UNIVERSITY OF COLORADO - BOULDER

ASEN 3113 THERMODYNAMICS AND HEAT TRANSFER

ASEN 3113: Crib Sheet Exam 2

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Contents

I. Cycles

A. Air-Standard Assumptions

- The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
- All the processes that make up the cycle are internally reversible.
- The combustion process is replaced by a heat-addition process from an external source (Fig. 9–8).
- The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.
- When using cold-air-standard assumptions, we can assume constant specific heats at room temperature(25°C or 77°F)

Compression Ratio:

$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_{\text{BDC}}}{V_{\text{TDC}}} \tag{1}$$

Mean Effective Pressure(MEP):

$$\text{MEP} = \frac{W_{\text{net}}}{V_{\max} - V_{\min}} = \frac{w_{\text{net}}}{v_{\max} - v_{\min}} \tag{2}$$

Isentropic Relations for an Ideal Gas:

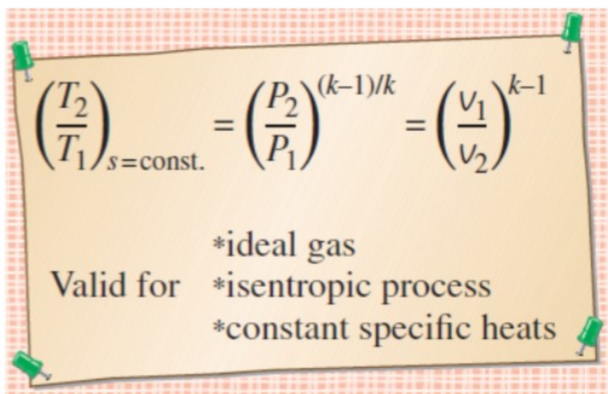


FIGURE 8-35
The isentropic relations of ideal gases are valid for the isentropic processes of ideal gases only.

Fig. 1 Isentropic relations - ideal gas

B. Otto Cycle - Ideal Cycle for Spark Ignition Engines

Processes relationships:

- 1-2 Isentropic compression
- 2-3 Constant-volume heat addition
- 3-4 Isentropic expansion
- 4-1 Constant-volume heat rejection

Closed system so we shall use internal energy.

$$q_{\text{in}} = u_3 - u_2 = c_v\,(T_3 - T_2) \tag{3}$$

$$q_{\text{out}} = u_4 - u_1 = c_v\,(T_4 - T_1) \tag{4}$$

$$\eta_{\text{th,Otto}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1\,(T_4/T_1 - 1)}{T_2\,(T_3/T_2 - 1)} \tag{5}$$

$$\eta_{\text{th,Otto}} = 1 - \frac{1}{r^{k-1}} \tag{6}$$

$$r = \frac{V_{\max}}{V_{\min}} = \frac{V_1}{V_2} = \frac{v_1}{v_2} \tag{7}$$

Basic process for solving assuming air-standard:
- Use internal energy relationships (u)
- During isentropc processes, 1-2 and 3-4, use v_r to determine the next state
- When determining actual specific volume values use $\frac{RT}{P}$
- Compression ratio from 3 to 4 is inverse of 1 to 2
- Need to use longer version of thermal efficiency, which means need qin and qout or wnet
- For isentropic processes the proportion between T1/T2, v1/v2, and vr1/vr2 are all equal so you can substitute those into equations for simplifications

Basic process for COLD-air-standard assumptions
- Assume constant specific heats for c_v and c_p
- Use isentropic relationships for processes 1 to 2 and 3 to 4 as k is constant
- Can use shortened version of thermal efficiency so you only need r and qin to get wnet

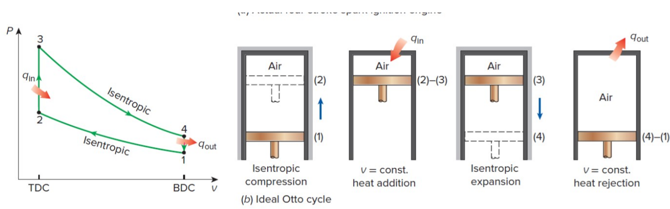


Fig. 2 Otto Cycle - also 4 stroke engines P-V

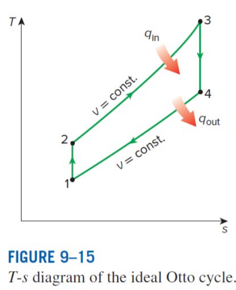


Fig. 3 Otto Cycle - also 4 stroke engines T-S

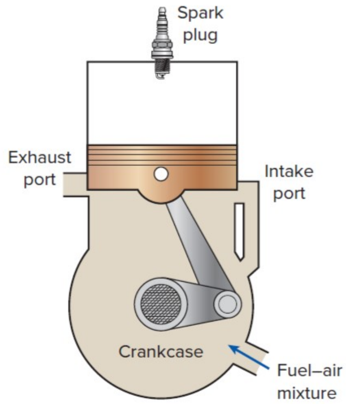


FIGURE 9–13
Schematic of a two-stroke reciprocating engine.

Fig. 4 Otto Cycle - 2 stroke

C. Diesel Cycle - Ideal Cycle for Compression-Ignition Engines

Processes relationships:

- 1-2 Isentropic compression
- 2-3 Constant-pressure heat addition
- 3-4 Isentropic expansion
- 4-1 Constant-volume heat rejection

Forms Closed system:

$$\begin{aligned} q_{\text{in}} &= P_2\left(v_3 - v_2\right) + \left(u_3 - u_2\right) \\ &= h_3 - h_2 = c_p\left(T_3 - T_2\right) \end{aligned} \tag{8}$$

$$q_{\text{out}} = u_4 - u_1 = c_v\left(T_4 - T_1\right) \tag{9}$$

Cutoff Ratio:

$$r_c = \frac{V_3}{V_2} = \frac{v_3}{v_2} \tag{10}$$

$$\eta_{\text{th,Diesel}} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k\left(r_c - 1\right)}\right] \tag{11}$$

$$\eta_{\text{th,Diesel}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{T_4 - T_1}{k\left(T_3 - T_2\right)} = 1 - \frac{T_1\left(T_4/T_1 - 1\right)}{kT_2\left(T_3/T_2 - 1\right)} \tag{12}$$

Basic process for solving assuming air-standard:

