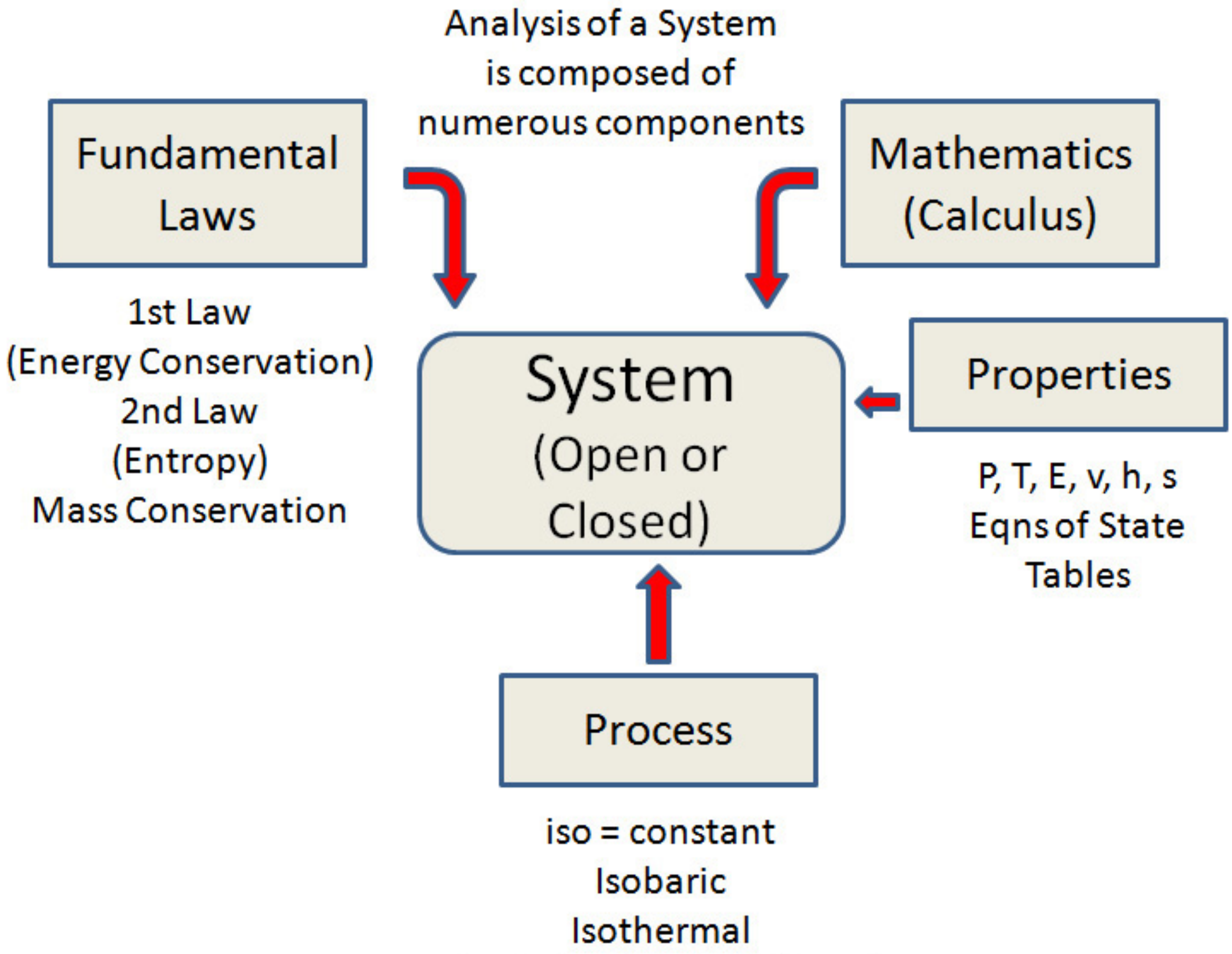
ES 3001 Thermodynamics

Mechanical Engineering Department

Worcester Polytechnic Institute

Lecture: First Law of Thermodynamics (Energy Conservation) and Evaluating Properties


Analysis of a System
is composed of
numerous components
Fundamental
Laws
1st Law
(Energy Conservation)
2nd Law
(Entropy)
Mass Conservation
Mathematics
(Calculus)
System
(Open or
Closed)
Properties
P, T, E, v, h, s
Eqns of State
Tables
Process
iso = constant
Isobaric
Isothermal

Isochoric = Constant Volume !

Energy (E) is most frequently expressed in terms of:

Kinetic Energy for a mass (m) at a velocity (V) (an Extensive Property)

$$KE = \frac{1}{2} m V^2$$

Frequently, one is interested in the change of KE from State 1 to State 2:

$$\Delta KE = \frac{1}{2} m (V_2^2 - V_1^2)$$

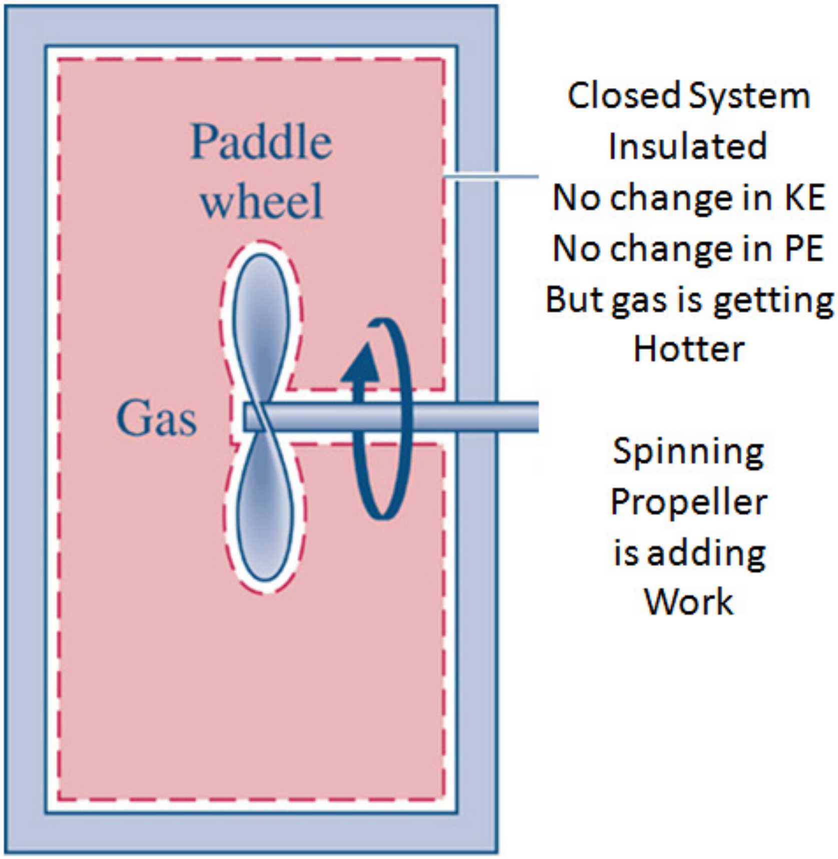
Potential Energy for a mass (m) in a gravational potential field (g) at a height z (an Extensive Property)

$$PE = m g z$$

Frequently, one is interested in the change of PE from State 1 to State 2:

$$\Delta PE = PE_2 - PE_1 = m\, g\, (z_2 - z_1)$$

Internal Energy (U): A measure of energy at a macroscopic level due to the molecular translation, vibration, rotation (an Extensive Property). Internal Energy can also be expressed as an intensive property u=U/m (internal energy per unit mass).



Closed System
Insulated
No change in KE
No change in PE
But gas is getting
Hotter

Spinning
Propeller
is adding
Work

Frequently, internal energy is presented in tables, such as Table A-4 for superheated water vapor.

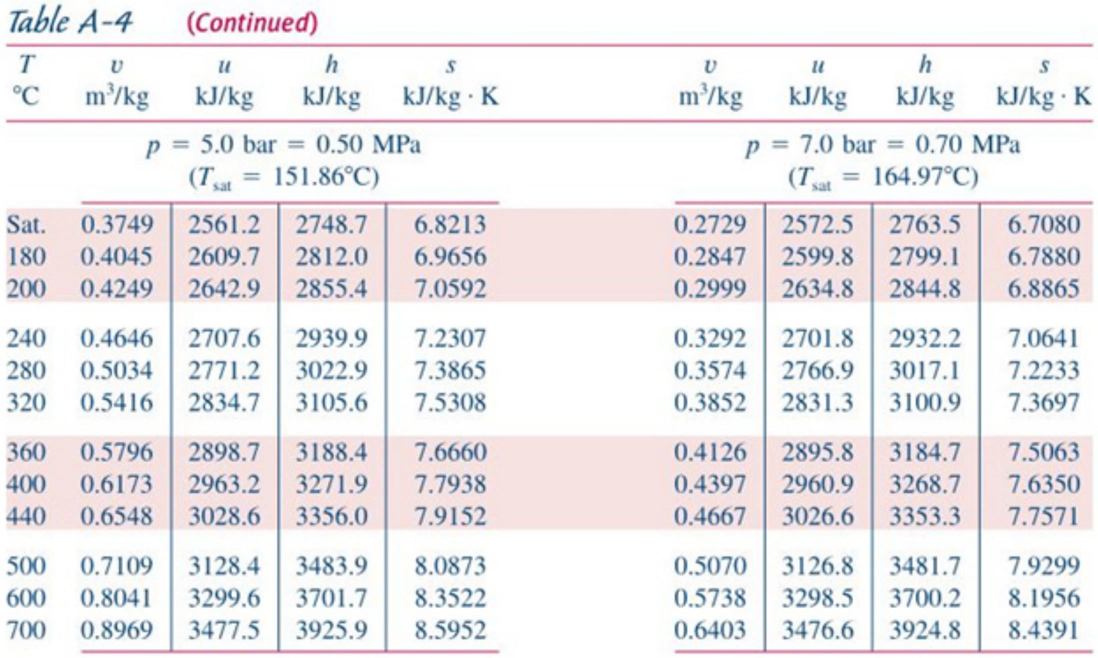
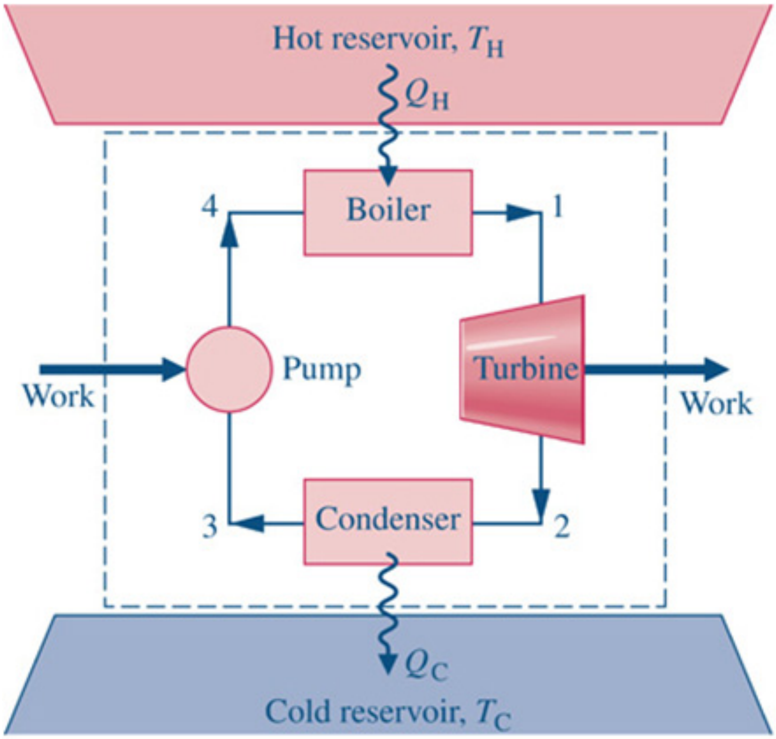


