19ME31 Engineering Thermodynamics L1

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Course Objective

To enable undergraduate students of Mechanical Engineering to apply concepts of energy, entropy and exergy to simple systems with justifiable assumptions through theoretical concepts and illustrations

Course Outcomes* – At the end of the course, the student will be able to

1. Apply concepts of energy conservation to open and closed systems
2. Arrive at benchmark performances of heat engines and refrigerator / heat pump and compute entropy changes.
3. Depict various thermodynamic processes on property diagrams, estimate properties of mixtures and quantify deviation from ideal gas behavior.
4. Calculate changes in properties during different ideal gas processes

Overview of the topics

Basic Concepts of Thermodynamics

First Law of Thermodynamics

Second Law of Thermodynamics

Entropy & Exergy

Thermodynamic Relations and Ideal Gas Mixtures

What is "Thermodynamics"

- Greek words ← **Early conceptualization**
  - *Therme* – heat
  - *Dynamis* - power
- All aspects of energy and energy transformations, not limited to
  - Power production
  - Refrigeration
  - Relationships among properties of matter

Present perspective

- Applications
  - Water heating, air-conditioner
  - Jet engines, power plants (conventional or otherwise)
  - Literally anywhere and everywhere

Basic Concepts of Thermodynamics

SNo	Topic	Hours
1	Macroscopic & Microscopic approach, Concept of Continuum, Thermodynamic system & control volume, Thermodynamic properties, Quasi static process, Thermodynamic Equilibrium	2
2	Temperature – Zeroth law of thermodynamics – Temperature scales. Pressure measurement – Barometer.	2
3	Energy and Work transfer – Forms of energy – forms of work transfer – point and path function.	1
4	Pure Substances– phases of pure substances – property diagrams – Property tables	2
5	Ideal gas equation of state – Compressibility factor – Vander Waals equation of state – vapor pressure and phase equilibrium.	2

I Law of Thermodynamics

SNo	Topic	Hours
1	Statement of I law, PMM1, application to Non-flow Systems – Ideal gas processes.	2
2	I law for Non-flow Systems – Vapor processes	2
3	Analysis of Flow Systems – Continuity equation (Mass balance) and Steady Flow Energy Equation (Energy balance)	2
4	Illustration in Some Steady flow Engineering Devices – nozzles, turbines, etc.	3

II Law of Thermodynamics

SNo	Topic	Hours
1	II Law – Statements of Kelvin Planck and Clausius; Equivalence	2
2	Thermal energy reservoirs, Heat engines, Refrigerators and Heat Pumps; PMM 2	2
3	Reversibility and Irreversibility – causes of irreversibility – types of irreversibility	2
4	Carnot – Reversed Carnot cycle – Carnot's theorem – Absolute Thermodynamic temperature scale	2

Entropy & Exergy

SNo	Topic	Hours
1	Entropy – Clausius Theorem, Clausius Inequality	2
2	Entropy of Isolated system	1
3	Entropy change of liquids, solids & ideal gases	2
4	Exergy – Reversible work and Irreversibility - II law efficiency	2
5	Exergy change for non flow system & flow streams	2
6	III law of Thermodynamics	1

Thermodynamic Relations & Ideal Gas Mixtures

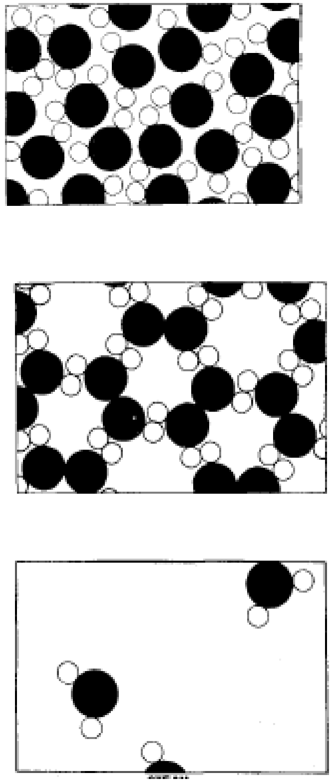
SNo	Topic	Hours
1	Thermodynamic potentials, Gibbs & Helmholtz functions	2
2	Maxwell Relations – T dS equations	2
3	Joule Kelvin effect & Clausius Clapeyron Equation	2
4	Ideal Gas Mixtures – Mass & Mole Fractions, Dalton's Law and Amagat-Leduc law	1
5	Properties of Ideal Gas mixture.	2

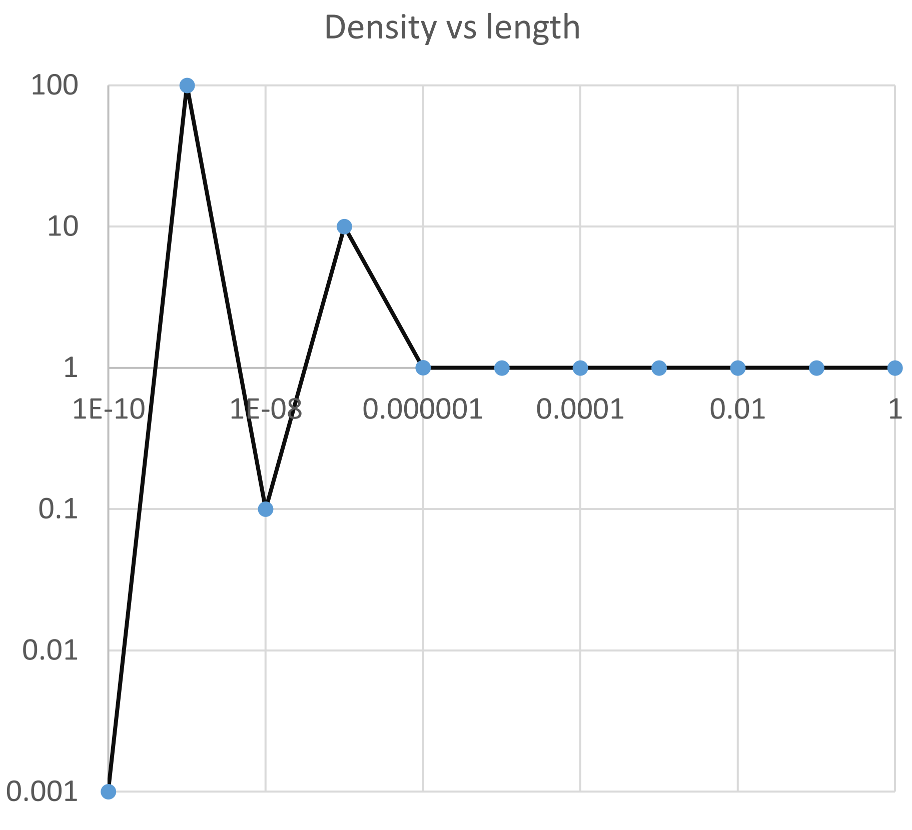
Basic Concepts of Thermodynamics - approaches

https://www.aarp.org/health/healthy-living/info-10-2013/coffee-for-health.html

Microscopic approach	Macroscopic approach
Explain physical phenomena on the basis of molecular behavior	No direct measurements at the microscopic scale
Kinetic theory – application of laws of mechanics to individual molecules Statistical thermodynamics – application of probability considerations to the very large number of molecules that constitute any macroscopic quantity of matter.	Classical thermodynamics – based on macroscopic measurement of properties. Eg. – temperature, pressure, etc. Laws of thermodynamics are based on macroscopic approach.

Basic Concepts of Thermodynamics - continuum





Concept of continuum

https://www.waterlogic.com/en-gb/resources/blog/styles-functions-water-taps/

Homework – find out the density of a water molecule in g/m^3

Basic Concepts of Thermodynamics – Systems

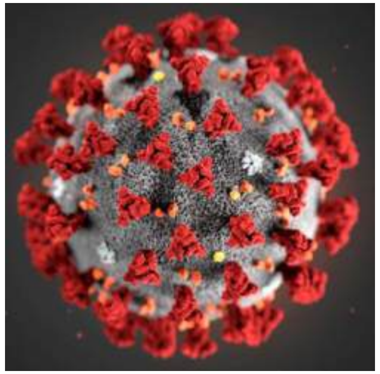
Thermodynamic System
- Any quantity of matter or a fixed region in space on which we focus our attention for the purpose of analysis
- Has a boundary – fixed or moving, real or imaginary

Interaction
- Energy (closed system)
- Mass and / or Energy (open system)
- Nothing (isolated system)

Surrounding - Everything (not anything) apart from the system

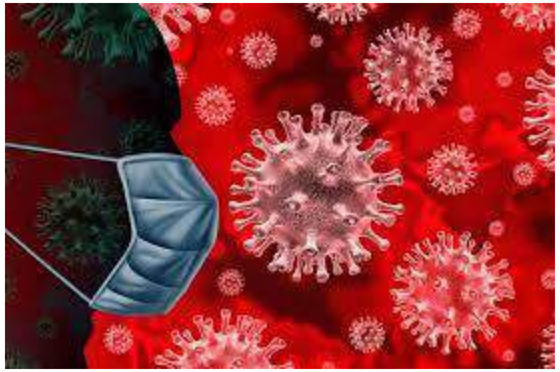
Assignment – Energy consumption by a single corona virus

Thermodynamic System – Control Mass



https://www.newscientist.com/term/covid-19/

Thermodynamic System - Control Volume

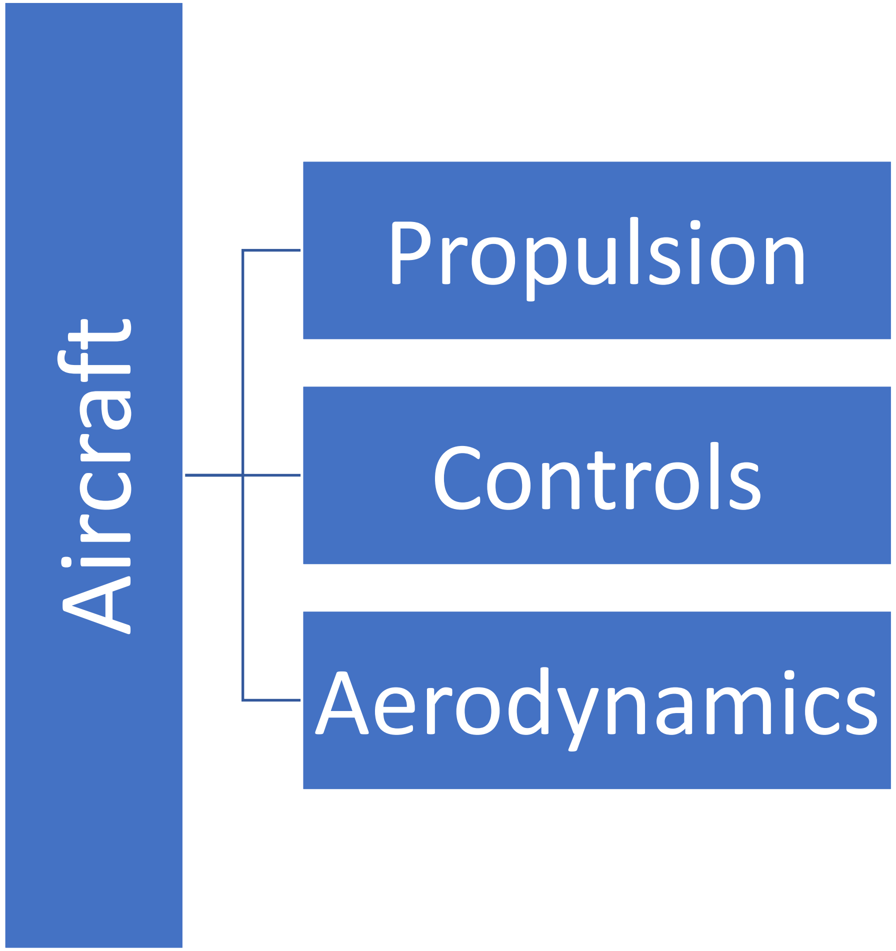


https://www.drugtargetreview.com/news/57328/researchers-work-to-create-a-covid-19-viral-epitope-map/

Test of learning – System + Surrounding = ?

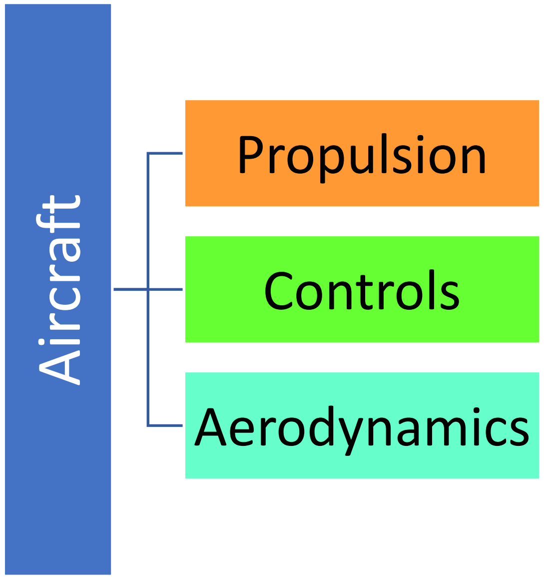
Some Engineering Systems

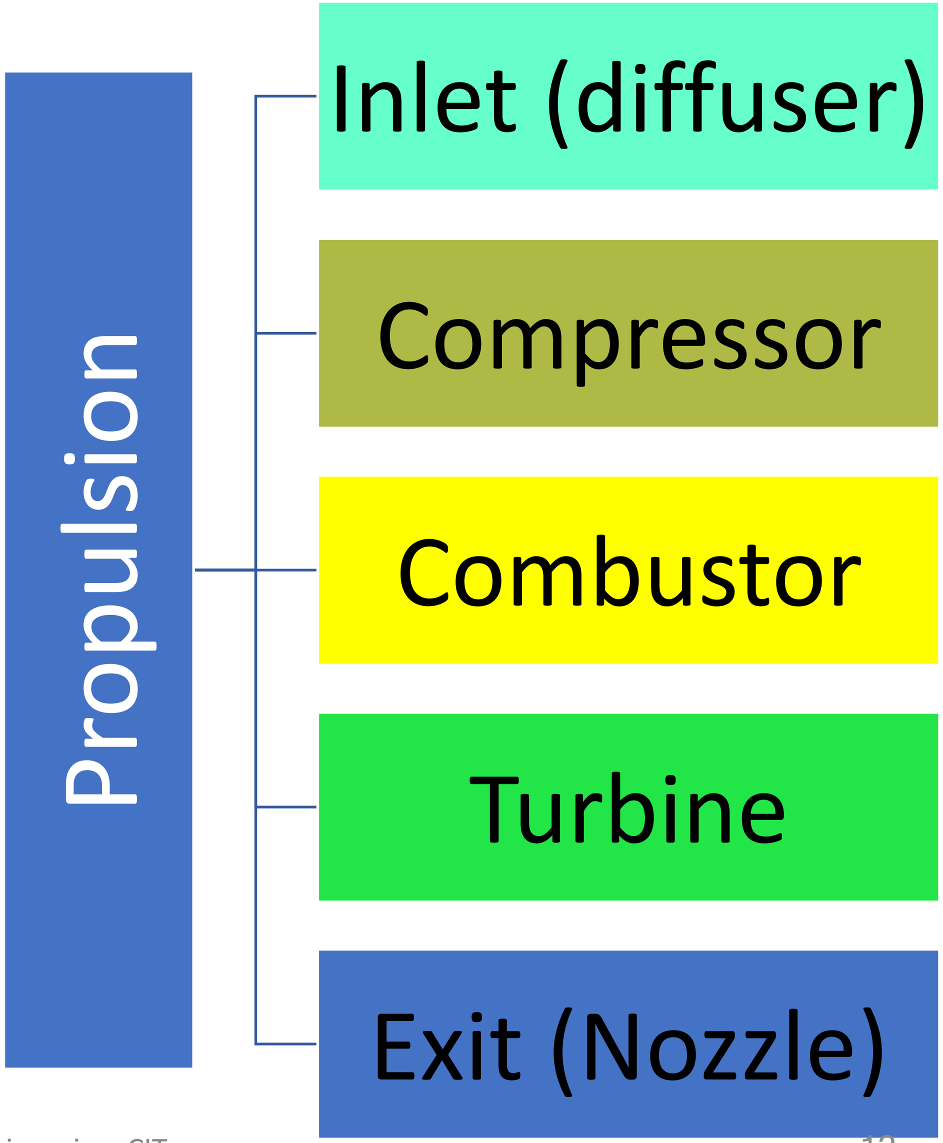
https://www.airbus.com/newsroom/press-releases/en/2019/05/airbus-and-sas-scandinavian-airlines-sign-hybrid-and-electric-aircraft-research-agreement.html



- A system can comprise multiple systems; when individual sub-systems is being analysed, the rest can be treated as a surrounding
- Any system can be viewed from an engineering perspective

Some Engineering Systems (contd.)





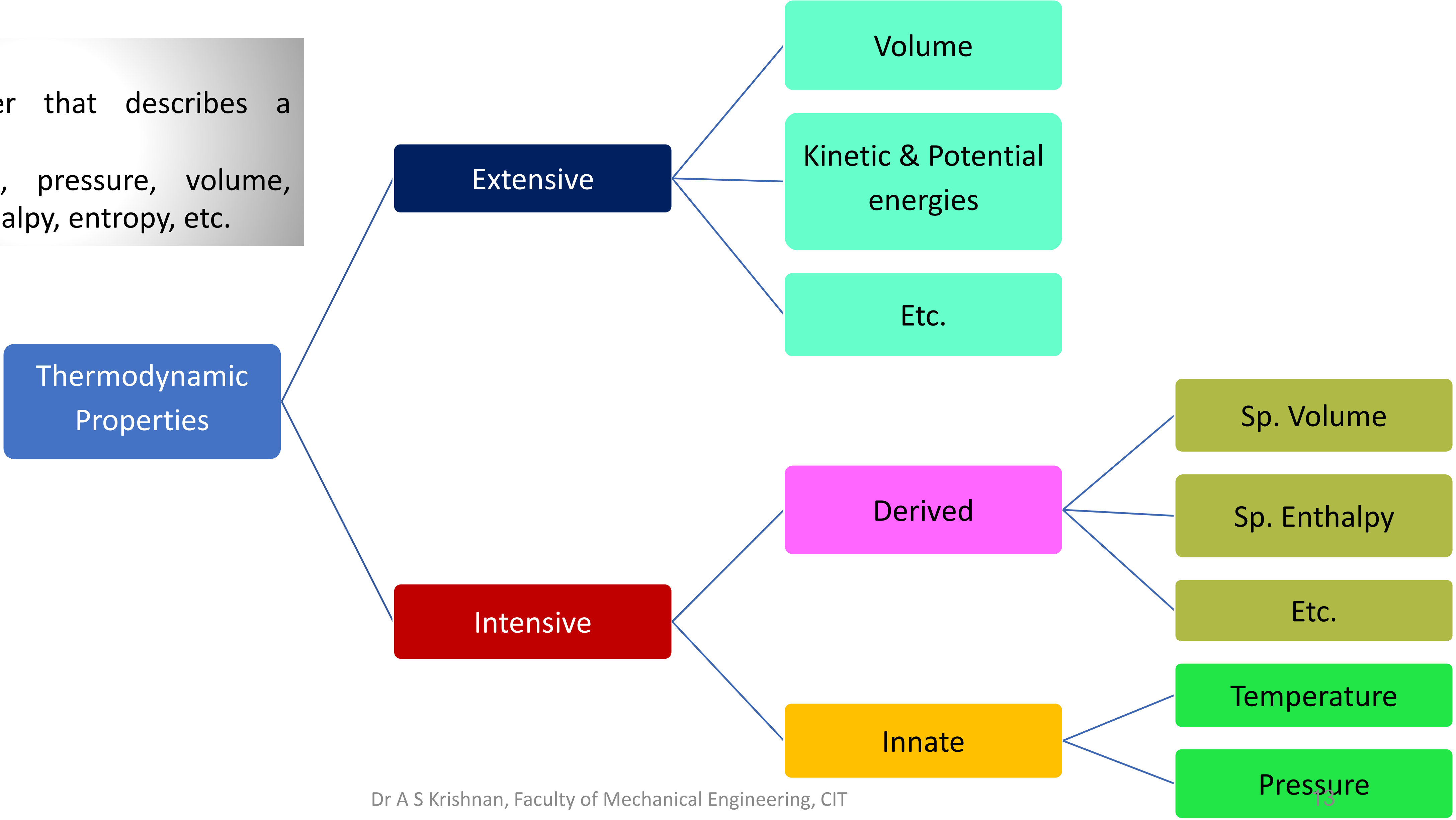
- A system can comprise multiple systems; when individual sub-systems is being analysed, the rest can be treated as a surrounding
- Any system can be viewed from an engineering perspective

Test of learning - Classify each of the system / sub-system as closed / open / isolated system

Thermodynamics – Properties

Property

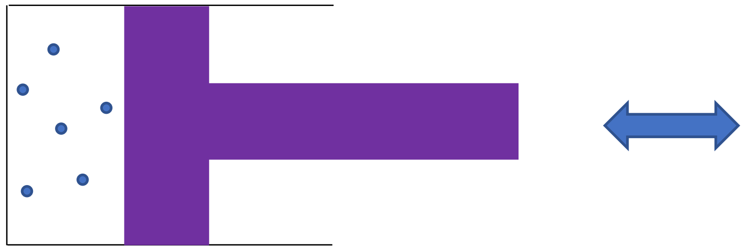
- A parameter that describes a system
- Temperature, pressure, volume, density, enthalpy, entropy, etc.



State, Process, Equilibrium

State – Defined by thermodynamic properties

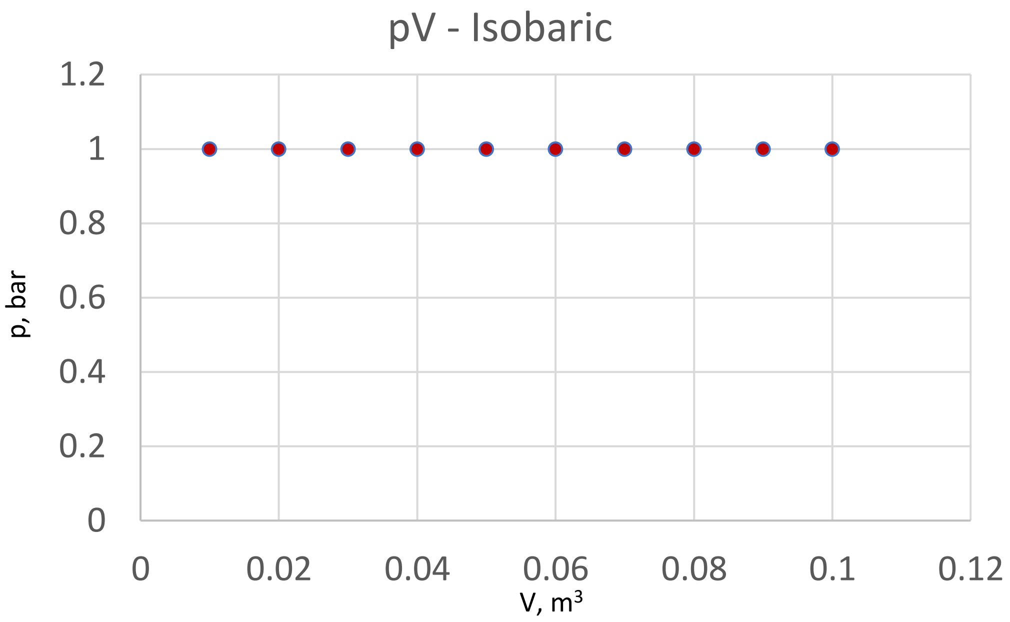
Process – Change of State



Thermodynamic equilibrium –

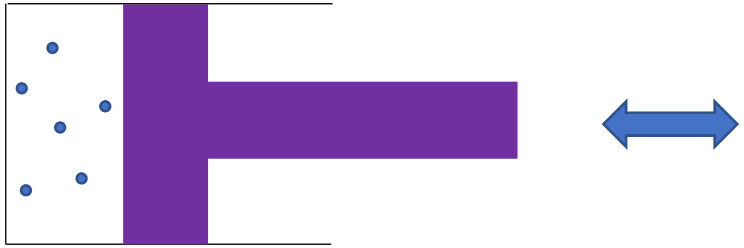
When the system is in equilibrium with the surroundings with respect to

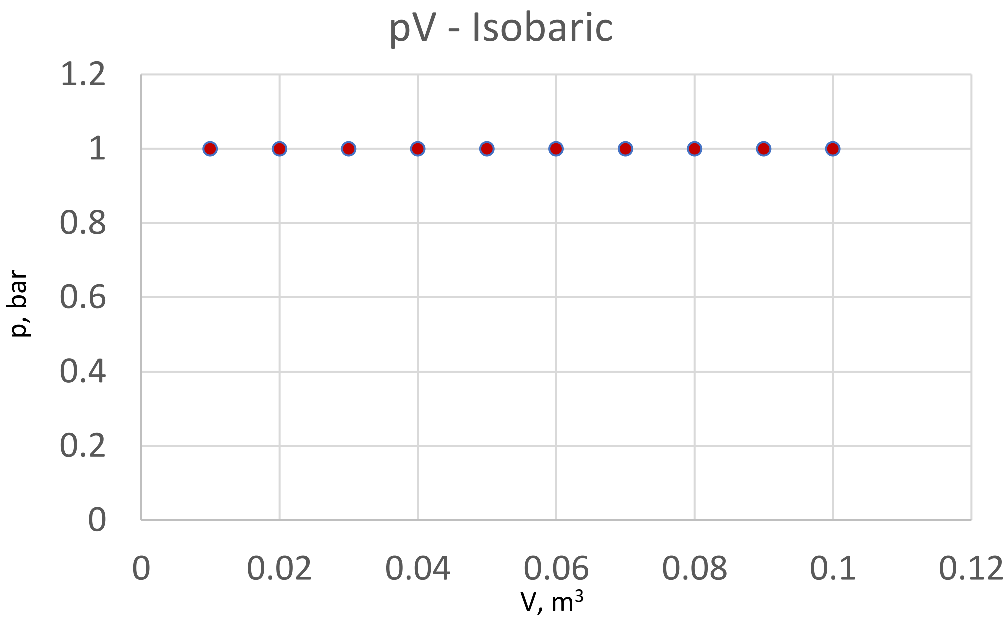
1. Mechanical – no unbalanced forces
2. Thermal – no variation in temperature
3. Phase – mass of each phase reaches an equilibrium, remains unchanged thereafter
4. Chemical – no change in composition with time

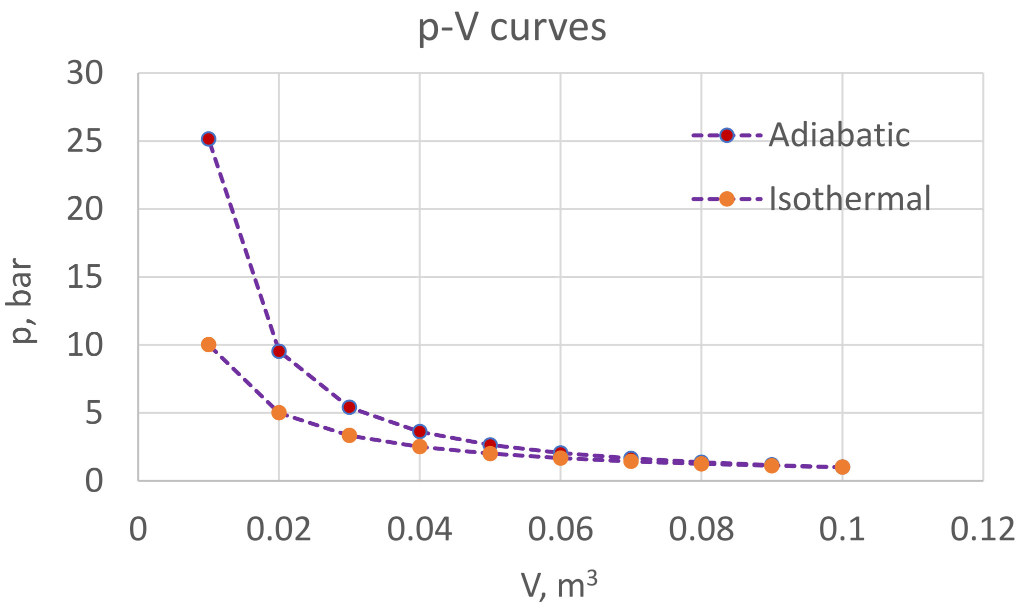


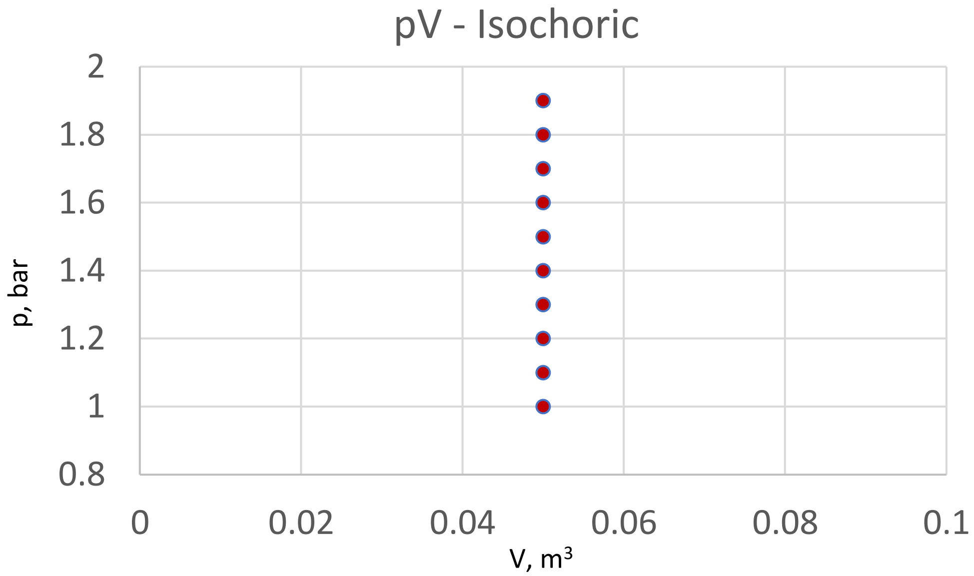
Quasi-static process – A process that happens so slowly that the system is in equilibrium with the surroundings at every state

Processes (contd.)









Engineering Thermodynamics
Lecture 2

Today’s discussion

- Properties – a small review & numerical example
- Thermal equilibrium & Zeroth law of Thermodynamics
- Temperature scale & numerical example
- Some of the explanation(s) could be deliberately missed, and posted as assignments / homework. This is to develop self-learning.

Some properties

S No.	Property	SI Units	Extensive / Intensive
1	Mass	kg	Extensive
2	Length	m	Extensive
3	time	s	Intensive
4	Temperature	K	Intensive
5	Force	N or $kgms^{-2}$	Extensive
6	Pressure	Pa or N/m^2	Intensive
7	Energy (PE, KE, IE, etc)	J	Extensive
8	Entropy	J/K	Extensive
9	Power	W	Extensive

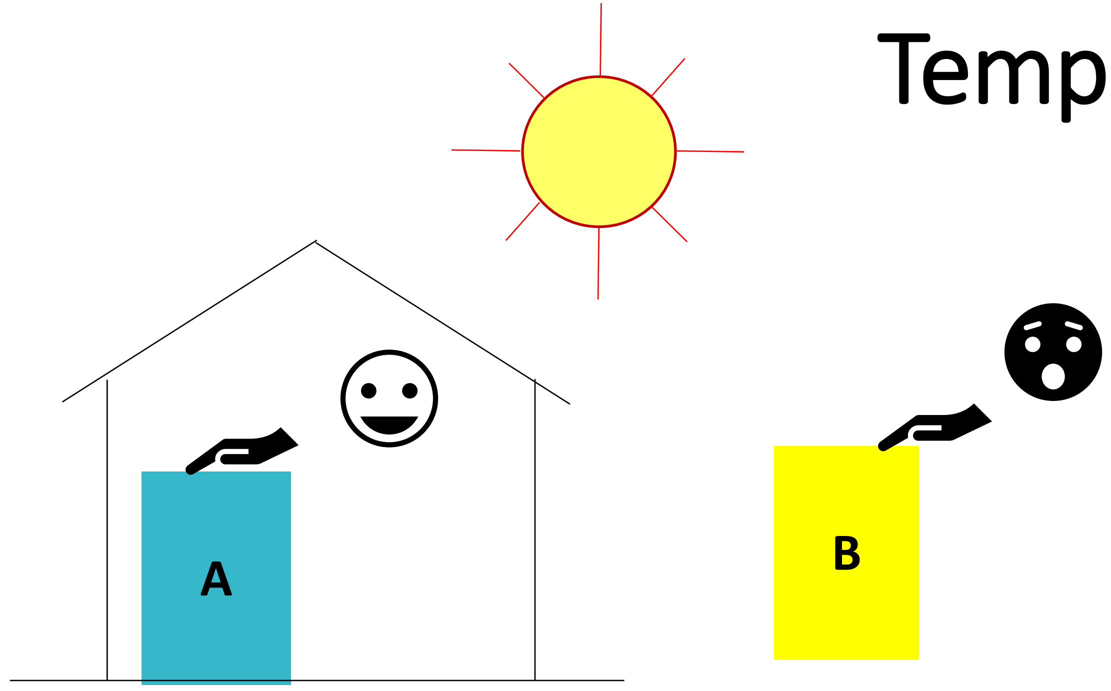
Food for thought - Time and pressure are extensive properties – argue for and against

Conversion of an extensive property to an intensive property

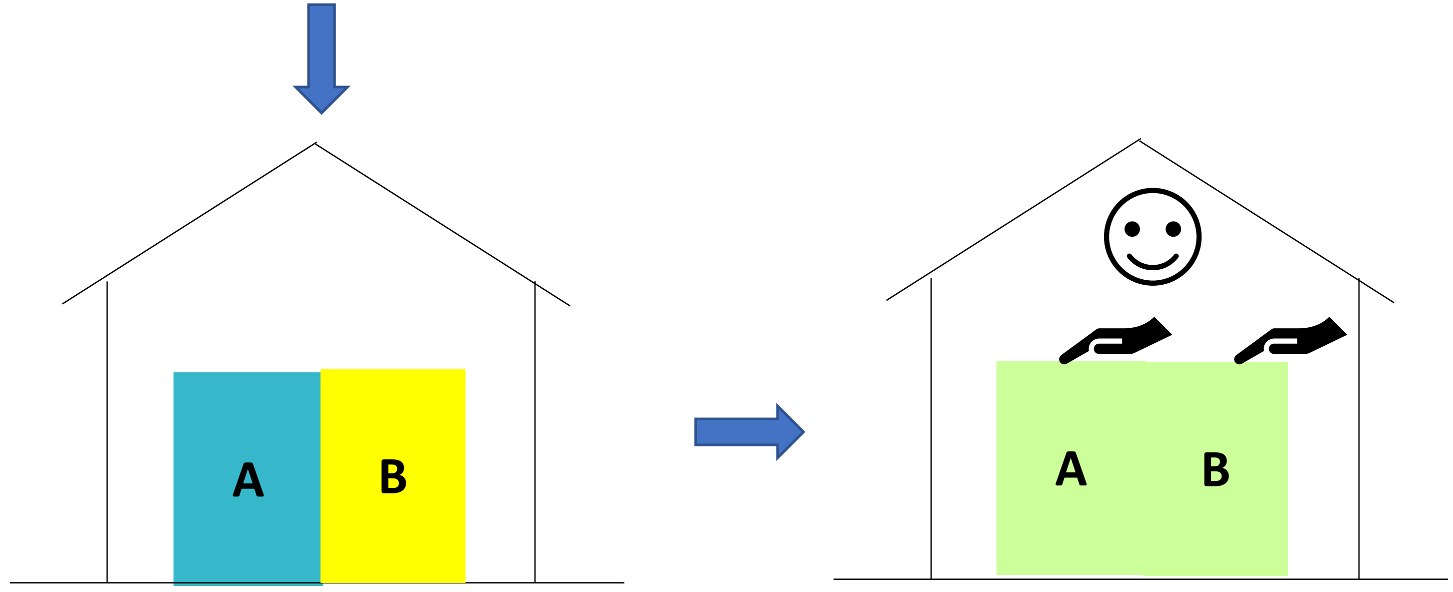
SNo	Property	Symbol	Units	Corresponding Intensive Property	Symbol	Units
1	Volume	V	m^3	Sp. Volume (reciprocal of density)	v	m^3/kg
2	Force	F	N	Sp. Force (acceleration)	f	m/s^2
3	Kinetic energy (½ mc^2)	KE	J	Sp. Kinetic energy (½ c^2)	ke	J/kg
4	Potential energy (mgz)	PE	J	Sp. Potential energy (gh)	pe	J/kg
5	Internal energy	U	J	Sp. Internal energy	u	J/kg
6	Enthalpy	H	J	Sp. Enthalpy	h	J/kg
7	Entropy	S	J/K	Sp. Entropy	s	J/kgK

A freely falling body has a total energy of 100 J. At a specific instant, it has a specific potential energy of 2 J/kg and a kinetic energy of 45 J. Compute the (a) mass of the object (b) the velocity of the object and its height above the ground, at that instant.