- Use relative pressures for isentropic processes to get Pr2 and Pr4
- Need to use enthalpy(h) for qin as the process is not constant volume
- Can use internal energy for qout as the process is constant volume
- Can only use relative volumes to determine compression ratio when process is isentropic, this means you cannot use relative volumes for cutoff ratio but you can use Temperature proportions
- Because it is an ideal gas you can sub volume ratios for temperature ratios at the same states

Basic process for COLD-air-standard assumptions

- Can use short cut equation for thermal efficiency that only needs k, r, and r_c
- Assume constant specific heats
- Can use isentropic relations from 1-2 and 3-4

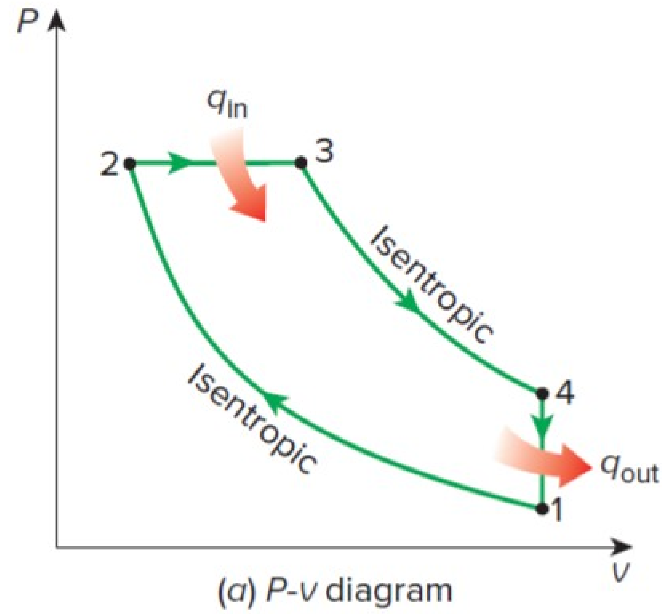


Fig. 5 Diesel - PV

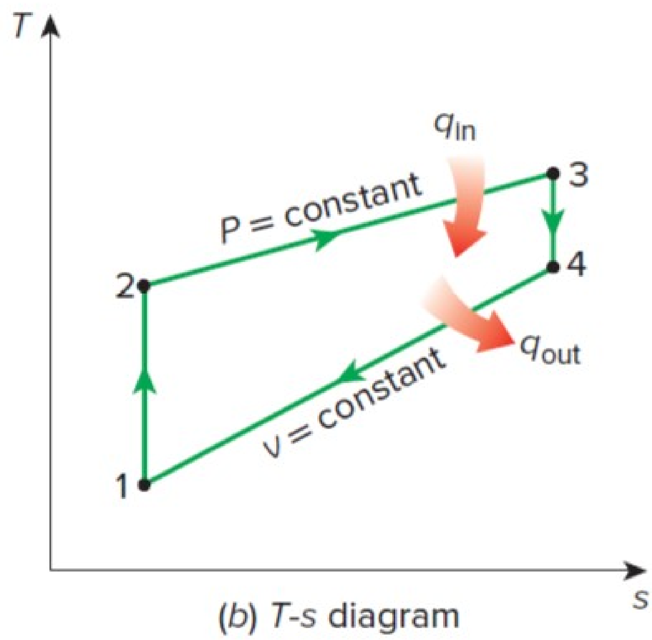


Fig. 6 Diesel - TS

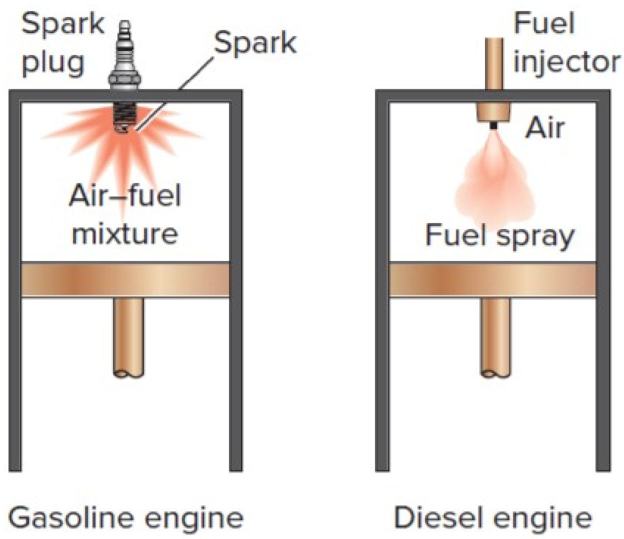


FIGURE 9–20
In diesel engines, the spark plug is replaced by a fuel injector, and only air is compressed during the compression process.

Fig. 7 Diesel - general

D. Brayton Cycle - Ideal Cycle for Gas Turbine Engines

Processes relationships:

- 1-2 Isentropic compression (in a compressor)
- 2-3 Constant-pressure heat addition
- 3-4 Isentropic expansion (in a turbine)
- 4-1 Constant-pressure heat rejection

Modeled as closed-system:

$$q_{\text{in}} = h_3 - h_2 = c_p\,(T_3 - T_2) \tag{13}$$

$$q_{\text{out}} = h_4 - h_1 = c_p\,(T_4 - T_1) \tag{14}$$

$$\eta_{\text{th, Brayton}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} = 1 - \frac{c_p\,(T_4 - T_1)}{c_p\,(T_3 - T_2)} = 1 - \frac{T_1\,(T_4/T_1 - 1)}{T_2\,(T_3/T_2 - 1)} \tag{15}$$

$$\eta_{\text{th, Brayton}} = 1 - \frac{1}{r_p^{(k-1)/k}} \tag{16}$$

$$r_p = \frac{P_2}{P_1} \tag{17}$$

Work in happens through the compressor which is processes 1-2:

$$w_{\text{comp,in}} = h_2 - h_1 \tag{18}$$

Work out happens through the turbine which is processes 3-4:

$$w_{\text{turb,out}} = h_3 - h_4 \tag{19}$$

Back work ratio is the ratio between the work in and the work out:

$$r_{bw} = \frac{w_{\text{comp,in}}}{w_{\text{turb,out}}} \tag{20}$$

Basic process for solving assuming air-standard:
- Use relative pressure relationships
- For both qin and qout, need to use change in enthalpy(h) as there is no constant volume processes
- If given back work ratio then you need to only solve for compressor or turbine work in order to get the other
- net work on system is difference in work from compressor to turbine
- Pressure ratio and compression ratio ARE NOT THE SAME
- Pressures at 2 and 3 are equal and 1 and 4 are equal