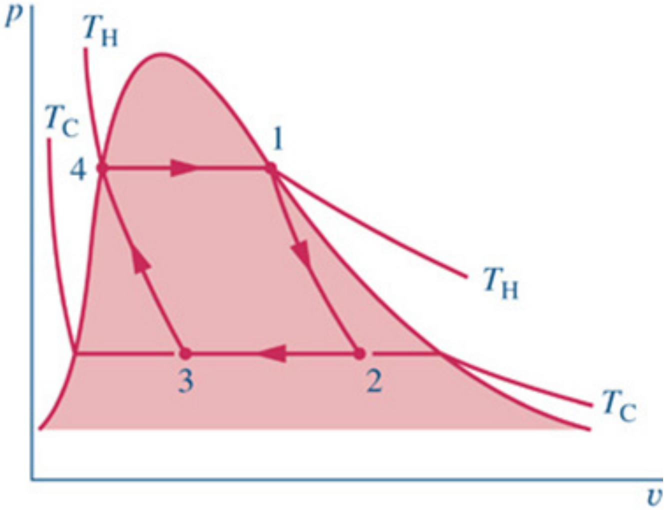
Table A-4 **(Continued)**

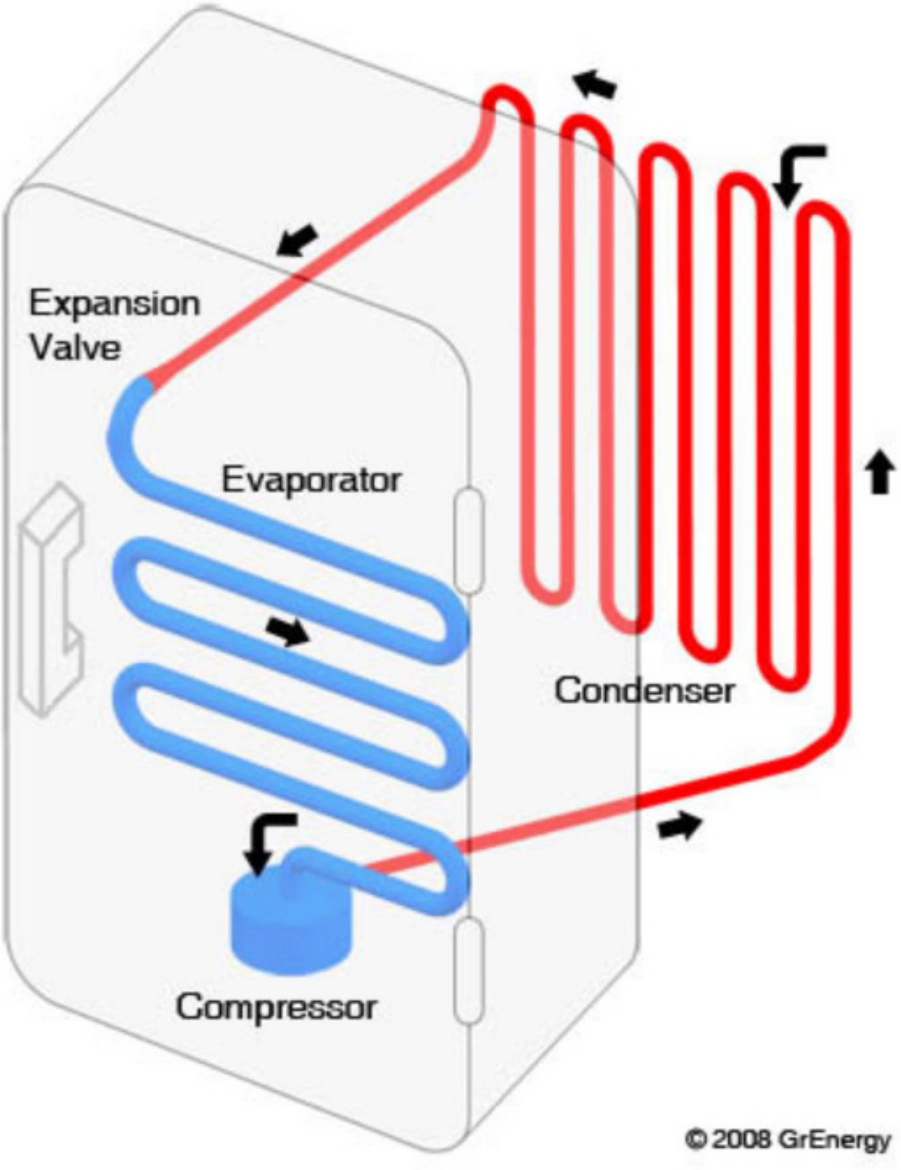
T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 5.0 bar = 0.50 MPa (T_{sat} = 151.86°C)				p = 7.0 bar = 0.70 MPa (T_{sat} = 164.97°C)			
Sat.	0.3749	2561.2	2748.7	6.8213	0.2729	2572.5	2763.5	6.7080
180	0.4045	2609.7	2812.0	6.9656	0.2847	2599.8	2799.1	6.7880
200	0.4249	2642.9	2855.4	7.0592	0.2999	2634.8	2844.8	6.8865
240	0.4646	2707.6	2939.9	7.2307	0.3292	2701.8	2932.2	7.0641
280	0.5034	2771.2	3022.9	7.3865	0.3574	2766.9	3017.1	7.2233
320	0.5416	2834.7	3105.6	7.5308	0.3852	2831.3	3100.9	7.3697
360	0.5796	2898.7	3188.4	7.6660	0.4126	2895.8	3184.7	7.5063
400	0.6173	2963.2	3271.9	7.7938	0.4397	2960.9	3268.7	7.6350
440	0.6548	3028.6	3356.0	7.9152	0.4667	3026.6	3353.3	7.7571
500	0.7109	3128.4	3483.9	8.0873	0.5070	3126.8	3481.7	7.9299
600	0.8041	3299.6	3701.7	8.3522	0.5738	3298.5	3700.2	8.1956
700	0.8969	3477.5	3925.9	8.5952	0.6403	3476.6	3924.8	8.4391

The Design and Analysis of many engineering systems requires thermodynamics (in addition to fluid mechanics, heat transfer, structural analysis, etc.)

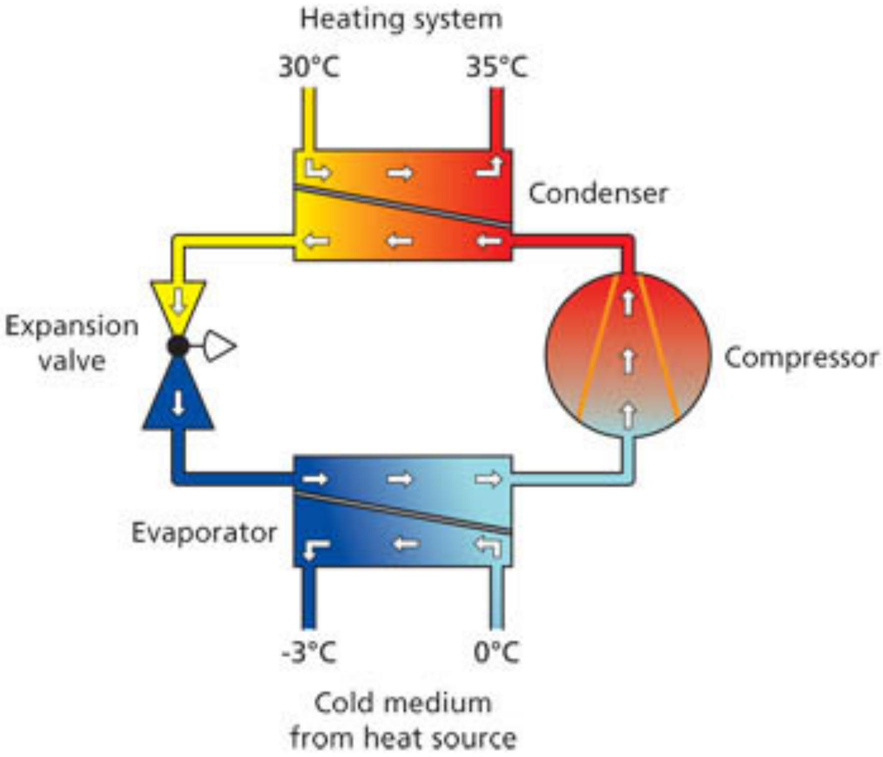
Consider a Simple Power System. Thermodynamics establishes the limits on the Maximum Power Out (Work Out) for a given Qin for a particular system of interest.


Hot reservoir, T_H
Q_H
Boiler
4
1
Pump
Turbine
Work
Work
Condenser
3
2
Q_C
Cold reservoir, T_C


p
T_H
T_C
1
4
T_H
3
2
T_C
v


Expansion Valve
Evaporator
Condenser
Compressor
© 2008 GrEnergy

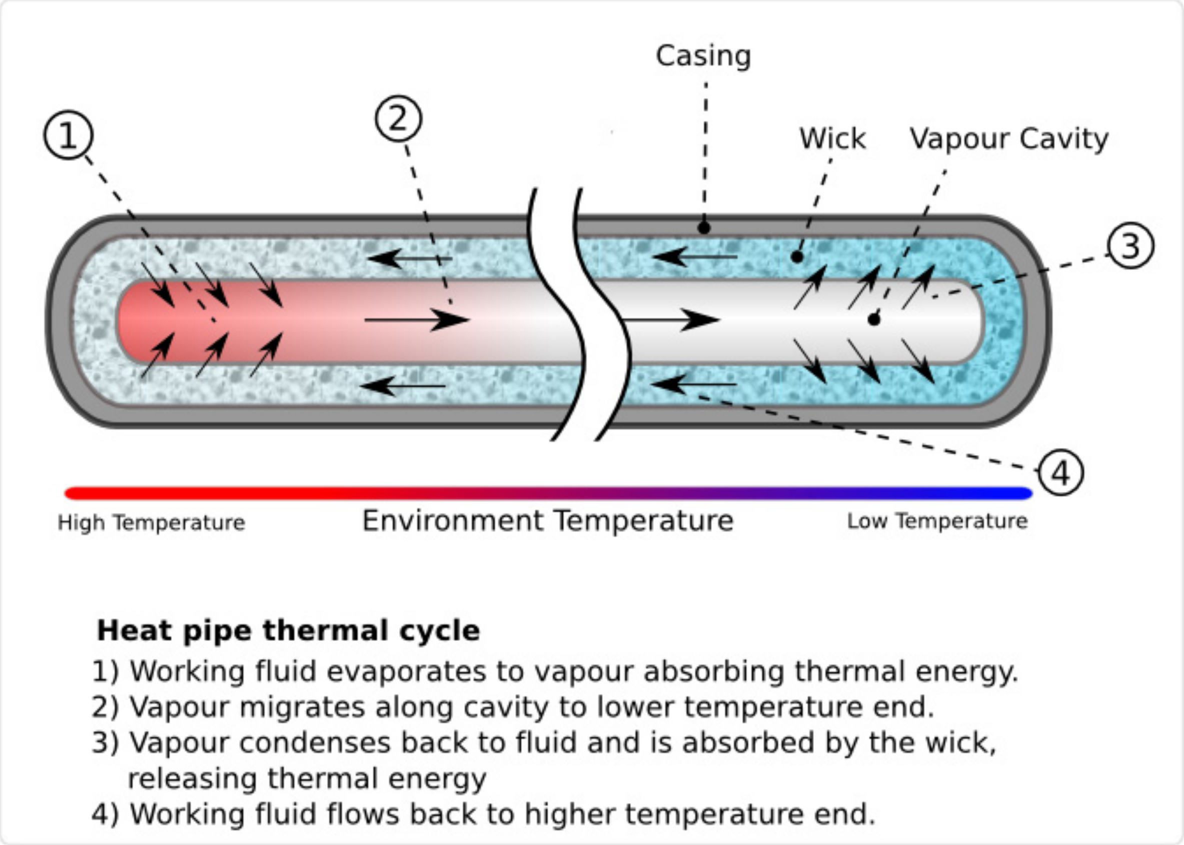
http://www.grenergy.co.uk/content/Products-HeatPumps



- The **Compressor** compresses the refrigerant gas and when this happens the gas gets hot as shown by the red colour in the diagram.
- This hot refrigerant gas then passes to the **Condenser**. The condenser is a heat exchanger which enables your heating system to extract the heat energy from the refrigerant gas. As heat is absorbed from the gas it condenses back into a liquid, still at high pressure as depicted by the orange then yellow colour.
- Having given up a lot of its heat energy, the refrigerant then passes to the **Expansion Valve**. The expansion valve is basically a small hole. On one side of the hole is high-pressure refrigerant liquid (yellow) and on the other side is a low-pressure area (dark blue). The dark blue side is at low pressure because the compressor is sucking the refrigerant out of that side of the system.
- As the liquid refrigerant passes through the hole to the low pressure side, it immediately boils and evaporates (dark blue), its temperature dropping rapidly to minus 33°C as described above. This very cold gas is then channelled to another heat exchanger, the **Evaporator**, which allows it to absorb heat from the outside air (Air Source Heat Pump – ASHP) or the ground (Ground Source Heat Pump – GSHP). As it absorbs heat, the gas warms up (light blue) after which it is channelled back to the compressor.
- The refrigerant gas is sucked up by the **Compressor**, and the cycle repeats.