Temperature – sense of hot or cold

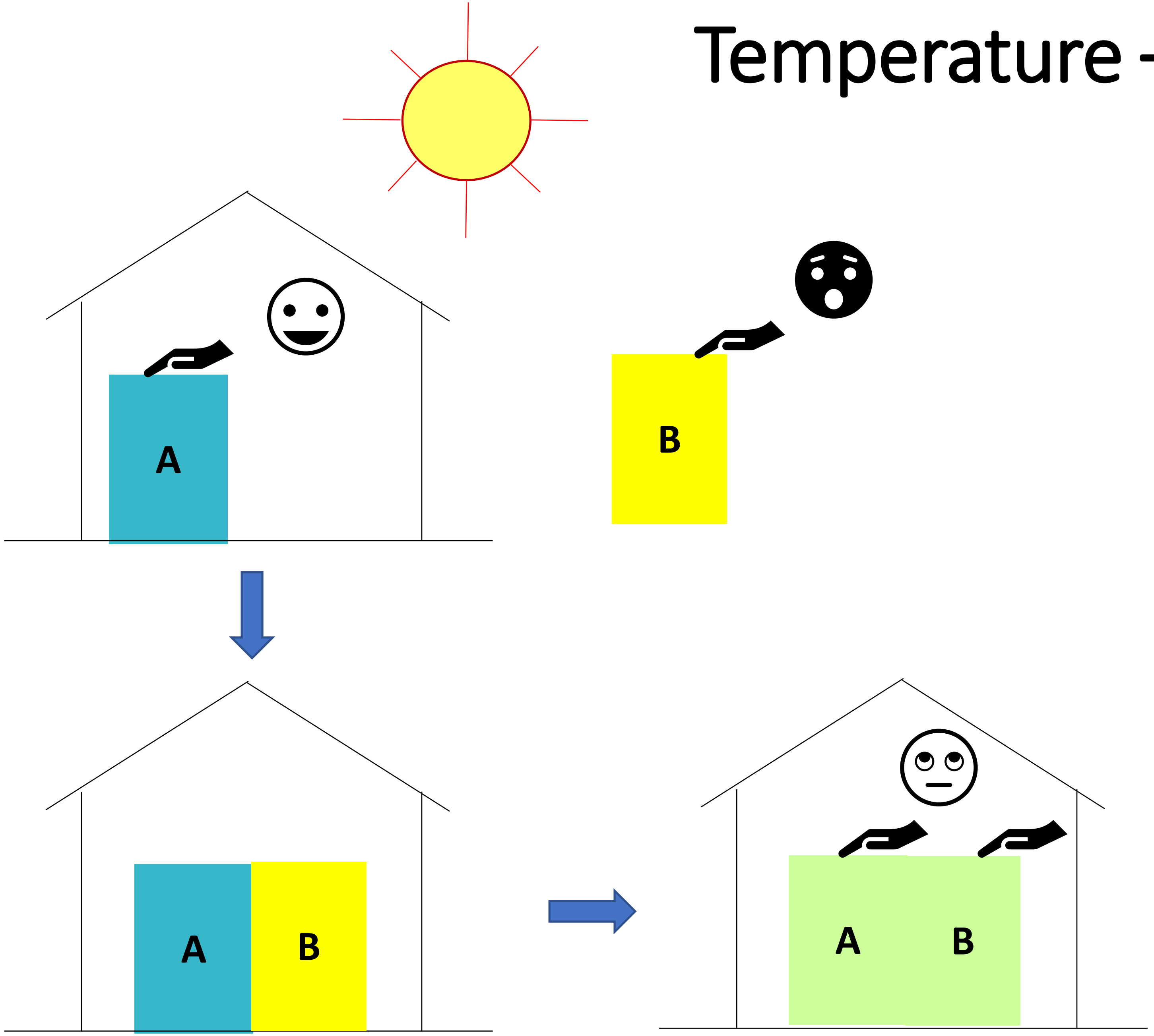


A and B are of the same material



What if A and B are not of the same material?

Temperature – sense of hot or cold

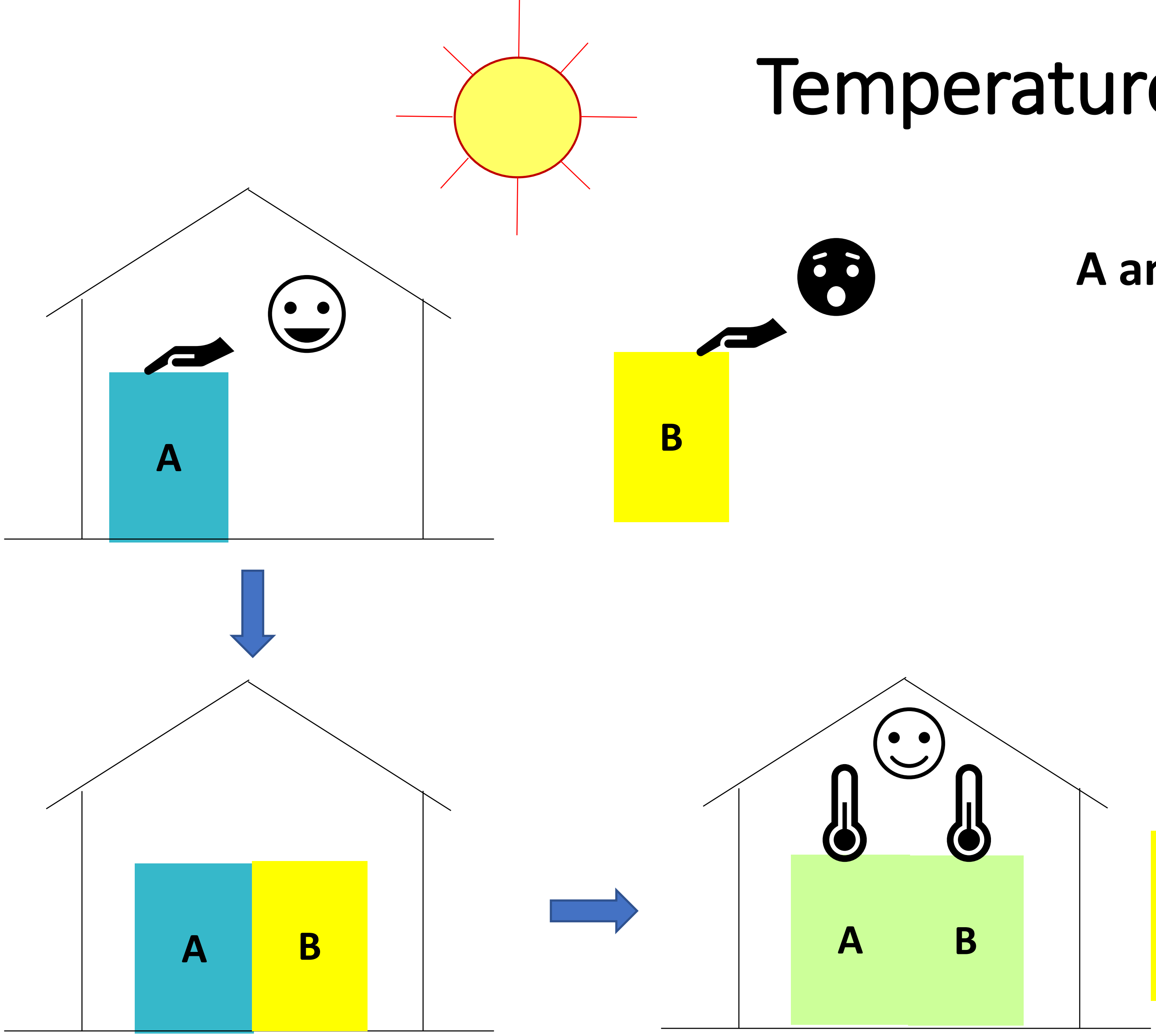


A and B are not of the same material

Our sense of temperature is unreliable

We need a system to judge if they are in equilibrium → Thermometer

Temperature – sense of hot or cold



A and B are not of the same material

Zeroth Law of Thermodynamics

When any two bodies are separately in thermal equilibrium with a third, they are also in thermal equilibrium with each other.

Thermometers

Utilize a change in property of the “thermometric” material with respect to change in temperature

- Hg in glass, Alcohol in glass – expansion
- RTD, Thermistor – change in resistance
- Thermocouple – EMF
- Constant volume gas thermometer – volumetric expansion of gas

Temperature scales & relation between them

Temperature scale	Symbol	History
Celsius	°C	1948, Formerly called as Centigrade; named after Swedish astronomer A. Celsius (1701-1744)
Fahrenheit	°F	Named after German instrument maker G. Fahrenheit (1686-1736)
Kelvin	K	Named after Lord Kelvin (1824-1907)
Rankine	R	Named after William Rankine (1820-1872)

$$T(°F) = 1.8\,T(°C) + 32$$

$$T(K) = T(°C) + 273.15$$

$$T(R) = 1.8\,T(K)$$

$$T(R) = T(°F) + 459.67$$

Convert the following into other three temperature scales

°C	°F	K	R
32	92	403	600

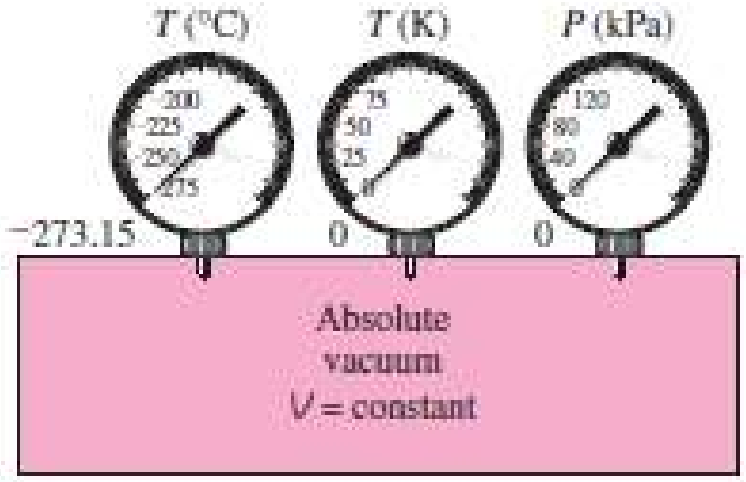
Thermodynamic temperature scale – one which is independent of properties of a substance

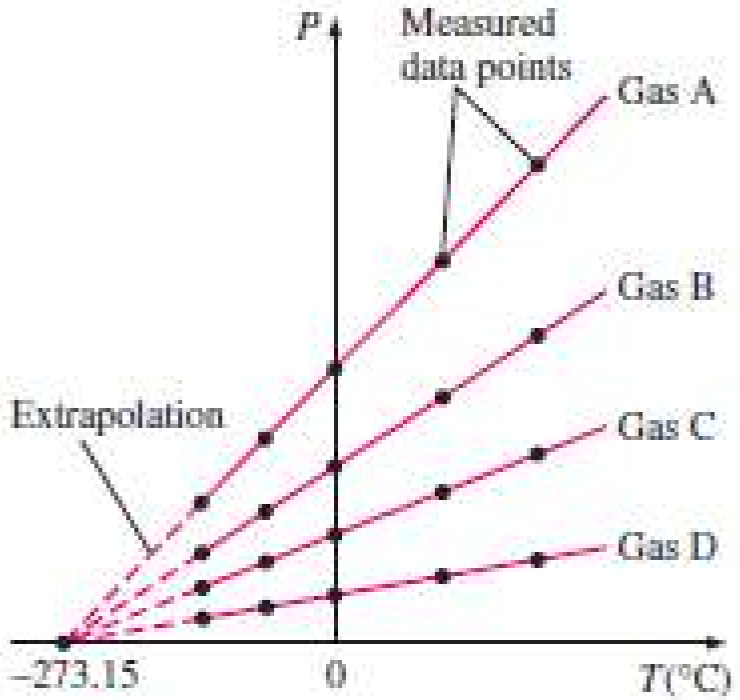
Engineering Thermodynamics
Lecture 3

Today’s discussion

- Constant volume gas thermometer
- Pressure – gage and absolute
- Boyle’s, Charles's and Gay-Lussac’s laws
- Energy & Work transfer

The Constant volume gas thermometer[1]





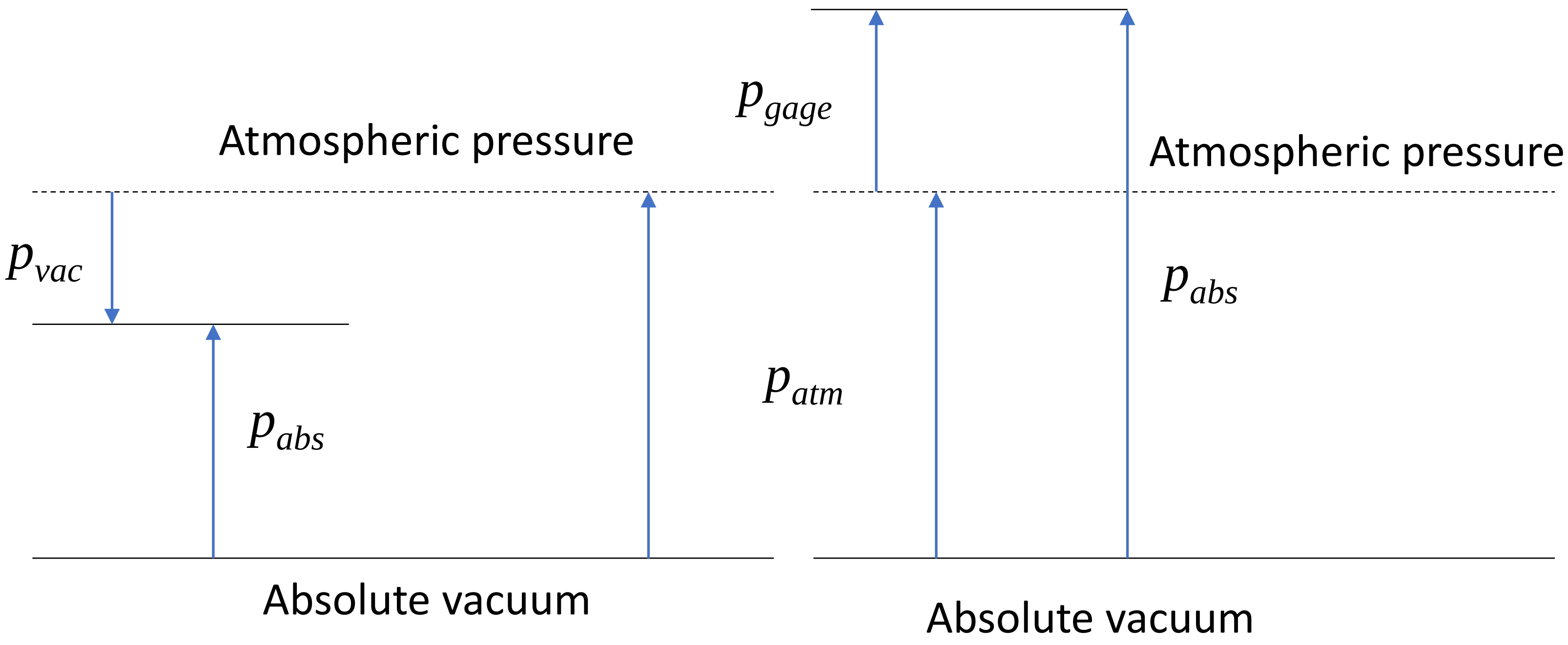
Thermodynamic temperature scale – one which is independent of properties of a substance

Why so? One may seek Ref [4] to have an explanation.

Pressure [1]

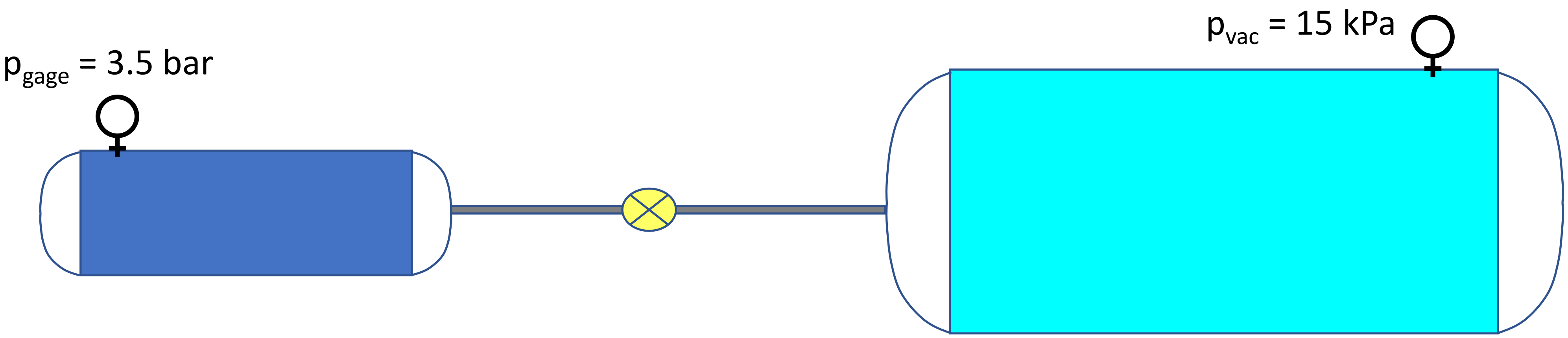
$$p_{gage} = p_{abs} - p_{atm}$$

$$p_{vac} = p_{atm} - p_{abs}$$



Pressure (contd.)

1. A pressure gage reads a value of 1.5 bar. What is the absolute pressure?
2. The absolute pressure of a system is 0.75 bar. Calculate the vacuum pressure.
3. Two tanks are connected to each other as shown in figure below. Gages are installed to measure the pressure levels in the tanks. Calculate the absolute pressure difference between the two. The atmospheric pressure may be taken as 1 bar.



Boyle's law, Charles's law & Gay-Lussac's law

- 1662 – Robert Boyle (Englishman); experiments in a vacuum chamber
- 1787 Jacques Charles
- 1808 – Joseph Louis Gay-Lussac (Frenchman)

$$p \propto \frac{1}{V}\Big|_T \rightarrow pV = constant = C_1$$

$$V \propto T\Big|_p \rightarrow \frac{V}{T} = constant = C_2$$

$$p \propto T\Big|_V \rightarrow \frac{p}{T} = constant = C_3$$

$$pV.\frac{V}{T}.\frac{p}{T} = C_1C_2C_3 \rightarrow \left(\frac{pV}{T}\right)^2 = C_4 \rightarrow \frac{pV}{T} = C_5 \rightarrow \frac{pv}{T} = C_6$$

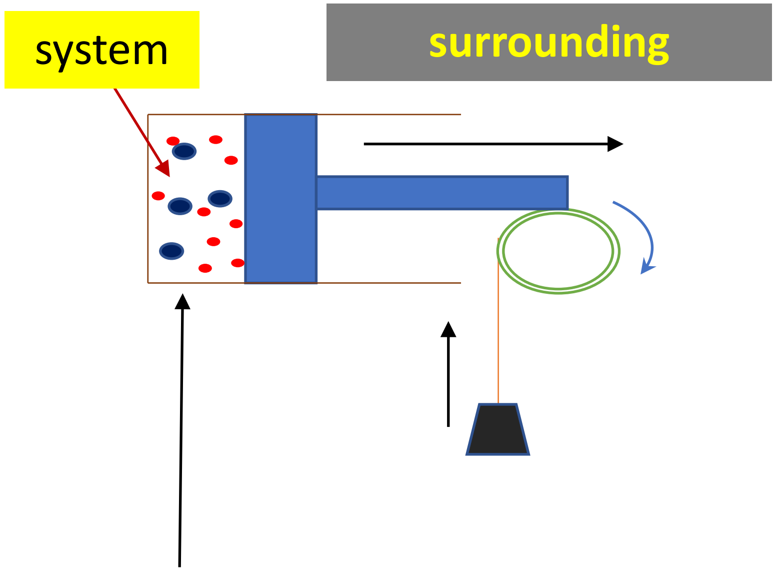
$$\frac{pv}{T} = R \rightarrow pv = RT$$

The Ideal Gas Equation

HW: Find out the conditions under which the above laws are valid

Energy & Work

- Energy – the capacity to do work
- Work – Work is said to be done when the sole effect of the system on the surroundings could be reduced to lifting of a mass.



It is to be noted that the continuum assumption is valid. The circles of different colour and sizes only to indicate a mixture of gases.

$$dW = \vec{F}.\overrightarrow{ds}$$

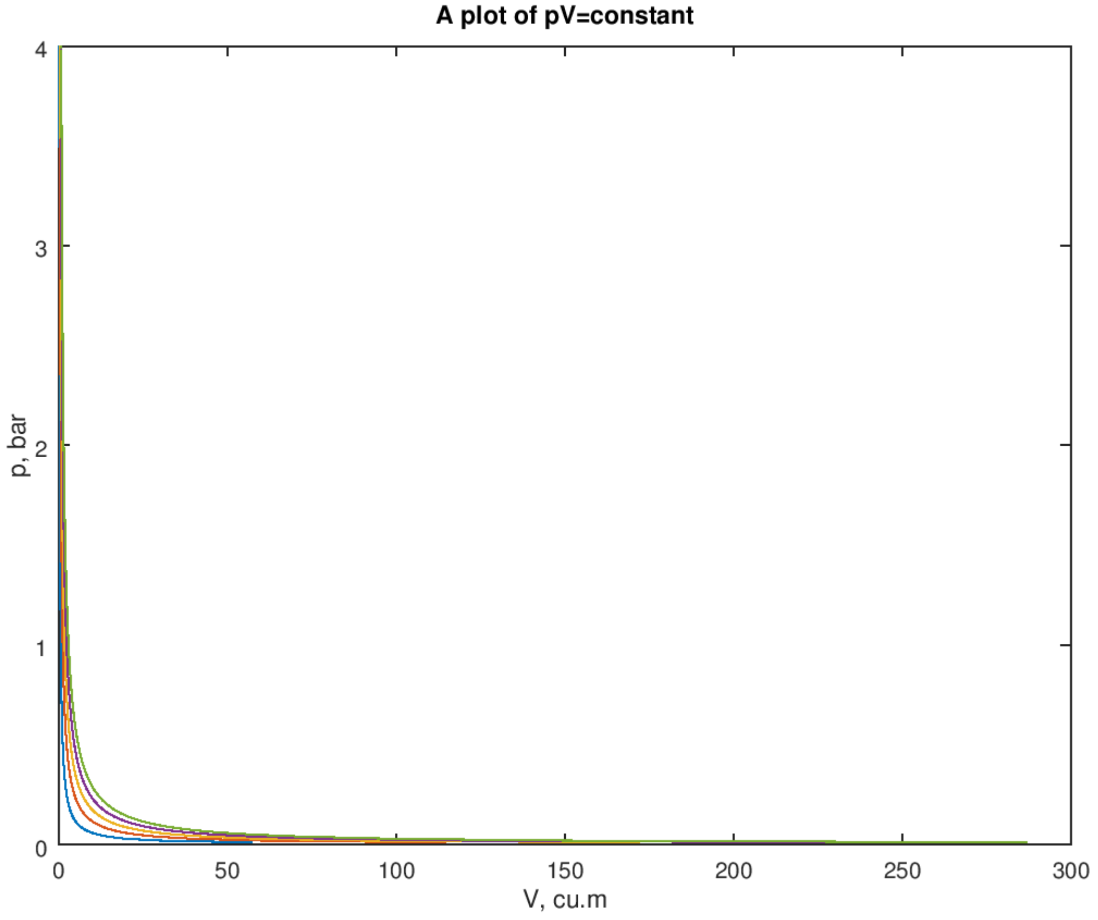
$$\vec{F} = p\vec{A} = \hat{n}pA$$

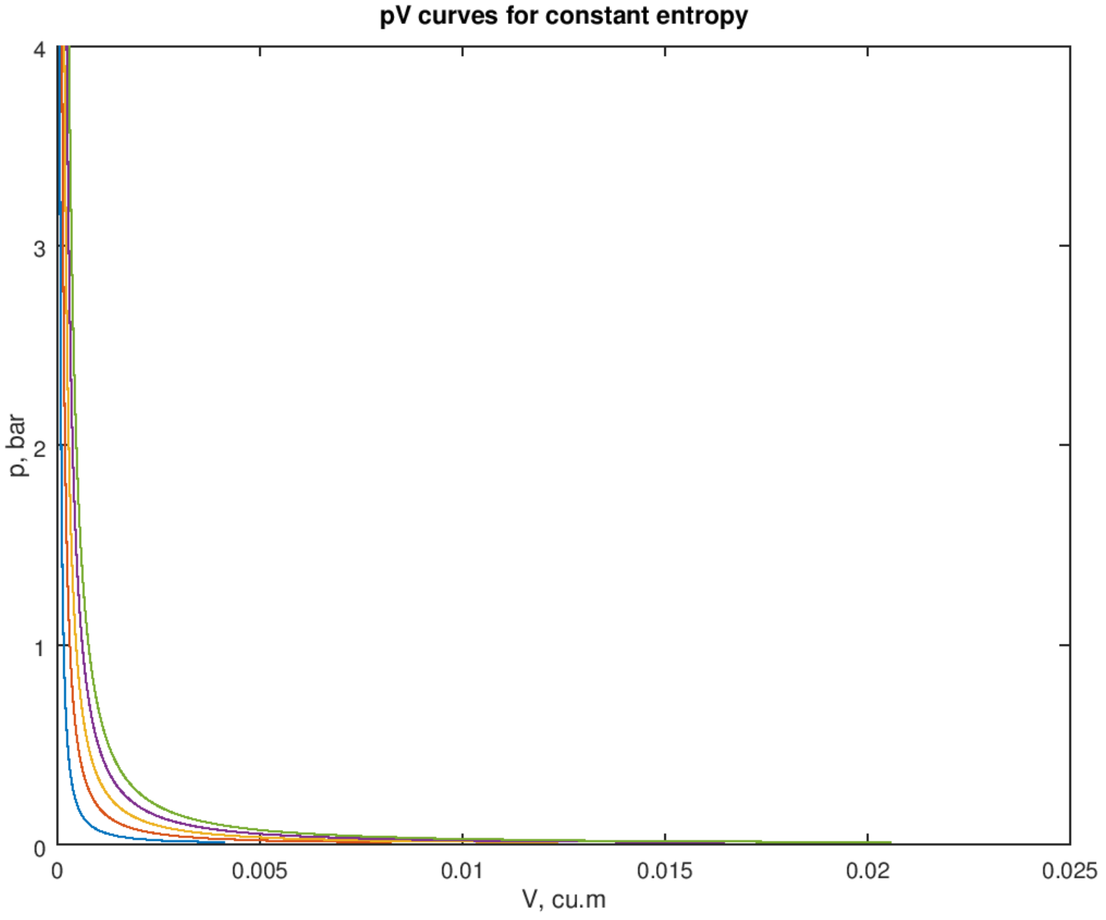
This could be either positive or negative, depending on the directions of $\vec{A}$ and $\overrightarrow{ds}$ → $dW = p\vec{A}.\overrightarrow{ds} = pdV$

If $\vec{A}$ is defined to be positive into the piston and $\overrightarrow{ds}$ positive towards right, then dW is positive when piston moves outward.