Basic process for COLD-air-standard assumptions
- Assume constant specific heats for c_v and c_p
- Use isentropic relationships for processes 1 to 2 and 3 to 4 as k is constant
- Can use shortened version of thermal efficiency so you only need rp and k

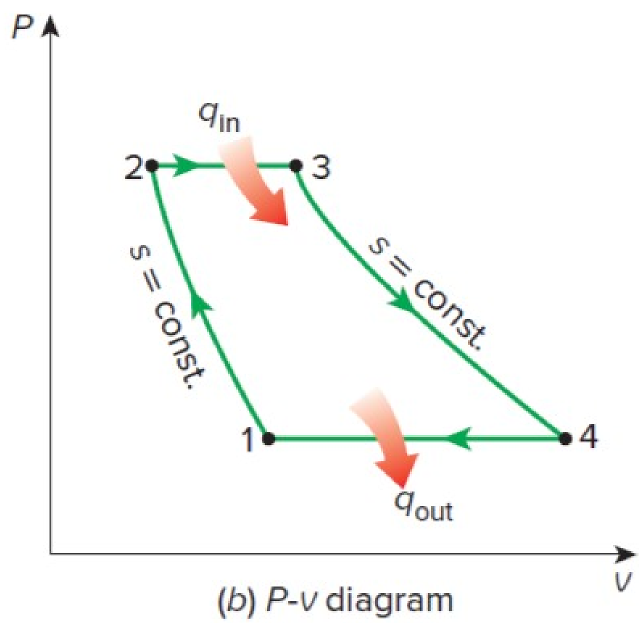


Fig. 8 Brayton - PV

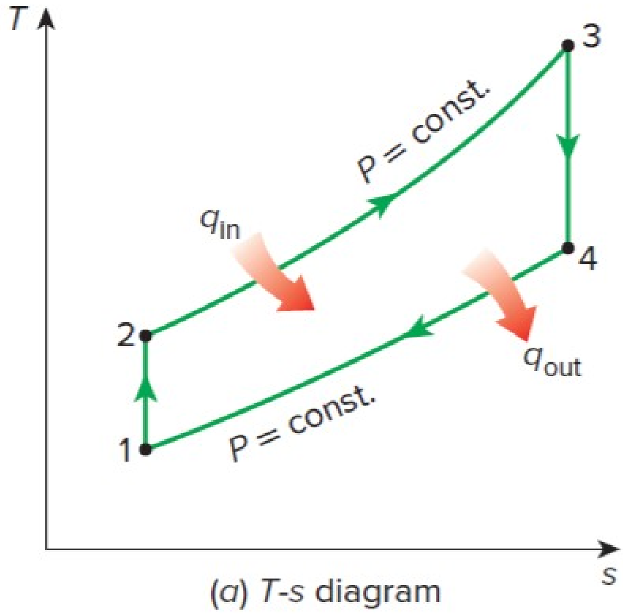


Fig. 9 Brayton - TS

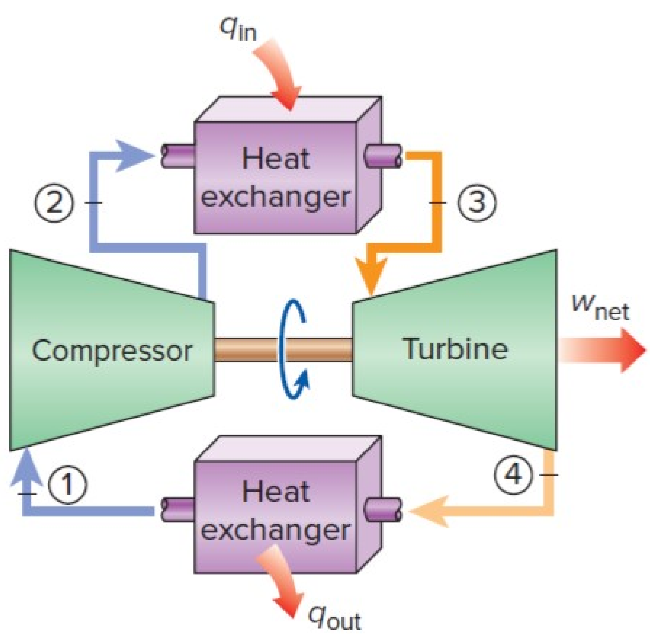


FIGURE 9–26
A closed-cycle gas-turbine engine.

Fig. 10 Brayton - General

E. Deviation of Actual Gas-Turbine Cycles from Idealized Ones

In actual Idealized Gas-Turbine cycles, the compressor and turbine have separate efficiencies that determine the work put in and taken out of the system, respectively. To solve these problems, one must isentropic quantities denoted by a subscript s to find the actual quantities denoted by subscript a.

$$\eta_C = \frac{w_s}{w_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1} \tag{21}$$

$$\eta_T = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \tag{22}$$

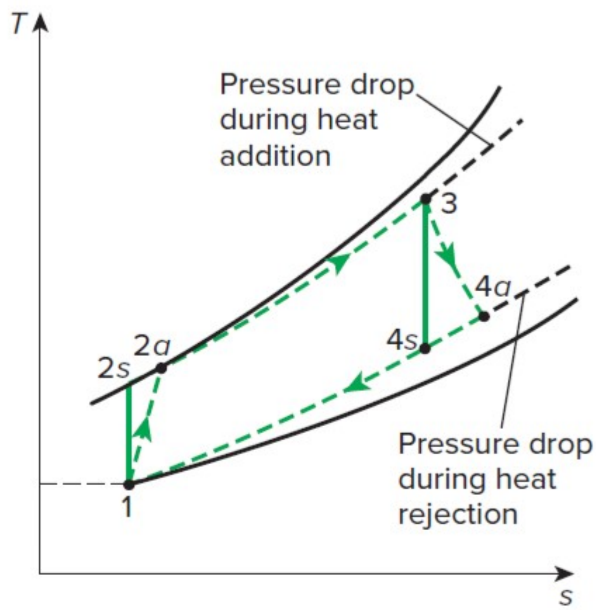


FIGURE 9–32
The deviation of an actual gas-turbine cycle from the ideal Brayton cycle as a result of irreversibilities.