http://www.grenergy.co.uk/content/Products-HeatPumps

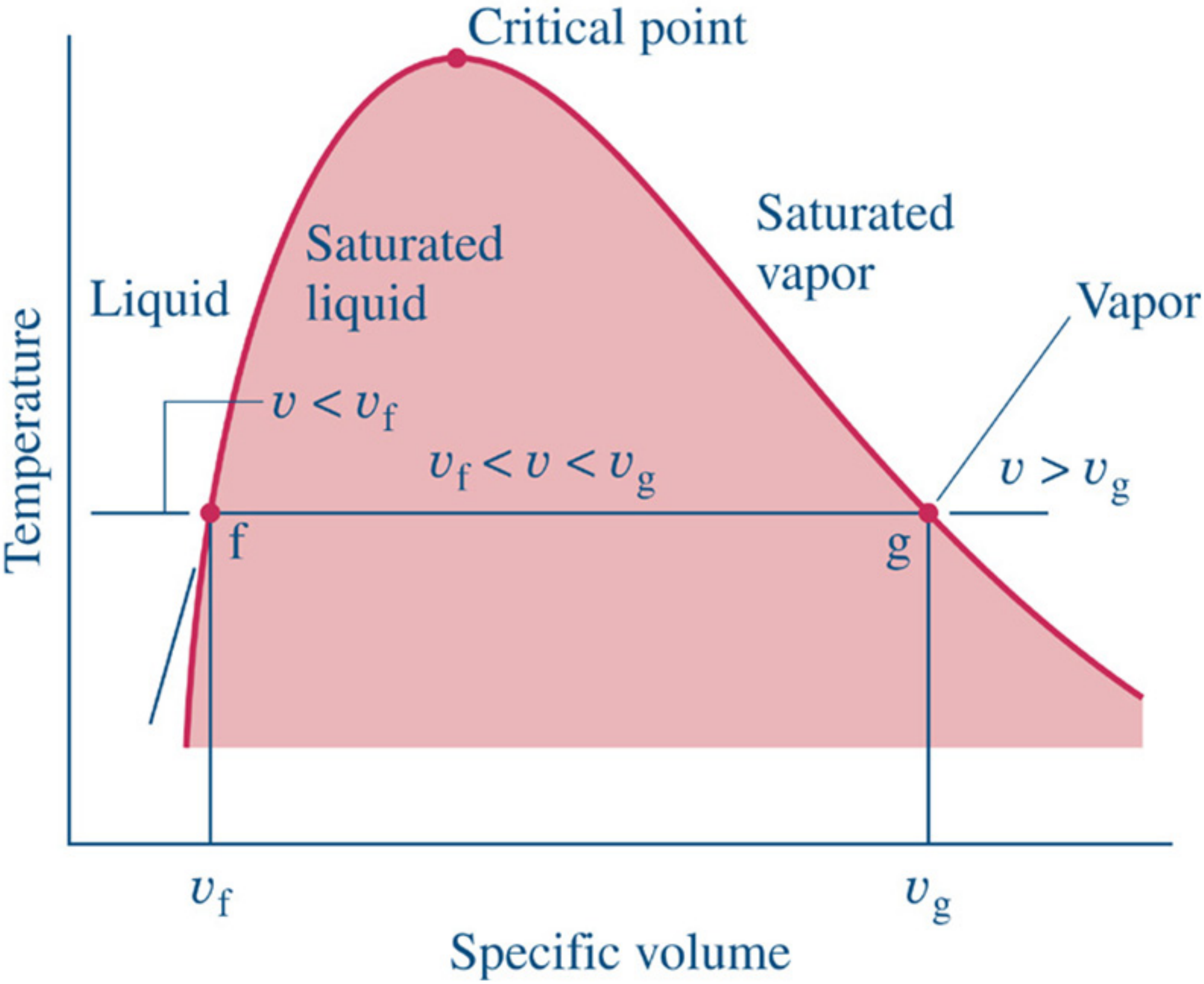
http://en.wikipedia.org/wiki/File:Heat_Pipe_Mechanism.png

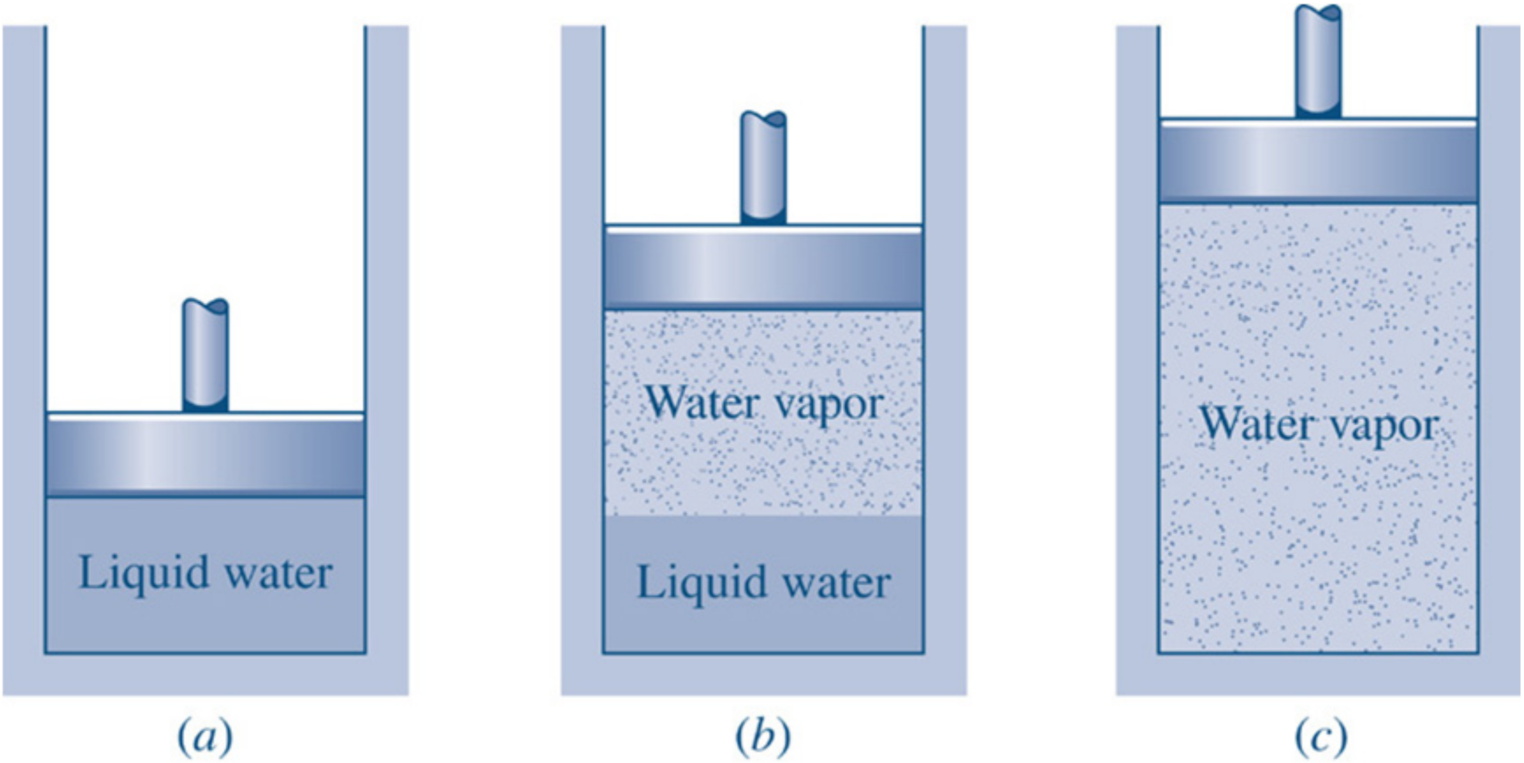

Casing
①
②
Wick
Vapour Cavity
③
④
High Temperature
Environment Temperature
Low Temperature

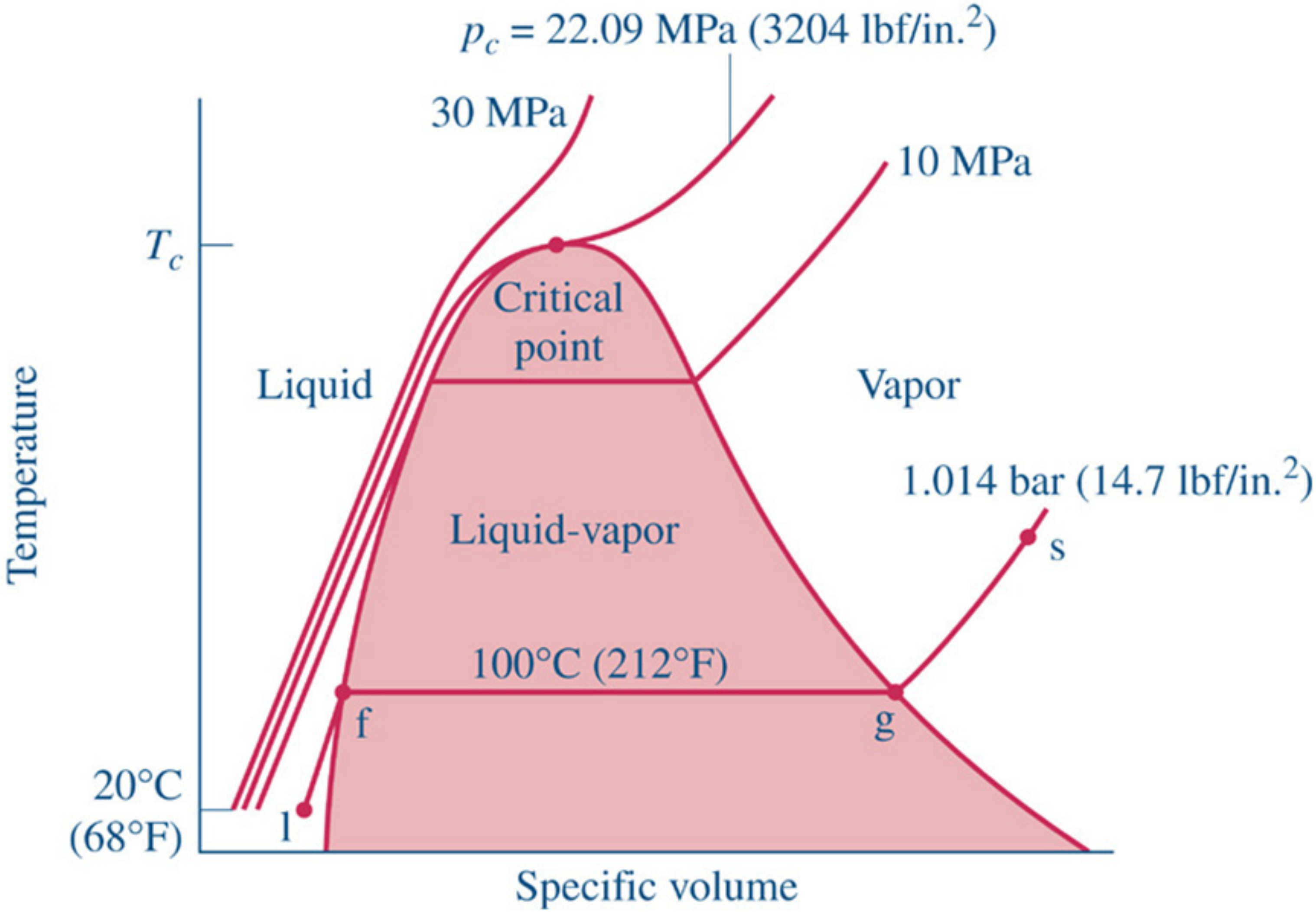
Heat pipe thermal cycle

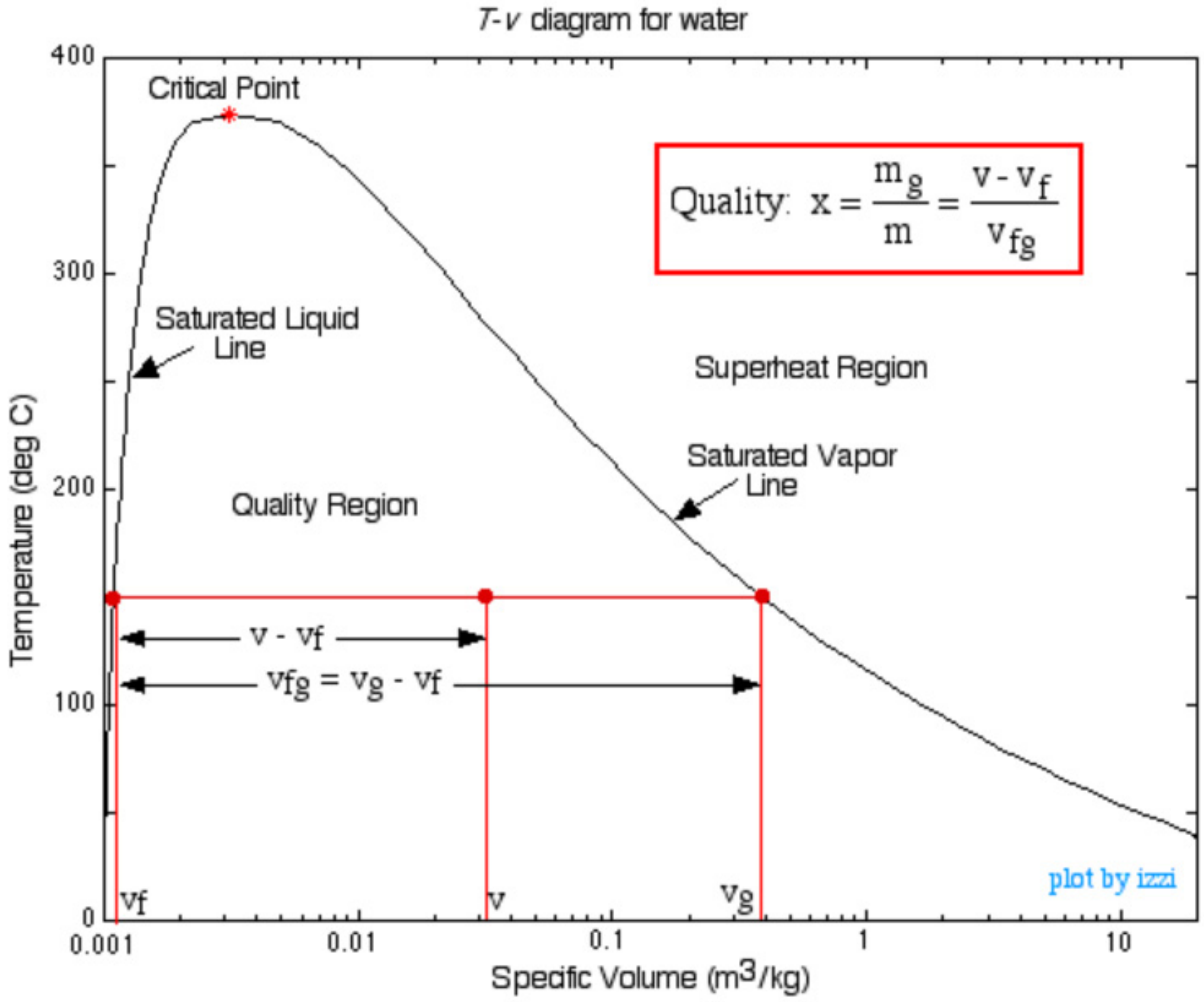
1) Working fluid evaporates to vapour absorbing thermal energy.
2) Vapour migrates along cavity to lower temperature end.
3) Vapour condenses back to fluid and is absorbed by the wick, releasing thermal energy
4) Working fluid flows back to higher temperature end.