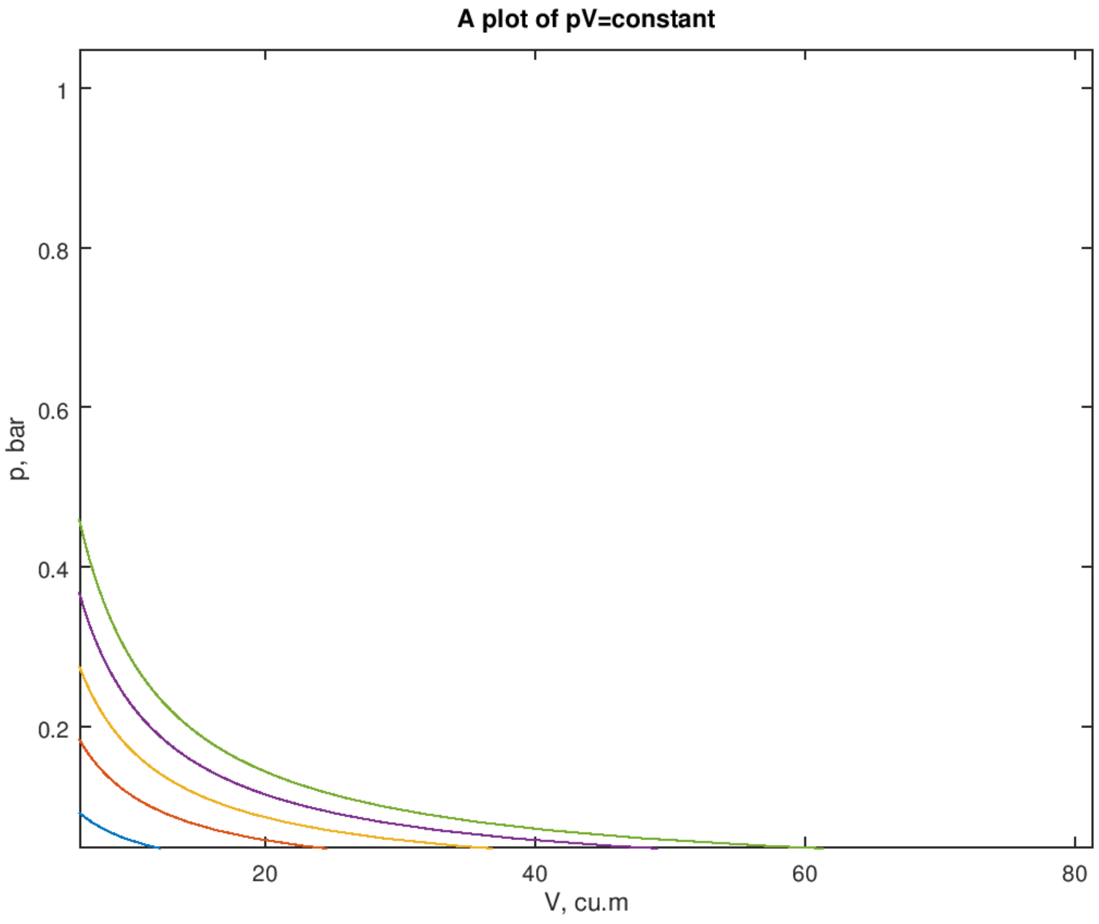
Work is positive when done by the system on the surrounding

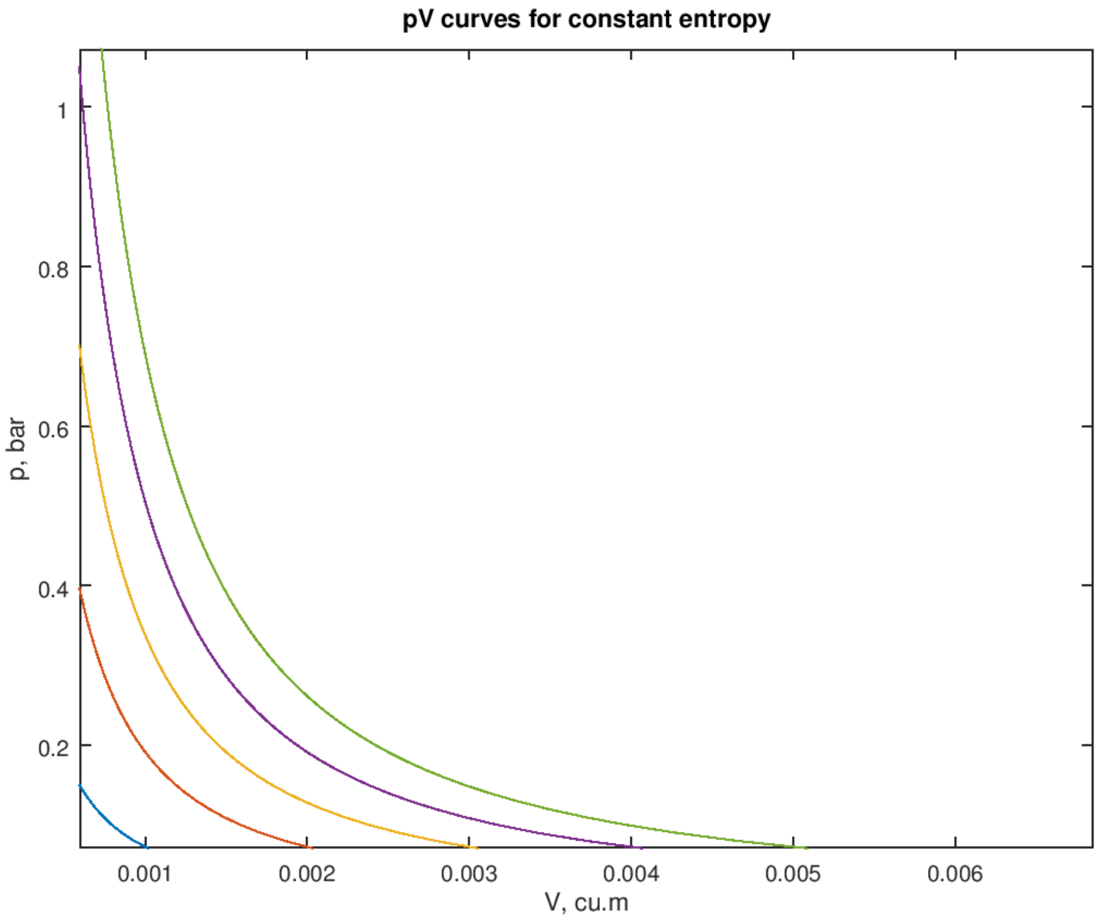
pV curves for isothermal and isentropic processes





pV curves for isothermal and isentropic processes





Engineering Thermodynamics
Lecture 4

Today's discussion

- Ideal Gas Equation
- Forms of Energy & Work
- Path & Point Function
- Numerical example

The ideal gas equation & its variants

$pv = RT$

p – pressure, Pa; v - sp. Volume, m^3/kg
T - temperature, K; R – Gas constant, ?

$$R = \frac{pv}{T} : \frac{N/m^2 \, m^3/kg}{K} = \frac{Nm}{kgK} = \frac{J}{kgK}$$

$\frac{pV}{m} = RT$

V - Volume, m^3;
m - mass, kg

$pV = mRT$

$pV = nMRT$

n – No. of moles; M – molecular mass, kg/kmol

$pV = n\bar{R}T$

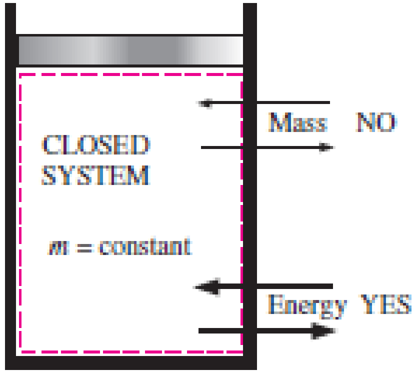
$\bar{R}$ – Universal Gas Constant, 8314 J/kmol-K

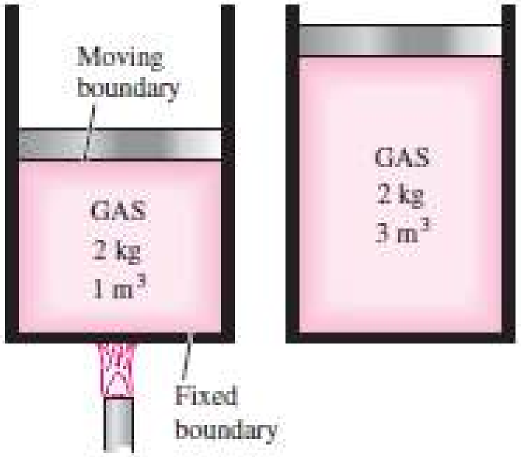
Molar masses and Gas constants

SNo.	Gas	Molecular Mass, kg/kmol	Gas Constant, J/kgK
1	He	4.003	2076.9
2	Ne	20.18	412.0
3	A	39.95	208.1
4	H_2	2.016	4124.0
5	N_2	28.02	296.7
6	O_2	32	259.8
7	CO_2	44.01	188.9
8	NH_3	17.03	488.2
9	CH_4	16.03	518.7
10	Air	29	286.7

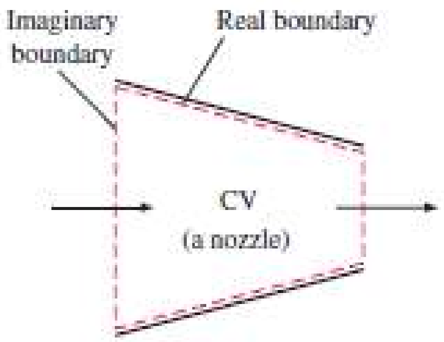
Energy & Work [1]

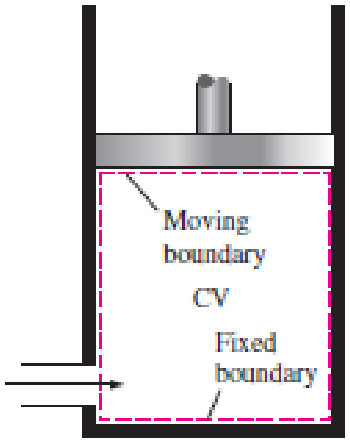
- A closed system interacts with surroundings energy (heat and / or work) transfer through its boundaries

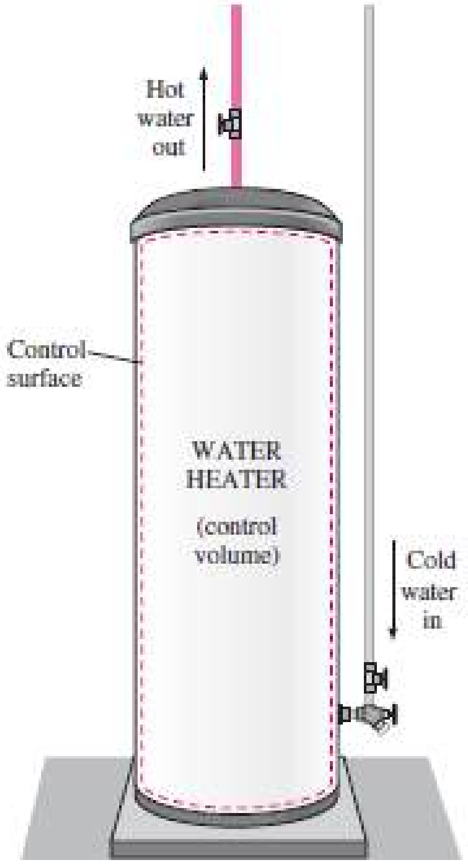




- An open system interacts with surroundings mass and energy.







Forms of energy

Energy

- Macroscopic
- Microscopic

Macroscopic

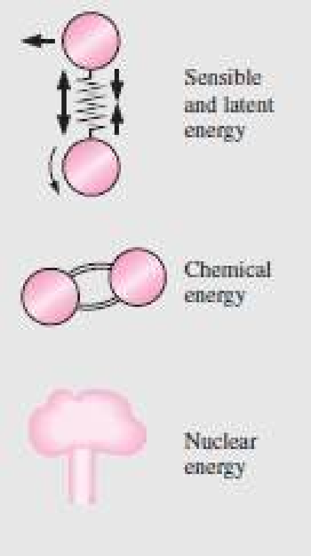
Relative to an outside reference frame:

- Motion
- Gravity
- Surface tension
- Magnetism
- Electricity

Microscopic

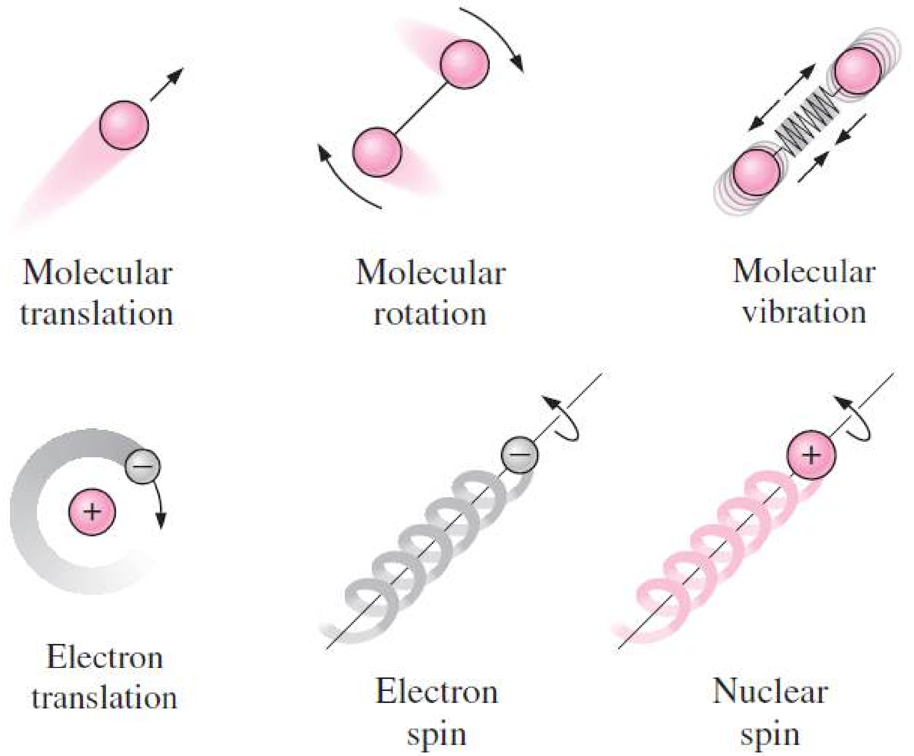
- Molecular structure of the system
- Degree of molecular activity
- Internal energy

- **Kinetic energy**
- **Potential energy**
- **Internal energy**



Microscopic energy

- Sensible



- Latent – energy of bonding between the molecules; strongest in solids and weakest in gases

- Chemical – energy associated with atomic bonds in a molecule

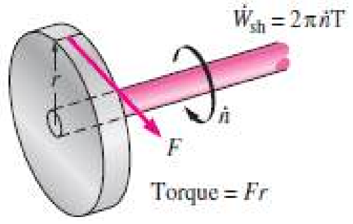
- Nuclear – energy associated strong bonds within the nucleus of an atom.

Forms of work

- Electrical
- Magnetic
- Mechanical – F.ds
    - Shaft work
    - Spring work
    - Work on elastic solid bars
    - Work done on stretching of a liquid film
    - Work done to raise and / or to accelerate an object

Mechanical Work[1]

- Shaft work

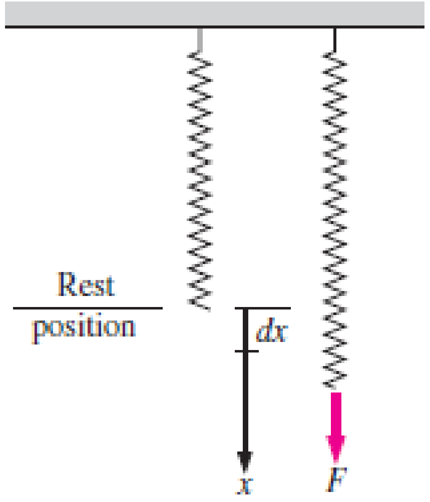


$$T = Fr \quad \rightarrow \quad F = \frac{T}{r} \qquad s = (2\pi r)n$$

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

$$\dot{W}_{sh} = 2\pi\dot{n}T \qquad \text{(kW)}$$

- Spring work

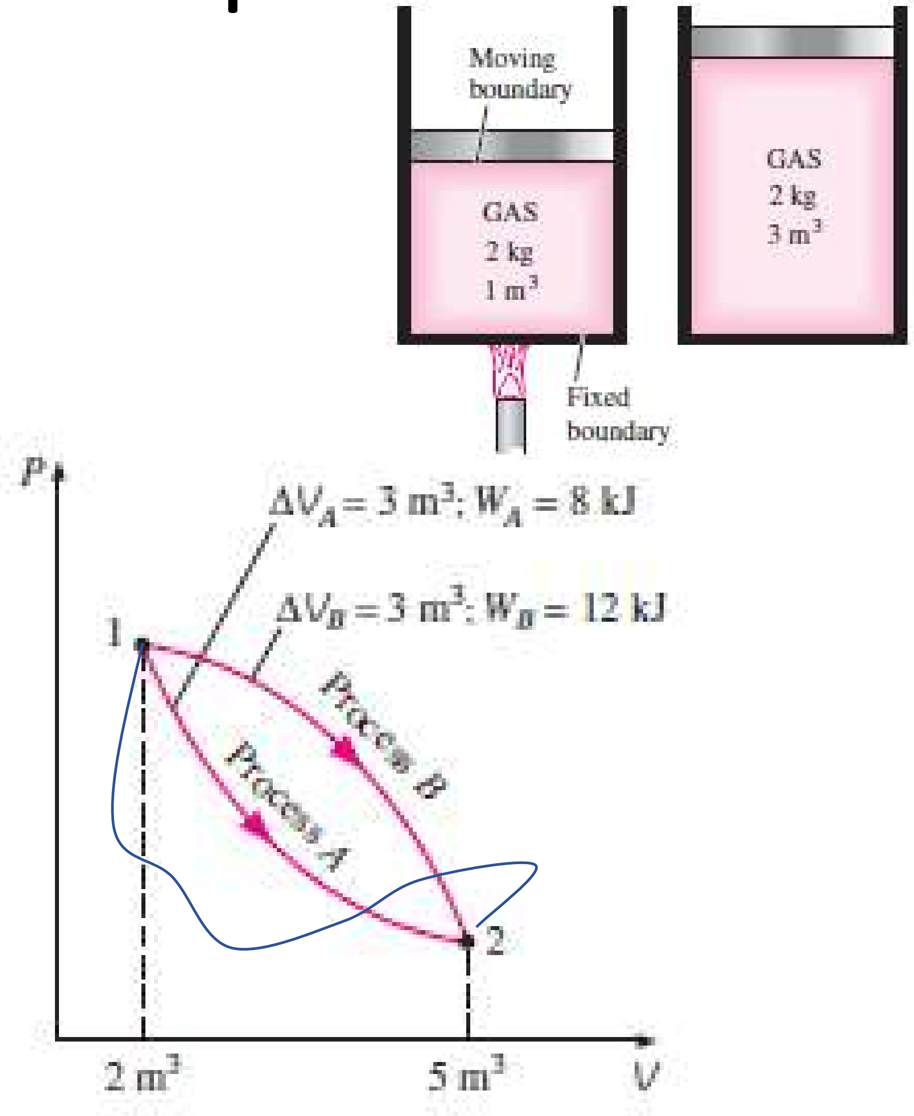


$$\delta W_{spring} = F\,dx$$

$$F = kx \qquad \text{(kN)}$$

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

Path & point functions[1]



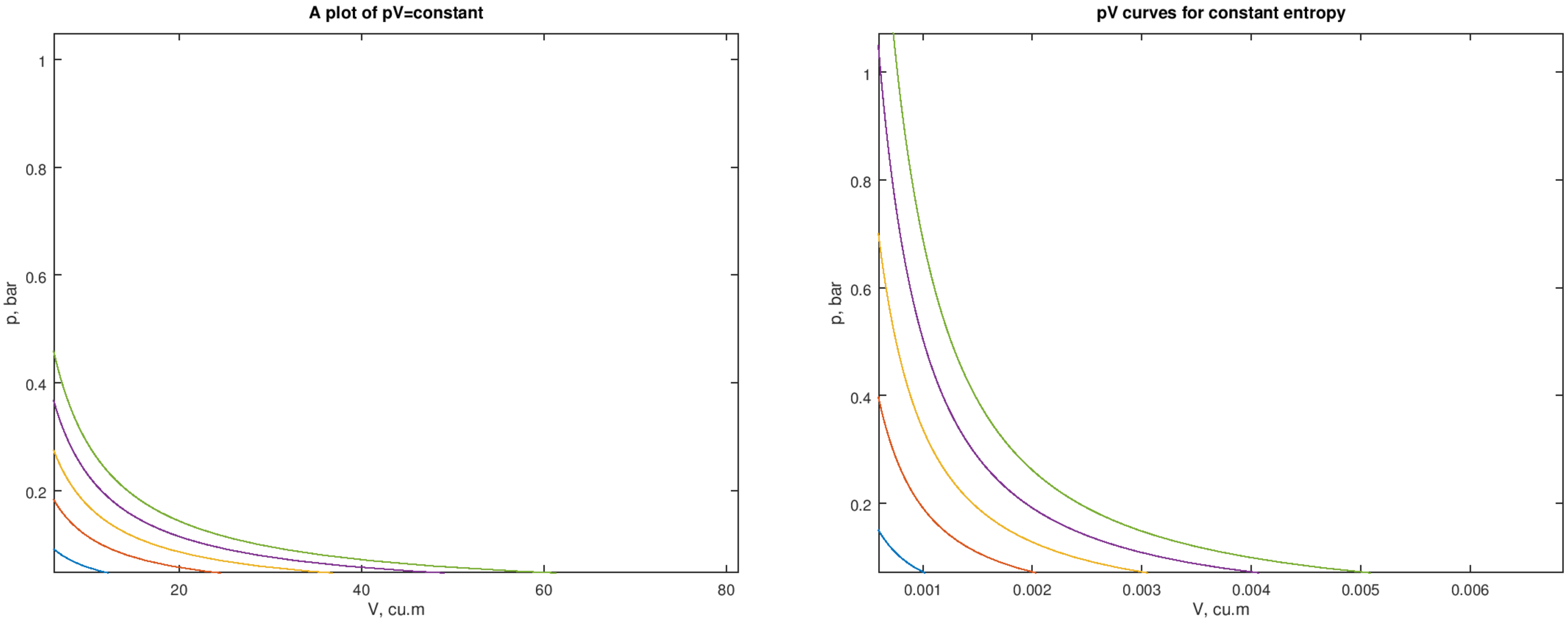
- Point function
  - Independent of path of process
  - Eg. – pressure, volume, temperature, etc.
  - have exact differentials

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

- Path function
  - depends on path of process
  - have inexact differentials
  - Eg. – Work transfer, heat transfer, etc.

$$\int_1^2 \delta W = W_{12} \qquad (not\ \Delta W)$$

pV curves for isothermal and isentropic processes

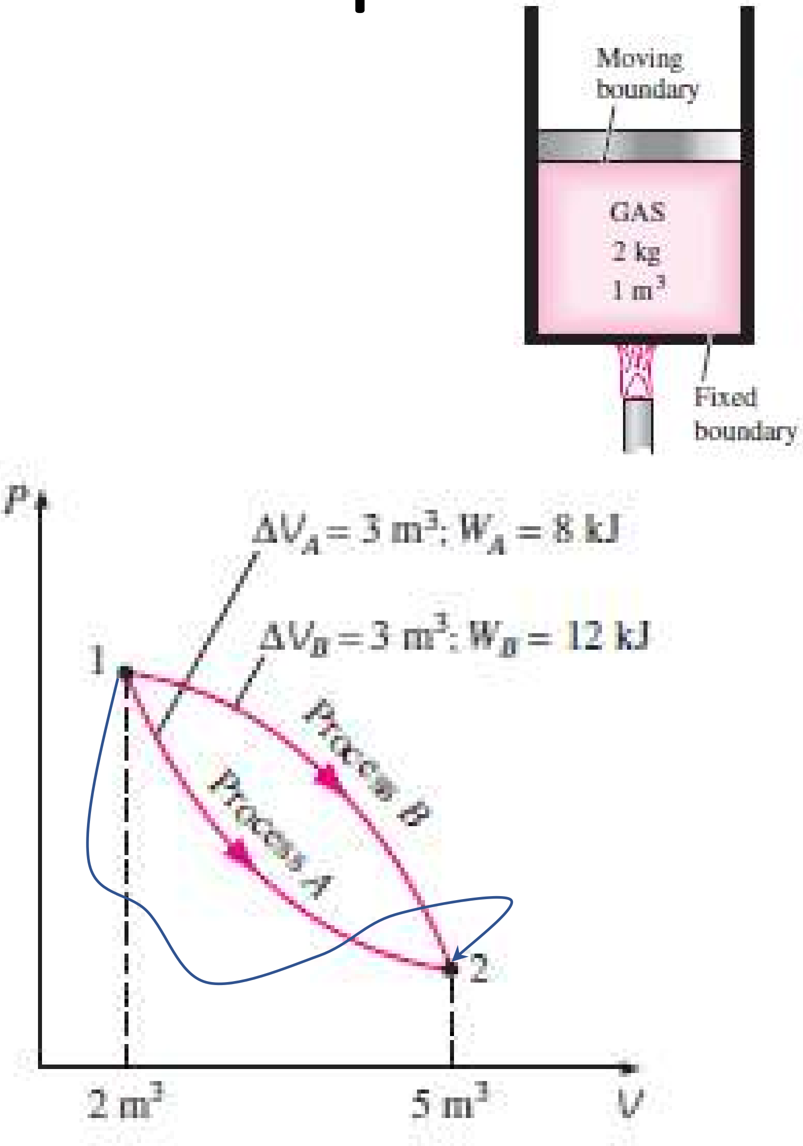


Engineering Thermodynamics
Lecture 5

Today’s discussion

- Path & Point Function
- Processes
  - Generation of pV isotherms for different temperatures - demonstration
  - Generation of pV isotherms for different temperatures - exercise

Path & point functions[1]



- Point function
  - Independent of path of process
  - Eg. – pressure, volume, temperature, etc.
  - have exact differentials

$$\int_1^2 dV = V_2 - V_1 = \Delta V$$

- Path function
  - depends on path of process
  - have inexact differentials
  - Eg. – Work transfer, heat transfer, etc.

$$\int_1^2 \delta W = W_{12} \qquad (not\ \Delta W)$$

Exact & Inexact differentials

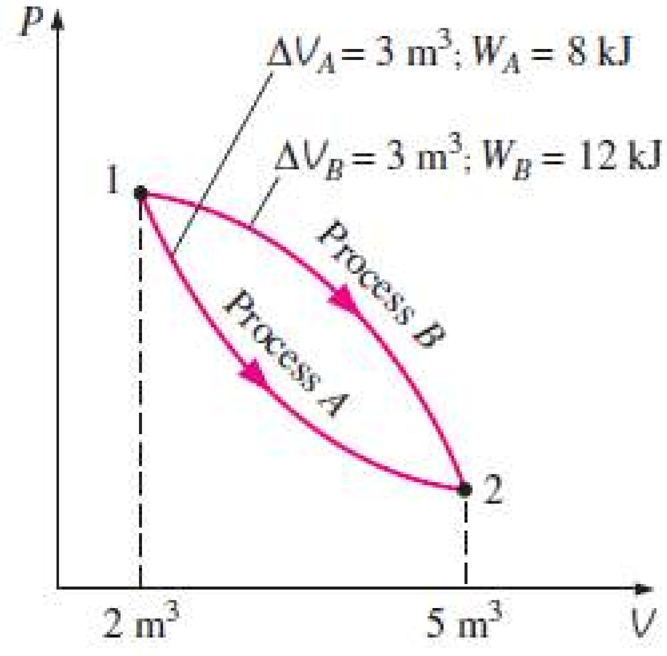
Definition of Δx

$$\Delta x = x_2 - x_1$$

Definition of $\int dx$ between 1 and 2

$$\int_1^2 dx = x_2 - x_1 = \Delta x$$

Exact differential



- Point functions

$$\int_1^2 dp = p_2 - p_1 = \Delta p \qquad \int_1^2 dV = V_2 - V_1 = \Delta V \qquad \int_1^2 dv = v_2 - v_1 = \Delta v$$

- Path functions

$$\int_1^2 \delta W = \int_1^2 pdV = W_{12} \neq \Delta W$$

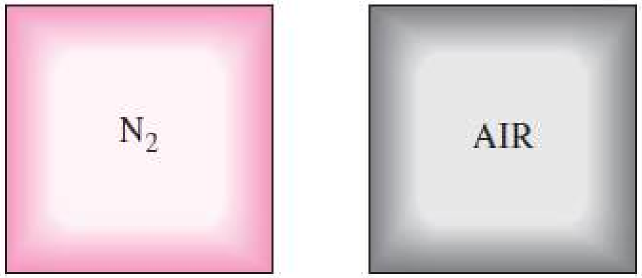
Engineering Thermodynamics
Lecture 6

Today's discussion

- Pure substance – Phases, Property diagrams, Tables
- Compressibility Factor & van der Waal Equation of state

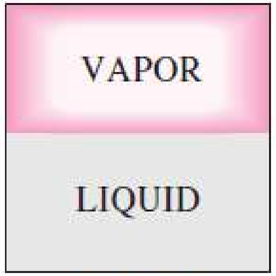
Pure substance

- One which has homogenous chemical composition throughout
  - Example – N_2, O_2, H_2, Air, water
- Impure – the composition of the system varies
  - Example – mixture of oil and water
- Phases of pure substances
  - Solid
  - Liquid
  - gas



Pure substances – contd.