Fig. 11 Brayton - Non-idealized

Basic process for solving assuming air-standard:
- Use relative pressure relationships
- For both qin and qout, need to use change in enthalpy(h) as there is no constant volume processes
- If given back work ratio then you need to only solve for compressor or turbine work in order to get the other
- net work on system is difference in work from compressor to turbine
- Pressure ratio and compression ratio ARE NOT THE SAME
- Pressures at 2 and 3 are equal and 1 and 4 are equal
- Need to use compressor and turbine efficiencies in combination with isentropic enthalpies to determine actual enthalpies
- When determining qin and qout, you must use actual enthalpies and not isentropic ones

Basic process for COLD-air-standard assumptions
- Assume constant specific heats for c_v and c_p
- Use isentropic relationships for processes 1 to 2 and 3 to 4 as k is constant
- Can use shortened version of thermal efficiency so you only need rp and k

F. Brayton With Regeneration

Regenerator is recommended only when the turbine exhaust temperature is higher than the compressor exit temperature.

$$q_{\text{regen,act}} = h_5 - h_2 \tag{23}$$

$$q_{\text{regen,max}} = h_{5'} - h_2 = h_4 - h_2 \tag{24}$$

$$\epsilon = \frac{q_{\text{regen,act}}}{q_{\text{regen,max}}} = \frac{h_5 - h_2}{h_4 - h_2} \tag{25}$$

With cold-air-standard assumptions:

$$\epsilon \cong \frac{T_5 - T_2}{T_4 - T_2} \tag{26}$$

$$\eta_{\text{th,regen}} = 1 - \left(\frac{T_1}{T_3}\right)\left(r_p\right)^{(k-1)/k} \tag{27}$$

Basic process for solving assuming air-standard:

- qin is now the difference between h3 and h5 because of the regeneration
- qout is now the difference between h6 and h1
- heat saved because of regeneration is the difference between h5 and h2
- use effectiveness to determine h4 or h5
- if effectiveness is 100% then h5 is equal to h4
- rest of the process is the same as the original Brayton cycle

Basic process for COLD-air-standard assumptions

- Assume constant specific heats for c_v and c_p
- Use isentropic relationships for processes 1 to 2 and 3 to 4 as k is constant
- Can use shortened version of thermal efficiency so you only need rp and k
- Can use shortened equation for thermal efficiecy

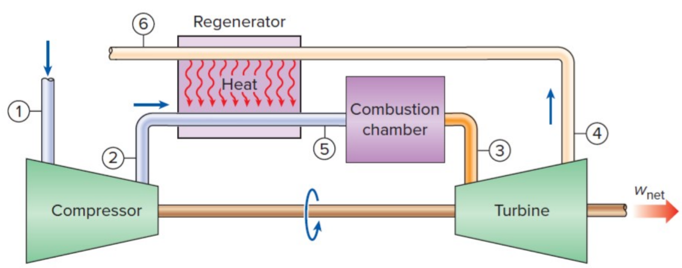


Fig. 12 Brayton - Regenerator

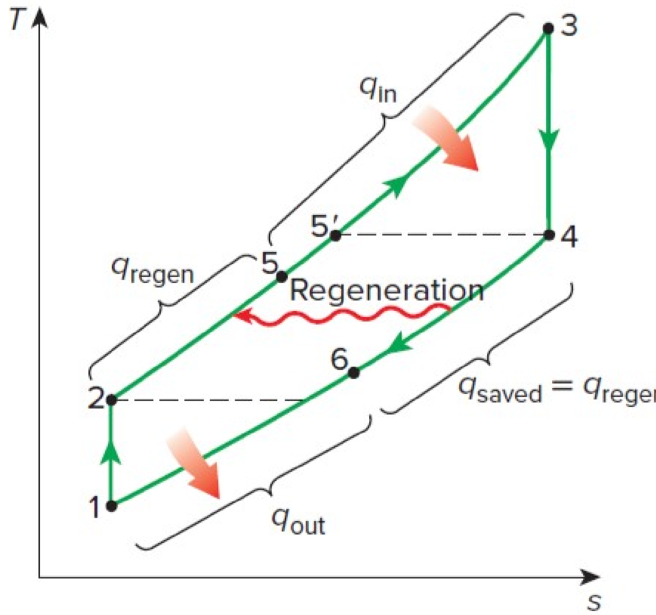


FIGURE 9–35

T-*s* diagram of a Brayton cycle with regeneration.

Fig. 13 Brayton - Regenerator TS

G. Carnot Vapor Cycle

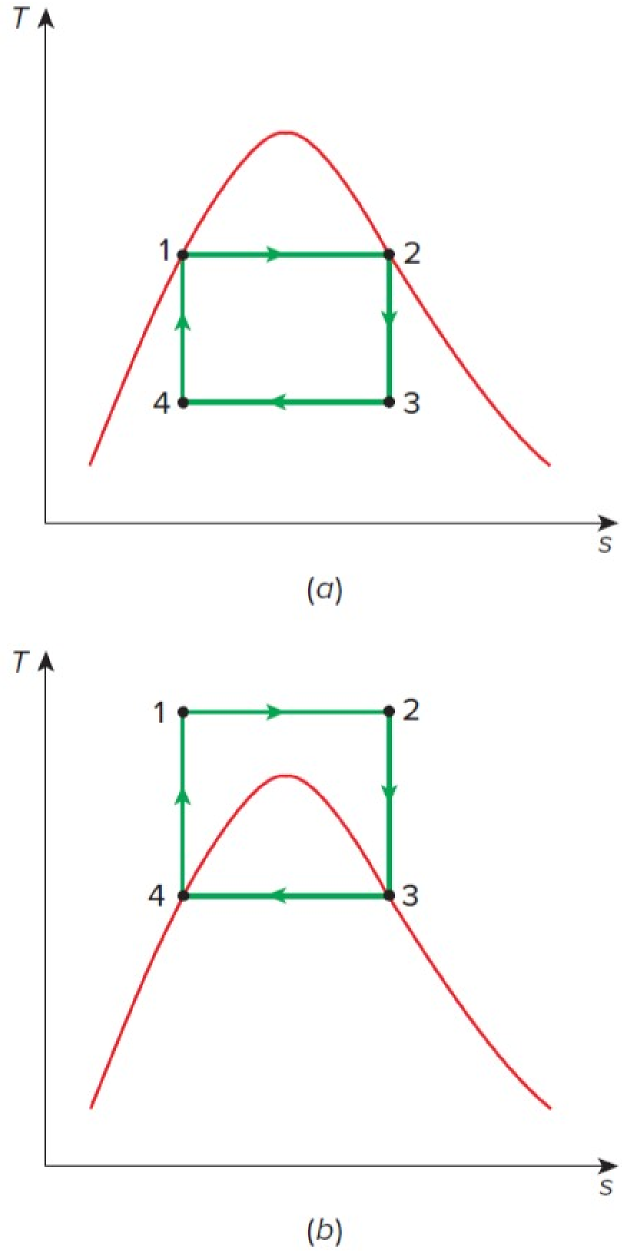


FIGURE 9–38
T-s diagram of two Carnot vapor cycles.