http://en.wikipedia.org/wiki/File:Heat_Pipe_Mechanism.png

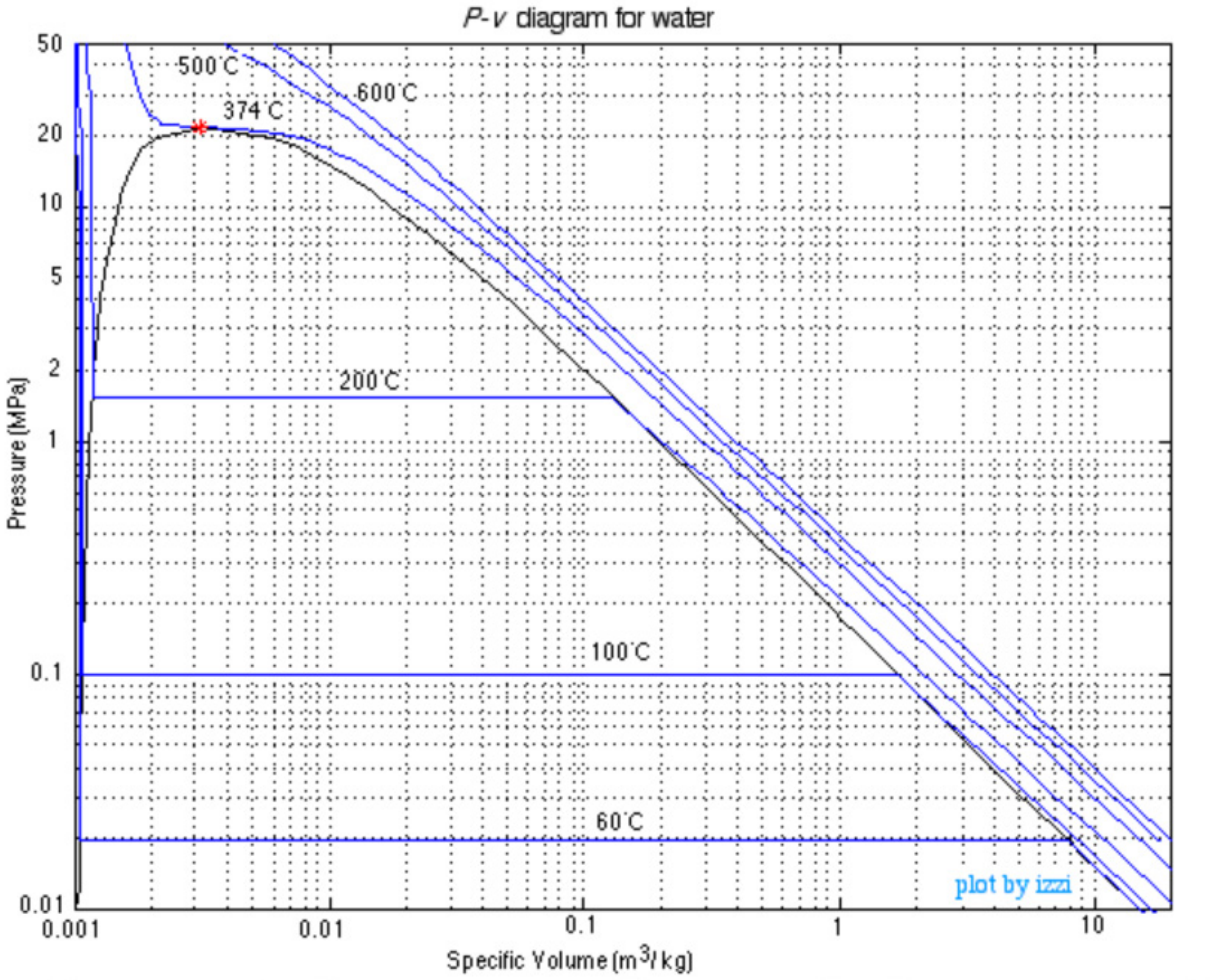

Critical point
Saturated liquid
Saturated vapor
Liquid
Vapor
$v < v_f$
$v_f < v < v_g$
$v > v_g$
f
g
Temperature
v_f
v_g
Specific volume


Liquid water
Water vapor
Liquid water
Water vapor
(a)
(b)
(c)

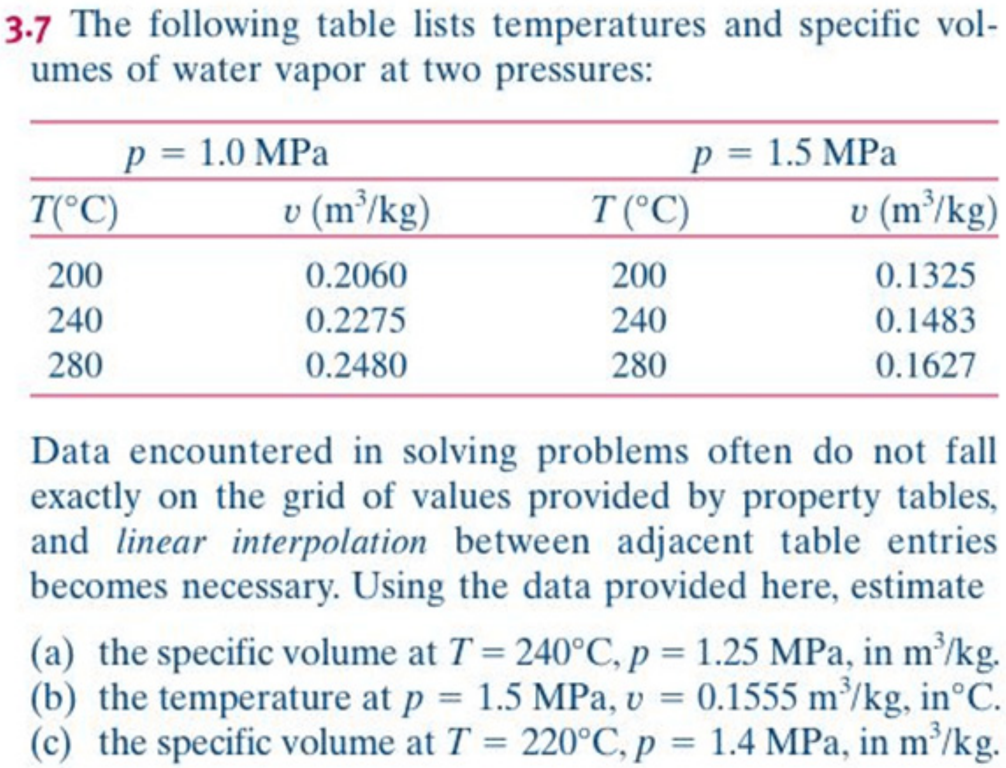

p_c = 22.09 MPa (3204 lbf/in.^{2})
30 MPa
10 MPa
T_c
Critical point
Liquid
Vapor
1.014 bar (14.7 lbf/in.^{2})
s
Liquid-vapor
100°C (212°F)
f
g
20°C (68°F)
l
Temperature
Specific volume



http://www.engineeringthermodynamics.org/Intro/Chapt.1_6/Chapter2a.html



http://www.engineeringthermodynamics.org/Intro/Chapt.1_6/Chapter2a.html



3.7 The following table lists temperatures and specific volumes of water vapor at two pressures:

$p = 1.0$ MPa		$p = 1.5$ MPa	
T(°C)	v (m^3/kg)	T (°C)	v (m^3/kg)
200	0.2060	200	0.1325
240	0.2275	240	0.1483
280	0.2480	280	0.1627

Data encountered in solving problems often do not fall exactly on the grid of values provided by property tables, and *linear interpolation* between adjacent table entries becomes necessary. Using the data provided here, estimate

(a) the specific volume at $T = 240$°C, $p = 1.25$ MPa, in m^3/kg.
(b) the temperature at $p = 1.5$ MPa, $v = 0.1555$ m^3/kg, in°C.
(c) the specific volume at $T = 220$°C, $p = 1.4$ MPa, in m^3/kg.

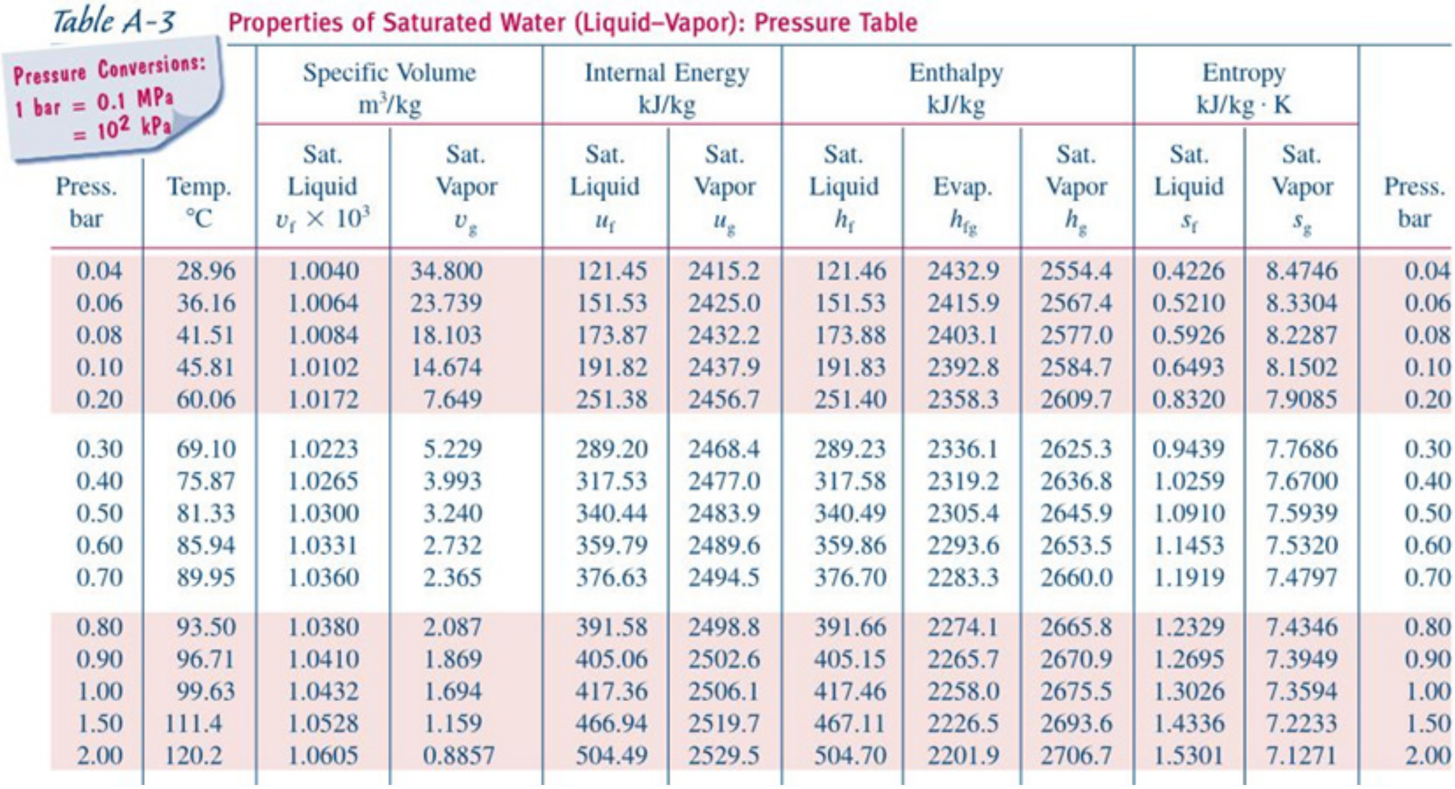


Table A-3 **Properties of Saturated Water (Liquid–Vapor): Pressure Table**

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bar
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70
0.80	93.50	1.0380	2.087	391.58	2498.8	391.66	2274.1	2665.8	1.2329	7.4346	0.80
0.90	96.71	1.0410	1.869	405.06	2502.6	405.15	2265.7	2670.9	1.2695	7.3949	0.90
1.00	99.63	1.0432	1.694	417.36	2506.1	417.46	2258.0	2675.5	1.3026	7.3594	1.00
1.50	111.4	1.0528	1.159	466.94	2519.7	467.11	2226.5	2693.6	1.4336	7.2233	1.50
2.00	120.2	1.0605	0.8857	504.49	2529.5	504.70	2201.9	2706.7	1.5301	7.1271	2.00