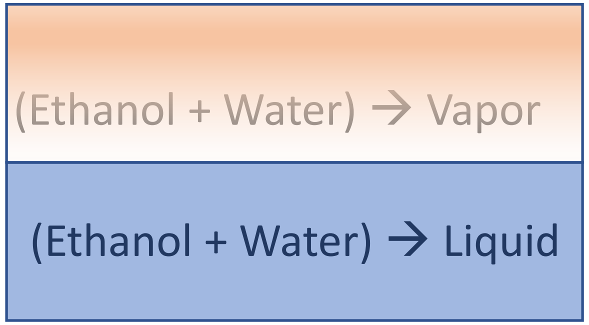
- Pure substances



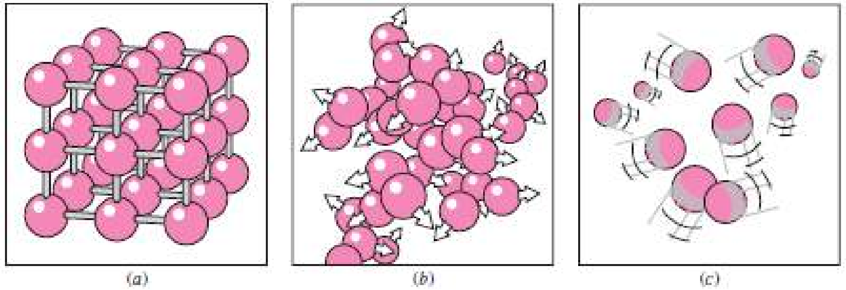
(a) H_2O

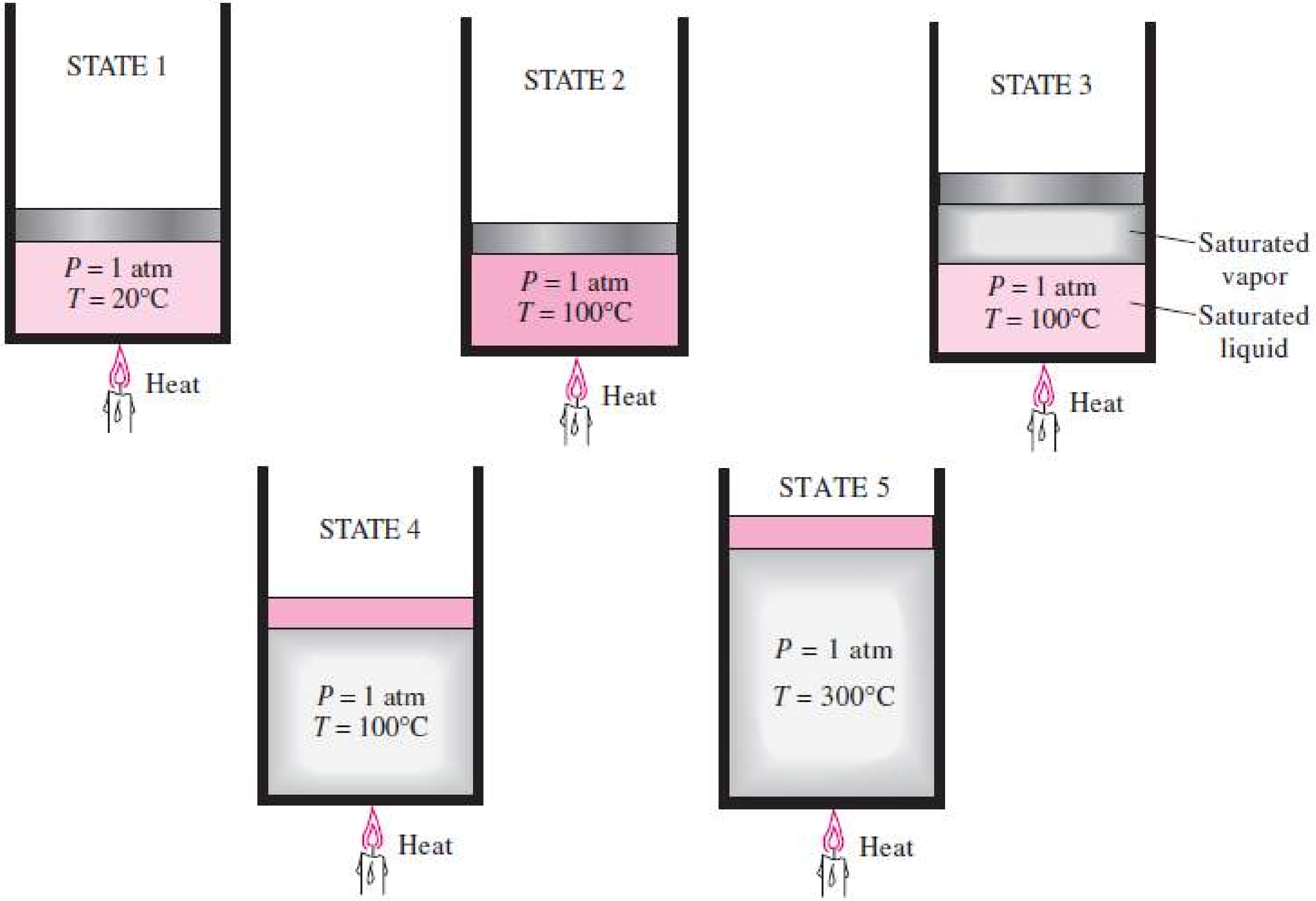
- Not Pure substances

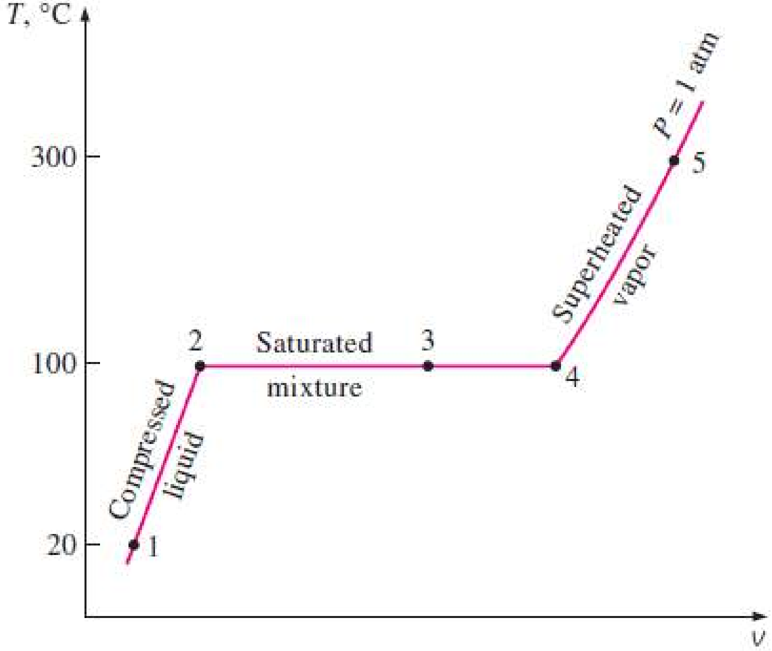
(b) AIR



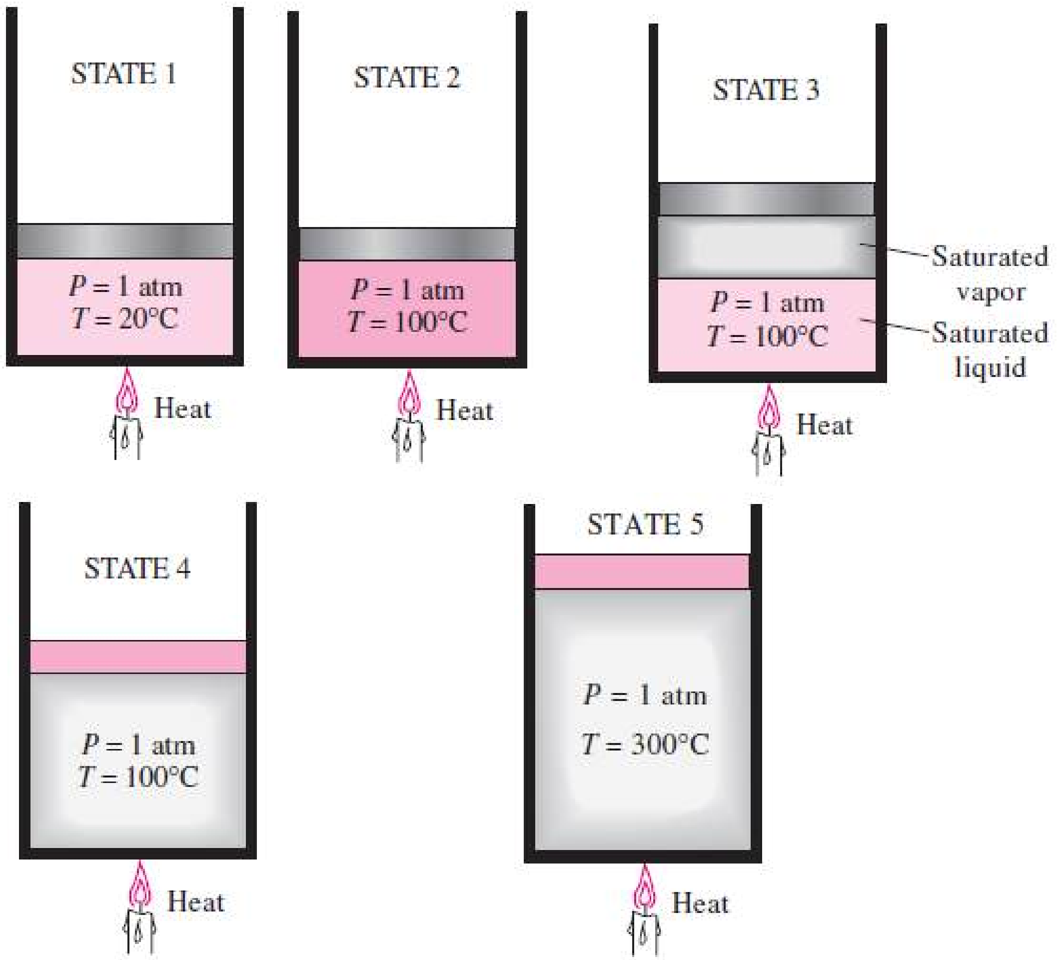
Pure substances

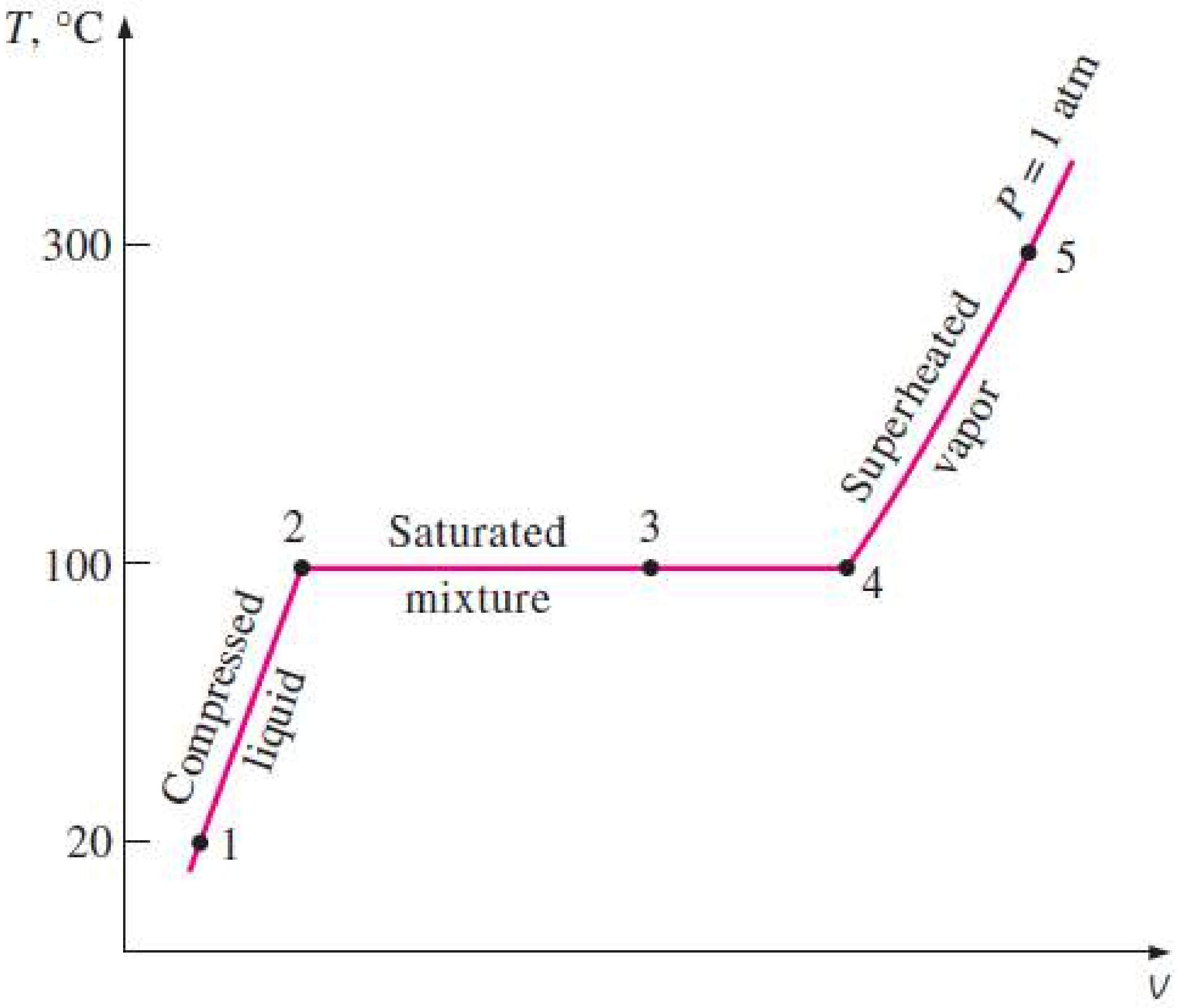






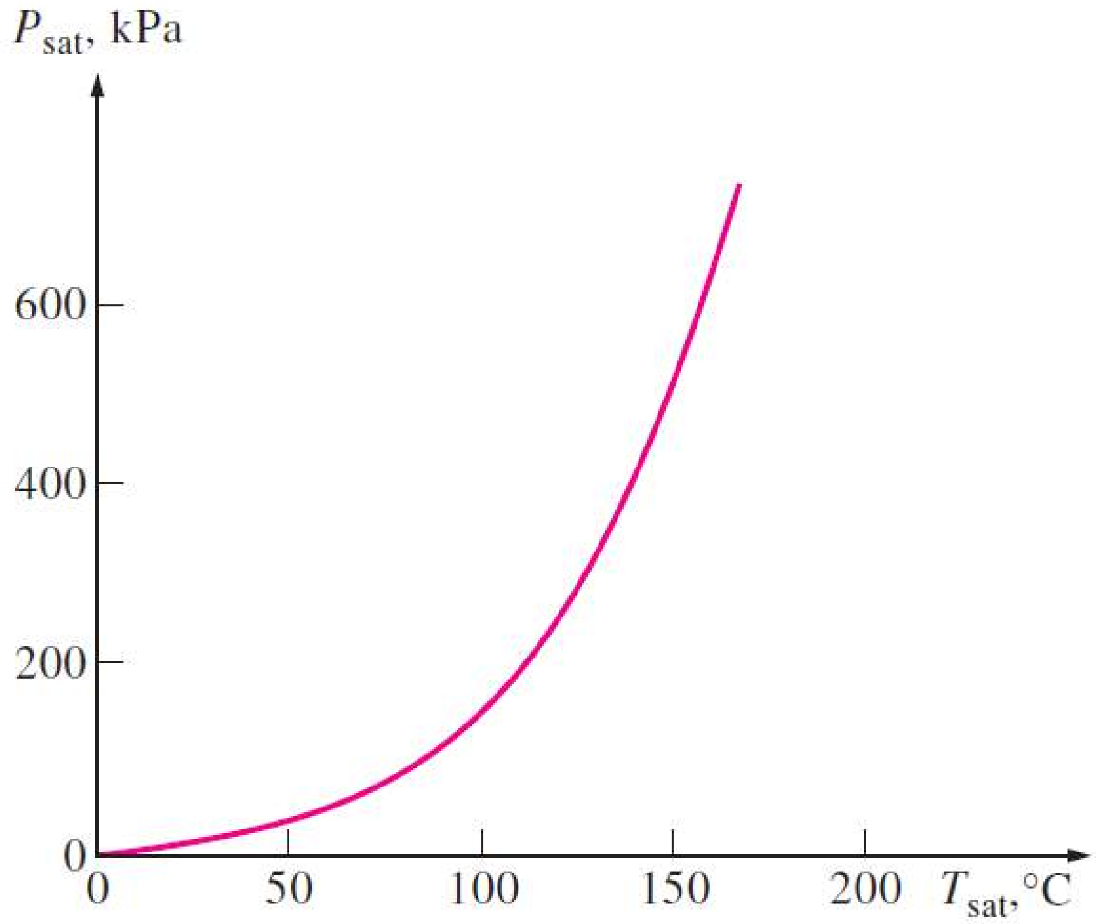
Pure substances



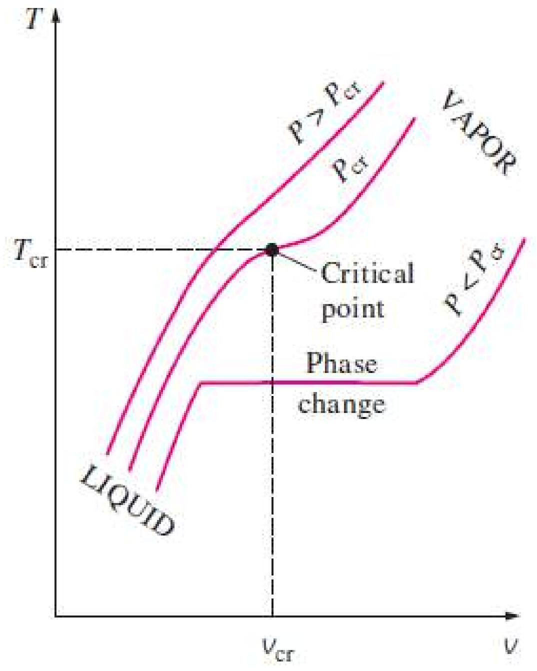


Pure substances – the saturation pressure

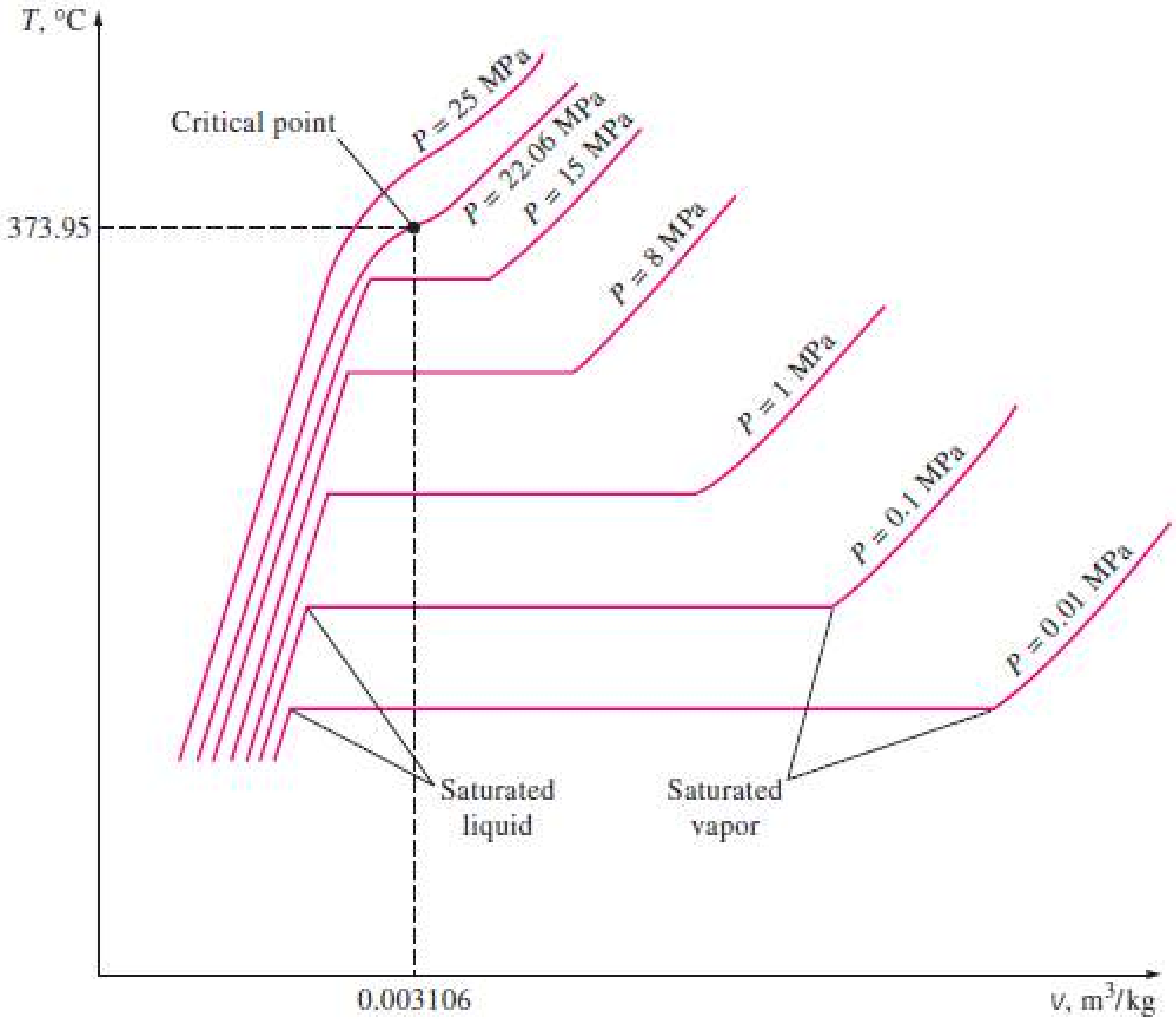
T, °C	P_{sat}, kPa
0	0.61
50	12.35
100	101.4
150	476.2
200	1555
250	3976
300	8588



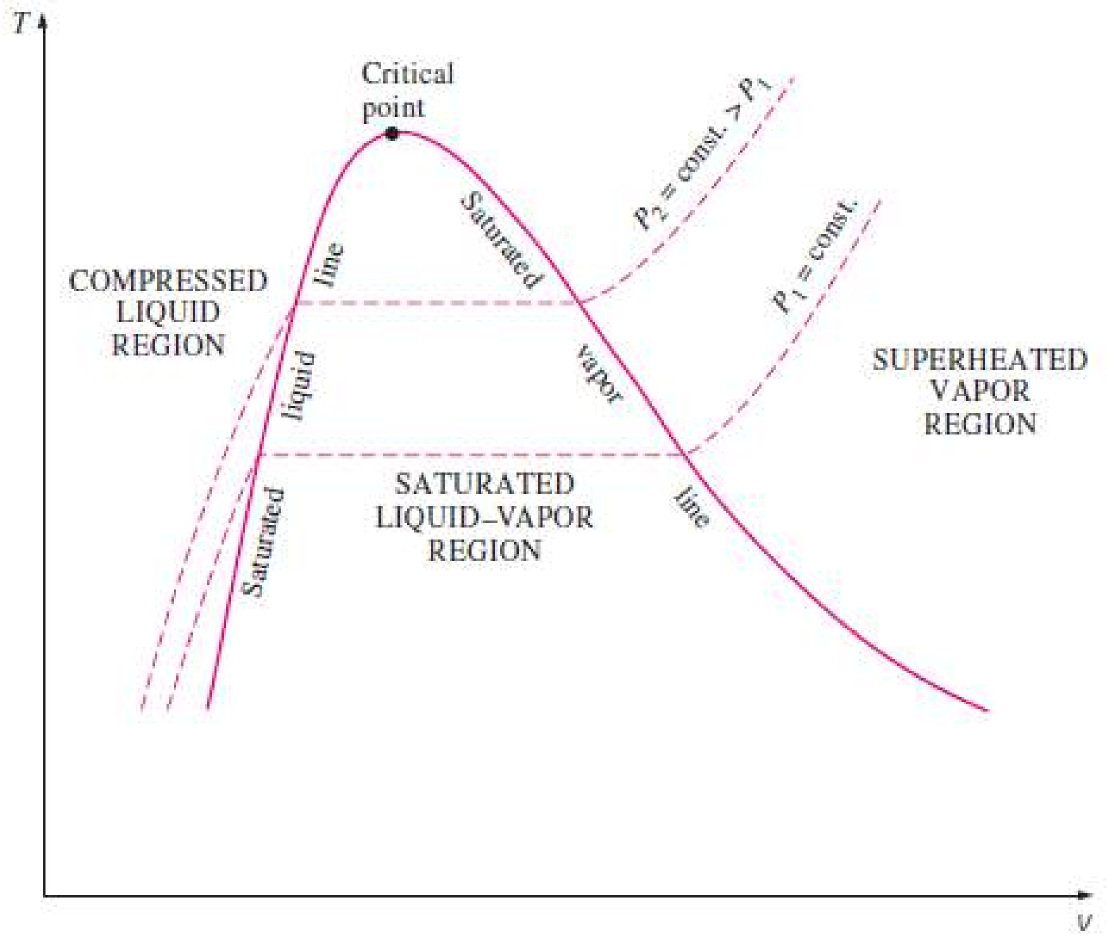
Pure substances – Tv diagram

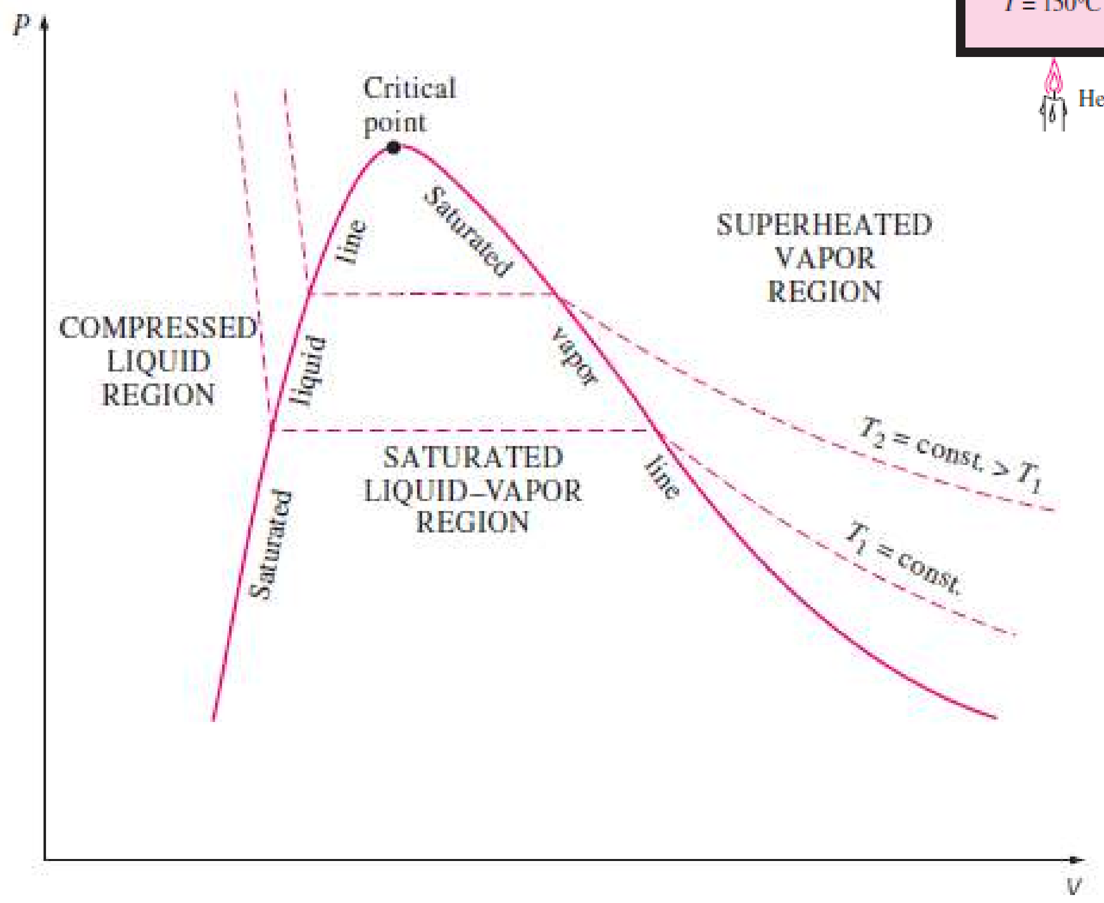


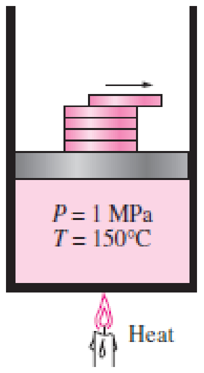
No distinct phase change beyond critical point



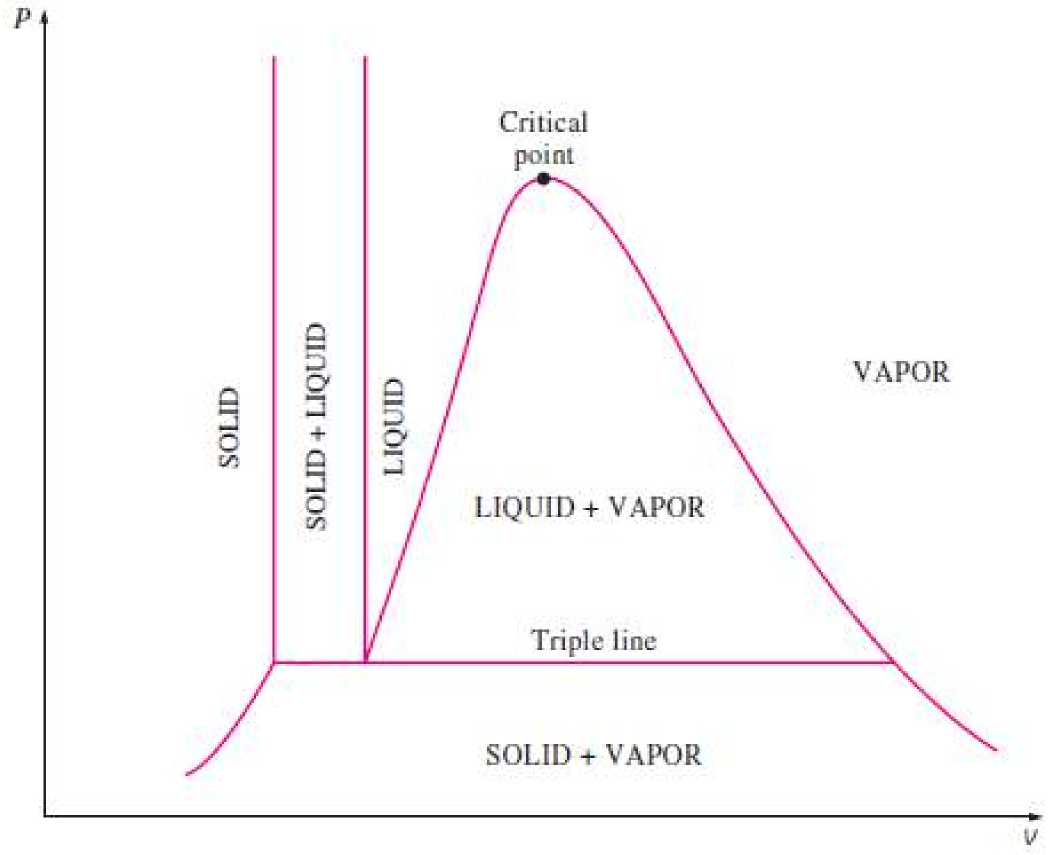
Pure substances – Tv & pV diagrams



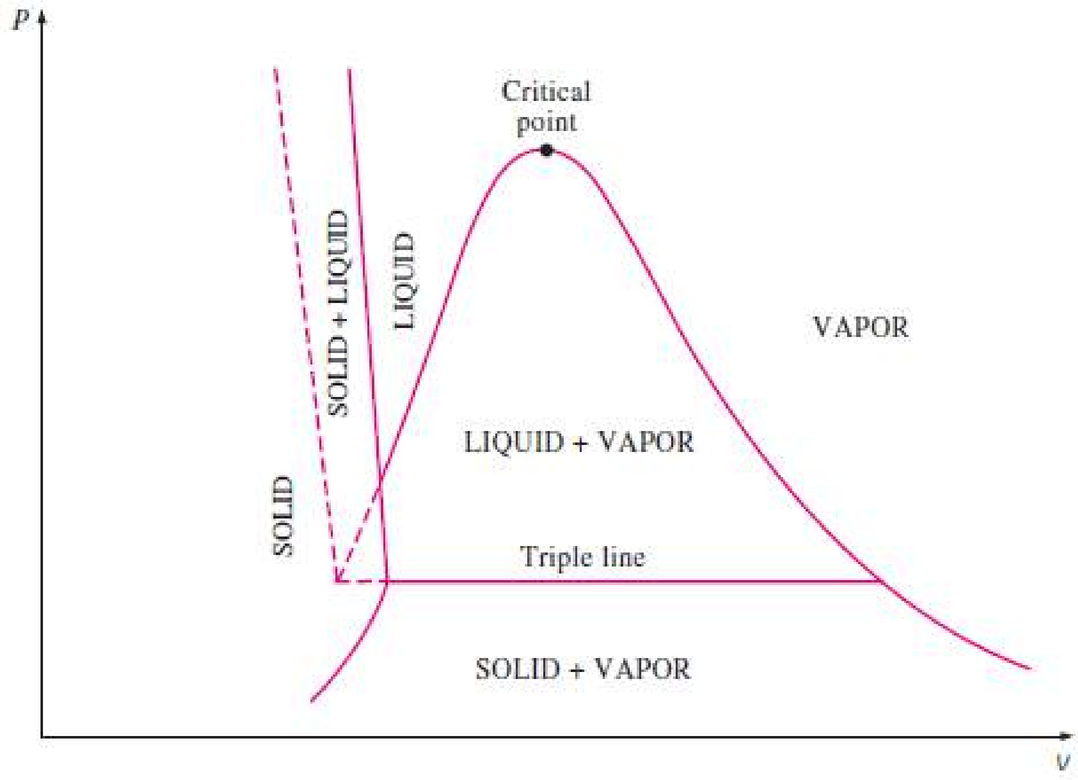




Phase diagrams (including solid phase)

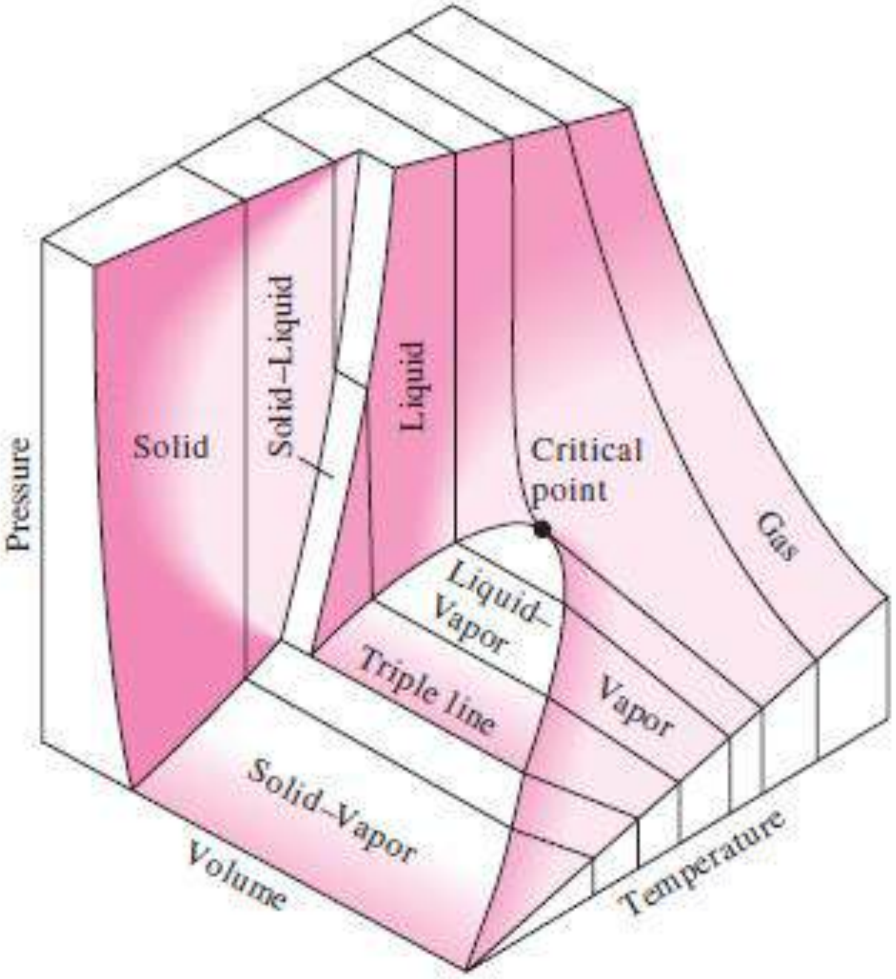


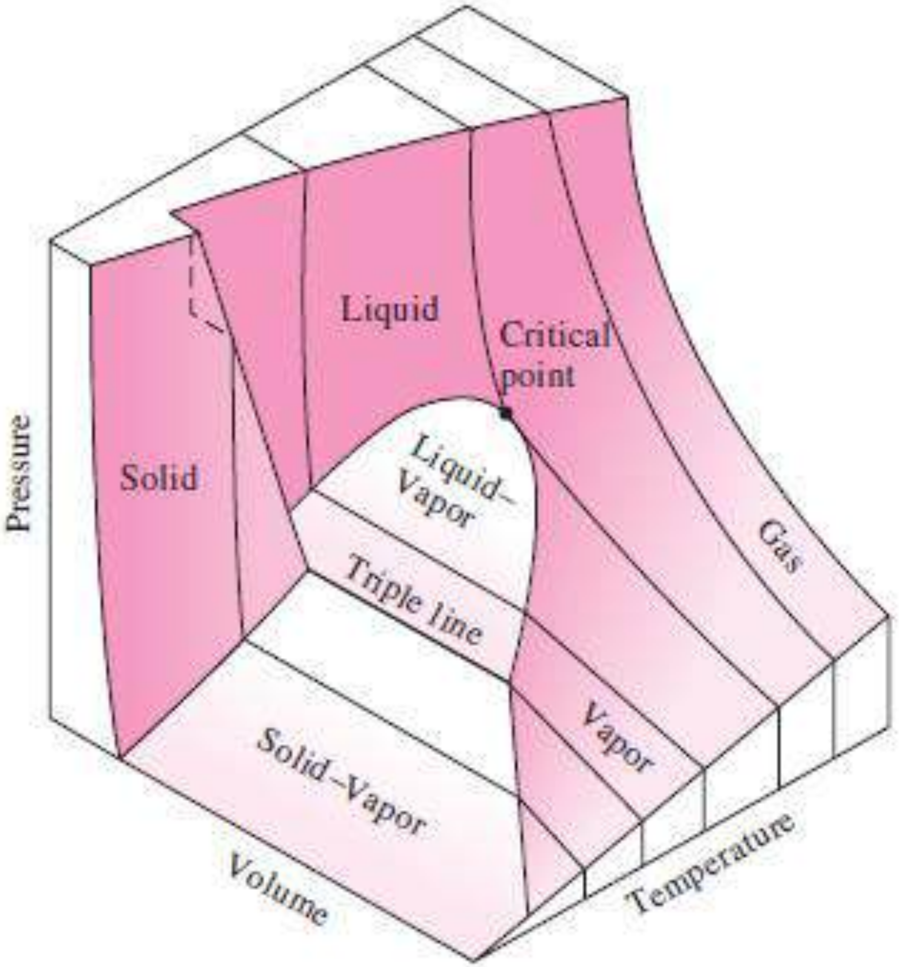
- Substances that contract on freezing



- Substances that expand on freezing

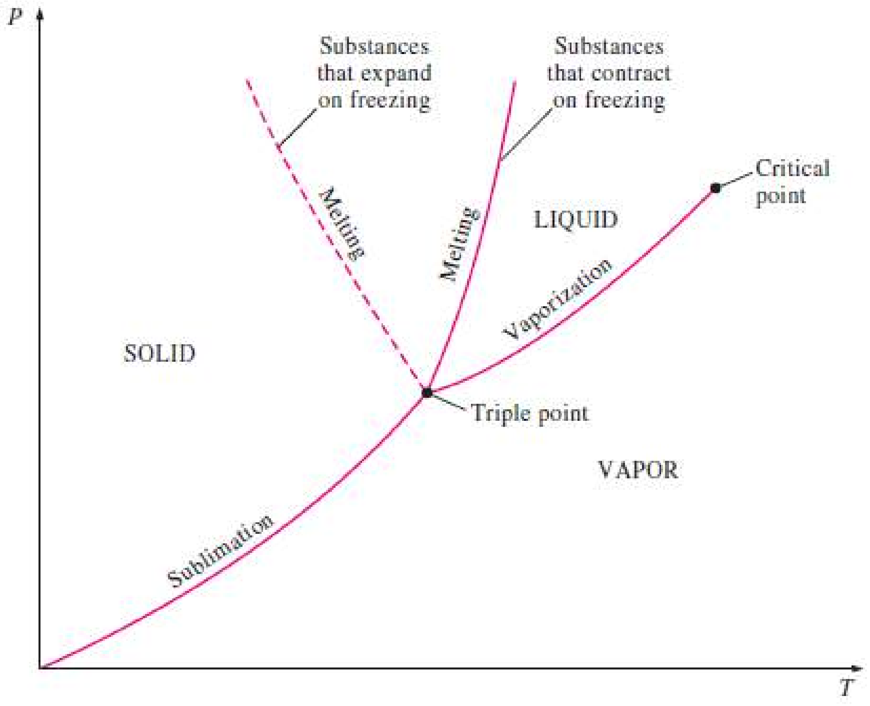
The pVT surface





- **Substances that contract on freezing**
- **Substances that expand on freezing**