Fig. 14 Carnot Vapor Cycle

H. Rankine Cycle: Ideal Cycle for Vapor Power Cycles

Processes relationships:

- 1-2 Isentropic compression in a pump
- 2-3 Constant-pressure heat addition in a boiler
- 3-4 Isentropic expansion in a turbine
- 4-1 Constant-pressure heat rejection in a condenser

$$w_{\text{pump,in}} = h_2 - h_1 \tag{28}$$

$$w_{\text{pump,in}} = v\left(P_2 - P_1\right) \tag{29}$$

Where:

$$h_1 = h_{f\,@P_1} \text{ and } v \cong v_1 = V_{f\,@P_1} \tag{30}$$

$$\begin{aligned} q_{\text{in}} &= h_3 - h_2 \\ w_{\text{turb , out}} &= h_3 - h_4 \\ q_{\text{out}} &= h_4 - h_1 \end{aligned} \tag{31}$$

Basic process for solving assuming air-standard:

- From state 1 determine h1 and v1, this is the fluid as it is a saturated fluid
- State 2 and state 3 have the same Pressures
- State 4 and state 1 have the same pressures
- State 4 is a liquid gas mixture so you can use s to determine the quality of the mixture as s3 equals s4

Basic process for COLD-air-standard assumptions

- Assume constant specific heats for c_v and c_p
- Use isentropic relationships for processes 1 to 2 and 3 to 4 as k is constant
- If given heat rate, can determine thermal efficiency easily from shortened equation

$$\eta_{\text{th}} = \frac{w_{\text{net}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}} \tag{32}$$

$$\eta_{\text{th}} = \frac{3412(\text{Btu/kWh})}{\text{Heat rate (Btu/kWh)}} \tag{33}$$

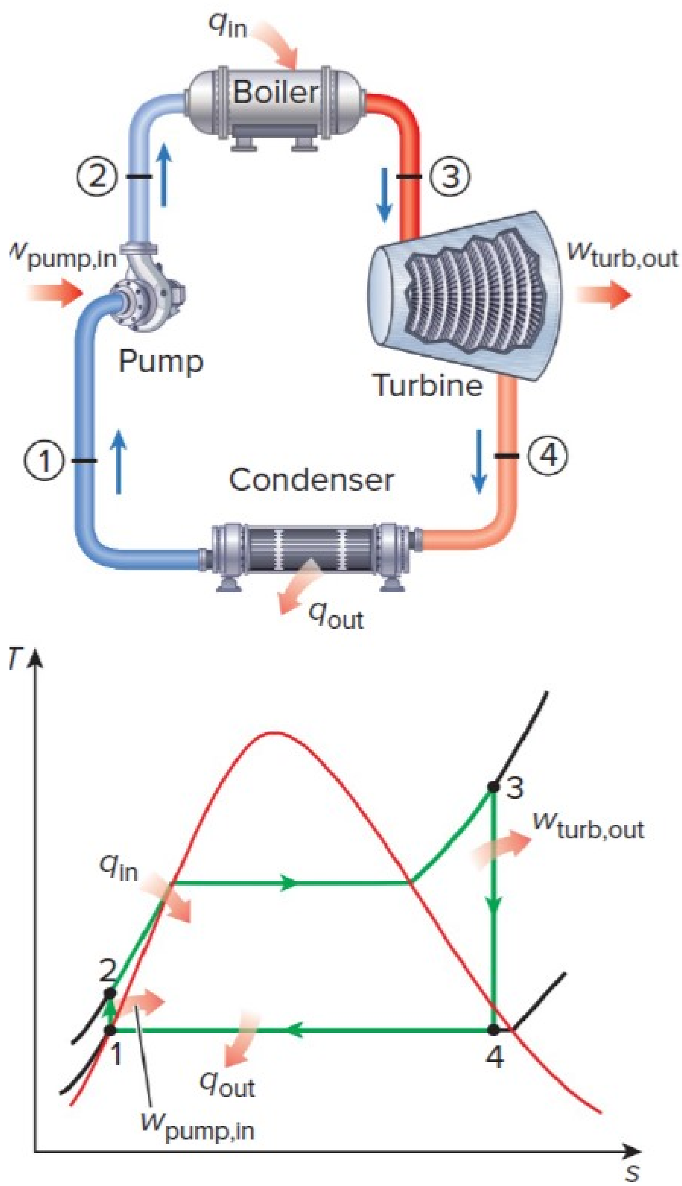


FIGURE 9–39
The simple ideal Rankine cycle.

Fig. 15 Rankine Cycle

I. Deviation of Actual Vapor Power Cycles from Idealized ones

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s}-h_1}{h_{2a}-h_1}$$
$$\eta_T = \frac{w_a}{w_s} = \frac{h_3-h_{4a}}{h_3-h_{4s}} \tag{34}$$

Basic process for solving assuming air-standard:

- From state 1 determine h1 and v1, this is the fluid as it is a saturated fluid

- State 2 and state 3 have the same Pressures
- State 4 and state 1 have the same pressures
- State 4 is a liquid gas mixture so you can use s to determine the quality of the mixture as s3 equals s4
- Similar to Brayton non ideal, need to take into consideration the efficiencies of the turbines and compressor to determine the actual enthalpies for h4 and h2

Basic process for COLD-air-standard assumptions

- Assume constant specific heats for c_v and c_p
- Use isentropic relationships for processes 1 to 2 and 3 to 4 as k is constant
- If given heat rate, can determine thermal efficiency easily from shortened equation