Once the substance (frequently water) is completely vapor, then Table A-4 Gives SUPERheated data

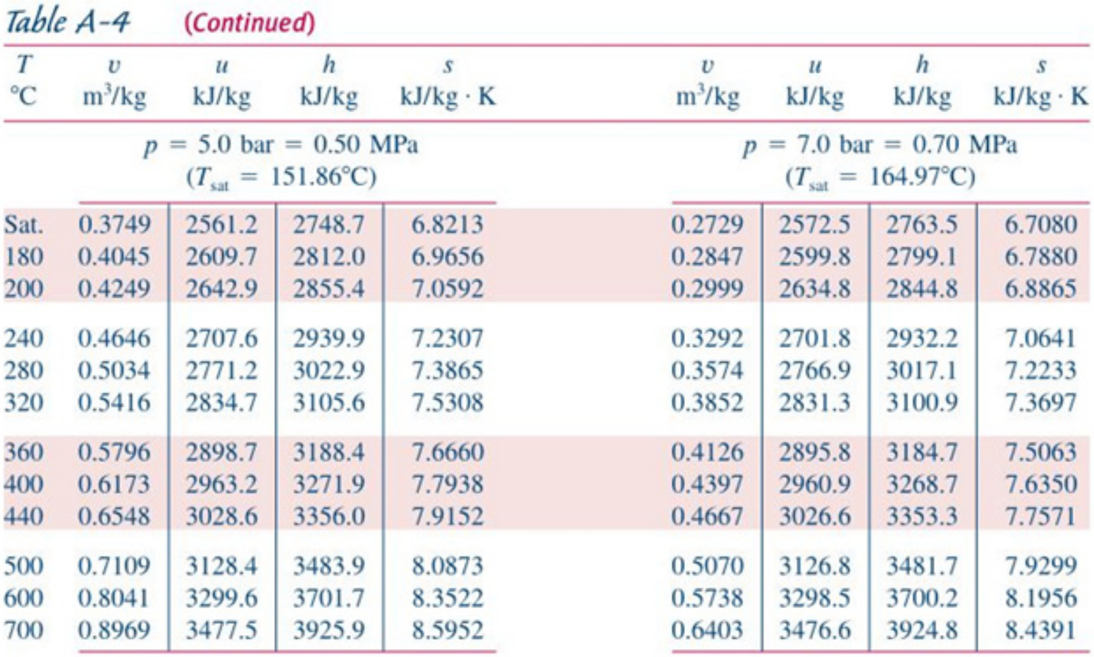


Table A-4 **(Continued)**

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 5.0 bar = 0.50 MPa (T_{sat} = 151.86°C)				p = 7.0 bar = 0.70 MPa (T_{sat} = 164.97°C)			
Sat.	0.3749	2561.2	2748.7	6.8213	0.2729	2572.5	2763.5	6.7080
180	0.4045	2609.7	2812.0	6.9656	0.2847	2599.8	2799.1	6.7880
200	0.4249	2642.9	2855.4	7.0592	0.2999	2634.8	2844.8	6.8865
240	0.4646	2707.6	2939.9	7.2307	0.3292	2701.8	2932.2	7.0641
280	0.5034	2771.2	3022.9	7.3865	0.3574	2766.9	3017.1	7.2233
320	0.5416	2834.7	3105.6	7.5308	0.3852	2831.3	3100.9	7.3697
360	0.5796	2898.7	3188.4	7.6660	0.4126	2895.8	3184.7	7.5063
400	0.6173	2963.2	3271.9	7.7938	0.4397	2960.9	3268.7	7.6350
440	0.6548	3028.6	3356.0	7.9152	0.4667	3026.6	3353.3	7.7571
500	0.7109	3128.4	3483.9	8.0873	0.5070	3126.8	3481.7	7.9299
600	0.8041	3299.6	3701.7	8.3522	0.5738	3298.5	3700.2	8.1956
700	0.8969	3477.5	3925.9	8.5952	0.6403	3476.6	3924.8	8.4391

We rarely use the Compressed Liquid tables. Generally, the values are very close to those in the saturated tables at the given temperature. That is, changing the pressure of a liquid does not significantly change the state properties (other than pressure).

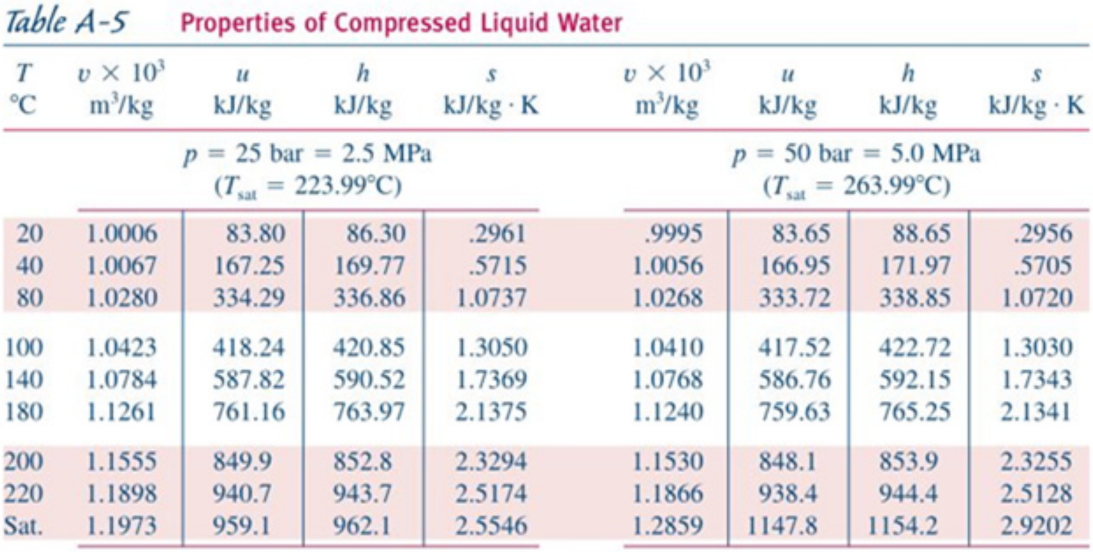


Table A-5 **Properties of Compressed Liquid Water**

T °C	$v \times 10^3$ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	$v \times 10^3$ m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 25 bar = 2.5 MPa (T_{sat} = 223.99°C)				p = 50 bar = 5.0 MPa (T_{sat} = 263.99°C)			
20	1.0006	83.80	86.30	.2961	.9995	83.65	88.65	.2956
40	1.0067	167.25	169.77	.5715	1.0056	166.95	171.97	.5705
80	1.0280	334.29	336.86	1.0737	1.0268	333.72	338.85	1.0720
100	1.0423	418.24	420.85	1.3050	1.0410	417.52	422.72	1.3030
140	1.0784	587.82	590.52	1.7369	1.0768	586.76	592.15	1.7343
180	1.1261	761.16	763.97	2.1375	1.1240	759.63	765.25	2.1341
200	1.1555	849.9	852.8	2.3294	1.1530	848.1	853.9	2.3255
220	1.1898	940.7	943.7	2.5174	1.1866	938.4	944.4	2.5128
Sat.	1.1973	959.1	962.1	2.5546	1.2859	1147.8	1154.2	2.9202

****

In engineering thermodynamics the change in energy of a system is composed of three contributions:

- ►Kinetic energy
- ►Gravitational potential energy
- ►Internal energy

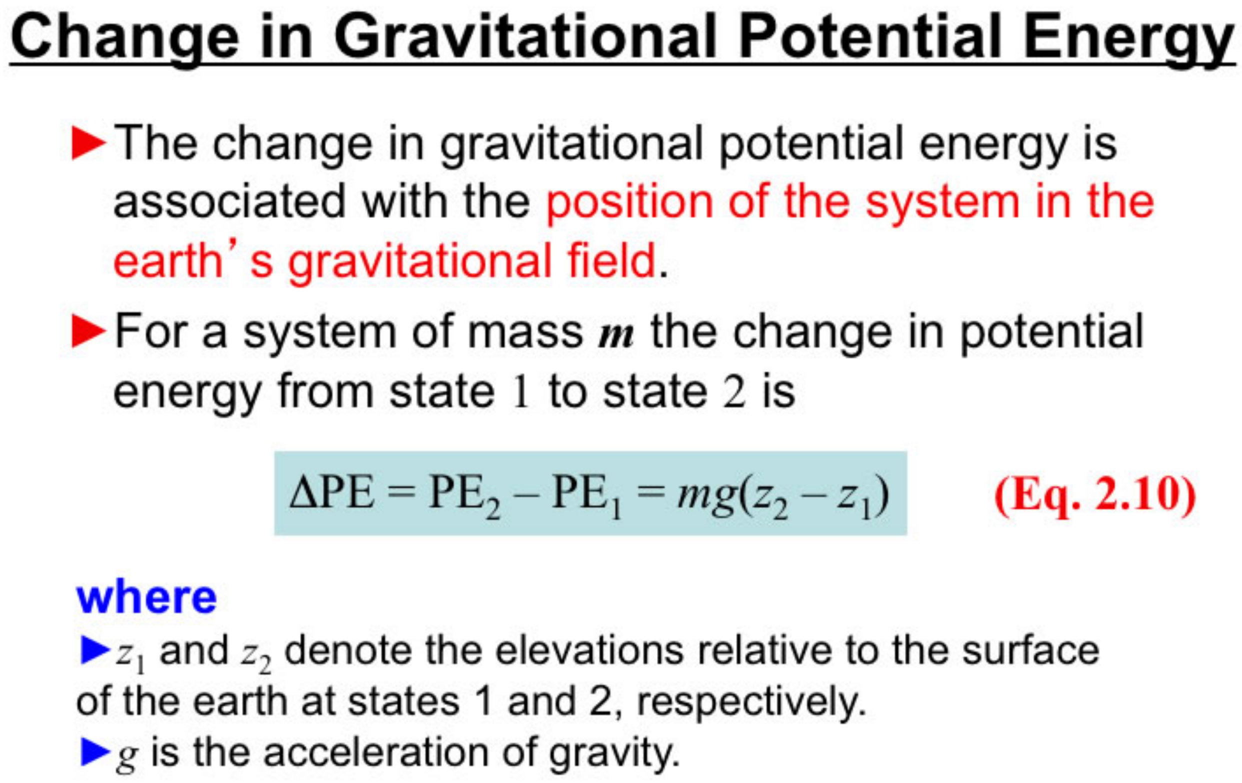
Change in Kinetic Energy

- ►The change in kinetic energy is associated with the motion of the system as a whole relative to an external coordinate frame such as the surface of the earth.
- ►For a system of mass ***m*** the change in kinetic energy from state 1 to state 2 is

$$\Delta \mathrm{KE} = \mathrm{KE}_2 - \mathrm{KE}_1 = \frac{1}{2} m \left(\mathrm{V}_2^2 - \mathrm{V}_1^2 \right) \qquad \textbf{(Eq. 2.5)}$$

where

- ►V_1 and V_2 denote the velocities at their respective states.
- ►The symbol Δ denotes: final value minus initial value.



Change in Gravitational Potential Energy

- The change in gravitational potential energy is associated with the position of the system in the earth's gravitational field.
- For a system of mass m the change in potential energy from state 1 to state 2 is

$$\Delta \mathrm{PE} = \mathrm{PE}_2 - \mathrm{PE}_1 = mg(z_2 - z_1) \qquad \textbf{(Eq. 2.10)}$$

where

- z_1 and z_2 denote the elevations relative to the surface of the earth at states 1 and 2, respectively.
- g is the acceleration of gravity.

Change in Internal Energy

- The change in internal energy is associated with the makeup of the system, including its chemical composition.
- There is no simple expression comparable to Eqs. 2.5 and 2.10 for evaluating internal energy change for a wide range of applications. In most cases we will evaluate internal energy change using data from tables in appendices of the textbook.
- Like kinetic and gravitational potential energy, internal energy is an extensive property.
  - Internal energy is represented by U.
  - The specific internal energy on a mass basis is u.
  - The specific internal energy on a molar basis is $\bar{u}$.