The p-T diagram



19ME31 Engineering Thermodynamics (L7)

Dr A S Krishnan / Dr D P Sam Solomon
Faculty of Mechanical Engineering
Coimbatore Institute of Technology

Course Objective

To enable undergraduate students of Mechanical Engineering to apply concepts of energy, entropy and exergy to simple systems with justifiable assumptions through theoretical concepts and illustrations

Course Outcomes* – At the end of the course, the student will be able to

1. Apply concepts of energy conservation to open and closed systems
2. Arrive at benchmark performances of heat engines and refrigerator / heat pump and compute entropy changes.
3. Depict various thermodynamic processes on property diagrams, estimate properties of mixtures and quantify deviation from ideal gas behavior.
4. Calculate changes in properties during different ideal gas processes

Basic Concepts of Thermodynamics

First Law of Thermodynamics

Second Law of Thermodynamics

Entropy & Exergy

Thermodynamic Relations and Ideal Gas Mixtures

Basic Concepts of Thermodynamics

SNo	Topic	Hours
1	Macroscopic & Microscopic approach, Concept of Continuum, Thermodynamic system & control volume, Thermodynamic properties, Quasi static process, Thermodynamic Equilibrium	2
2	Temperature – Zeroth law of thermodynamics – Temperature scales. Pressure measurement – Barometer.	2
3	Energy and Work transfer – Forms of energy – forms of work transfer – point and path function.	1
4	Pure Substances– phases of pure substances – property diagrams – Property tables	2
5	Ideal gas equation of state – Compressibility factor – Vander Waals equation of state – vapor pressure and phase equilibrium.	2

Today’s discussion

- Compressibility Factor & van der Waal Equation of state
- Numerical problems – Self study

The ideal gas equation & its variants

$pv = RT$

p – pressure, Pa; v - sp. Volume, m^3/kg
T - temperature, K; R – Gas constant, ?

$$R = \frac{pv}{T} : \frac{N/m^2 \; m^3/kg}{K} = \frac{Nm}{kgK} = \frac{J}{kgK}$$

$\frac{pV}{m} = RT$

V - Volume, m^3;
m - mass, kg

$pV = mRT$

$pV = nMRT$

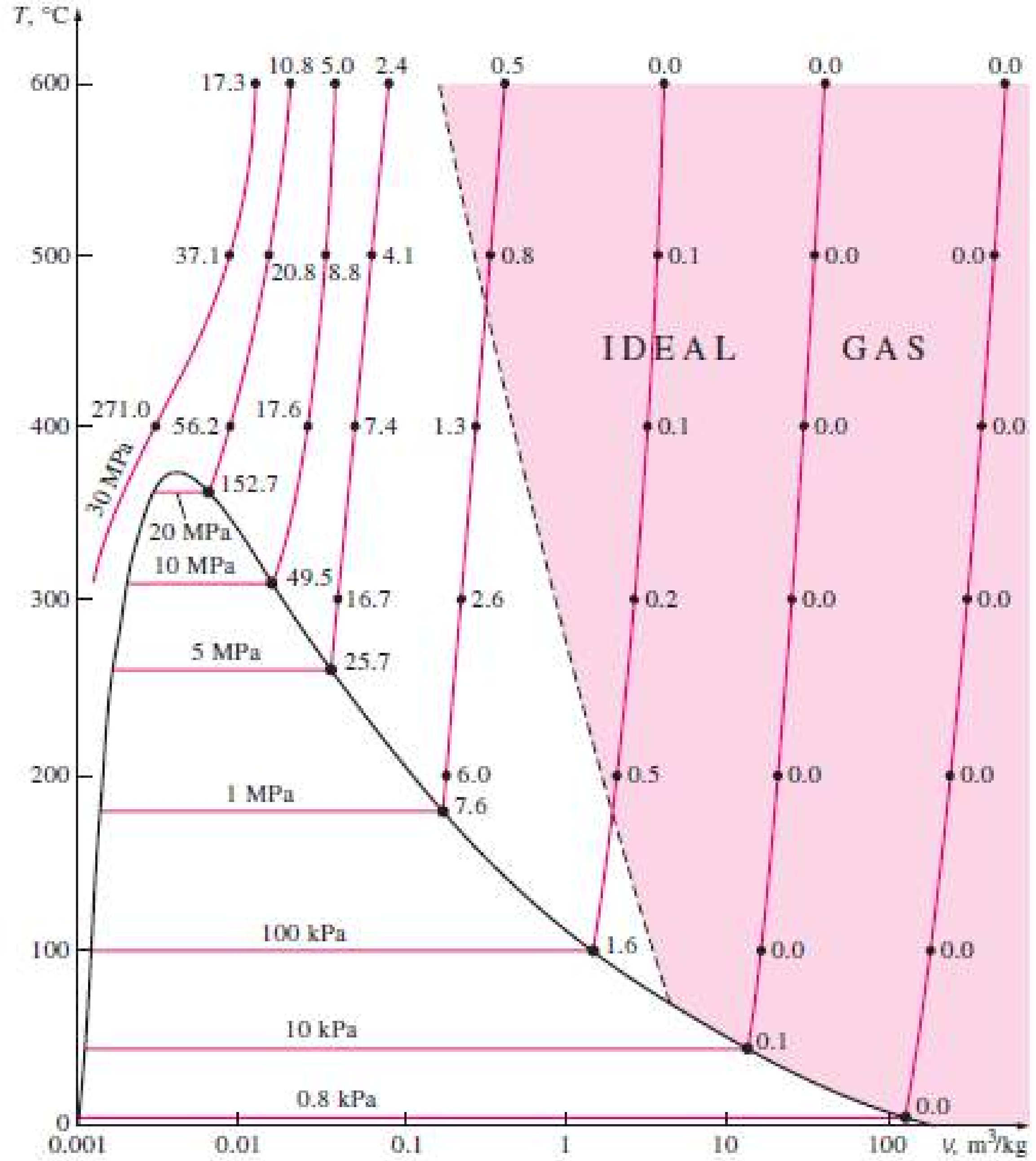
n – No. of moles; M – molecular mass, kg/kmol

$pV = n\bar{R}T$

$\bar{R}$ – Universal Gas Constant, 8314 J/kmol-K

Validity – low pressures and high temperatures
How low pressure and how high temperature?

Deviation from Ideal gas behavior



$pv \neq RT?$ $\quad \frac{pv}{RT} \neq 1$

$\frac{pv_{act}}{RT} = Z\ (say)$ → Compressibility factor

$v_{act} = \frac{ZRT}{p}$ & $v_{ideal} = \frac{RT}{p}$ ⇒ $Z = \frac{v_{act}}{v_{ideal}}$

Compressibility factor

Actual	Ideal
$Z = \begin{cases} < 1 \\ = 1 \\ > 1 \end{cases}$	$Z = 1$

Different gases behave differently @ same (p, T); but quite same @ normalized (p, T)

Reduced pressure

$$p_R = \frac{p}{p_{crit}}$$

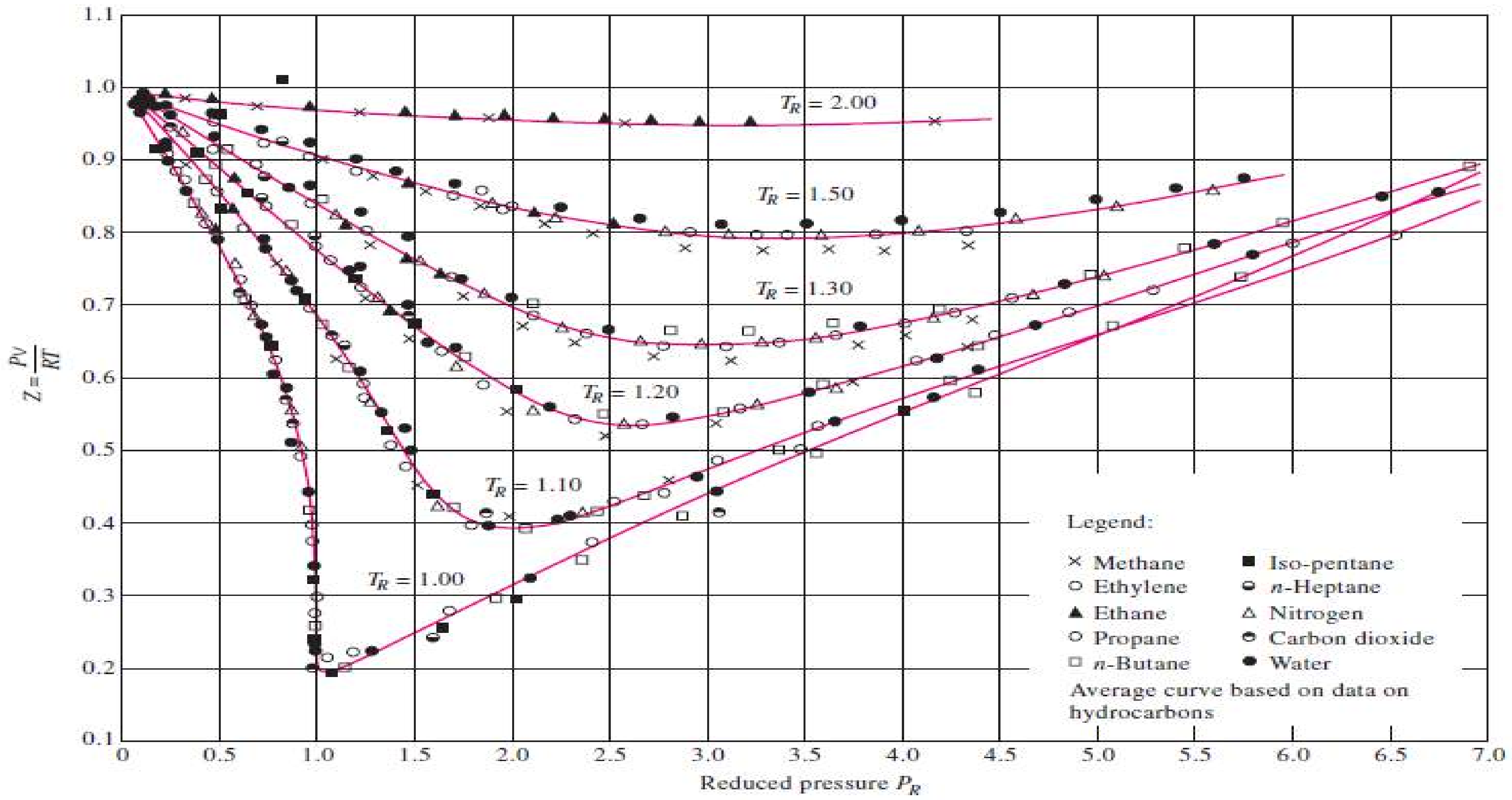
Reduced Temperature

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

Reduced Volume

$$v_R = \frac{v_{act}}{RT_{crit}/p_{crit}}$$

Z is approx. same for all gases @ (p_R, T_R)
→ principle of corresponding states



T_R = 2.00
T_R = 1.50
T_R = 1.30
T_R = 1.20
T_R = 1.10
T_R = 1.00
$Z = \frac{PV}{RT}$
Reduced pressure P_R
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Legend:
Methane
Ethylene
Ethane
Propane
n-Butane
Iso-pentane
n-Heptane
Nitrogen
Carbon dioxide
Water
Average curve based on data on hydrocarbons

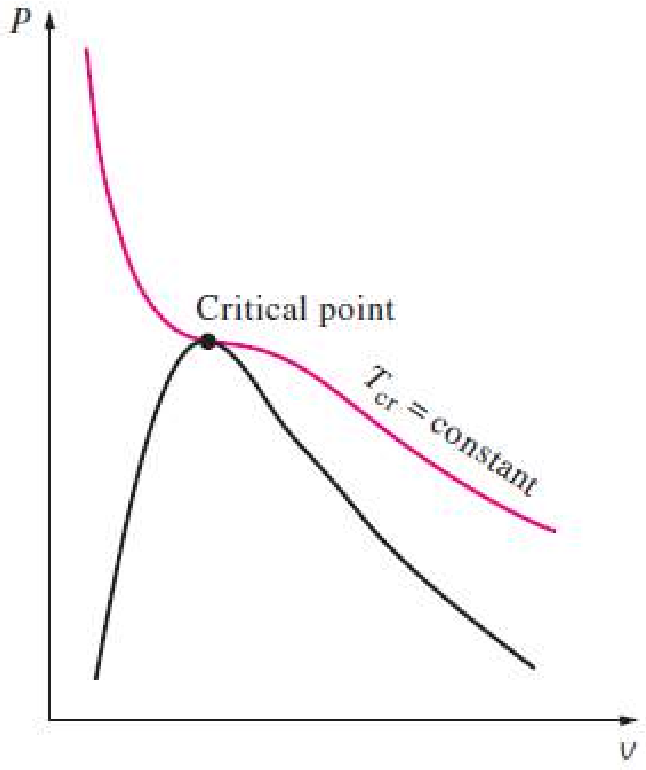
Determine the specific volume of refrigerant-134a at 1 MPa and 50°C, using (*a*) the ideal-gas equation of state and (*b*) the generalized compressibility chart. Compare the values obtained to the actual value of 0.021796 m^3/kg and determine the error involved in each case.

The Van der Waals equation of state

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

Inter-molecular attractive forces (↑ $\frac{a}{v^2}$)

Volume of molecules (↑ b)



How to find the constants ***a*** & ***b***?

Evaluate the I & II derivative of p w.r.t v, and equate to zero

$$a = \frac{27R^2T_{crit}^2}{64p_{crit}}$$

$$b = \frac{RT_{crit}}{8p_{crit}}$$

Data of critical pressure & temperature

TABLE A-1

Molar mass, gas constant, and critical-point properties

				Critical-point properties		
Substance	**Formula**	**Molar mass, *M* kg/kmol**	**Gas constant, *R* kJ/(kg · K)***	**Temperature, K**	**Pressure, MPa**	**Volume, m^3/kmol**
Air	—	28.97	0.2870	132.5	3.77	0.0883
Ammonia	NH_3	17.03	0.4882	405.5	11.28	0.0724
Argon	Ar	39.948	0.2081	151	4.86	0.0749
Benzene	C_6H_6	78.115	0.1064	562	4.92	0.2603
Bromine	Br_2	159.808	0.0520	584	10.34	0.1355
n-Butane	C_4H_{10}	58.124	0.1430	425.2	3.80	0.2547
Carbon dioxide	CO_2	44.01	0.1889	304.2	7.39	0.0943
Carbon monoxide	CO	28.011	0.2968	133	3.50	0.0930
Carbon tetrachloride	CCl_4	153.82	0.05405	556.4	4.56	0.2759
Chlorine	Cl_2	70.906	0.1173	417	7.71	0.1242
Chloroform	$CHCl_3$	119.38	0.06964	536.6	5.47	0.2403
Dichlorodifluoromethane (R-12)	CCl_2F_2	120.91	0.06876	384.7	4.01	0.2179
Dichlorofluoromethane (R-21)	$CHCl_2F$	102.92	0.08078	451.7	5.17	0.1973
Ethane	C_2H_6	30.070	0.2765	305.5	4.48	0.1480
Ethyl alcohol	C_2H_5OH	46.07	0.1805	516	6.38	0.1673
Ethylene	C_2H_4	28.054	0.2964	282.4	5.12	0.1242

Data of critical pressure & temperature

Ethylene	C_2H_4	[illegible]	[illegible]	[illegible]		
Helium	He	4.003	2.0769	5.3	0.23	0.0578
n-Hexane	C_6H_{14}	86.179	0.09647	507.9	3.03	0.3677
Hydrogen (normal)	H_2	2.016	4.1240	33.3	1.30	0.0649
Krypton	Kr	83.80	0.09921	209.4	5.50	0.0924
Methane	CH_4	16.043	0.5182	191.1	4.64	0.0993
Methyl alcohol	CH_3OH	32.042	0.2595	513.2	7.95	0.1180
Methyl chloride	CH_3Cl	50.488	0.1647	416.3	6.68	0.1430
Neon	Ne	20.183	0.4119	44.5	2.73	0.0417
Nitrogen	N_2	28.013	0.2968	126.2	3.39	0.0899
Nitrous oxide	N_2O	44.013	0.1889	309.7	7.27	0.0961
Oxygen	O_2	31.999	0.2598	154.8	5.08	0.0780
Propane	C_3H_8	44.097	0.1885	370	4.26	0.1998
Propylene	C_3H_6	42.081	0.1976	365	4.62	0.1810
Sulfur dioxide	SO_2	64.063	0.1298	430.7	7.88	0.1217
Tetrafluoroethane (R-134a)	CF_3CH_2F	102.03	0.08149	374.3	4.067	0.1847
Trichlorofluoromethane (R-11)	CCl_3F	137.37	0.06052	471.2	4.38	0.2478
Water	H_2O	18.015	0.4615	647.3	22.09	0.0568
Xenon	Xe	131.30	0.06332	289.8	5.88	0.1186

*The unit kJ/(kg · K) is equivalent to kPa · m^3/(kg · K). The gas constant is calculated from $R = R_u/M$, where R_u = 8.314 kJ/(kmol · K) and *M* is the molar mass.

Source: K. A. Kobe and R. E. Lynn, Jr., *Chemical Review* 52 (1953), pp. 117–236; and ASHRAE, *Handbook of Fundamentals*, (Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1993), pp. 16.4 and 36.1.

Temperature Scales

- Ice Point: the temperature at which a mixture of ice and water are in equilibrium at a pressure of 1 atmosphere.
- Steam Point: the temperature at which water vapor condenses at a pressure of 1 atmosphere
- Two point scales – when temperature values are assigned at two different points (0^oC and 100^oC & 32^oF and 212^oF)
- Kelvin scale
  - Lowest temperature is absolute zero (0 K)
  - Only one non-zero reference point needs to be assigned to establish the slope of linear scale.

Example 1

The pressure in a constant gas thermometer is measured as 32 mm of mercury above atmospheric pressure at triple point. Determine the temperature in °C, when the pressure is 76 mm of mercury above atmospheric pressure. The barometer reads 752 mm of mercury.

Given: $P_{atm} = 752\, mm\ of\ Hg, P_{gauge,tp} = 32\, mm\ of\ Hg, P_{gauge,1} = 76\, mm\ of\ Hg, T_{tp} = 273.15\ K$

Solution: $P_{tp} = P_{atm} + P_{gauge,tp} = 752 + 32 = 784\, mm\ of\ Hg$

$$P_1 = P_{atm} + P_{gauge,1} = 752 + 76 = 828\, mm\ of\ Hg$$

$$P_{tp} \propto T_{tp}$$

$$\frac{P_{tp}}{T_{tp}} = \frac{P_1}{T_1}$$

$$T_1 = \frac{P_1 * T_{tp}}{P_{tp}} = \frac{828 * 273.15}{784} = 288.48\ K$$

Example 2

The temperature scale of a certain thermometer is given by the relation, $T = A\ln p + B$, where A and B are constants, and 'p' is the thermometric property of the fluid in thermometer. At ice point and steam point, if the thermometric property is found to be 1.5 and 7.5 respectively, what will be the temperature corresponding to the thermometric property of 3.5 on Celsius scale??

Given: $P_i = 1.5, T_i = 0°\text{C}, P_s = 7.5, T_s = 100°\text{C}, P = 3.5, T = ??$

Solution:

$$T = A\ln p + B$$
$$T_i = A\, ln\, p_i + B$$
$$T_s = A\, ln\, p_s + B$$

$$A\ln 1.5 + B = 0 \quad \rightarrow \quad ①$$
$$A\ln 7.5 + B = 100 \quad \rightarrow \quad ②$$

Solving Equations 1 and 2

$$A = 62.13, B = -25.2$$
$$T = 62.13\ln 3.5 - 25.2 = 52.64°\text{C}$$

Example 3

It is proposed to construct a new scale with the value 5°N assigned to ice point and 20°N to steam point. The pressure of an ideal gas at constant volume is considered as a thermometric property.

a) Set up a linear relationship between pressure and temperature in °N on a new scale.

b)What is the Kelvin absolute zero on this scale?

c)Derive an expression between °N and K.

<u>Solution</u>:

$$T = aP + b$$

In Celsius Scale, $T_i = 0℃, T_s = 100℃$

$$T_i = aP_i + b$$
$$T_s = aP_s + b$$

By substituting the corresponding values,

$$aP_i + b = 0$$
$$aP_s + b = 100$$

On solving the above equations

$a(P_s - P_i) = 100$ $\quad a = \frac{100}{(P_s - P_i)}$ $\quad b = -aP_i = \frac{-100P_i}{(P_s - P_i)}$

$$T(^\circ C) = aP + b = \frac{100\ P}{(P_s - P_i)} - \frac{100\ P_i}{(P_s - P_i)} = \frac{100(P - P_i)}{(P_s - P_i)}$$

$$\frac{T(^\circ C)}{100} = \frac{(P - P_i)}{(P_s - P_i)} \longrightarrow (1)$$

In the New scale, $T_i = 5^0 N, T_s = 20^0 N$

$$T_i = cP_i + d$$
$$T_s = cP_s + d$$

By substituting the corresponding values,

$$cP_i + d = 5$$
$$cP_s + d = 20$$

On solving the above equations

$c(P_s - P_i) = 15$ $\quad c = \frac{15}{(P_s - P_i)}$ $\quad d = 5 - cP_i = 5 - \frac{15P_i}{(P_s - P_i)}$

$$T(^0 N) = cP + d = \frac{15\ P}{(P_s - P_i)} + 5 - \frac{15\ P_i}{(P_s - P_i)} = 5 + \frac{15(P - P_i)}{(P_s - P_i)}$$

$$\frac{T(^0 N) - 5}{15} = \frac{(P - P_i)}{(P_s - P_i)} \longrightarrow (2)$$

From Equations 1 and 2

$$\frac{T(^\circ C)}{100} = \frac{T(^0 N) - 5}{15}$$

b) T = 0 K = -273^{0}C

$$\frac{T(°C)}{100} = \frac{T(^0N) - 5}{15}$$

$$T(^0N) = 15\,\frac{T(°C)}{100} + 5 = 15\left(\frac{-273}{100}\right) + 5 = -35.95^0N$$

$$0\;K = -273°C = -35.95^0N$$

c) $\frac{T(°C)}{100} = \frac{T(^0N)-5}{15}$

$$\frac{T(K) - 273}{100} = \frac{T(^0N) - 5}{15}$$

$$T(K) = \left[\frac{100}{15}\left(T(^0N) - 5\right)\right] + 273$$

Engineering Thermodynamics
Lecture 8

I Law of Thermodynamics

SNo	Topic	Hours
1	Statement of I law, PMM1, application to Non-flow Systems – Ideal gas processes.	2
2	I law for Non-flow Systems – Vapor processes	2
3	Analysis of Flow Systems – Continuity equation (Mass balance) and Steady Flow Energy Equation (Energy balance)	2
4	Illustration in Some Steady flow Engineering Devices – nozzles, turbines, etc.	3

I Law statement, PMM 1

Applications to Non-flow systems; Ideal gas processes

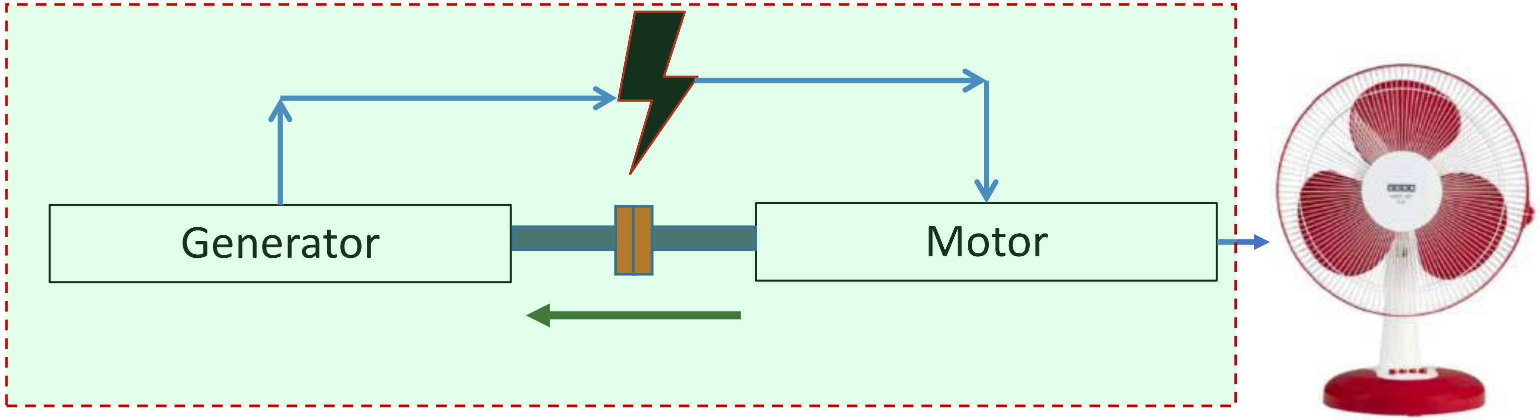
Statement of I law of TD & PMM1

- I law of thermodynamics – statement of principle of conservation of energy
  - Energy can neither be created nor be destroyed, but can only be converted from one form to another
- Some more statements
  - For any cycle of a closed system, the net heat transfer equals the net work
  - The total work is the same in all adiabatic processes between any two equilibrium states having the same kinetic and potential energies

The Perpetual Motion Machine of 1st kind (PMM1)

- **Perpetual Motion Machine of 1st kind**
  - A machine which violates the first law
  - Operates in a cycle and produces more work than the net amount of heat into the system
  - A system that operates in such a way that it produces no other effect on the surroundings other than delivery of useful work
  - Generates energy from nowhere

Example of a perpetual motion machine of 1st kind

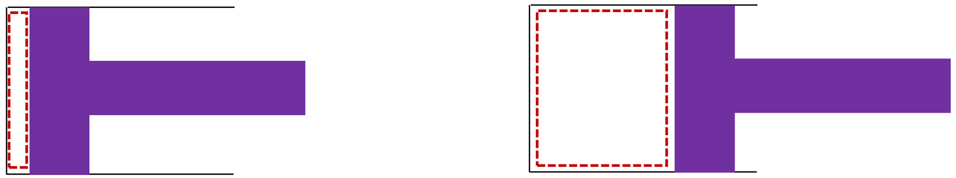


There are 3 kinds of PMMs !

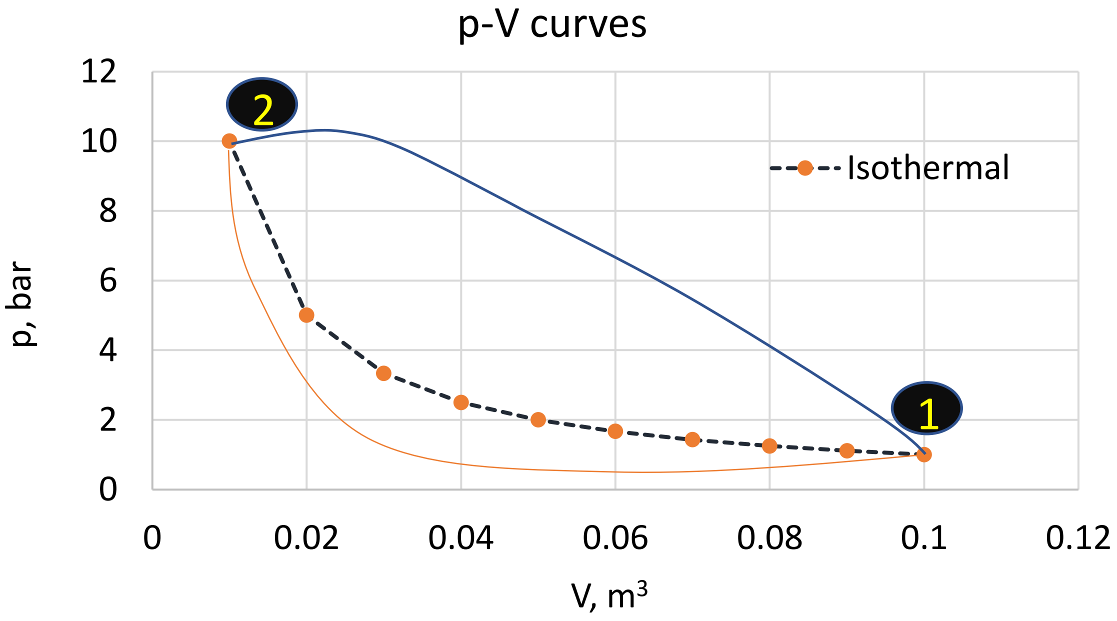
Thermodynamic Cycle

Frictionless piston cylinder arrangement

Process 1 - 2



Process 2 - 1



- Process – A system is said to have undergone a process if there is a change in its state. Types of processes – isothermal, adiabatic, polytropic, etc.
- Cycle – A system is said to have undergone a cycle if it returns to its initial state at the end of a process. [Initial & final states are identical for a cycle.

Can there be useful work out in a cycle if onward & return paths are same ?
If not, when can there be useful work out?

"Net heat in" & "Net work out"

- Net heat in:

$$Q_{in} = Q_1 + Q_3 + Q_4$$

$$Q_{out} = Q_2$$

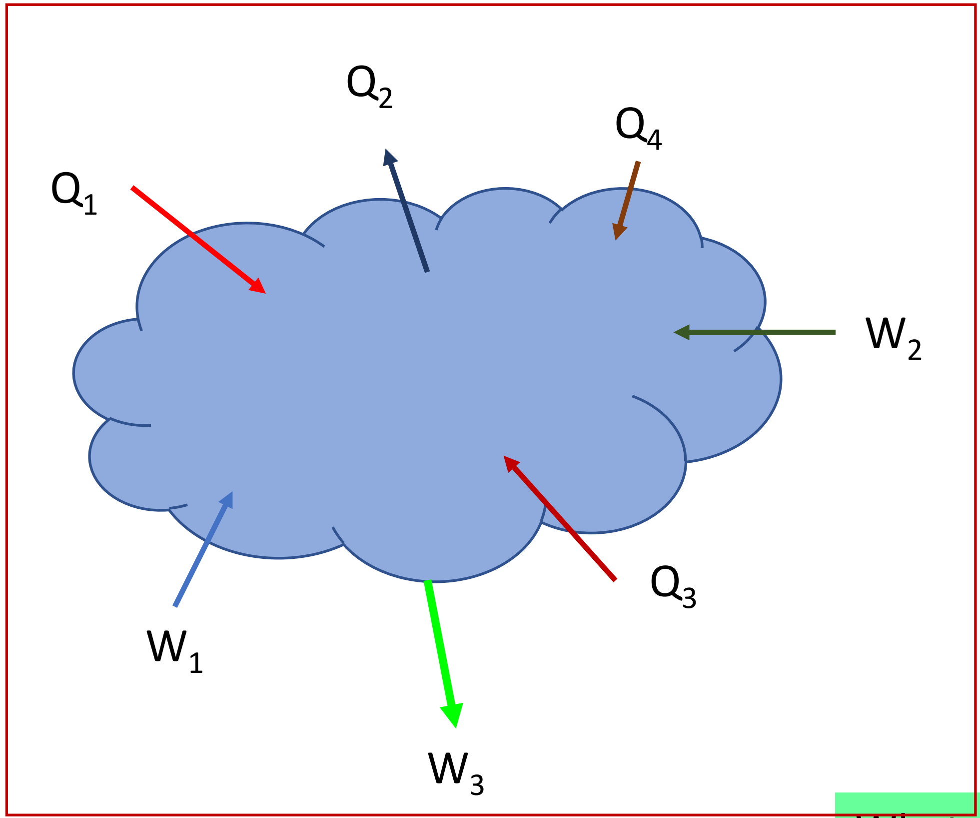
$$Q_{net,in} = Q_{in} - Q_{out}$$

- Net work out

$$W_{in} = W_1 + W_2$$

$$W_{out} = W_3$$

$$W_{net,out} = W_{out} - W_{in}$$



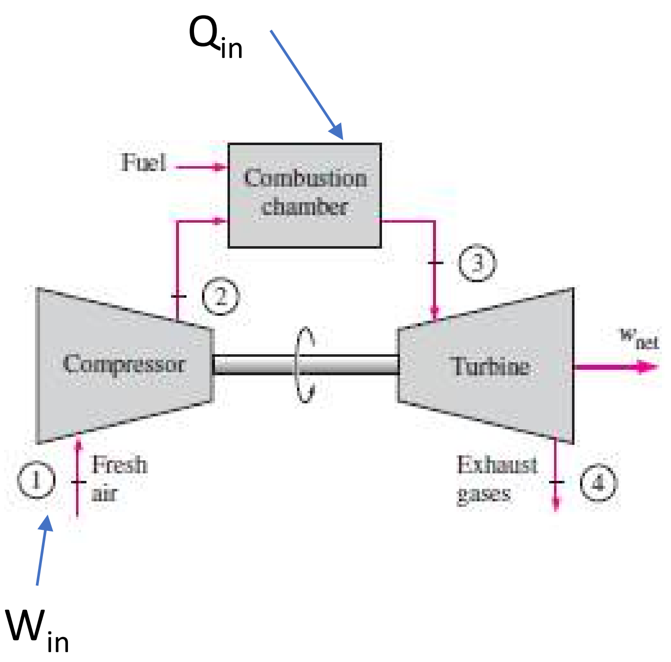
SNo.	Q, J	W, J
1	100	150
2	200	50
3	350	400
4	200	NA
Net, in	450	----
Net, out	----	200

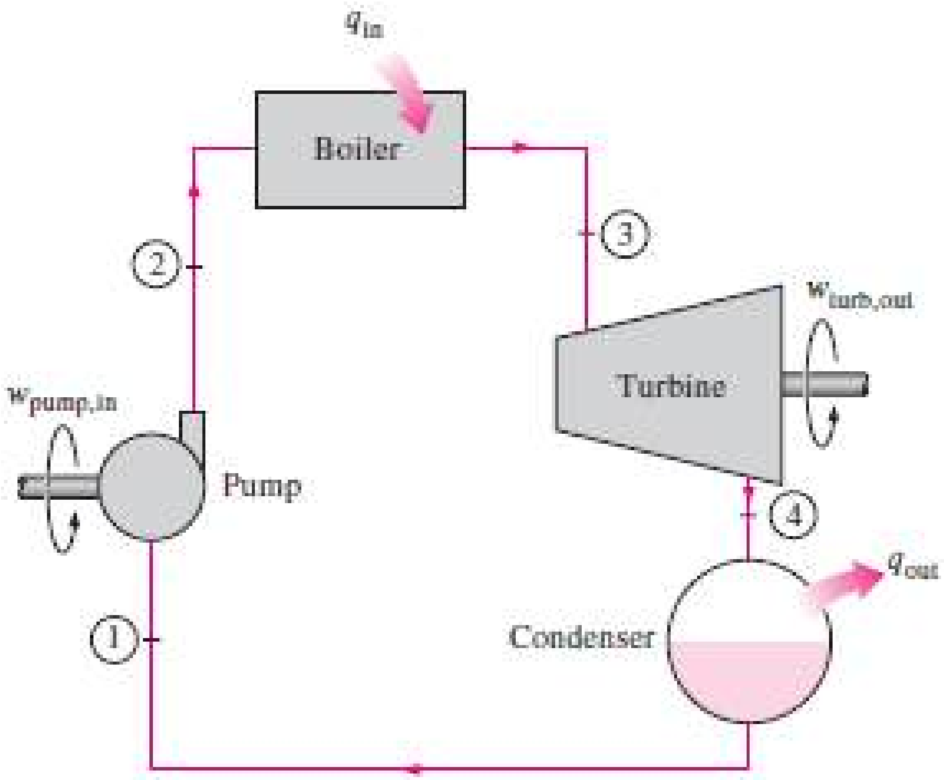
Net heat into the system = 450 J
Net work out of the system = 200 J

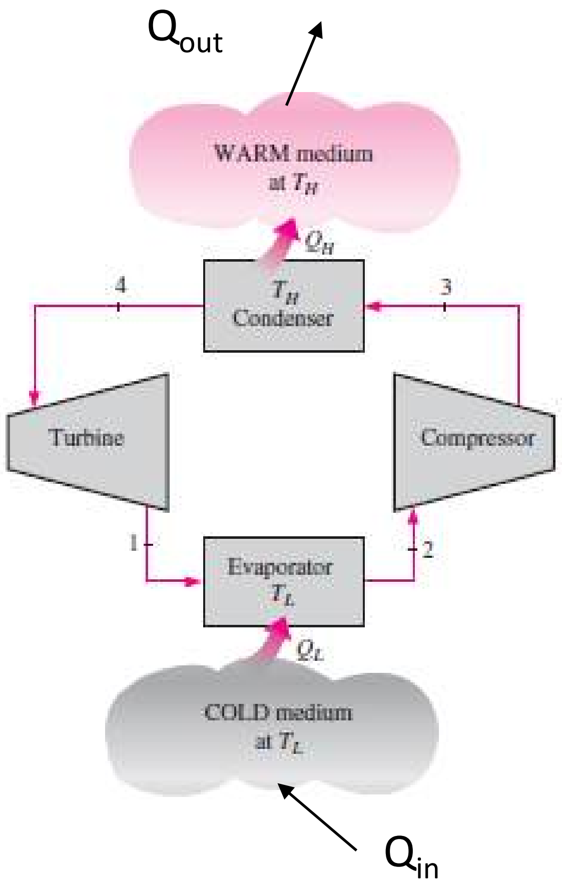
What about the difference (250 J) in energy?