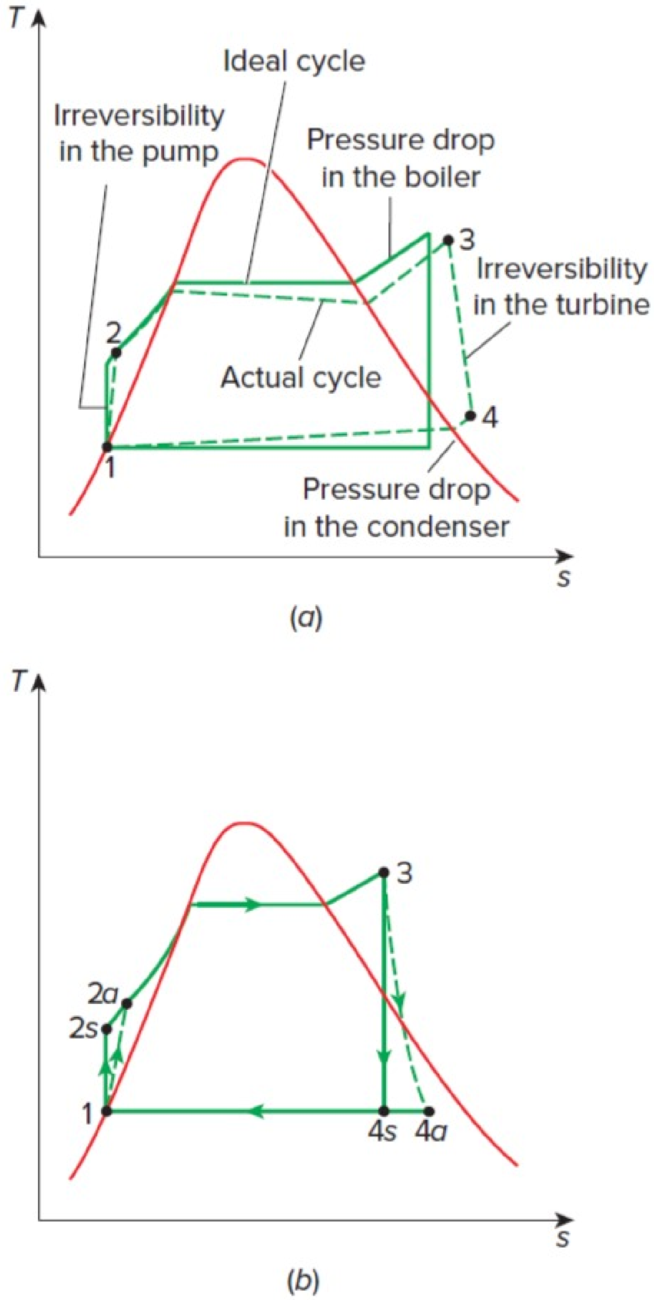


FIGURE 9–41

(*a*) Deviation of actual vapor power cycle from the ideal Rankine cycle. (*b*) The effect of pump and turbine irreversibilities on the ideal Rankine cycle.

Fig. 16 Rankine Cycle - actual cycle

J. Reheat Rankine Cycle - Ideal

$$q_{\text{in}} = q_{\text{primary}} + q_{\text{reheat}} = (h_3 - h_2) + (h_5 - h_4) \tag{35}$$

$$w_{\text{turb,out}} = w_{\text{turb, }I} + w_{\text{turb,II}} = (h_3 - h_4) + (h_5 - h_6) \tag{36}$$

Basic process for solving assuming air-standard:
- From state 1 determine h1 and v1, this is the fluid as it is a saturated fluid
- State 2 and state 3 have the same Pressures
- State 4 and state 5 have the same pressures
- State 1 and state 6 have the same pressures
- State 6 is a liquid gas mixture so you can use s to determine the quality of the mixture as s5 equals s6
- T3 = T5

Basic process for COLD-air-standard assumptions
- Assume constant specific heats for c_v and c_p
- Use isentropic relationships for processes 1 to 2 and 3 to 4 as k is constant
- If given heat rate, can determine thermal efficiency easily from shortened equation

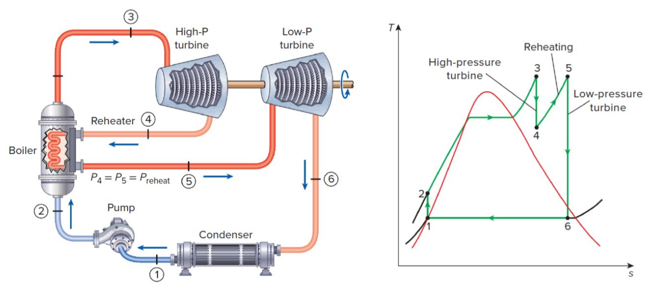


FIGURE 9–48
The ideal reheat Rankine cycle. and

Fig. 17 Rankine Cycle - Ideal Reheat

K. Refrigerators and heat pumps

$$\begin{aligned} \text{COP}_\text{R} &= \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{\text{net,in}}} \\ \text{COP}_\text{HP} &= \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{\text{net, in}}} \end{aligned} \tag{37}$$

L. Reversed Carnot Cycle

$$\begin{aligned} \text{COP}_{\text{R, Carnot}} &= \frac{1}{T_H/T_L - 1} \\ \text{COP}_{\text{HP,Carnot}} &= \frac{1}{1 - T_L/T_H} \end{aligned} \tag{38}$$