Change in Energy of a System

- In summary, the change in energy of a system from state 1 to state 2 is

$$E_2 - E_1 = (U_2 - U_1) + (\mathrm{KE}_2 - \mathrm{KE}_1) + (\mathrm{PE}_2 - \mathrm{PE}_1)$$

(Eq. 2.27a)

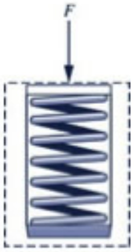
$$\Delta E = \Delta U + \Delta \mathrm{KE} + \Delta \mathrm{PE}$$ **(Eq. 2.27b)**

- It is frequently the *changes* in the *energy* of a system between states that have significance.

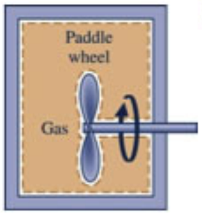
Energy Transfer by Work

- Energy can be transferred to and from closed systems by two means only:
  - Work
  - Heat
- You have studied work in mechanics and those concepts are retained in the study of thermodynamics.

Illustrations of Work



- When a spring is compressed, energy is transferred to the spring by work.
- When a gas in a closed vessel is stirred, energy is transferred to the gas by work.



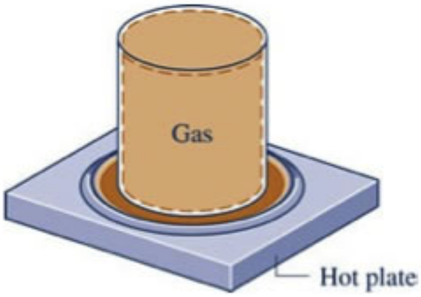
Energy Transfer by Work

- ►The symbol W denotes an amount of energy transferred across the boundary of a system by work.
- ►Since engineering thermodynamics is often concerned with internal combustion engines, turbines, and electric generators whose purpose is to do work, it is convenient to regard the work done by a system as positive.
  - ►$W > 0$: work ***done by*** the system
  - ►$W < 0$: work ***done on*** the system

The same sign convention is used for the rate of energy transfer by work (power!), denoted by $\dot{W}$.

Energy Transfer by Heat

- ►Energy transfers by heat are induced only as a result of a temperature difference between the system and its surroundings.
- ►Net energy transfer by heat occurs only in the direction of decreasing temperature.

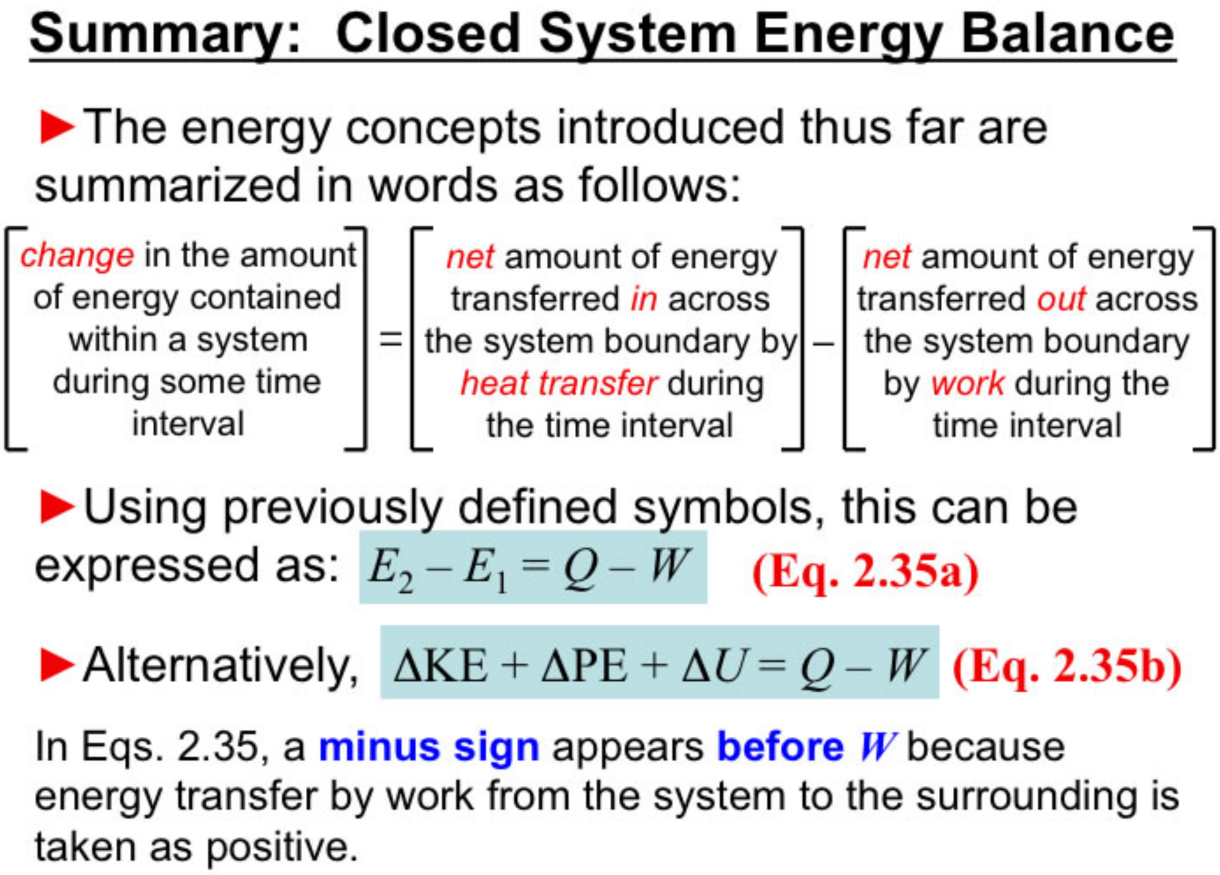


Energy Transfer by Heat

- ►The symbol Q denotes an amount of energy transferred across the boundary of a system by heat transfer.
- ►Heat transfer into a system is taken as positive and heat transfer from a system is taken as negative:
  - ►$Q > 0$: heat transfer ***to the*** system
  - ►$Q < 0$: heat transfer ***from*** the system

The same sign convention is used for the rate of energy transfer by heat, denoted by $\dot{Q}$.

- ►If a system undergoes a process involving no heat transfer with its surroundings, that process is called *adiabatic*.



Summary: Closed System Energy Balance

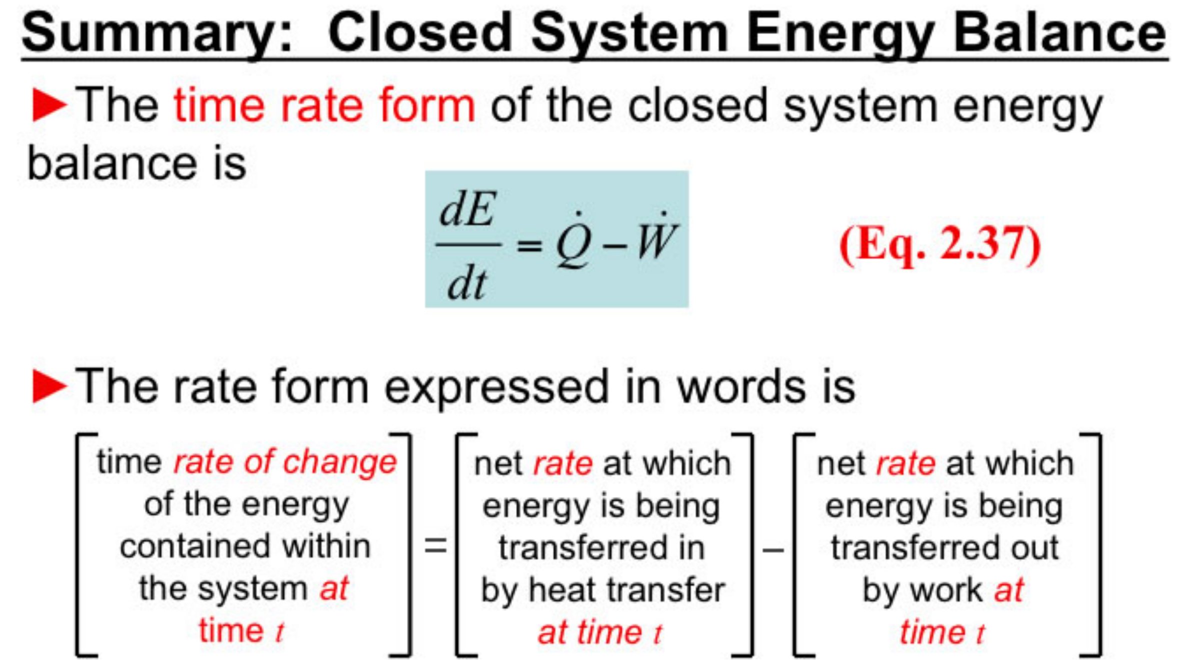
- The energy concepts introduced thus far are summarized in words as follows:

$$\begin{bmatrix}\textit{change}\text{ in the amount}\\ \text{of energy contained}\\ \text{within a system}\\ \text{during some time}\\ \text{interval}\end{bmatrix} = \begin{bmatrix}\textit{net}\text{ amount of energy}\\ \text{transferred }\textit{in}\text{ across}\\ \text{the system boundary by}\\ \textit{heat transfer}\text{ during}\\ \text{the time interval}\end{bmatrix} - \begin{bmatrix}\textit{net}\text{ amount of energy}\\ \text{transferred }\textit{out}\text{ across}\\ \text{the system boundary}\\ \text{by }\textit{work}\text{ during the}\\ \text{time interval}\end{bmatrix}$$

- Using previously defined symbols, this can be expressed as: $E_2 - E_1 = Q - W$ **(Eq. 2.35a)**

- Alternatively, $\Delta\text{KE} + \Delta\text{PE} + \Delta U = Q - W$ **(Eq. 2.35b)**

In Eqs. 2.35, a **minus sign** appears **before W** because energy transfer by work from the system to the surrounding is taken as positive.



Summary: Closed System Energy Balance

- The time rate form of the closed system energy balance is

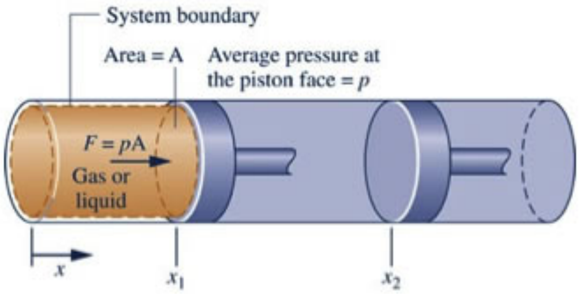
$$\frac{dE}{dt} = \dot{Q} - \dot{W} \qquad \textbf{(Eq. 2.37)}$$

- The rate form expressed in words is

$$\begin{bmatrix}\text{time }\textit{rate of change}\\ \text{of the energy}\\ \text{contained within}\\ \text{the system }\textit{at}\\ \textit{time } t\end{bmatrix} = \begin{bmatrix}\text{net }\textit{rate}\text{ at which}\\ \text{energy is being}\\ \text{transferred in}\\ \text{by heat transfer}\\ \textit{at time } t\end{bmatrix} - \begin{bmatrix}\text{net }\textit{rate}\text{ at which}\\ \text{energy is being}\\ \text{transferred out}\\ \text{by work }\textit{at}\\ \textit{time } t\end{bmatrix}$$

Modeling Expansion and Compression Work

► A case having many practical applications is a gas (or liquid) undergoing an expansion (or compression) process while confined in a piston-cylinder assembly.


System boundary
Area = A
Average pressure at the piston face = p
$F = p\mathrm{A}$
Gas or liquid
x
x_1
x_2

► During the process, the gas exerts a normal force on the piston, $F = p\mathrm{A}$, where p is the pressure at the interface between the gas and piston and A is the area of the piston face.

Modeling Expansion and Compression Work

- ►From mechanics, the work done by the gas as the piston face moves from x_1 to x_2 is given by

$$W = \int F dx = \int p A dx$$

- ►Since the product $A dx = dV$, where V is the volume of the gas, this becomes

$$W = \int_{V_1}^{V_2} p dV \qquad \textbf{(Eq. 2.17)}$$

- ►For a compression, dV is negative and so is the value of the integral, in keeping with the sign convention for work.

Modeling Expansion and Compression Work

►To perform the integral of **Eq. 2.17** requires a relationship between gas pressure at the interface between the gas and piston and the total gas volume.

►During an actual expansion of a gas such a relationship may be difficult, or even impossible, to obtain owing to non-equilibrium effects during the process – for example, effects related to combustion in the cylinder of an automobile engine.

►In most such applications, the work value can be obtained only by experiment.