If, there are no other interaction between system & surroundings, this difference is stored in the system – Internal energy.

Examples of multiple energy interaction[1]





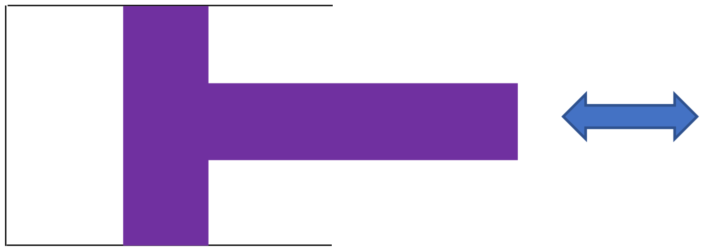


Work-done ; The Piston cylinder arrangement

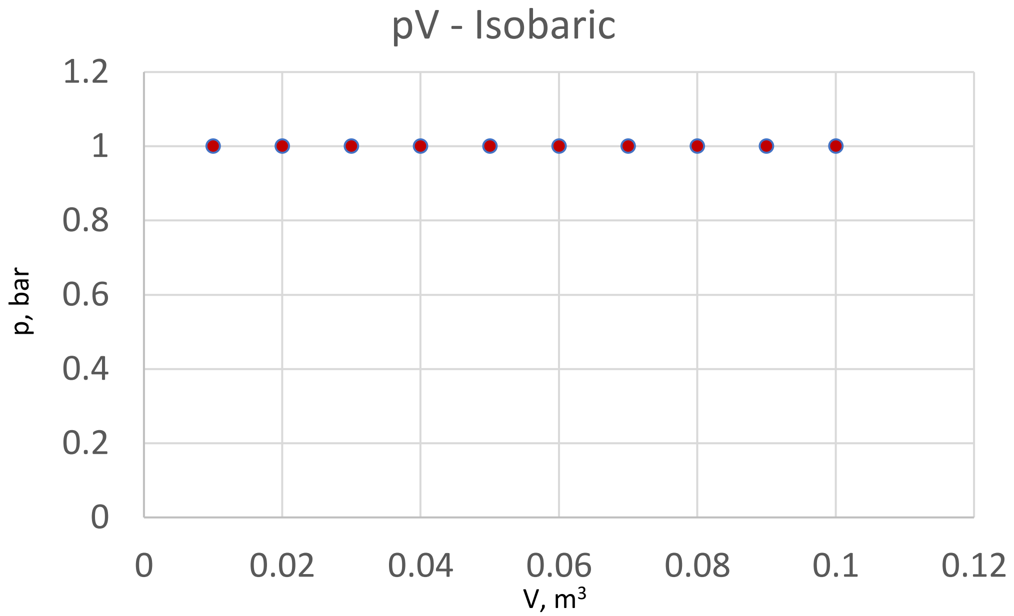
- An ideal (frictionless) arrangement
- Gas - ideal

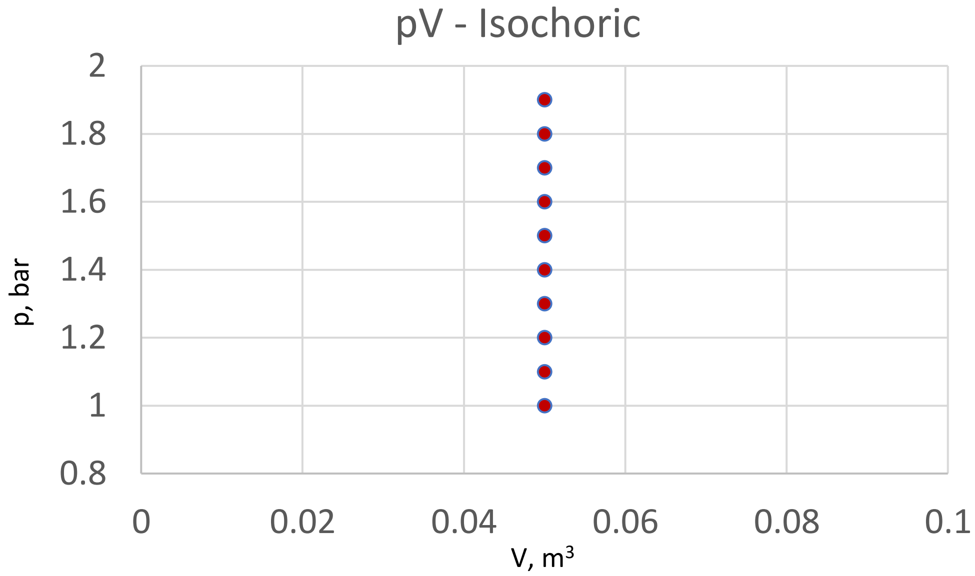
$$pV = mRT$$

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



- Fictitious experiments
  - Isobaric
  - Isochoric – can this be done?
  - Work done – depends on the process
- Work is done by the gas / work is done on the gas?





Work-done for different types of processes

- Isobaric process:

$$W = \int_{V_1}^{V_2} p dV = p \int_{V_1}^{V_2} dV = p\Delta V = \pm$$

[redacted]

- Isentropic process:

$$W = \int_{V_1}^{V_2} p dV = C \int_{V_1}^{V_2} \frac{1}{V^{\gamma}} dV = C \left[\frac{V^{(-\gamma+1)}}{-\gamma+1} \right]_{V_1}^{V_2} = \pm$$

[redacted]

$$C = pV^{\gamma}$$

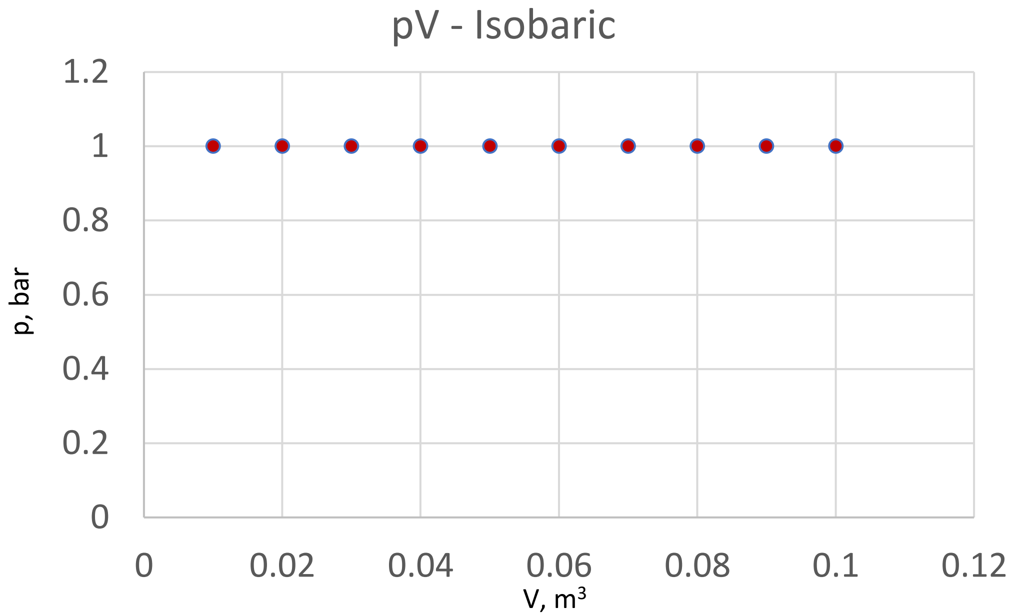
- Isothermal process:

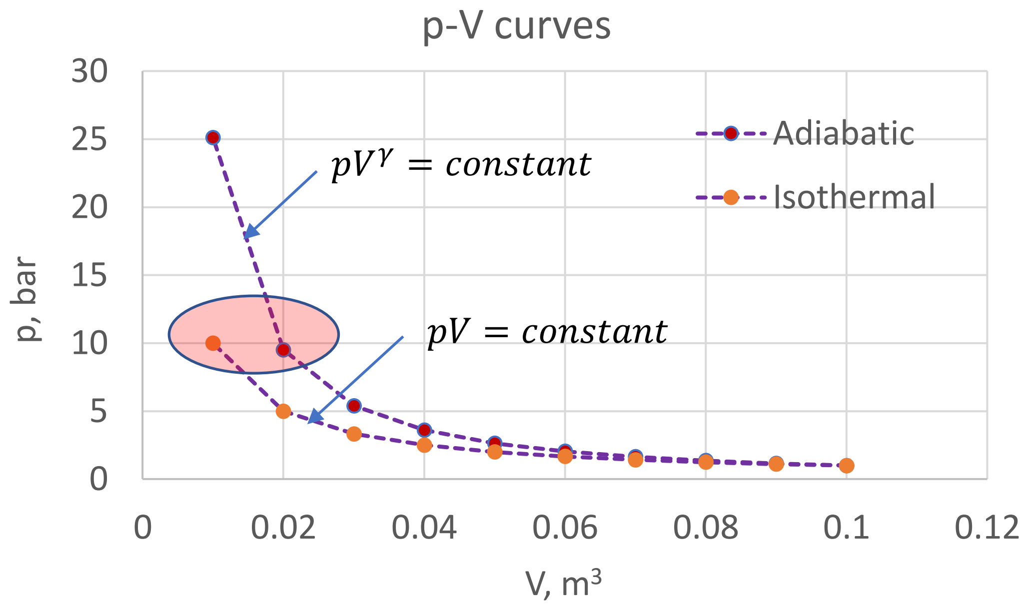
$$W = \int_{V_1}^{V_2} p dV = C \int_{V_1}^{V_2} \frac{1}{V} dV = C ln \frac{V_2}{V_1} = \pm$$

[redacted]

$$C = pV$$

*** The answers are jumbled ***





Engineering Thermodynamics
Lecture 9 & 10

pdV work, net heat in & net work out - review

I law for closed systems

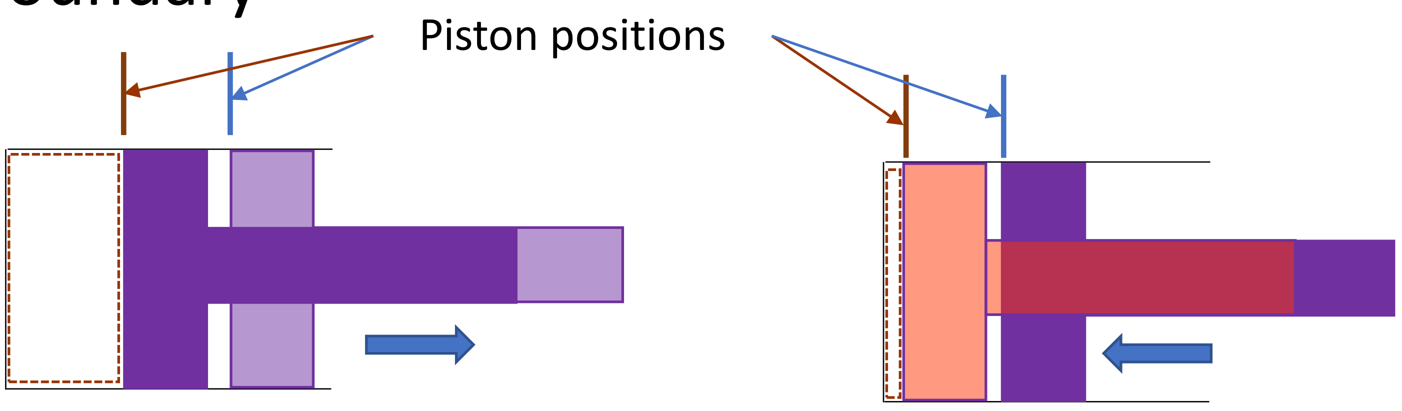
* process
* cycle

Steps in problem solving

Numerical Illustration

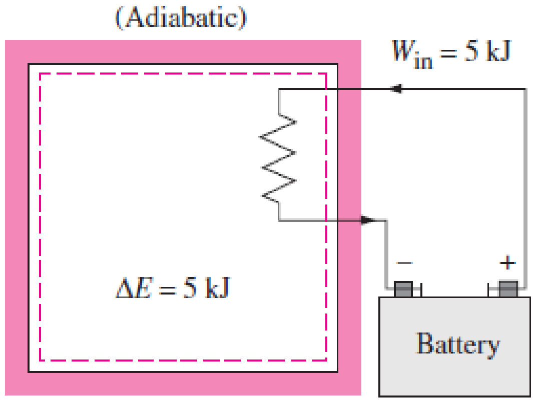
pdV work – Boundary work

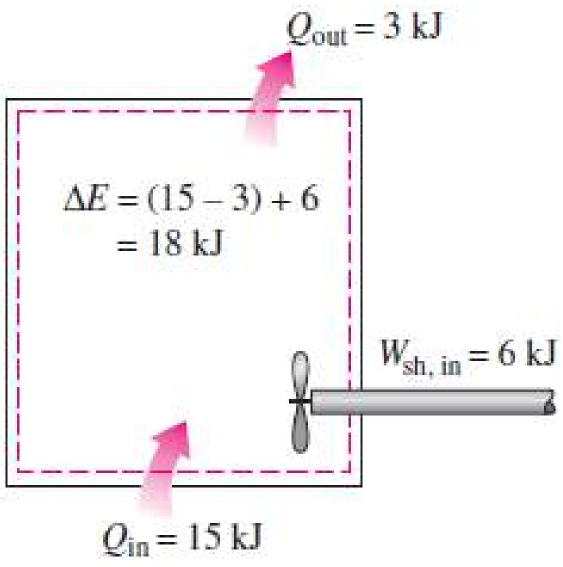
- There is a movement of at least one boundary



$$W = \int_{V_1}^{V_2} pdV = W_{bound}$$

Non-boundary works





"Net heat in" & "Net work out"

- Net heat in:

$$Q_{in} = Q_1 + Q_3 + Q_4$$

$$Q_{out} = Q_2$$

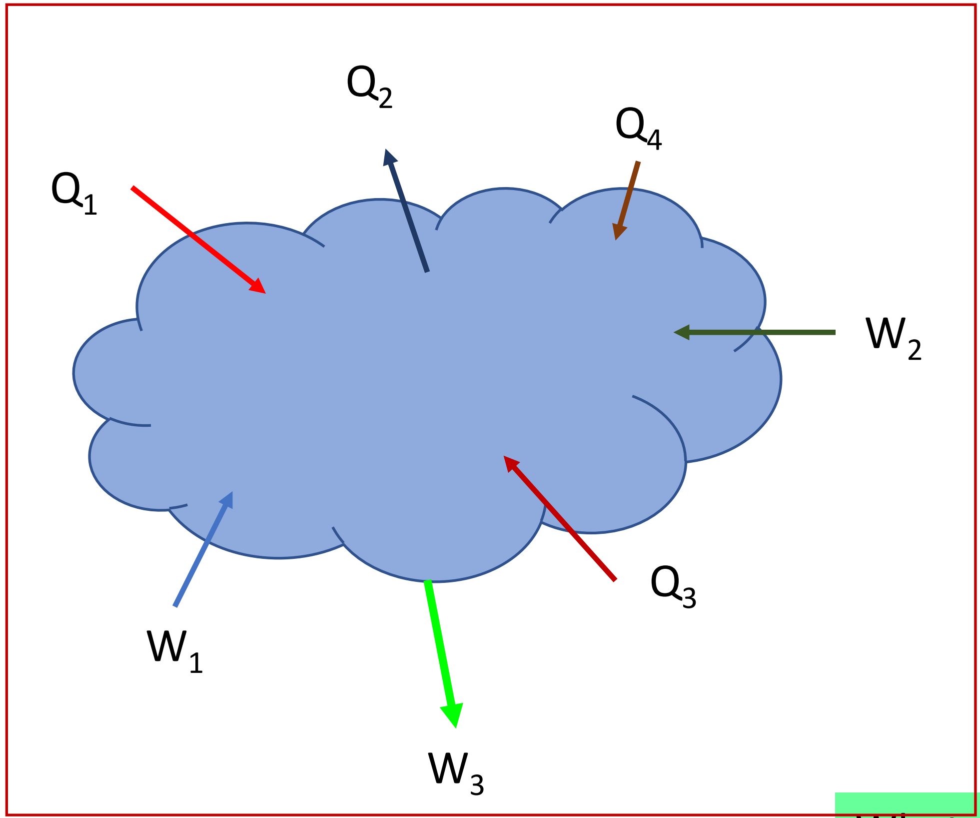
$$Q_{net,in} = Q_{in} - Q_{out}$$

- Net work out

$$W_{in} = W_1 + W_2$$

$$W_{out} = W_3$$

$$W_{net,out} = W_{out} - W_{in}$$



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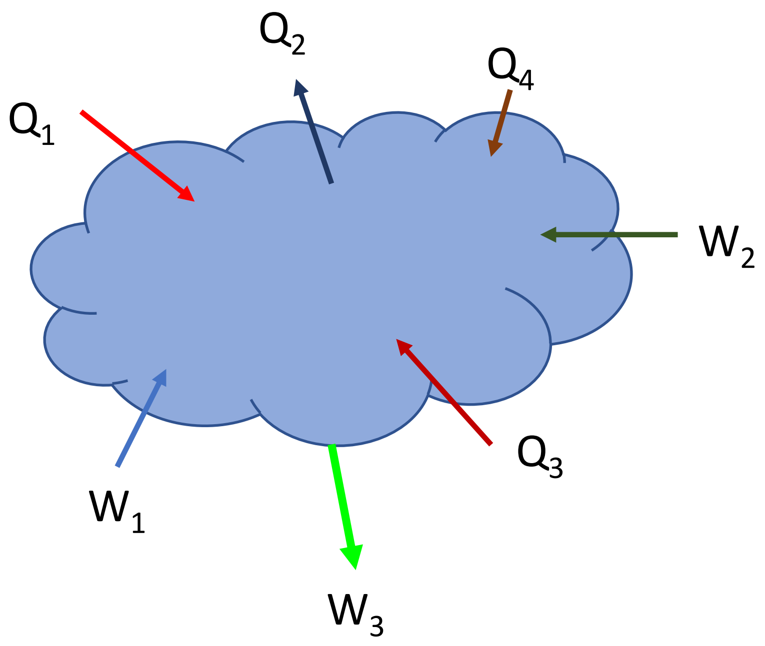
Net, in	450	----
Net, out	----	200

Net heat into the system = 450 J
Net work out of the system = 200 J

What about the difference (250 J) in energy?

If, there are no other interaction between system & surroundings, this difference is stored in the system – energy.

Change in the energy of the system



- Energy of the system – a property of the system
  - Internal energy
  - Kinetic energy
  - Potential energy
- I law for a closed system undergoing a process

$$Q_{net,in} - W_{net,out} = \Delta E \rightarrow E_2 - E_1$$

$$\Delta E = \Delta PE + \Delta KE + \Delta U \qquad \Delta U = U_2 - U_1$$

$$\Delta PE = mg\Delta z \qquad \Delta KE = \frac{1}{2}m(c_2^2 - c_1^2)$$

$$\Delta z = z_2 - z_1$$

Energy interaction mechanisms

- Heat
- Work
- Mass

Zero for closed systems

$$E_{in} - E_{out} = Q_{in} - Q_{out} + W_{in} - W_{out} + Energy_{mass,in} - Energy_{mass,out}$$

Other forms of the energy conservation equation

- Unit mass basis

$$q_{net,in} - w_{net,out} = \Delta e$$

$$\Delta e = \Delta pe + \Delta ke + \Delta u$$

$$\Delta pe = g\Delta z$$

$$\Delta z = z_2 - z_1$$

$$\Delta ke = \frac{1}{2}(c_2^2 - c_1^2)$$

$$\Delta u = u_2 - u_1$$

Parameter per unit mass → specific parameter

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

$$\Delta E = \Delta PE + \Delta KE + \Delta U$$

$$\Delta PE = mg\Delta z$$

$$\Delta z = z_2 - z_1$$

$$\Delta KE = \frac{1}{2}m(c_2^2 - c_1^2)$$

$$\Delta U = U_2 - U_1$$

- Rate basis $\left(\dot{x} = \frac{dx}{dt}\right)$

$$\dot{Q}_{net,in} - \dot{W}_{net,out} = \Delta\dot{E}$$

$$\Delta\dot{E} = \Delta\dot{PE} + \Delta\dot{KE} + \Delta\dot{U}$$

$$\Delta\dot{PE} = mg\Delta\dot{z}$$

$$\Delta\dot{z} = \frac{z_2 - z_1}{\Delta t}$$

$$\Delta\dot{KE} = \frac{1}{2}m\frac{(c_2^2 - c_1^2)}{\Delta t}$$

$$\Delta\dot{U} = \frac{U_2 - U_1}{\Delta t}$$

Other forms (contd.)

- On unit mass & rate basis

$$q_{net,in} - w_{net,out} = \Delta e$$

$$\Delta e = \Delta pe + \Delta ke + \Delta u$$

$$\Delta pe = g\Delta z$$

$$\Delta z = z_2 - z_1$$

$$\Delta ke = \frac{1}{2}(c_2^2 - c_1^2)$$

$$\Delta u = u_2 - u_1$$

$$\dot{q}_{net,in} - \dot{w}_{net,out} = \Delta \dot{e}$$

$$\Delta \dot{e} = \Delta \dot{pe} + \Delta \dot{ke} + \Delta \dot{u}$$

$$\Delta \dot{pe} = g\Delta \dot{z}$$

$$\Delta \dot{z} = \frac{z_2 - z_1}{\Delta t}$$

$$\Delta \dot{ke} = \frac{1}{2}\frac{(c_2^2 - c_1^2)}{\Delta t}$$

$$\Delta \dot{u} = \frac{u_2 - u_1}{\Delta t}$$

I law for a closed system undergoing a cycle

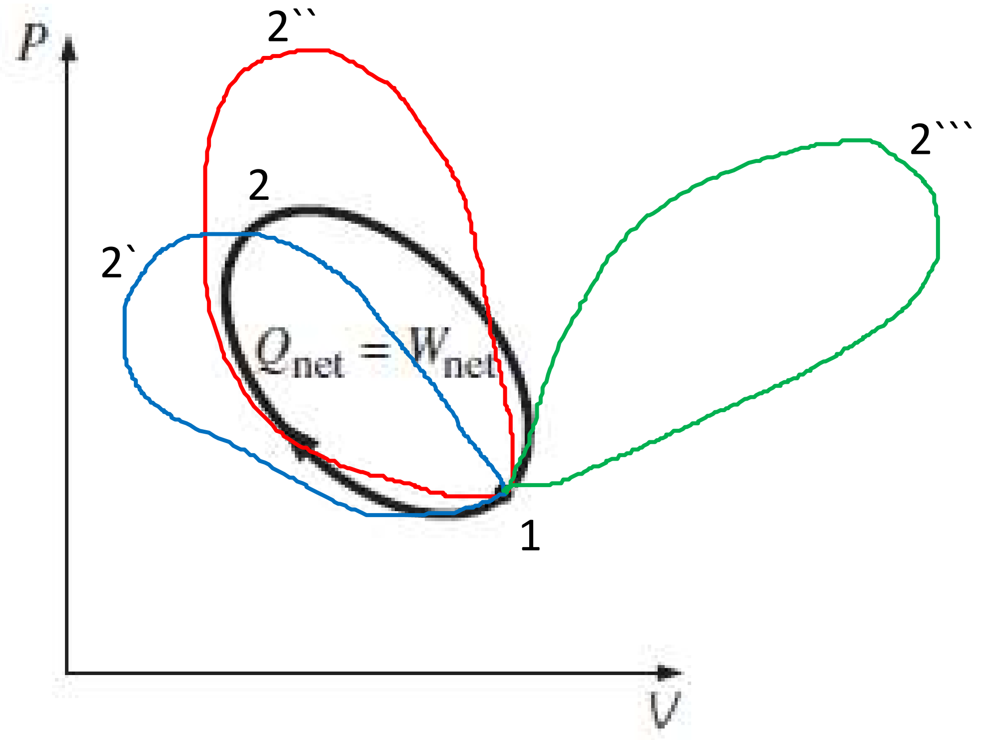
- Energy of a system is a property (like temperature, pressure, volume etc.)

$$\oint \delta Q_{net,in} - \oint \delta W_{net,out} = 0$$

$$Q_{net,in} = W_{net,out}$$

Rate basis

$$\dot{Q}_{net,in} = \dot{W}_{net,out}$$



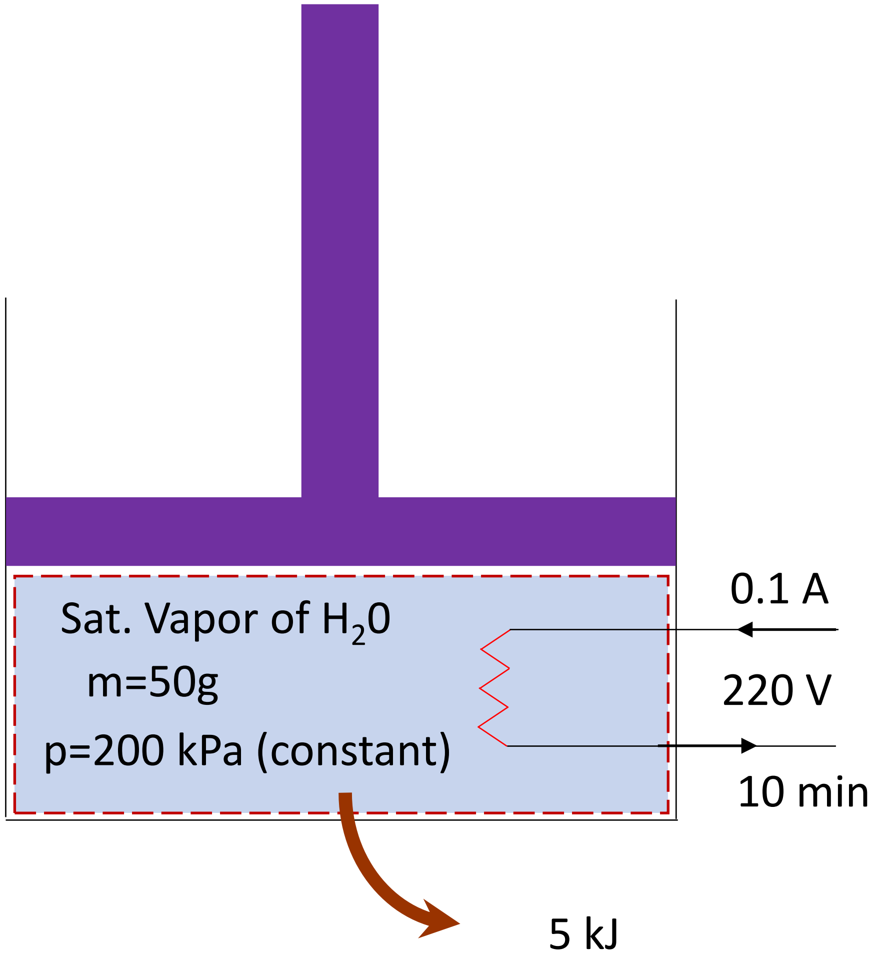
Steps in problem solving

Identify	the system & draw a sketch of it
List	the given information on the sketch
Check	for special processes
State	assumptions (if any)
Apply	the conservation equations
Draw	the process diagrams
Determine	the required properties & unknowns

Illustration

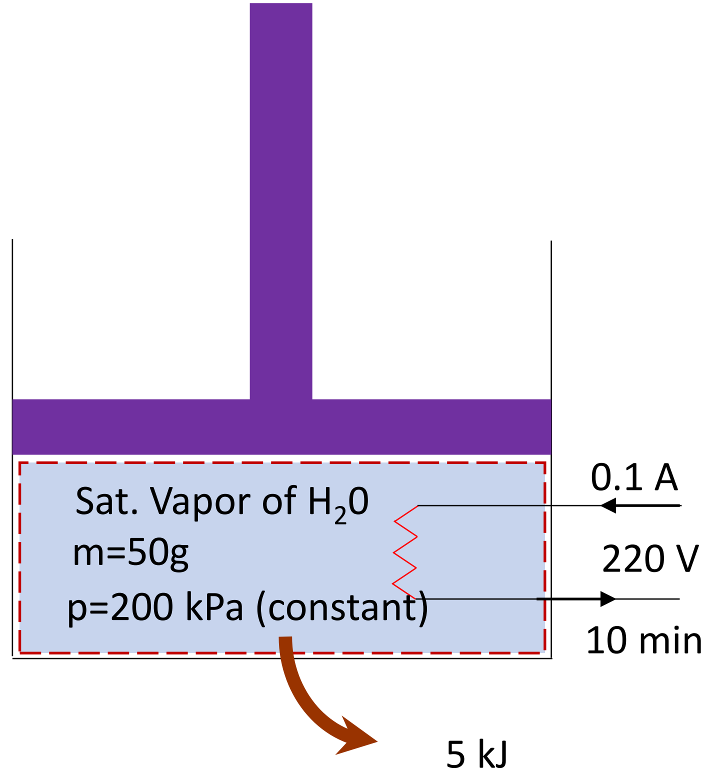
- A piston-cylinder device contains 50 g of saturated water vapor that is maintained at a constant pressure of 200 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.1 A for 10 minutes from a 220 V source. At the same time, a heat loss of 5 kJ occurs. (a) Show that for a closed system the boundary work and the change in internal energy can be combined into one term and (b) determine the final temperature of the steam.

The system under analysis



1. Identification of system & sketch
   a) Closed system
   b) Boundary work – yes
   c) Heat interaction - yes
2. List information on sketch
3. Special process – constant pressure process
4. Assumptions
   a) The tank is stationary, hence changes in KE and PE are zero.
   b) The electrical wires form a very small part of the system and hence energy changes of them can be neglected

The system under analysis (contd.)