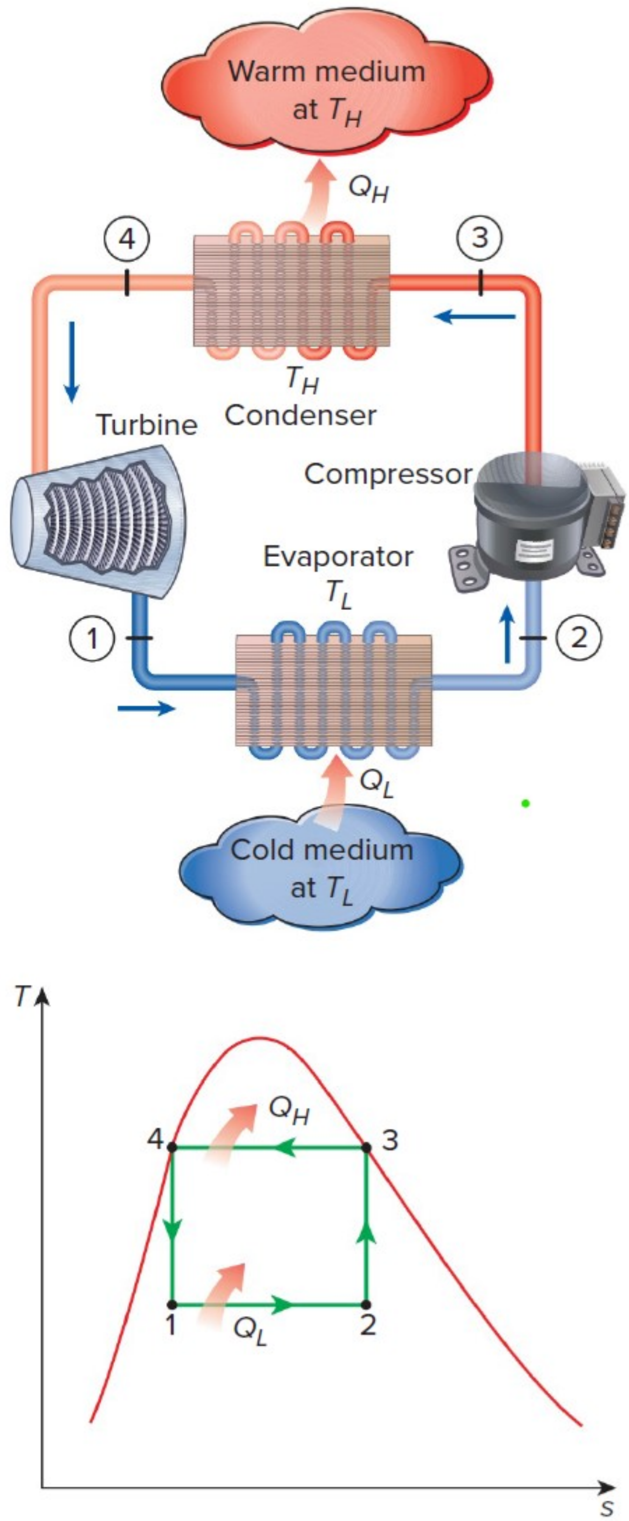


FIGURE 9–52

Schematic of a Carnot refrigerator and T-s diagram of the reversed Carnot cycle.

Fig. 18[17]**Carnot**

M. Ideal Vapor-Compression Fridge Cycle

Processes relationships:

- 1-2 Isentropic compression in a compressor
- 2-3 Constant-pressure heat rejection in a condenser
- 3-4 Throttling in an expansion device
- 4-1 Constant-pressure heat absorption in an evaporator

$$\begin{aligned} \mathrm{COP_R} &= \frac{q_L}{w_{\mathrm{net,in}}} = \frac{h_1-h_4}{h_2-h_1} \\ \mathrm{COP_{HP}} &= \frac{q_H}{w_{\mathrm{net,in}}} = \frac{h_2-h_3}{h_2-h_1} \end{aligned} \tag{39}$$

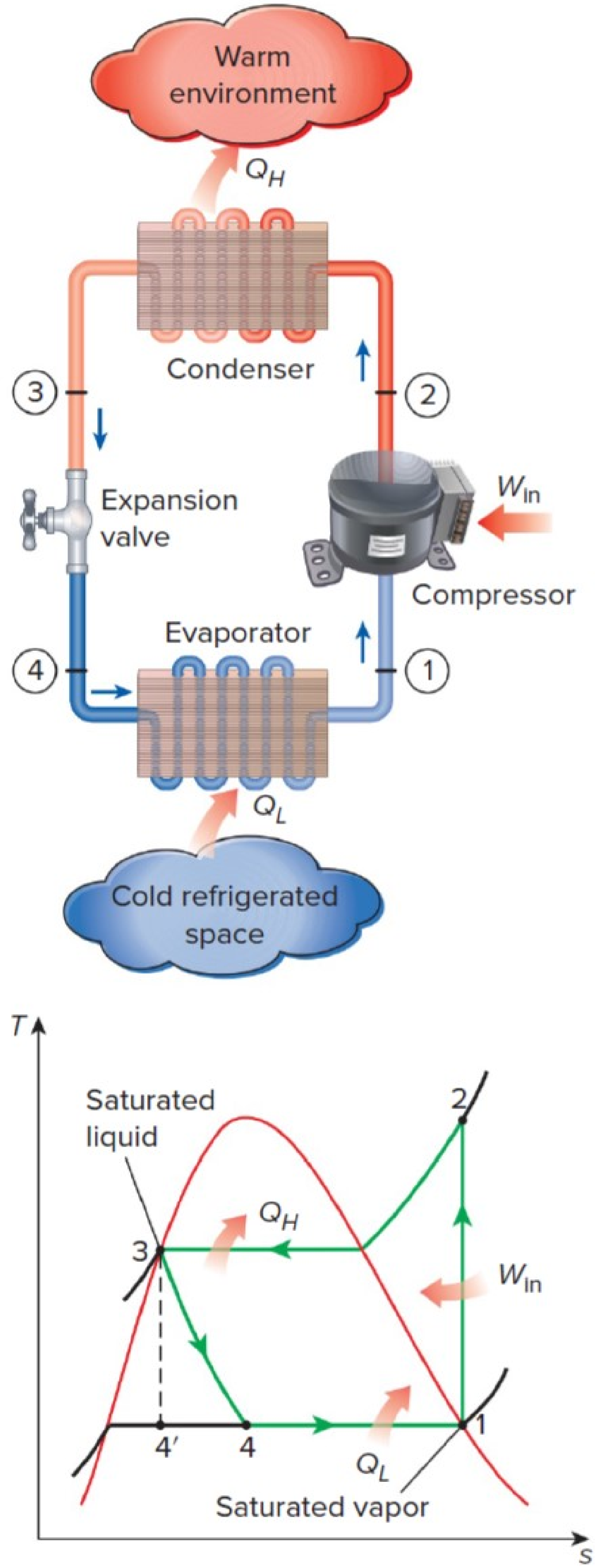


FIGURE 9–53
Schematic and *T-s* diagram for the ideal vapor-compression refrigeration cycle.