Modeling Expansion and Compression Work

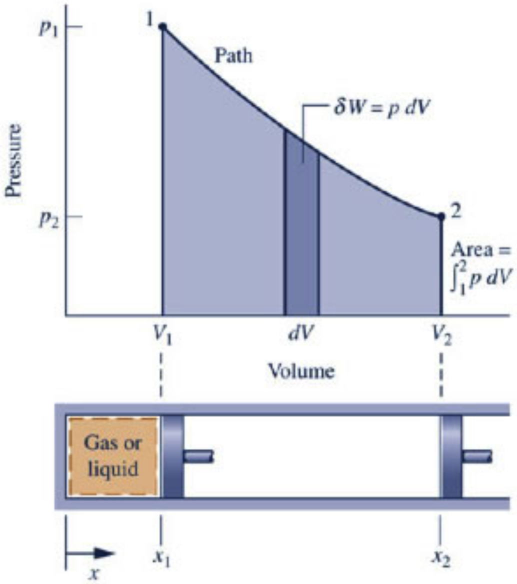
►**Eq. 2.17** can be applied to evaluate the work of idealized processes during which the pressure p in the integrand is the pressure of the entire quantity of the gas undergoing the process and not only the pressure at the piston face.

►For this we imagine the gas undergoes a sequence of equilibrium states during the process. Such an idealized expansion (or compression) is called a ***quasiequilibrium*** process.

Modeling Expansion and Compression Work

►In a quasiequilibrium expansion, the gas moves along a pressure-volume curve, or path, as shown.

►Applying **Eq. 2.17**, the work done by the gas on the piston is given by the **area** under the curve of pressure versus volume.



Modeling Expansion and Compression Work

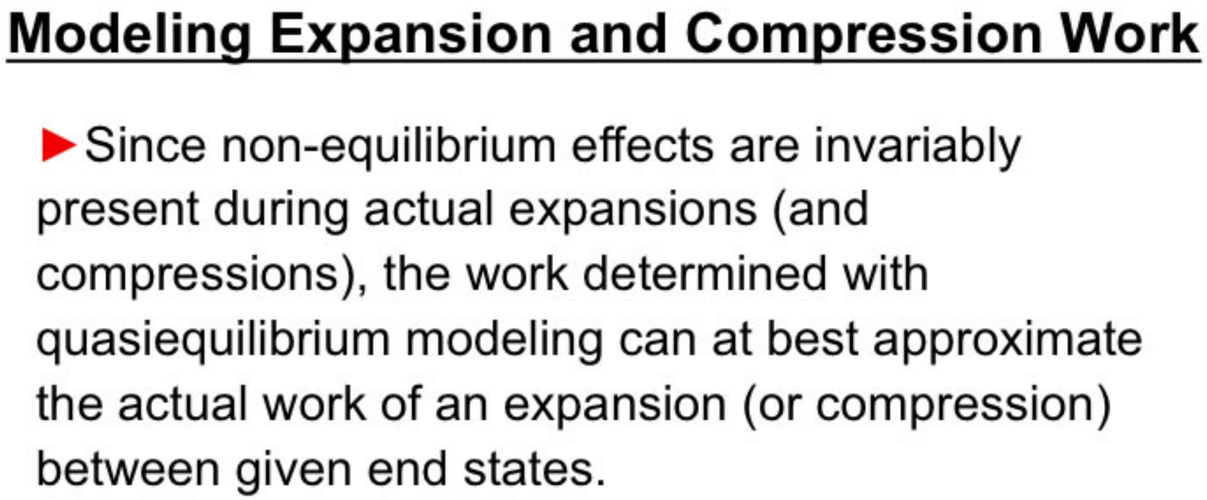
►When the pressure-volume relation required by **Eq. 2.17** to evaluate work in a quasiequilibrium expansion (or compression) is expressed as an equation, the evaluation of expansion or compression work can be simplified.

►An example is a quasiequilibrium process described by $pV^n = constant$, where n is a constant. This is called a *polytropic process*.

►For the case $n = 1$, $pV = constant$ and **Eq. 2.17** gives

$$W = (constant)\ln\left(\frac{V_2}{V_1}\right)$$

where $constant = p_1V_1 = p_2V_2$.



Modeling Expansion and Compression Work

- ►Since non-equilibrium effects are invariably present during actual expansions (and compressions), the work determined with quasiequilibrium modeling can at best approximate the actual work of an expansion (or compression) between given end states.

You will need to analyze the integral of PdV in order to estimate the work associated with volume expansions/compressions.

$$W = \int_{V_1}^{V_2} p\, dV$$

So, for polytropic situations: pV^n = constant, then

$$W = \int_{V_1}^{V_2} \frac{constant}{V^n} dV = constant \int_{V_1}^{V_2} V^{-n} dV$$

But, most gas situations will use Tables that have combined the Internal Energy (U) with the pV and a thermodynamic term (Enthalpy, H or h) is documented.

That is: $H = U + pV$

$h = u + pv$

(more on this when we reach Chapter 3)

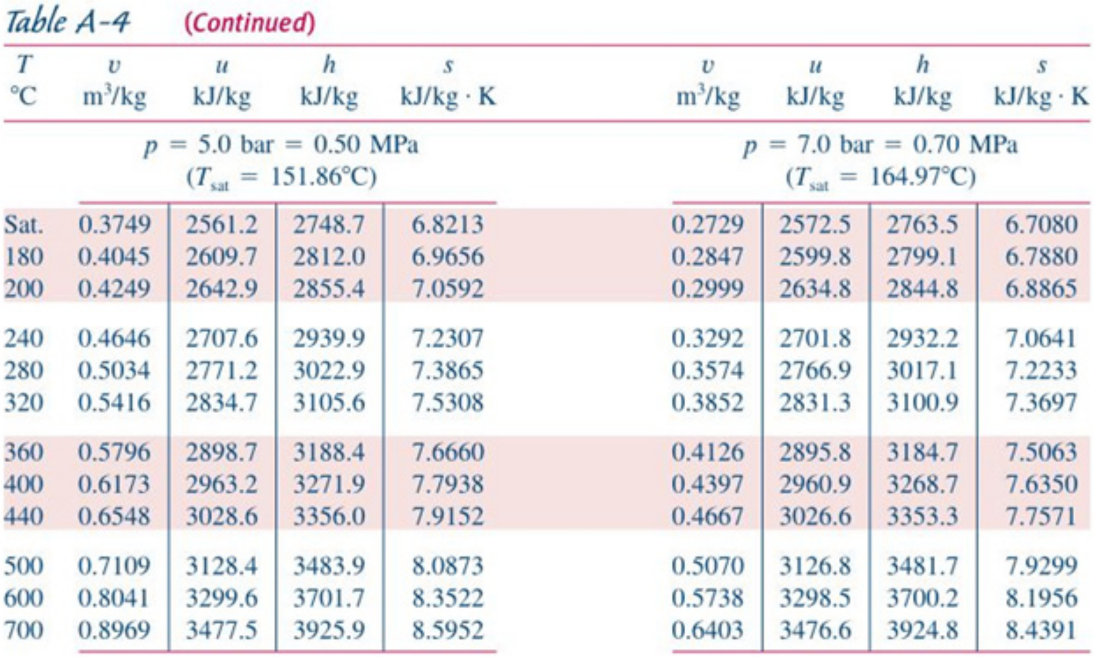
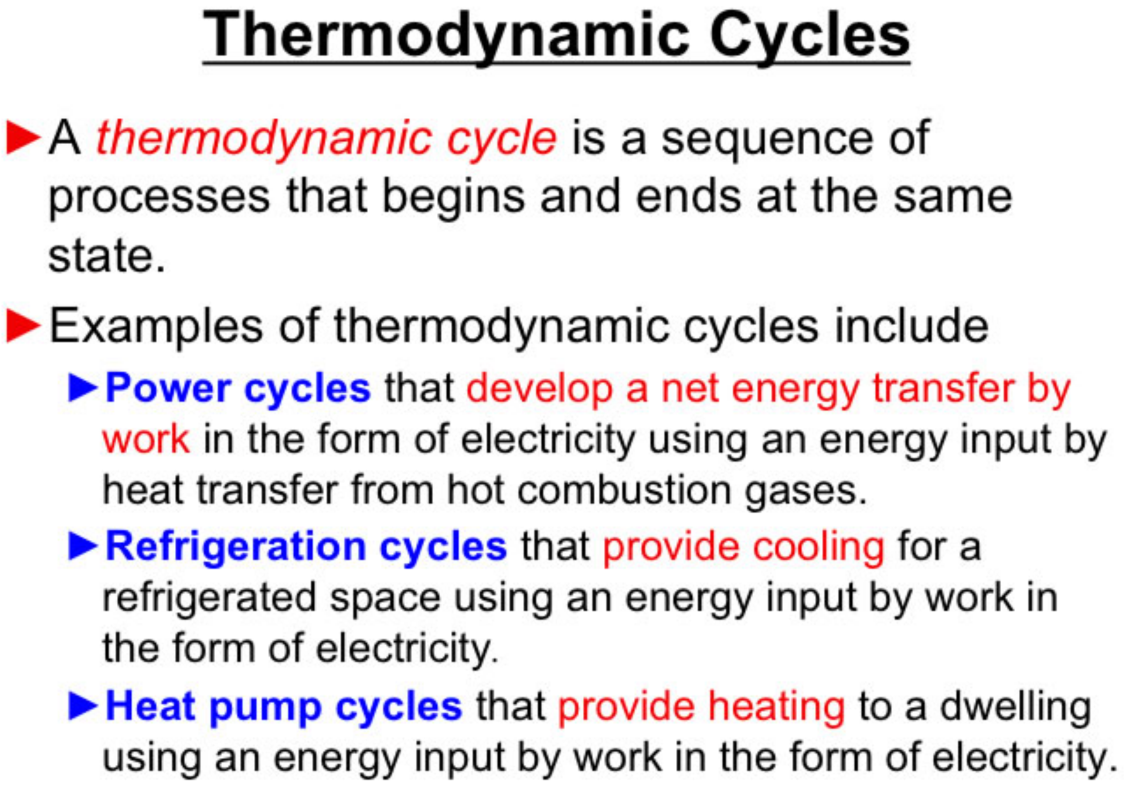


Table A-4 (Continued)

T	v	u	h	s	v	u	h	s
°C	m³/kg	kJ/kg	kJ/kg	kJ/kg · K	m³/kg	kJ/kg	kJ/kg	kJ/kg · K
	p = 5.0 bar = 0.50 MPa (T_{sat} = 151.86°C)				p = 7.0 bar = 0.70 MPa (T_{sat} = 164.97°C)			
Sat.	0.3749	2561.2	2748.7	6.8213	0.2729	2572.5	2763.5	6.7080
180	0.4045	2609.7	2812.0	6.9656	0.2847	2599.8	2799.1	6.7880
200	0.4249	2642.9	2855.4	7.0592	0.2999	2634.8	2844.8	6.8865
240	0.4646	2707.6	2939.9	7.2307	0.3292	2701.8	2932.2	7.0641
280	0.5034	2771.2	3022.9	7.3865	0.3574	2766.9	3017.1	7.2233
320	0.5416	2834.7	3105.6	7.5308	0.3852	2831.3	3100.9	7.3697
360	0.5796	2898.7	3188.4	7.6660	0.4126	2895.8	3184.7	7.5063
400	0.6173	2963.2	3271.9	7.7938	0.4397	2960.9	3268.7	7.6350
440	0.6548	3028.6	3356.0	7.9152	0.4667	3026.6	3353.3	7.7571
500	0.7109	3128.4	3483.9	8.0873	0.5070	3126.8	3481.7	7.9299
600	0.8041	3299.6	3701.7	8.3522	0.5738	3298.5	3700.2	8.1956
700	0.8969	3477.5	3925.9	8.5952	0.6403	3476.6	3924.8	8.4391

Modes of Heat Transfer

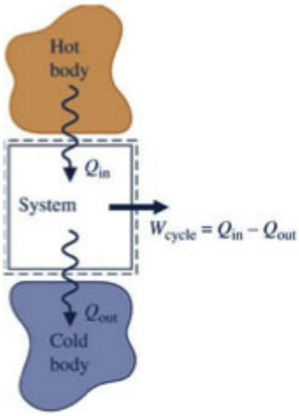
- For any particular application, energy transfer by heat can occur by one or more of three modes:
    - conduction
    - radiation
    - convection