$H = U + pV$

Enthalpy

$h = u + pv$

Sp. Enthalpy

5. Conservation equations

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

Z e r o

$$\Delta E = \Delta PE + \Delta KE + \Delta U$$

$$Q_{in} - Q_{out} + W_{in} - W_{out} = \Delta U$$

$$-Q_{out} + Volts.I\Delta t - pdV = U_2 - U_1$$

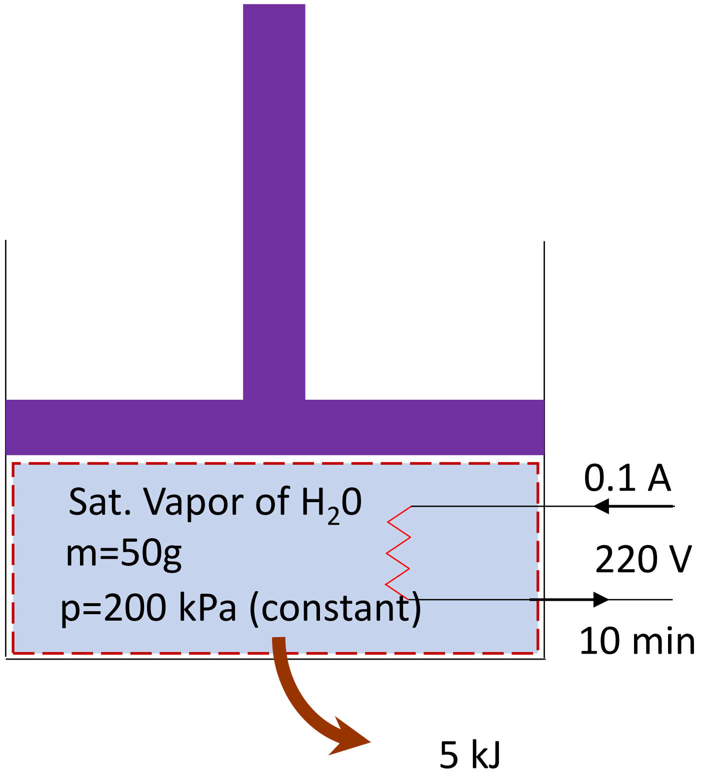
$$-Q_{out} + Volts.I\Delta t - p(V_2 - V_1) = U_2 - U_1$$

$$-Q_{out} + Volts.I\Delta t = p(V_2 - V_1) + U_2 - U_1$$

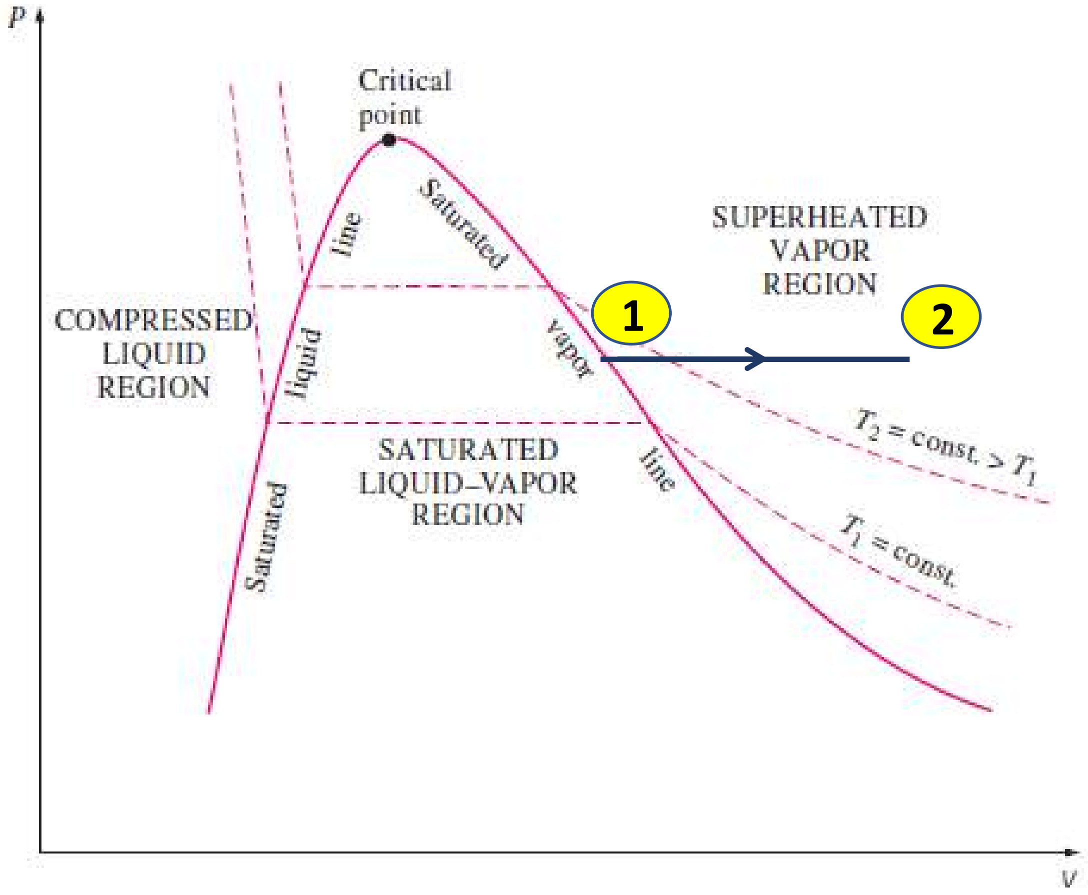
$$-Q_{out} + Volts.I\Delta t = (U_2 + pV_2) - (U_1 + pV_1)$$

$$-Q_{out} + Volts.I\Delta t = H_2 - H_1 = \Delta H$$

The system under analysis (contd.)

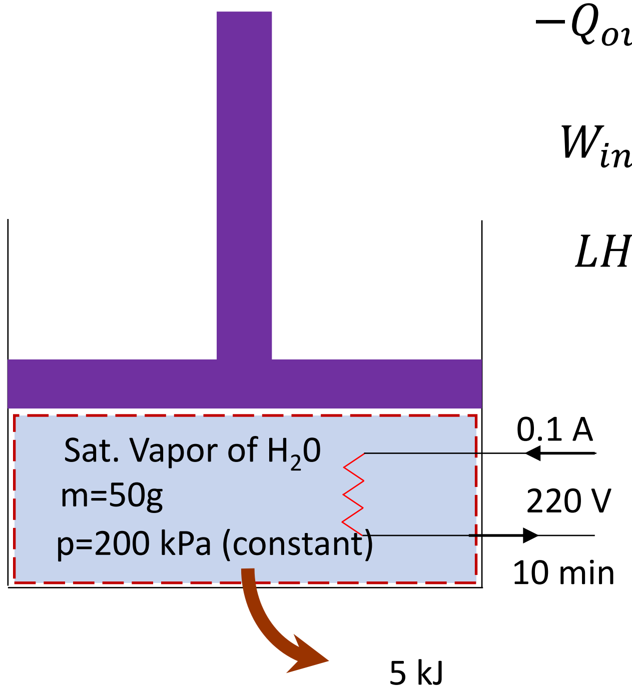


6. Process diagram



The system under analysis (contd.)

7. Determine the required properties & unknowns



$$-Q_{out} + Volts.I\Delta t = H_2 - H_1$$

$$W_{in} = Volts.I\Delta t = 220(0.1)(600) = 13.2\ kJ$$

$$LHS = 13.2 - 5 = 8.2\ kJ$$

From property tables, sp. Enthalpy of saturated vapor at 200 kPa

$h_1 = h_g$ =2706.7 kJ/kg

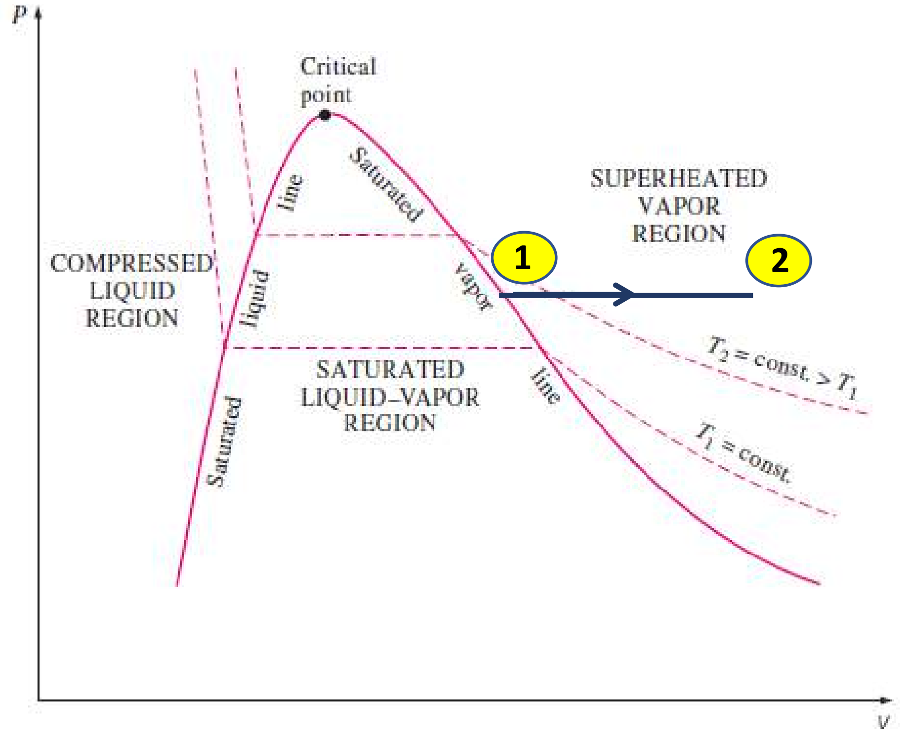
$$H_1 = mh_1 = 0.05(2706.7) = 135.34\ kJ$$

$$H_2 = H_1 + 8.2 = 143.54\ kJ$$

$$h_2 = \frac{H_2}{m} = 2870.7\ kJ/kg$$

From property tables, for sp. Enthalpy of superheated vapor of 2870.7 kJ/kg at 200 kPa

$$T_2 = 200℃$$



Saturated water properties

TABLE A-5

Saturated water—Pressure table

H_2O

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/(kg · K): Sat. liquid, s_f	Entropy, kJ/(kg · K): Evap., s_{fg}	Entropy, kJ/(kg · K): Sat. vapor, s_g
0.6113	0.01	0.001000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
1.0	6.98	0.001000	129.21	29.30	2355.7	2385.0	29.30	2484.9	2514.2	0.1059	8.8697	8.9756
1.5	13.03	0.001001	87.98	54.71	2338.6	2393.3	54.71	2470.6	2525.3	0.1957	8.6322	8.8279
2.0	17.50	0.001001	67.00	73.48	2326.0	2399.5	73.48	2460.0	2533.5	0.2607	8.4629	8.7237
2.5	21.08	0.001002	54.25	88.48	2315.9	2404.4	88.49	2451.6	2540.0	0.3120	8.3311	8.6432
3.0	24.08	0.001003	45.67	101.04	2307.5	2408.5	101.05	2444.5	2545.5	0.3545	8.2231	8.5776
4.0	28.96	0.001004	34.80	121.45	2293.7	2415.2	121.46	2432.9	2554.4	0.4226	8.0520	8.4746
5.0	32.88	0.001005	28.19	137.81	2282.7	2420.5	137.82	2423.7	2561.5	0.4764	7.9187	8.3951
7.5	40.29	0.001008	19.24	168.78	2261.7	2430.5	168.79	2406.0	2574.8	0.5764	7.6750	8.2515
10	45.81	0.001010	14.67	191.82	2246.1	2437.9	191.83	2392.8	2584.7	0.6493	7.5009	8.1502
15	53.97	0.001014	10.02	225.92	2222.8	2448.7	225.94	2373.1	2599.1	0.7549	7.2536	8.0085
20	60.06	0.001017	7.649	251.38	2205.4	2456.7	251.40	2358.3	2609.7	0.8320	7.0766	7.9085
25	64.97	0.001020	6.204	271.90	2191.2	2463.1	271.93	2346.3	2618.2	0.8931	6.9383	7.8314
30	69.10	0.001022	5.229	289.20	2179.2	2468.4	289.23	2336.1	2625.3	0.9439	6.8247	7.7686
40	75.87	0.001027	3.993	317.53	2159.5	2477.0	317.58	2319.2	2636.8	1.0259	6.6441	7.6700
50	81.33	0.001030	3.240	340.44	2143.4	2483.9	340.49	2305.4	2645.9	1.0910	6.5029	7.5939
75	91.78	0.001037	2.217	384.31	2112.4	2496.7	384.39	2278.6	2663.0	1.2130	6.2434	7.4564
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271
0.225	124.00	0.001064	0.7933	520.47	2013.1	2533.6	520.72	2191.3	2712.1	1.5706	5.5173	7.0878
0.250	127.44	0.001067	0.7187	535.10	2002.1	2537.2	535.37	2181.5	2716.9	1.6072	5.4455	7.0527
0.275	130.60	0.001070	0.6573	548.59	1991.9	2540.5	548.89	2172.4	2721.3	1.6408	5.3801	7.0209
0.300	133.55	0.001073	0.6058	561.15	1982.4	2543.6	561.47	2163.8	2725.3	1.6718	5.3201	6.9919
0.325	136.30	0.001076	0.5620	572.90	1973.5	2546.4	573.25	2155.8	2729.0	1.7006	5.2646	6.9652
0.350	138.88	0.001079	0.5243	583.95	1965.0	2548.9	584.33	2148.1	2732.4	1.7275	5.2130	6.9405
0.375	141.32	0.001081	0.4914	594.40	1956.9	2551.3	594.81	2140.8	2735.6	1.7528	5.1647	6.9175
0.40	143.63	0.001084	0.4625	604.31	1949.3	2553.6	604.74	2133.8	2738.6	1.7766	5.1193	6.8959
0.45	147.93	0.001088	0.4140	622.77	1934.9	2557.6	623.25	2120.7	2743.9	1.8207	5.0359	6.8565
0.50	151.86	0.001093	0.3749	639.68	1921.6	2561.2	640.23	2108.5	2748.7	1.8607	4.9606	6.8213
0.55	155.48	0.001097	0.3427	655.32	1909.2	2564.5	665.93	2097.0	2753.0	1.8973	4.8920	6.7893
0.60	158.85	0.001101	0.3157	669.90	1897.5	2567.4	670.56	2086.3	2756.8	1.9312	4.8288	6.7600
0.65	162.01	0.001104	0.2927	683.56	1886.5	2570.1	684.28	2076.0	2760.3	1.9627	4.7703	6.7331
0.70	164.97	0.001108	0.2729	696.44	1876.1	2572.5	697.22	2066.3	2763.5	1.9922	4.7158	6.7080
0.75	167.78	0.001112	0.2556	708.64	1866.1	2574.7	709.47	2057.0	2766.4	2.0200	4.6647	6.6847
0.80	170.43	0.001115	0.2404	720.22	1856.6	2576.8	721.11	2048.0	2769.1	2.0462	4.6166	6.6628
0.85	172.96	0.001118	0.2270	731.27	1847.4	2578.7	732.22	2039.4	2771.6	2.0710	4.5711	6.6421
0.90	175.38	0.001121	0.2150	741.83	1838.6	2580.5	742.83	2031.1	2773.9	2.0946	4.5280	6.6226
0.95	177.69	0.001124	0.2402	751.95	1830.2	2582.1	753.02	2023.1	2776.1	2.1172	4.4869	6.6041
1.00	179.91	0.001127	0.19444	761.68	1822.0	2583.6	762.81	2015.3	2778.1	2.1387	4.4478	6.5865
1.10	184.09	0.001133	0.17753	780.09	1806.3	2586.4	781.34	2000.4	2871.7	2.1792	4.3744	6.5536
1.20	187.99	0.001139	0.16333	797.29	1791.5	2588.8	798.65	1986.2	2784.8	2.2166	4.3067	6.5233
1.30	191.64	0.001144	0.15125	813.44	1777.5	2591.0	814.93	1972.7	2787.6	2.2515	4.2438	6.4953

906

TABLE A-5

Saturated water—Pressure table

H_2O

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/(kg · K): Sat. liquid, s_f	Entropy, kJ/(kg · K): Evap., s_{fg}	Entropy, kJ/(kg · K): Sat. vapor, s_g
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271

Saturated water properties

H_2O

TABLE A-5

Saturated water—Pressure table

Press., MPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg — Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg — Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg — Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/(kg · K) — Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271

Superheated water properties

TABLE A-6

Superheated water

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)	v m³/kg	u kJ/kg	h kJ/kg	s kJ/(kg · K)
	P = 0.01 MPa (45.81°C)*				**P = 0.05 MPa (81.33°C)**				**P = 0.10 MPa (99.63°C)**			
Sat.†	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939	1.6940	2506.1	2675.5	7.3594
50	14.869	2443.9	2592.6	8.1749								
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947	1.6958	2506.7	2676.2	7.3614
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401	1.9364	2582.8	2776.4	7.6134
200	21.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580	2.172	2658.1	2875.3	7.8343
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556	2.406	2733.7	2974.3	8.0333
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373	2.639	2810.4	3074.3	8.2158
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642	3.103	2967.9	3278.2	8.5435
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546	3.565	3131.6	3488.1	8.8342
600	40.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178	4.028	3301.9	3704.4	9.0976
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599	4.490	3479.2	3928.2	9.3398
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852	4.952	3663.5	4158.6	9.5652
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967	5.414	3854.8	4396.1	9.7767
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964	5.875	4052.8	4640.3	9.9764
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859	6.337	4257.3	4891.0	10.1659
1200	67.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662	6.799	4467.7	5147.6	10.3463
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382	7.260	4683.5	5409.5	10.5183
	P = 0.20 MPa (120.23°C)				**P = 0.30 MPa (133.55°C)**				**P = 0.40 MPa (143.63°C)**			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780
	P = 0.50 MPa (151.86°C)				**P = 0.60 MPa (158.85°C)**				**P = 0.80 MPa (170.43°C)**			
Sat.	0.3749	2561.2	2748.7	6.8213	0.3157	2567.4	2756.8	6.7600	0.2404	2576.8	2769.1	6.6628
200	0.4249	2642.9	2855.4	7.0592	0.3520	2638.9	2850.1	6.9665	0.2608	2630.6	2839.3	6.8158
250	0.4744	2723.5	2960.7	7.2709	0.3938	2720.9	2957.2	7.1816	0.2931	2715.5	2950.0	7.0384
300	0.5226	2802.9	3064.2	7.4599	0.4344	2801.0	3061.6	7.3724	0.3241	2797.2	3056.5	7.2328
350	0.5701	2882.6	3167.7	7.6329	0.4742	2881.2	3165.7	7.5464	0.3544	2878.2	3161.7	7.4089
400	0.6173	2963.2	3271.9	7.7938	0.5137	2962.1	3270.3	7.7079	0.3843	2959.7	3267.1	7.5716
500	0.7109	3128.4	3483.9	8.0873	0.5920	3127.6	3482.8	8.0021	0.4433	3126.0	3480.6	7.8673
600	0.8041	3299.6	3701.7	7.3522	0.6697	3299.1	3700.9	8.2674	0.5018	3297.9	3699.4	8.1333
700	0.8969	3477.5	3925.9	8.5952	0.7472	3477.0	3925.3	8.5107	0.5601	3476.2	3924.2	8.3770
800	0.9896	3662.1	4156.9	8.8211	0.8245	3661.8	4156.5	8.7367	0.6181	3661.1	4155.6	8.6033
900	1.0822	3853.6	4394.7	9.0329	0.9017	3853.4	4394.4	8.9486	0.6761	3852.8	4393.7	8.8153
1000	1.1747	4051.8	4639.1	9.2328	0.9788	4051.5	4638.8	9.1485	0.7340	4051.0	4638.2	9.0153
1100	1.2672	4256.3	4889.9	9.4224	1.0559	4256.1	4889.6	9.3381	0.7919	4255.6	4889.1	9.2050
1200	1.3596	4466.8	5146.6	9.6029	1.1330	4466.5	5146.3	9.5185	0.8497	4466.1	5145.9	9.3855
1300	1.4521	4682.5	5408.6	9.7749	1.2101	4682.3	5408.3	9.6906	0.9076	4681.8	5407.9	9.5575

*The temperature in parentheses is the saturation temperature at the specified pressure.

†Properties of saturated vapor at the specified pressure.

908

TABLE A-6

Superheated water

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)	v m³/kg	u kJ/kg	h kJ/kg	s kJ/(kg · K)
	P = 0.20 MPa (120.23°C)				**P = 0.30 MPa (133.55°C)**				**P = 0.40 MPa (143.63°C)**			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780

TABLE A-6

Superheated water

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)	v m³/kg	u kJ/kg	h kJ/kg	s kJ/(kg·K)
	P = 0.20 MPa (120.23°C)				P = 0.30 MPa (133.55°C)				P = 0.40 MPa (143.63°C)			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780

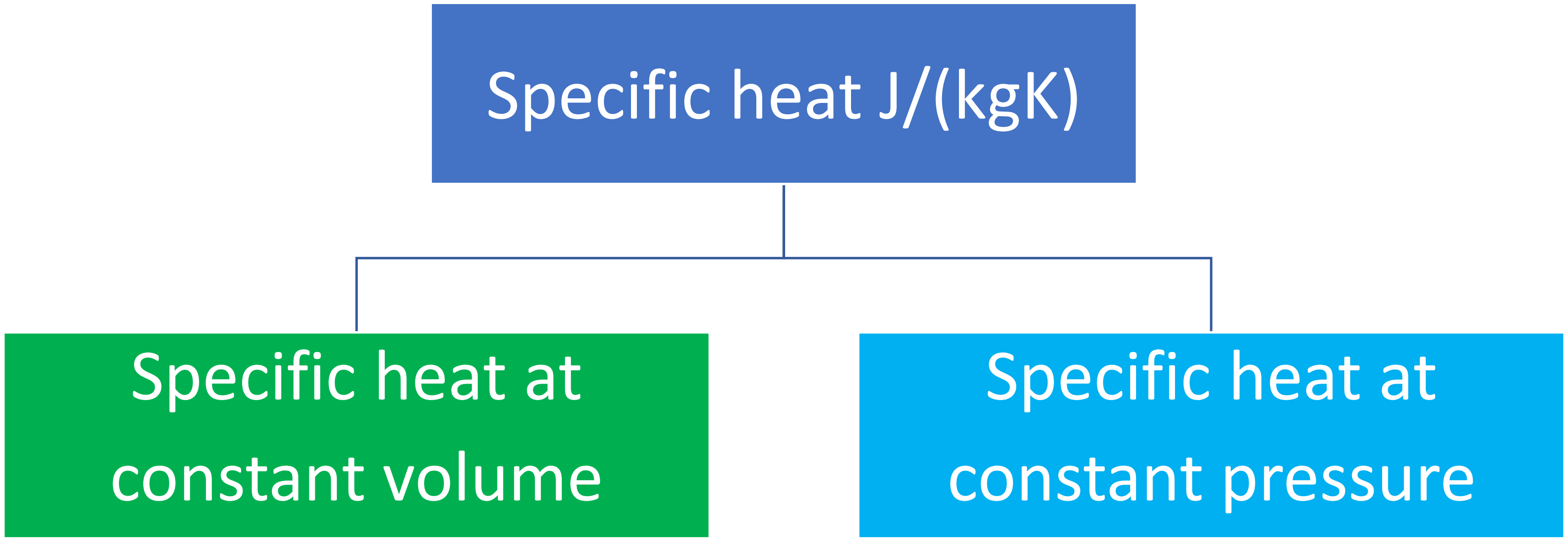
Engineering Thermodynamics
Lecture 11

Specific Heats

Numerical Illustration

Specific heat

- The amount of heat required to raise the temperature of a unit mass of a substance by a unit temperature.

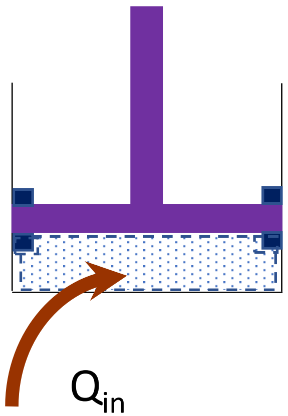


Steps in problem solving

1. **Identify** the system & draw a sketch of it
2. **List** the given information on the sketch
3. **Check** for special processes
4. **State** assumptions (if any)
5. **Apply** the conservation equations
6. **Draw** the process diagrams
7. **Determine** the required properties & unknowns

Specific heats (contd.)

Sp. Heat at const. volume: c_v



Mass = 1 kg
Volume = V, m^3
ΔT = 1 K

Applying the I law of TD for a process

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

$$dv = 0$$

Zero

$$q_{net,in} - w_{net,out} = \Delta e$$

Z e r o

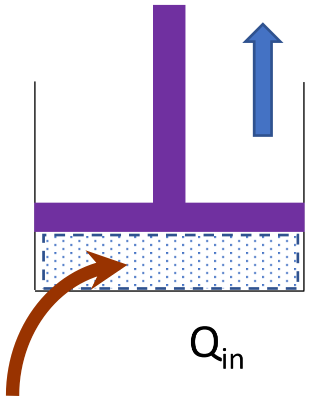
$$\Delta e = \Delta pe + \Delta ke + \Delta u$$

$$\delta q_{in} = du$$

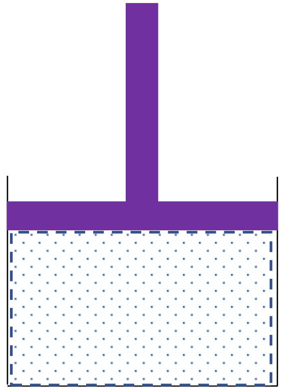
$$c_v dT = du$$

$$c_v = \left(\frac{du}{dT}\right)_v$$

Sp. Heat at const. pressure: c_p



Mass = 1 kg
Pressure = p, kPa
ΔT = 1 K



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

$$q_{net,in} - w_{net,out} = \Delta e$$

Z e r o

$$\Delta e = \Delta pe + \Delta ke + \Delta u$$

$$\delta w_{out} = pdv$$

$$c_p dT - \delta w_{out} = du$$

$$c_p dT - pdv = du$$

$$c_p dT = d(pv) + du$$

$$c_p dT = d(u + pv)$$

$$c_p dT = dh$$

$$c_p = \left(\frac{dh}{dT}\right)_p$$

Relation between specific heats

- The gas constant

$h = u + pv$ & $pv = RT$ → $h = u + RT$

$dh = du + d(RT)$

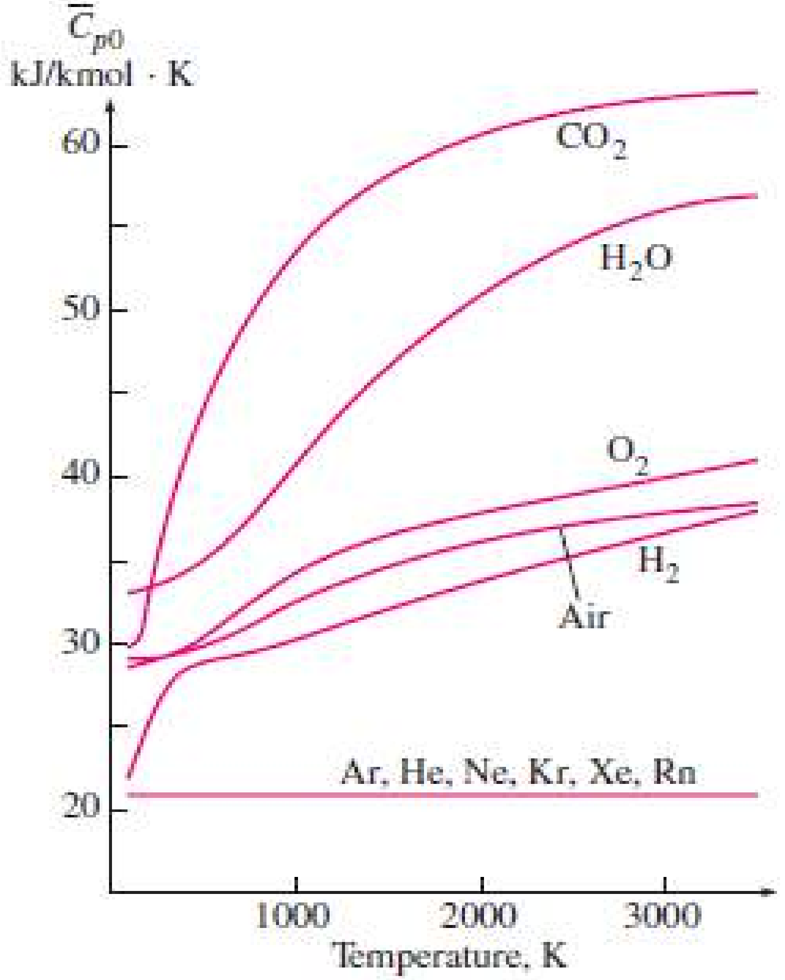
$dh - du = RdT$

$c_p dT - c_v dT = RdT$ → $(c_p - c_v)dT = RdT$

$\int_1^2 dh = c_p \int_1^2 dT$ $\quad h_2 - h_1 = c_p(T_2 - T_1)$

$\int_1^2 du = c_v \int_1^2 dT$

$$\boldsymbol{c_p - c_v = R}$$



- The ratio of specific heats

$$\boldsymbol{\frac{c_p}{c_v} = \gamma}$$

Saturated water properties

TABLE A-5

Saturated water—Pressure table

H_2O

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/(kg·K): Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.6113	0.01	0.001000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
1.0	6.98	0.001000	129.21	29.30	2355.7	2385.0	29.30	2484.9	2514.2	0.1059	8.8697	8.9756
1.5	13.03	0.001001	87.98	54.71	2338.6	2393.3	54.71	2470.6	2525.3	0.1957	8.6322	8.8279
2.0	17.50	0.001001	67.00	73.48	2326.0	2399.5	73.48	2460.0	2533.5	0.2607	8.4629	8.7237
2.5	21.08	0.001002	54.25	88.48	2315.9	2404.4	88.49	2451.6	2540.0	0.3120	8.3311	8.6432
3.0	24.08	0.001003	45.67	101.04	2307.5	2408.5	101.05	2444.5	2545.5	0.3545	8.2231	8.5776
4.0	28.96	0.001004	34.80	121.45	2293.7	2415.2	121.46	2432.9	2554.4	0.4226	8.0520	8.4746
5.0	32.88	0.001005	28.19	137.81	2282.7	2420.5	137.82	2423.7	2561.5	0.4764	7.9187	8.3951
7.5	40.29	0.001008	19.24	168.78	2261.7	2430.5	168.79	2406.0	2574.8	0.5764	7.6750	8.2515
10	45.81	0.001010	14.67	191.82	2246.1	2437.9	191.83	2392.8	2584.7	0.6493	7.5009	8.1502
15	53.97	0.001014	10.02	225.92	2222.8	2448.7	225.94	2373.1	2599.1	0.7549	7.2536	8.0085
20	60.06	0.001017	7.649	251.38	2205.4	2456.7	251.40	2358.3	2609.7	0.8320	7.0766	7.9085
25	64.97	0.001020	6.204	271.90	2191.2	2463.1	271.93	2346.3	2618.2	0.8931	6.9383	7.8314
30	69.10	0.001022	5.229	289.20	2179.2	2468.4	289.23	2336.1	2625.3	0.9439	6.8247	7.7686
40	75.87	0.001027	3.993	317.53	2159.5	2477.0	317.58	2319.2	2636.8	1.0259	6.6441	7.6700
50	81.33	0.001030	3.240	340.44	2143.4	2483.9	340.49	2305.4	2645.9	1.0910	6.5029	7.5939
75	91.78	0.001037	2.217	384.31	2112.4	2496.7	384.39	2278.6	2663.0	1.2130	6.2434	7.4564
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271
0.225	124.00	0.001064	0.7933	520.47	2013.1	2533.6	520.72	2191.3	2712.1	1.5706	5.5173	7.0878
0.250	127.44	0.001067	0.7187	535.10	2002.1	2537.2	535.37	2181.5	2716.9	1.6072	5.4455	7.0527
0.275	130.60	0.001070	0.6573	548.59	1991.9	2540.5	548.89	2172.4	2721.3	1.6408	5.3801	7.0209
0.300	133.55	0.001073	0.6058	561.15	1982.4	2543.6	561.47	2163.8	2725.3	1.6718	5.3201	6.9919
0.325	136.30	0.001076	0.5620	572.90	1973.5	2546.4	573.25	2155.8	2729.0	1.7006	5.2646	6.9652
0.350	138.88	0.001079	0.5243	583.95	1965.0	2548.9	584.33	2148.1	2732.4	1.7275	5.2130	6.9405
0.375	141.32	0.001081	0.4914	594.40	1956.9	2551.3	594.81	2140.8	2735.6	1.7528	5.1647	6.9175
0.40	143.63	0.001084	0.4625	604.31	1949.3	2553.6	604.74	2133.8	2738.6	1.7766	5.1193	6.8959
0.45	147.93	0.001088	0.4140	622.77	1934.9	2557.6	623.25	2120.7	2743.9	1.8207	5.0359	6.8565
0.50	151.86	0.001093	0.3749	639.68	1921.6	2561.2	640.23	2108.5	2748.7	1.8607	4.9606	6.8213
0.55	155.48	0.001097	0.3427	655.32	1909.2	2564.5	665.93	2097.0	2753.0	1.8973	4.8920	6.7893
0.60	158.85	0.001101	0.3157	669.90	1897.5	2567.4	670.56	2086.3	2756.8	1.9312	4.8288	6.7600
0.65	162.01	0.001104	0.2927	683.56	1886.5	2570.1	684.28	2076.0	2760.3	1.9627	4.7703	6.7331
0.70	164.97	0.001108	0.2729	696.44	1876.1	2572.5	697.22	2066.3	2763.5	1.9922	4.7158	6.7080
0.75	167.78	0.001112	0.2556	708.64	1866.1	2574.7	709.47	2057.0	2766.4	2.0200	4.6647	6.6847
0.80	170.43	0.001115	0.2404	720.22	1856.6	2576.8	721.11	2048.0	2769.1	2.0462	4.6166	6.6628
0.85	172.96	0.001118	0.2270	731.27	1847.4	2578.7	732.22	2039.4	2771.6	2.0710	4.5711	6.6421
0.90	175.38	0.001121	0.2150	741.83	1838.6	2580.5	742.83	2031.1	2773.9	2.0946	4.5280	6.6226
0.95	177.69	0.001124	0.2402	751.95	1830.2	2582.1	753.02	2023.1	2776.1	2.1172	4.4869	6.6041
1.00	179.91	0.001127	0.19444	761.68	1822.0	2583.6	762.81	2015.3	2778.1	2.1387	4.4478	6.5865
1.10	184.09	0.001133	0.17753	780.09	1806.3	2586.4	781.34	2000.4	2871.7	2.1792	4.3744	6.5536
1.20	187.99	0.001139	0.16333	797.29	1791.5	2588.8	798.65	1986.2	2784.8	2.2166	4.3067	6.5233
1.30	191.64	0.001144	0.15125	813.44	1777.5	2591.0	814.93	1972.7	2787.6	2.2515	4.2438	6.4953

906

TABLE A-5

Saturated water—Pressure table

H_2O

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/(kg·K): Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271

Saturated water properties

TABLE A-5

Saturated water—Pressure table

H_2O

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg · K)		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271

Superheated water properties

TABLE A-6

Superheated water

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)	v m³/kg	u kJ/kg	h kJ/kg	s kJ/(kg·K)
	P = 0.01 MPa (45.81°C)*				**P = 0.05 MPa (81.33°C)**				**P = 0.10 MPa (99.63°C)**			
Sat.†	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939	1.6940	2506.1	2675.5	7.3594
50	14.869	2443.9	2592.6	8.1749								
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947	1.6958	2506.7	2676.2	7.3614
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401	1.9364	2582.8	2776.4	7.6134
200	21.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580	2.172	2658.1	2875.3	7.8343
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556	2.406	2733.7	2974.3	8.0333
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373	2.639	2810.4	3074.3	8.2158
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642	3.103	2967.9	3278.2	8.5435
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546	3.565	3131.6	3488.1	8.8342
600	40.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178	4.028	3301.9	3704.4	9.0976
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599	4.490	3479.2	3928.2	9.3398
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852	4.952	3663.5	4158.6	9.5652
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967	5.414	3854.8	4396.1	9.7767
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964	5.875	4052.8	4640.3	9.9764
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859	6.337	4257.3	4891.0	10.1659
1200	67.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662	6.799	4467.7	5147.6	10.3463
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382	7.260	4683.5	5409.5	10.5183
	P = 0.20 MPa (120.23°C)				**P = 0.30 MPa (133.55°C)**				**P = 0.40 MPa (143.63°C)**			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780
	P = 0.50 MPa (151.86°C)				**P = 0.60 MPa (158.85°C)**				**P = 0.80 MPa (170.43°C)**			
Sat.	0.3749	2561.2	2748.7	6.8213	0.3157	2567.4	2756.8	6.7600	0.2404	2576.8	2769.1	6.6628
200	0.4249	2642.9	2855.4	7.0592	0.3520	2638.9	2850.1	6.9665	0.2608	2630.6	2839.3	6.8158
250	0.4744	2723.5	2960.7	7.2709	0.3938	2720.9	2957.2	7.1816	0.2931	2715.5	2950.0	7.0384
300	0.5226	2802.9	3064.2	7.4599	0.4344	2801.0	3061.6	7.3724	0.3241	2797.2	3056.5	7.2328
350	0.5701	2882.6	3167.7	7.6329	0.4742	2881.2	3165.7	7.5464	0.3544	2878.2	3161.7	7.4089
400	0.6173	2963.2	3271.9	7.7938	0.5137	2962.1	3270.3	7.7079	0.3843	2959.7	3267.1	7.5716
500	0.7109	3128.4	3483.9	8.0873	0.5920	3127.6	3482.8	8.0021	0.4433	3126.0	3480.6	7.8673
600	0.8041	3299.6	3701.7	7.3522	0.6697	3299.1	3700.9	8.2674	0.5018	3297.9	3699.4	8.1333
700	0.8969	3477.5	3925.9	8.5952	0.7472	3477.0	3925.3	8.5107	0.5601	3476.2	3924.2	8.3770
800	0.9896	3662.1	4156.9	8.8211	0.8245	3661.8	4156.5	8.7367	0.6181	3661.1	4155.6	8.6033
900	1.0822	3853.6	4394.7	9.0329	0.9017	3853.4	4394.4	8.9486	0.6761	3852.8	4393.7	8.8153
1000	1.1747	4051.8	4639.1	9.2328	0.9788	4051.5	4638.8	9.1485	0.7340	4051.0	4638.2	9.0153
1100	1.2672	4256.3	4889.9	9.4224	1.0559	4256.1	4889.6	9.3381	0.7919	4255.6	4889.1	9.2050
1200	1.3596	4466.8	5146.6	9.6029	1.1330	4466.5	5146.3	9.5185	0.8497	4466.1	5145.9	9.3855
1300	1.4521	4682.5	5408.6	9.7749	1.2101	4682.3	5408.3	9.6906	0.9076	4681.8	5407.9	9.5575

*The temperature in parentheses is the saturation temperature at the specified pressure.