II. Heat Transfer

A. Conduction

Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.

$$\dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \tag{40}$$

where k = thermal conductivity [W/m*K]

Thermal Diffusivity:

$$\alpha = \frac{\text{Heat conduction}}{\text{Heat storage}} = \frac{k}{\rho c_p} \quad \left(\mathrm{m}^2/\mathrm{s}\right) \tag{41}$$

B. Convection

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion.

$$\dot{Q}_{\text{conv}} = hA_s\left(T_s - T_\infty\right) \tag{42}$$

where h is the convection heat transfer coefficient [W/m^2*K]

C. Radiation

Radiation is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s\left(T_s^4 - T_{\text{surr } r}^4\right) \tag{43}$$

Combined heat transfer:

$$\begin{aligned}
\dot{Q}_{\text{total}} &= \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = h_{\text{conv}} A_s\left(T_s - T_{\text{surr}}\right) + \varepsilon\sigma A_s\left(T_s^4 - T_{\text{surr}}^4\right) \\
\dot{Q}_{\text{total}} &= h_{\text{combined}} A_s\left(T_s - T_\infty\right) \quad (\mathrm{W}) \\
h_{\text{combined}} &= h_{\text{conv}} + h_{\text{rad}} = h_{\text{conv}} + \varepsilon\sigma\left(T_s + T_{\text{surr}}\right)\left(T_s^2 + T_{\text{surr}}^2\right)
\end{aligned} \tag{44}$$

D. Thermal Resistance

Conduction:

$$\begin{aligned}
\dot{Q}_{\text{cond, wall}} &= \tfrac{T_1 - T_2}{R_{\text{wall}}} \\
R_{\text{wall}} &= \tfrac{L}{kA} \quad (\mathrm{K/W})
\end{aligned} \tag{45}$$

Convection:

$$\dot{Q}_{\text{conv}} = \frac{T_s - T_\infty}{R_{\text{conv}}} \tag{46}$$

$$R_{\text{conv}} = \frac{1}{hA_s} \quad (\mathrm{K/W}) \tag{47}$$

Radiation:

$$\begin{gathered}
\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s\left(T_s^4 - T_{\text{surr}}^4\right) = h_{\text{rad}} A_s\left(T_s - T_{\text{surr}}\right) = \tfrac{T_s - T_{\text{surr}}}{R_{\text{rad}}} \\
R_{\text{rad}} = \tfrac{1}{h_{\text{rad}} A_s}(\mathrm{K/W})
\end{gathered} \tag{48}$$

Example:

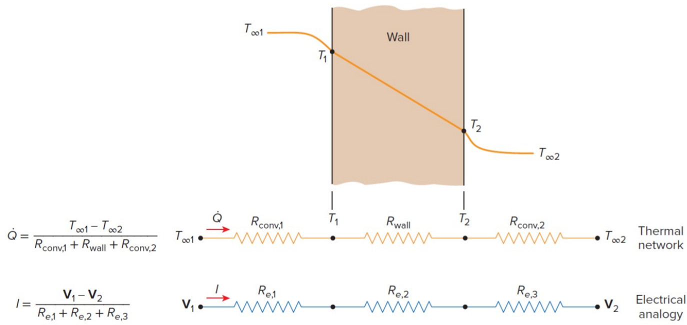
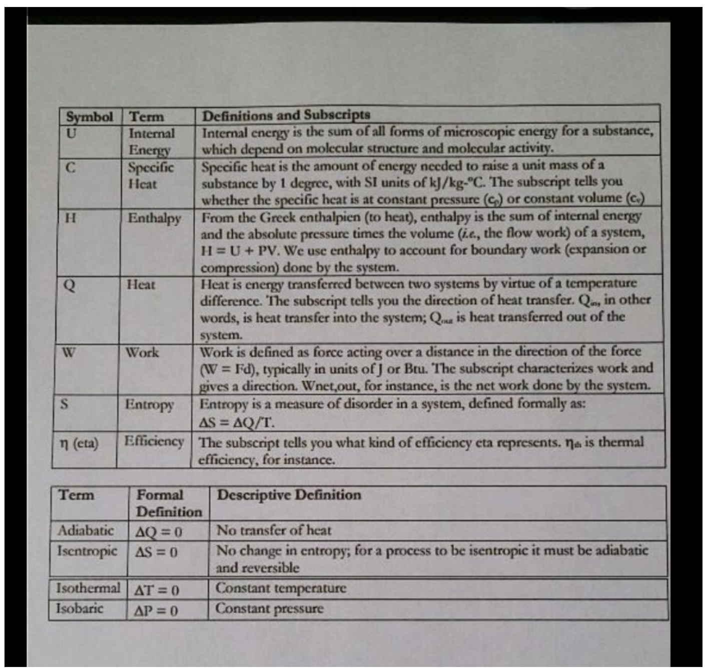


FIGURE 17–6
The thermal resistance network for heat transfer through a plane wall subjected to convection on both sides, and the electrical analogy.

Fig. 20 Thermal Resistivity

III. Other Useful Pics and Things



Symbol	Term	Definitions and Subscripts
U	Internal Energy	Internal energy is the sum of all forms of microscopic energy for a substance, which depend on molecular structure and molecular activity.
C	Specific Heat	Specific heat is the amount of energy needed to raise a unit mass of a substance by 1 degree, with SI units of kJ/kg-°C. The subscript tells you whether the specific heat is at constant pressure (c_p) or constant volume (c_v)
H	Enthalpy	From the Greek enthalpien (to heat), enthalpy is the sum of internal energy and the absolute pressure times the volume (*i.e.*, the flow work) of a system, $H = U + PV$. We use enthalpy to account for boundary work (expansion or compression) done by the system.
Q	Heat	Heat is energy transferred between two systems by virtue of a temperature difference. The subscript tells you the direction of heat transfer. Q_{in}, in other words, is heat transfer into the system; Q_{out} is heat transferred out of the system.
W	Work	Work is defined as force acting over a distance in the direction of the force ($W = Fd$), typically in units of J or Btu. The subscript characterizes work and gives a direction. Wnet,out, for instance, is the net work done by the system.
S	Entropy	Entropy is a measure of disorder in a system, defined formally as: $\Delta S = \Delta Q/T$.
η (eta)	Efficiency	The subscript tells you what kind of efficiency eta represents. η_{th} is thermal efficiency, for instance.

Term	Formal Definition	Descriptive Definition
Adiabatic	$\Delta Q = 0$	No transfer of heat
Isentropic	$\Delta S = 0$	No change in entropy; for a process to be isentropic it must be adiabatic and reversible
Isothermal	$\Delta T = 0$	Constant temperature
Isobaric	$\Delta P = 0$	Constant pressure

Fig. 21 useful things