$dS \geq \frac{\delta Q}{T}$$

$$\Delta S_{\text{sys}} = S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{\text{gen}}$$

$$S_{\text{gen}} = \Delta S_{\text{total}} = \Delta S_{\text{sys}} + \Delta S_{\text{surr}} \geq 0$$

$$S_{\text{gen}} \begin{cases} > 0 & \text{Irreversible process} \\ = 0 & \text{Reversible process} \\ < 0 & \text{Impossible process} \end{cases}$$

2nd Law: Entropy Relationship

- Gases

$$ds = \frac{du}{T} + \frac{P}{T} dV$$

$$s_2 - s_1 = c_{V,\text{avg}} \ln \frac{T_2}{T_1} + R \ln \frac{V_2}{V_1}$$

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1} \quad (\text{kJ/kg} \cdot \text{K})$$

$$ds = \frac{dh}{T} - \frac{V}{T} dP$$

$$s_2 - s_1 = c_{p,\text{avg}} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

- Liquid and Solid

$$ds = \frac{du}{T} = \frac{c}{T} dT$$

Liquids, solids: $s_2 - s_1 = \int_1^2 c(T) \frac{dT}{T} \cong c_{\text{avg}} \ln \frac{T_2}{T_1} \quad (\text{kJ/kg} \cdot \text{K})$

- Phase change

Flow pure substance phase change tables and charts

- System Entropy

Closed system:
$$\sum \frac{Q_k}{T_k} + S_{\text{gen}} = \Delta S_{\text{system}} = S_2 - S_1 \quad (\text{kJ/K})$$

$$\sum \frac{Q_k}{T_k} + \sum m_i s_i - \sum m_e s_e + S_{\text{gen}} = (S_2 - S_1)_{\text{CV}} \quad (\text{kJ/K})$$

$$\sum \frac{\dot{Q}_k}{T_k} + \sum \dot{m}_i s_i - \sum \dot{m}_e s_e + \dot{S}_{\text{gen}} = dS_{\text{CV}}/dt \quad (\text{kW/K})$$

- Irreversibility (I)

$$I = T_0 S_{\text{gen}}$$

- Is the portion of total energy available to do work
- Also it is A Measure of Work Potential

$$\underbrace{X_{in} - X_{out}}_{\text{Net exergy transfer by heat, work, and mass}} - \underbrace{X_{destroyed}}_{\text{Exergy destruction}} = \underbrace{\Delta X_{system}}_{\text{Change in exergy}}$$

$$\underbrace{\dot{X}_{in} - \dot{X}_{out}}_{\text{Rate of net exergy transfer by heat, work, and mass}} - \underbrace{\dot{X}_{destroyed}}_{\text{Rate of exergy destruction}} = \underbrace{\dot{\Delta X}_{system}}_{\text{Rate of change of exergy}}$$

$$(x_{in} - x_{out}) - x_{destroyed} = \Delta x_{system}$$

- Since flow energy is the sum of nonflow energy and the flow energy, the exergy of flow is the sum of the exergies of nonflow exergy and flow exergy.

$$\begin{aligned}W_{\text{total useful}} &= -(U_0 - U) - P_0(V_0 - V) + T_0(S_0 - S) \\&= (U - U_0) + P_0(V - V_0) - T_0(S - S_0)\end{aligned}$$

$$X = (U - U_0) + P_0(V - V_0) - T_0(S - S_0) + m \frac{\vec{V}^2}{2} + mgz$$

$$\begin{aligned}\phi &= (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{\vec{V}^2}{2} + gz \\&= (e - e_0) + P_0(v - v_0) - T_0(s - s_0)\end{aligned}$$

- Since flow energy is the sum of nonflow energy and the flow energy, the exergy of flow is the sum of the exergies of nonflow exergy and flow exergy.

$$\begin{aligned}
 x_{\text{flowing fluid}} &= x_{\text{nonflowing fluid}} + x_{\text{flow exergy}} \\
 &= (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{\vec{V}^2}{2} + gz + (P - P_0)v \\
 &= (u + Pv) - (u_0 + P_0v_0) - T_0(s - s_0) + \frac{\vec{V}^2}{2} + gz \\
 &= (h - h_0) - T_0(s - s_0) + \frac{\vec{V}^2}{2} + gz
 \end{aligned}$$

The flow (or stream) exergy is given by

$$\psi = (h - h_0) - T_0(s - s_0) + \frac{\vec{V}^2}{2} + gz$$