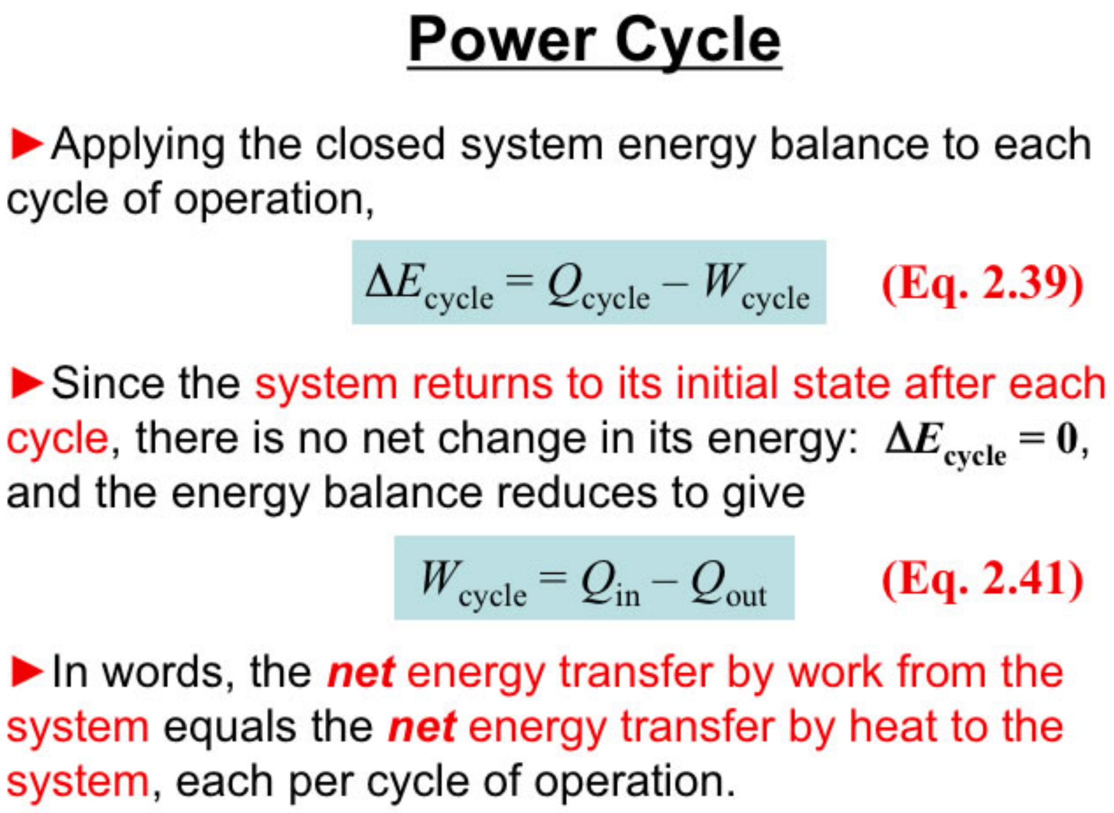
Thermodynamic Cycles

- A *thermodynamic cycle* is a sequence of processes that begins and ends at the same state.
- Examples of thermodynamic cycles include
  - **Power cycles** that develop a net energy transfer by work in the form of electricity using an energy input by heat transfer from hot combustion gases.
  - **Refrigeration cycles** that provide cooling for a refrigerated space using an energy input by work in the form of electricity.
  - **Heat pump cycles** that provide heating to a dwelling using an energy input by work in the form of electricity.

Power Cycle



- ►A system undergoing a power cycle is shown at right.
- ►The energy transfers by heat and work shown on the figure are each positive in the direction of the accompanying arrow. This convention is commonly used for analysis of thermodynamic cycles.
  - ►W_{cycle} is the **net energy transfer by work** from the system per cycle of operation – in the form of electricity, typically.
  - ►Q_{in} is the **heat transfer of energy to the system** per cycle from the hot body – drawn from hot gases of combustion or solar radiation, for instance.
  - ►Q_{out} is the **heat transfer of energy from the system** per cycle to the cold body – discharged to the surrounding atmosphere or nearby lake or river, for example.



Power Cycle

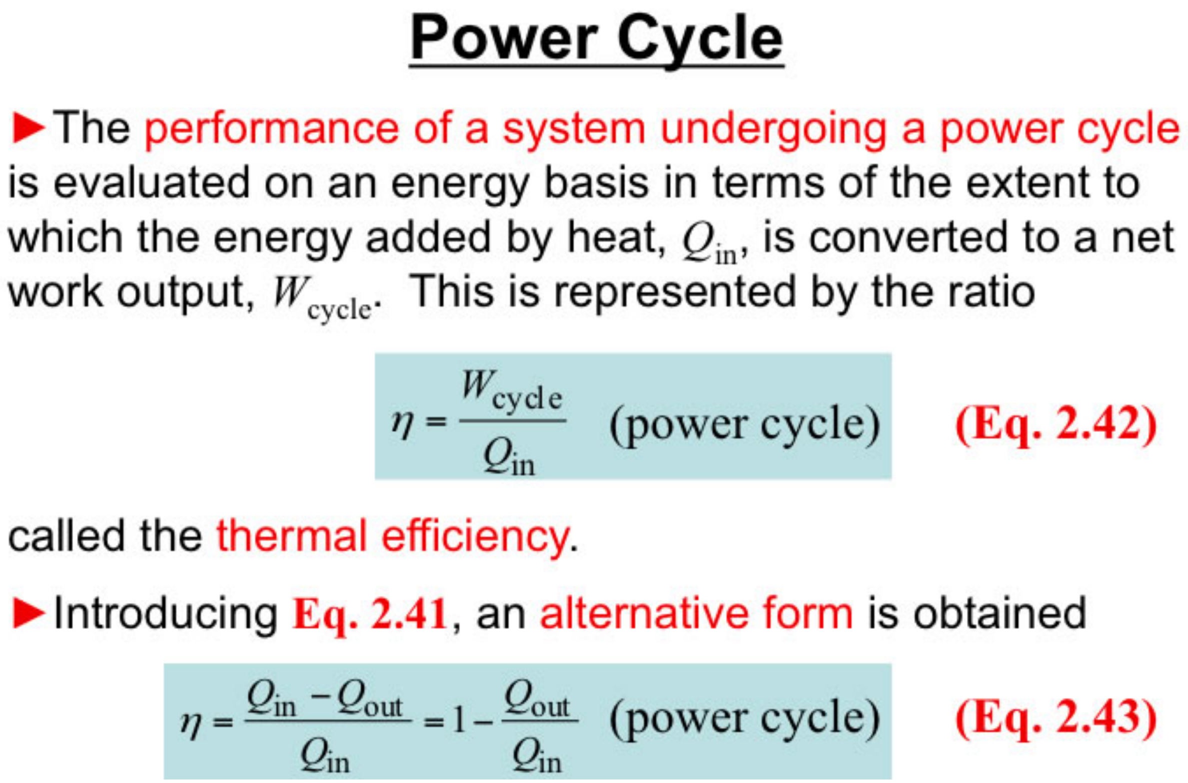
- ►Applying the closed system energy balance to each cycle of operation,

$$\Delta E_{\text{cycle}} = Q_{\text{cycle}} - W_{\text{cycle}} \qquad \textbf{(Eq. 2.39)}$$

- ►Since the system returns to its initial state after each cycle, there is no net change in its energy: $\boldsymbol{\Delta E_{\text{cycle}} = 0}$, and the energy balance reduces to give

$$W_{\text{cycle}} = Q_{\text{in}} - Q_{\text{out}} \qquad \textbf{(Eq. 2.41)}$$

- ►In words, the ***net*** energy transfer by work from the system equals the ***net*** energy transfer by heat to the system, each per cycle of operation.



Power Cycle

- ►The performance of a system undergoing a power cycle is evaluated on an energy basis in terms of the extent to which the energy added by heat, Q_{in}, is converted to a net work output, W_{cycle}. This is represented by the ratio

$$\eta = \frac{W_{\text{cycle}}}{Q_{\text{in}}} \quad \text{(power cycle)} \qquad \textbf{(Eq. 2.42)}$$

called the thermal efficiency.

- ►Introducing **Eq. 2.41**, an alternative form is obtained

$$\eta = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} \quad \text{(power cycle)} \qquad \textbf{(Eq. 2.43)}$$

Power Cycle

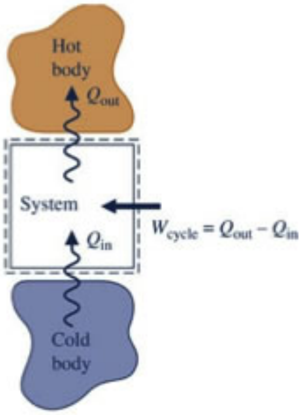
►Using the second law of thermodynamics (Chapter 5), we will show that the value of thermal efficiency must be less than unity: $\eta < 1$ (< 100%). That is, only a portion of the energy added by heat, Q_{in}, can be obtained as work. The remainder, Q_{out}, is discharged.

Example: A system undergoes a power cycle while receiving 1000 kJ by heat transfer from hot combustion gases at a temperature of 500 K and discharging 600 kJ by heat transfer to the atmosphere at 300 K. Taking the combustion gases and atmosphere as the hot and cold bodies, respectively, determine for the cycle, the net work developed, in kJ, and the thermal efficiency.

►Substituting into **Eq. 2.41**, $W_{cycle} = 1000\text{ kJ} - 600\text{ kJ} = \underline{400\text{ kJ}}$.

►Then, with **Eq. 2.42**, $\eta = 400\text{ kJ}/1000\text{ kJ} = \underline{0.4\ (40\%)}$. Note the thermal efficiency is commonly reported on a percent basis.

Refrigeration Cycle



► A system undergoing a refrigeration cycle is shown at right.

► As before, the energy transfers are each positive in the direction of the accompanying arrow.

► W_{cycle} is the **net energy transfer by work** to the system per cycle of operation, usually in the form of electricity.

► Q_{in} is the **heat transfer of energy to the system** per cycle from the cold body – drawn from a freezer compartment, for example.

► Q_{out} is the **heat transfer of energy from the system** per cycle to the hot body – discharged to the space surrounding the refrigerator, for instance.

Refrigeration Cycle

► Since the system returns to its initial state after each cycle, there is no net change in its energy: $\Delta E_{cycle} = 0$, and the energy balance reduces to give

$$W_{cycle} = Q_{out} - Q_{in} \qquad \textbf{(Eq. 2.44)}$$

► In words, the ***net*** energy transfer by work to the system equals the ***net*** energy transfer by heat from the system, each per cycle of operation.

Refrigeration Cycle

► The performance of a system undergoing a refrigeration cycle is evaluated on an energy basis as the ratio of energy drawn from the cold body, Q_{in}, to the net work required to accomplish this effect, W_{cycle}:

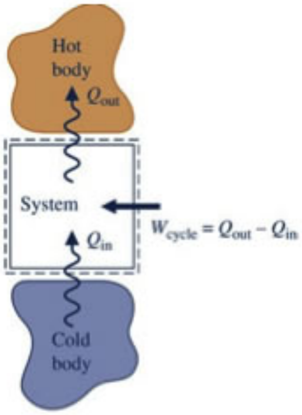
$$\beta = \frac{Q_{\text{in}}}{W_{\text{cycle}}} \quad \text{(refrigeration cycle)} \qquad \textbf{(Eq. 2.45)}$$

called the coefficient of performance for the refrigeration cycle.

► Introducing **Eq. 2.44**, an alternative form is obtained

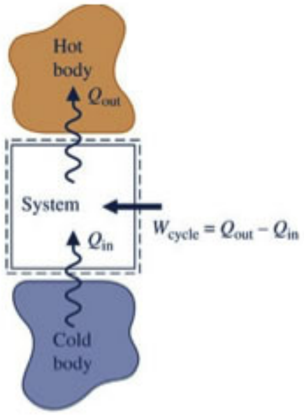
$$\beta = \frac{Q_{\text{in}}}{Q_{\text{out}} - Q_{\text{in}}} \quad \text{(refrigeration cycle)} \qquad \textbf{(Eq. 2.46)}$$

Heat Pump Cycle



- The heat pump cycle analysis closely parallels that given for the refrigeration cycle. The same figure applies:
  - But now the focus is on Q_{out}, which is the **heat transfer of energy from the system** per cycle to the hot body – such as to the living space of a dwelling.
  - Q_{in} is the **heat transfer of energy to the system** per cycle from the cold body – drawn from the surrounding atmosphere or the ground, for example.

Heat Pump Cycle



► As before, W_{cycle} is the **net energy transfer by work** to the system per cycle, usually provided in the form of electricity.

► As for the refrigeration cycle, the energy balance reads

$$W_{cycle} = Q_{out} - Q_{in} \qquad \textbf{(Eq. 2.44)}$$

Heat Pump Cycle

► The performance of a system undergoing a heat pump cycle is evaluated on an energy basis as the ratio of energy provided to the hot body, Q_{out}, to the net work required to accomplish this effect, W_{cycle}:

$$\gamma = \frac{Q_{out}}{W_{cycle}} \quad \text{(heat pump cycle)} \qquad \textbf{(Eq. 2.47)}$$

called the coefficient of performance for the heat pump cycle.

► Introducing **Eq. 2.44**, an alternative form is obtained

$$\gamma = \frac{Q_{out}}{Q_{out} - Q_{in}} \quad \text{(heat pump cycle)} \qquad \textbf{(Eq. 2.48)}$$

Heat Pump Cycle

Example: A system undergoes a heat pump cycle while discharging 900 kJ by heat transfer to a dwelling at 20°C and receiving 600 kJ by heat transfer from the outside air at 5°C. Taking the dwelling and outside air as the hot and cold bodies, respectively, determine for the cycle, the net work input, in kJ, and the coefficient of performance.

- ► Substituting into **Eq. 2.44**, $W_{\text{cycle}} = 900 \text{ kJ} - 600 \text{ kJ} = \underline{300 \text{ kJ}}$.
- ► Then, with **Eq. 2.47**, $\gamma = 900 \text{ kJ}/300 \text{ kJ} = \underline{3.0}$. Note the coefficient of performance is reported as its numerical value, as calculated here.

Go to the: [next lecture | chapter top | previous lecture]

**Copyright © J.M. Sullivan, Jr., (2004-2012)
All Rights Reserved.**