†Properties of saturated vapor at the specified pressure.

908

TABLE A-6

Superheated water

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)	v m³/kg	u kJ/kg	h kJ/kg	s kJ/(kg·K)
	P = 0.20 MPa (120.23°C)				**P = 0.30 MPa (133.55°C)**				**P = 0.40 MPa (143.63°C)**			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780

TABLE A-6

Superheated water

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)	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/(kg·K)
	P = **0.20 MPa (120.23°C)**				*P* = **0.30 MPa (133.55°C)**				*P* = **0.40 MPa (143.63°C)**			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780

Engineering Thermodynamics
Lecture 12

Numerical Problem

I Law of TD for open systems

Steps in problem solving

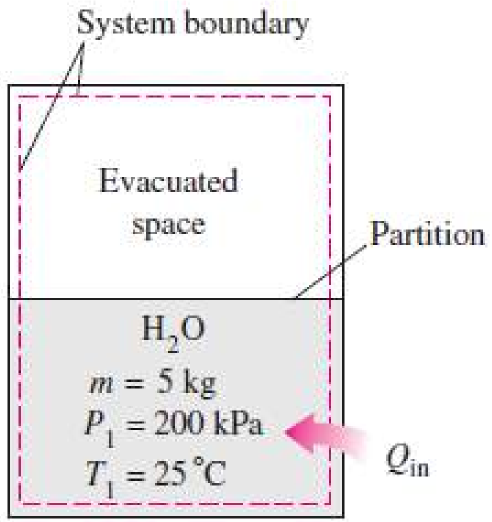
Identify	the system & draw a sketch of it
List	the given information on the sketch
Check	for special processes
State	assumptions (if any)
Apply	the conservation equations
Draw	the process diagrams
Determine	the required properties & unknowns

Numerical example

- A rigid tank is divided into two equal parts by a partition. Initially, one side of the tank contains 5 kg of water at 200 kPa & 25 °C, and the other side is evacuated. The partition is then removed and water expands to the entire tank. The water is allowed to exchange heat with the surroundings until the temperature in the tank returns to the initial value. Determine the (a) volume of the tank (b) final pressure and (c) heat transferred during the process.

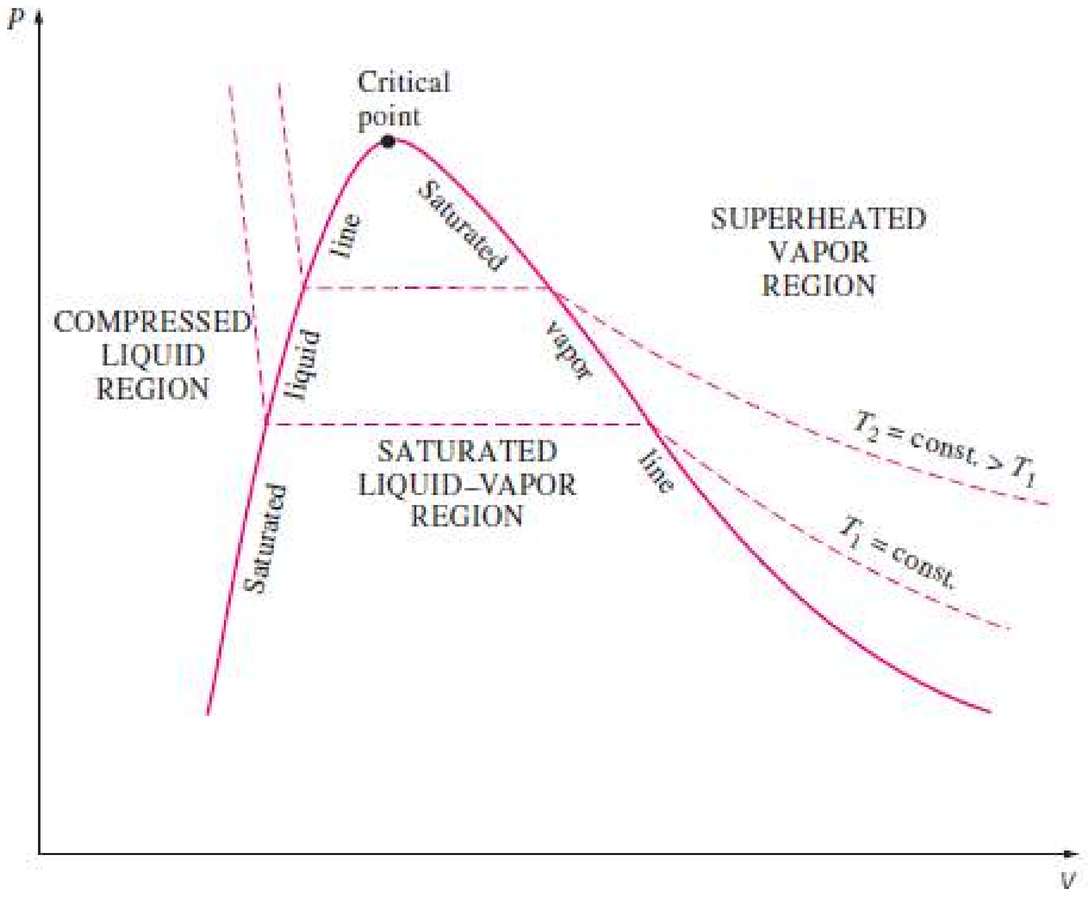
The system

- Water in a tank with partition
- Partition removed and system allowed to equilibrate with surroundings, and ***temperature returns to initial value***
- Assumptions
  - The system is stationary
  - Heat is transferred into the system
  - There is no change in the volume of the tank
  - There are no shaft work, electrical or any other kind of work interaction.
- State of the system – compressed liquid; approximating it to be a saturated liquid (with respect to specific volume alone)



$v_1 = v_f\ at\ 25°C = 0.001003\ m^3/kg$ $\qquad V_1 = mv_1 = 0.005\ m^3$

Therefore, volume of the tank ⟶ $V_{tank} = 0.01\ m^3 = V_2$


p
Critical point
Saturated liquid line
Saturated vapor line
SUPERHEATED VAPOR REGION
COMPRESSED LIQUID REGION
SATURATED LIQUID–VAPOR REGION
T2 = const. > T1
T1 = const.
v

The system

$$v_2 = \frac{V_{tank}}{m} = 0.002\ m^3/\text{kg}$$

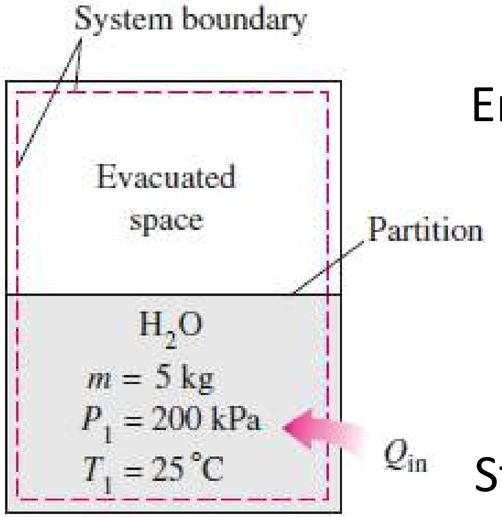
At 25°C

v_f =0.001003 m³/kg and v_g =43.36 m³/kg

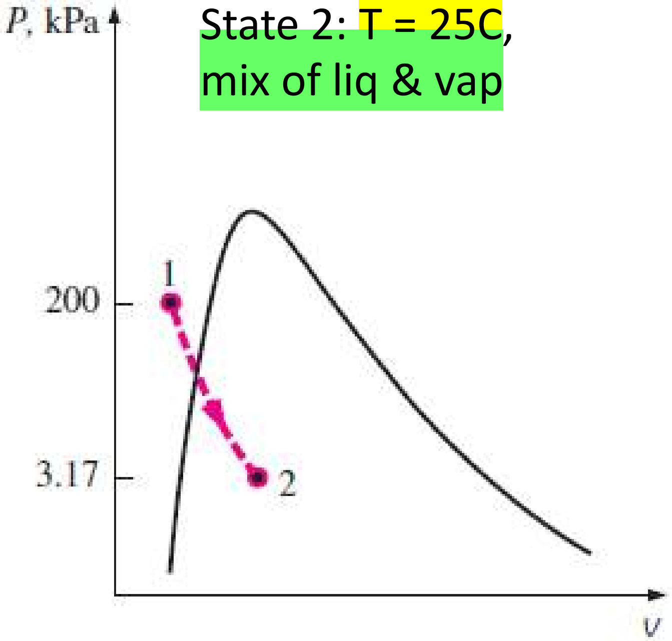
$$v_f < v_2 < v_g$$

The state of the system is saturated mixture

$$p_2 = p_{sat} @ 25°\text{C} = 3.169\ kPa$$



State 2: T = 25C, mix of liq & vap



Energy conservation → $E_{in} - E_{out} = \Delta E$

$Q_{in} = \Delta U = m\Delta u$

$Q_{in} = m(u_2 - u_1)$

$$u_1 = 104.88 \frac{kJ}{kg}\ at\ 25\ \ \text{C}$$

Steam quality (dryness fraction)

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.002 - 0.001}{43.34 - 0.001} = 2.3 \times 10^{-5}$$

$v_{fg} = v_g - v_f$

Int. energy @ 2

$$u_2 = u_f + x_2 u_{fg}$$

Heat transferred into the system ?

Saturated water properties (temperature table)

H₂O

TABLE A-4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m³/kg: Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/(kg · K): Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6113	0.001000	206.14	0.0	2375.3	2375.3	0.01	2501.3	2501.4	0.000	9.1562	9.1562
5	0.8721	0.001000	147.12	20.97	2361.3	2382.3	20.98	2489.6	2510.6	0.0761	8.9496	9.0257
10	1.2276	0.001000	106.38	42.00	2347.2	2389.2	42.01	2477.7	2519.8	0.1510	8.7498	8.9008
15	1.7051	0.001001	77.93	62.99	2333.1	2396.1	62.99	2465.9	2528.9	0.2245	8.5569	8.7814
20	2.339	0.001002	57.79	83.95	2319.0	2402.9	83.96	2454.1	2538.1	0.2966	8.3706	8.6672
25	3.169	0.001003	43.36	104.88	2304.9	2409.8	104.89	2442.3	2547.2	0.3674	8.1905	8.5580
30	4.246	0.001004	32.89	125.78	2290.8	2416.6	125.79	2430.5	2556.3	0.4369	8.0164	8.4533
35	5.628	0.001006	25.22	146.67	2276.7	2423.4	146.68	2418.6	2565.3	0.5053	7.8478	8.3531
40	7.384	0.001008	19.52	167.56	2262.6	2430.1	167.57	2406.7	2574.3	0.5725	7.6845	8.2570
45	9.593	0.001010	15.26	188.44	2248.4	2436.8	188.45	2394.8	2583.2	0.6387	7.5261	8.1648
50	12.349	0.001012	12.03	209.32	2234.2	2443.5	209.33	2382.7	2592.1	0.7038	7.3725	8.0763
55	15.758	0.001015	9.568	230.21	2219.9	2450.1	230.23	2370.7	2600.9	0.7679	7.2234	7.9913
60	19.940	0.001017	7.671	251.11	2205.5	2456.6	251.13	2358.5	2609.6	0.8312	7.0784	7.9096
65	25.03	0.001020	6.197	272.02	2191.1	2463.1	272.06	2346.2	2618.3	0.8935	6.9375	7.8310
70	31.19	0.001023	5.042	292.95	2176.6	2469.6	292.98	2333.8	2626.8	0.9549	6.8004	7.7553
75	38.58	0.001026	4.131	313.90	2162.0	2475.9	313.93	2321.4	2635.3	1.0155	6.6669	7.6824
80	47.39	0.001029	3.407	334.86	2147.4	2482.2	334.91	2308.8	2643.7	1.0753	6.5369	7.6122
85	57.83	0.001033	2.828	355.84	2132.6	2488.4	355.90	2296.0	2651.9	1.1343	6.4102	7.5445
90	70.14	0.001036	2.361	376.85	2117.7	2494.5	376.92	2283.2	2660.1	1.1925	6.2866	7.4791
95	84.55	0.001040	1.982	397.88	2102.7	2500.6	397.96	2270.2	2668.1	1.2500	6.1659	7.4159
	Sat. press., MPa											
100	0.10135	0.001044	1.6729	418.94	2087.6	2506.5	419.04	2257.0	2676.1	1.3069	6.0480	7.3549
105	0.12082	0.001048	1.4194	440.02	2072.3	2512.4	440.15	2243.7	2683.8	1.3630	5.9328	7.2958
110	0.14327	0.001052	1.2102	461.14	2057.0	2518.1	461.30	2230.2	2691.5	1.4185	5.8202	7.2387
115	0.16906	0.001056	1.0366	482.30	2041.4	2523.7	482.48	2216.5	2699.0	1.4734	5.7100	7.1833
120	0.19853	0.001060	0.8919	503.50	2025.8	2529.3	503.71	2202.6	2706.3	1.5276	5.6020	7.1296
125	0.2321	0.001065	0.7706	524.74	2009.9	2534.6	524.99	2188.5	2713.5	1.5813	5.4962	7.0775
130	0.2701	0.001070	0.6685	546.02	1993.9	2539.9	546.31	2174.2	2720.5	1.6344	5.3925	7.0269
135	0.3130	0.001075	0.5822	567.35	1977.7	2545.0	567.69	2159.6	2727.3	1.6870	5.2907	6.9777
140	0.3613	0.001080	0.5089	588.74	1961.3	2550.0	589.13	2144.7	2733.9	1.7391	5.1908	6.9299
145	0.4154	0.001085	0.4463	610.18	1944.7	2554.9	610.63	2129.6	2740.3	1.7907	5.0926	6.8833
150	0.4758	0.001091	0.3928	631.68	1927.9	2559.5	632.20	2114.3	2746.5	1.8418	4.9960	6.8379
155	0.5431	0.001096	0.3468	653.24	1910.8	2564.1	653.84	2098.6	2752.4	1.8925	4.9010	6.7935
160	0.6178	0.001102	0.3071	674.87	1893.5	2568.4	675.55	2082.6	2758.1	1.9427	4.8075	6.7502
165	0.7005	0.001108	0.2727	696.56	1876.0	2572.5	697.34	2066.2	2763.5	1.9925	4.7153	6.7078
170	0.7917	0.001114	0.2428	718.33	1858.1	2576.5	719.21	2049.5	2768.7	2.0419	4.6244	6.6663
175	0.8920	0.001121	0.2168	740.17	1840.0	2580.2	741.17	2032.4	2773.6	2.0909	4.5347	6.6256
180	1.0021	0.001127	0.19405	762.09	1821.6	2583.7	763.22	2015.0	2778.2	2.1396	4.4461	6.5857
185	1.1227	0.001134	0.17409	784.10	1802.9	2587.0	785.37	1997.1	2782.4	2.1879	4.3586	6.5465
190	1.2544	0.001141	0.15654	806.19	1783.8	2590.0	807.62	1978.8	2786.4	2.2359	4.2720	6.5079
195	1.3978	0.001149	0.14105	828.37	1764.4	2592.8	829.98	1960.0	2790.0	2.2835	4.1863	6.4698

904

TABLE A-4

Saturated water—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
0.01	0.6113	0.001000	206.14	0.0	2375.3	2375.3	0.01	2501.3	2501.4	0.000	9.1562	9.1562
5	0.8721	0.001000	147.12	20.97	2361.3	2382.3	20.98	2489.6	2510.6	0.0761	8.9496	9.0257
10	1.2276	0.001000	106.38	42.00	2347.2	2389.2	42.01	2477.7	2519.8	0.1510	8.7498	8.9008
15	1.7051	0.001001	77.93	62.99	2333.1	2396.1	62.99	2465.9	2528.9	0.2245	8.5569	8.7814
20	2.339	0.001002	57.79	83.95	2319.0	2402.9	83.96	2454.1	2538.1	0.2966	8.3706	8.6672
25	3.169	0.001003	43.36	104.88	2304.9	2409.8	104.89	2442.3	2547.2	0.3674	8.1905	8.5580
30	4.246	0.001004	32.89	125.78	2290.8	2416.6	125.79	2430.5	2556.3	0.4369	8.0164	8.4533
35	5.628	0.001006	25.22	146.67	2276.7	2423.4	146.68	2418.6	2565.3	0.5053	7.8478	8.3531

Saturated water properties (pressure table)

H_2O

TABLE A-5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/(kg · K): Sat. liquid, s_f	Entropy, kJ/(kg · K): Evap., s_{fg}	Entropy, kJ/(kg · K): Sat. vapor, s_g
0.6113	0.01	0.001000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
1.0	6.98	0.001000	129.21	29.30	2355.7	2385.0	29.30	2484.9	2514.2	0.1059	8.8697	8.9756
1.5	13.03	0.001001	87.98	54.71	2338.6	2393.3	54.71	2470.6	2525.3	0.1957	8.6322	8.8279
2.0	17.50	0.001001	67.00	73.48	2326.0	2399.5	73.48	2460.0	2533.5	0.2607	8.4629	8.7237
2.5	21.08	0.001002	54.25	88.48	2315.9	2404.4	88.49	2451.6	2540.0	0.3120	8.3311	8.6432
3.0	24.08	0.001003	45.67	101.04	2307.5	2408.5	101.05	2444.5	2545.5	0.3545	8.2231	8.5776
4.0	28.96	0.001004	34.80	121.45	2293.7	2415.2	121.46	2432.9	2554.4	0.4226	8.0520	8.4746
5.0	32.88	0.001005	28.19	137.81	2282.7	2420.5	137.82	2423.7	2561.5	0.4764	7.9187	8.3951
7.5	40.29	0.001008	19.24	168.78	2261.7	2430.5	168.79	2406.0	2574.8	0.5764	7.6750	8.2515
10	45.81	0.001010	14.67	191.82	2246.1	2437.9	191.83	2392.8	2584.7	0.6493	7.5009	8.1502
15	53.97	0.001014	10.02	225.92	2222.8	2448.7	225.94	2373.1	2599.1	0.7549	7.2536	8.0085
20	60.06	0.001017	7.649	251.38	2205.4	2456.7	251.40	2358.3	2609.7	0.8320	7.0766	7.9085
25	64.97	0.001020	6.204	271.90	2191.2	2463.1	271.93	2346.3	2618.2	0.8931	6.9383	7.8314
30	69.10	0.001022	5.229	289.20	2179.2	2468.4	289.23	2336.1	2625.3	0.9439	6.8247	7.7686
40	75.87	0.001027	3.993	317.53	2159.5	2477.0	317.58	2319.2	2636.8	1.0259	6.6441	7.6700
50	81.33	0.001030	3.240	340.44	2143.4	2483.9	340.49	2305.4	2645.9	1.0910	6.5029	7.5939
75	91.78	0.001037	2.217	384.31	2112.4	2496.7	384.39	2278.6	2663.0	1.2130	6.2434	7.4564
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271
0.225	124.00	0.001064	0.7933	520.47	2013.1	2533.6	520.72	2191.3	2712.1	1.5706	5.5173	7.0878
0.250	127.44	0.001067	0.7187	535.10	2002.1	2537.2	535.37	2181.5	2716.9	1.6072	5.4455	7.0527
0.275	130.60	0.001070	0.6573	548.59	1991.9	2540.5	548.89	2172.4	2721.3	1.6408	5.3801	7.0209
0.300	133.55	0.001073	0.6058	561.15	1982.4	2543.6	561.47	2163.8	2725.3	1.6718	5.3201	6.9919
0.325	136.30	0.001076	0.5620	572.90	1973.5	2546.4	573.25	2155.8	2729.0	1.7006	5.2646	6.9652
0.350	138.88	0.001079	0.5243	583.95	1965.0	2548.9	584.33	2148.1	2732.4	1.7275	5.2130	6.9405
0.375	141.32	0.001081	0.4914	594.40	1956.9	2551.3	594.81	2140.8	2735.6	1.7528	5.1647	6.9175
0.40	143.63	0.001084	0.4625	604.31	1949.3	2553.6	604.74	2133.8	2738.6	1.7766	5.1193	6.8959
0.45	147.93	0.001088	0.4140	622.77	1934.9	2557.6	623.25	2120.7	2743.9	1.8207	5.0359	6.8565
0.50	151.86	0.001093	0.3749	639.68	1921.6	2561.2	640.23	2108.5	2748.7	1.8607	4.9606	6.8213
0.55	155.48	0.001097	0.3427	655.32	1909.2	2564.5	665.93	2097.0	2753.0	1.8973	4.8920	6.7893
0.60	158.85	0.001101	0.3157	669.90	1897.5	2567.4	670.56	2086.3	2756.8	1.9312	4.8288	6.7600
0.65	162.01	0.001104	0.2927	683.56	1886.5	2570.1	684.28	2076.0	2760.3	1.9627	4.7703	6.7331
0.70	164.97	0.001108	0.2729	696.44	1876.1	2572.5	697.22	2066.3	2763.5	1.9922	4.7158	6.7080
0.75	167.78	0.001112	0.2556	708.64	1866.1	2574.7	709.47	2057.0	2766.4	2.0200	4.6647	6.6847
0.80	170.43	0.001115	0.2404	720.22	1856.6	2576.8	721.11	2048.0	2769.1	2.0462	4.6166	6.6628
0.85	172.96	0.001118	0.2270	731.27	1847.4	2578.7	732.22	2039.4	2771.6	2.0710	4.5711	6.6421
0.90	175.38	0.001121	0.2150	741.83	1838.6	2580.5	742.83	2031.1	2773.9	2.0946	4.5280	6.6226
0.95	177.69	0.001124	0.2402	751.95	1830.2	2582.1	753.02	2023.1	2776.1	2.1172	4.4869	6.6041
1.00	179.91	0.001127	0.19444	761.68	1822.0	2583.6	762.81	2015.3	2778.1	2.1387	4.4478	6.5865
1.10	184.09	0.001133	0.17753	780.09	1806.3	2586.4	781.34	2000.4	2871.7	2.1792	4.3744	6.5536
1.20	187.99	0.001139	0.16333	797.29	1791.5	2588.8	798.65	1986.2	2784.8	2.2166	4.3067	6.5233
1.30	191.64	0.001144	0.15125	813.44	1777.5	2591.0	814.93	1972.7	2787.6	2.2515	4.2438	6.4953

906

H_2O

TABLE A-5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Specific volume, m³/kg: Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Internal energy, kJ/kg: Evap., u_{fg}	Internal energy, kJ/kg: Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Enthalpy, kJ/kg: Evap., h_{fg}	Enthalpy, kJ/kg: Sat. vapor, h_g	Entropy, kJ/(kg · K): Sat. liquid, s_f	Entropy, kJ/(kg · K): Evap., s_{fg}	Entropy, kJ/(kg · K): Sat. vapor, s_g
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271

Saturated water properties

H_2O

TABLE A-5

Saturated water—Pressure table

		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg · K)		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
Press., MPa												
0.100	99.63	0.001043	1.6940	417.36	2088.7	2506.1	417.46	2258.0	2675.5	1.3026	6.0568	7.3594
0.125	105.99	0.001048	1.3749	444.19	2069.3	2513.5	444.32	2241.0	2685.4	1.3740	5.9104	7.2844
0.150	111.37	0.001053	1.1593	466.94	2052.7	2519.7	467.11	2226.5	2693.6	1.4336	5.7897	7.2233
0.175	116.06	0.001057	1.0036	486.80	2038.1	2524.9	486.99	2213.6	2700.6	1.4849	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.49	2025.0	2529.5	504.70	2201.9	2706.7	1.5301	5.5970	7.1271

Superheated water properties

H_2O

TABLE A-6

Superheated water

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)	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/(kg · K)
	P = 0.01 MPa (45.81°C)*				*P* = 0.05 MPa (81.33°C)				*P* = 0.10 MPa (99.63°C)			
Sat.†	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939	1.6940	2506.1	2675.5	7.3594
50	14.869	2443.9	2592.6	8.1749								
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947	1.6958	2506.7	2676.2	7.3614
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401	1.9364	2582.8	2776.4	7.6134
200	21.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580	2.172	2658.1	2875.3	7.8343
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556	2.406	2733.7	2974.3	8.0333
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373	2.639	2810.4	3074.3	8.2158
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642	3.103	2967.9	3278.2	8.5435
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546	3.565	3131.6	3488.1	8.8342
600	40.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178	4.028	3301.9	3704.4	9.0976
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599	4.490	3479.2	3928.2	9.3398
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852	4.952	3663.5	4158.6	9.5652
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967	5.414	3854.8	4396.1	9.7767
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964	5.875	4052.8	4640.3	9.9764
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859	6.337	4257.3	4891.0	10.1659
1200	67.967	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662	6.799	4467.7	5147.6	10.3463
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382	7.260	4683.5	5409.5	10.5183
	P = 0.20 MPa (120.23°C)				*P* = 0.30 MPa (133.55°C)				*P* = 0.40 MPa (143.63°C)			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780
	P = 0.50 MPa (151.86°C)				*P* = 0.60 MPa (158.85°C)				*P* = 0.80 MPa (170.43°C)			
Sat.	0.3749	2561.2	2748.7	6.8213	0.3157	2567.4	2756.8	6.7600	0.2404	2576.8	2769.1	6.6628
200	0.4249	2642.9	2855.4	7.0592	0.3520	2638.9	2850.1	6.9665	0.2608	2630.6	2839.3	6.8158
250	0.4744	2723.5	2960.7	7.2709	0.3938	2720.9	2957.2	7.1816	0.2931	2715.5	2950.0	7.0384
300	0.5226	2802.9	3064.2	7.4599	0.4344	2801.0	3061.6	7.3724	0.3241	2797.2	3056.5	7.2328
350	0.5701	2882.6	3167.7	7.6329	0.4742	2881.2	3165.7	7.5464	0.3544	2878.2	3161.7	7.4089
400	0.6173	2963.2	3271.9	7.7938	0.5137	2962.1	3270.3	7.7079	0.3843	2959.7	3267.1	7.5716
500	0.7109	3128.4	3483.9	8.0873	0.5920	3127.6	3482.8	8.0021	0.4433	3126.0	3480.6	7.8673
600	0.8041	3299.6	3701.7	7.3522	0.6697	3299.1	3700.9	8.2674	0.5018	3297.9	3699.4	8.1333
700	0.8969	3477.5	3925.9	8.5952	0.7472	3477.0	3925.3	8.5107	0.5601	3476.2	3924.2	8.3770
800	0.9896	3662.1	4156.9	8.8211	0.8245	3661.8	4156.5	8.7367	0.6181	3661.1	4155.6	8.6033
900	1.0822	3853.6	4394.7	9.0329	0.9017	3853.4	4394.4	8.9486	0.6761	3852.8	4393.7	8.8153
1000	1.1747	4051.8	4639.1	9.2328	0.9788	4051.5	4638.8	9.1485	0.7340	4051.0	4638.2	9.0153
1100	1.2672	4256.3	4889.9	9.4224	1.0559	4256.1	4889.6	9.3381	0.7919	4255.6	4889.1	9.2050
1200	1.3596	4466.8	5146.6	9.6029	1.1330	4466.5	5146.3	9.5185	0.8497	4466.1	5145.9	9.3855
1300	1.4521	4682.5	5408.6	9.7749	1.2101	4682.3	5408.3	9.6906	0.9076	4681.8	5407.9	9.5575

*The temperature in parentheses is the saturation temperature at the specified pressure.

†Properties of saturated vapor at the specified pressure.

908

TABLE A-6

Superheated water

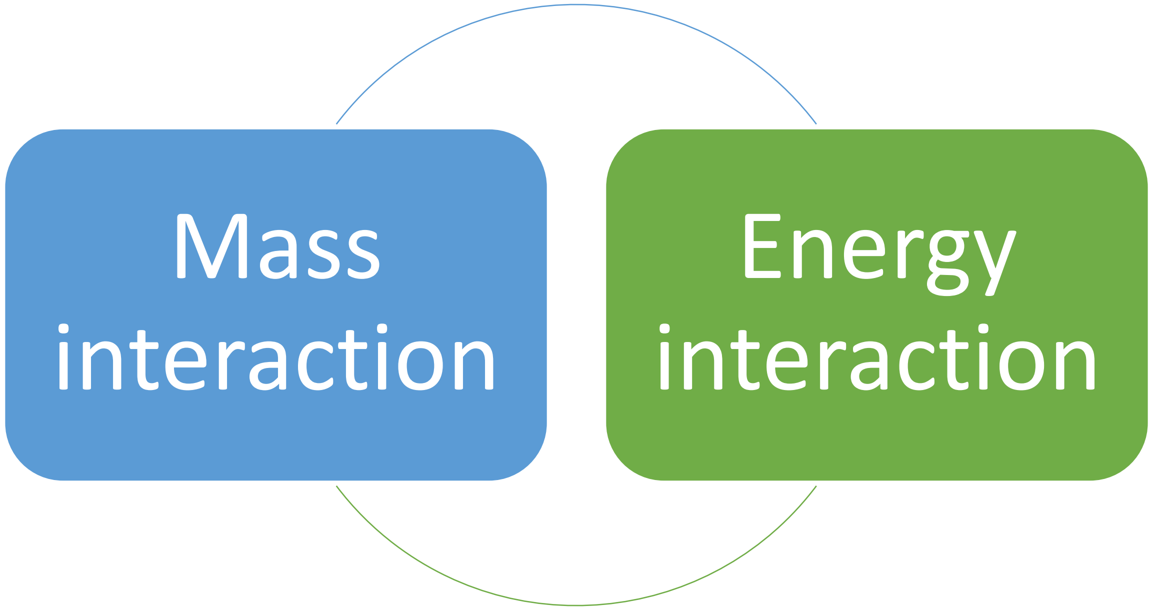
T °C	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/(kg · K)	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/(kg · K)	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/(kg · K)
	P = 0.20 MPa (120.23°C)				*P* = 0.30 MPa (133.55°C)				*P* = 0.40 MPa (143.63°C)			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780

TABLE A-6

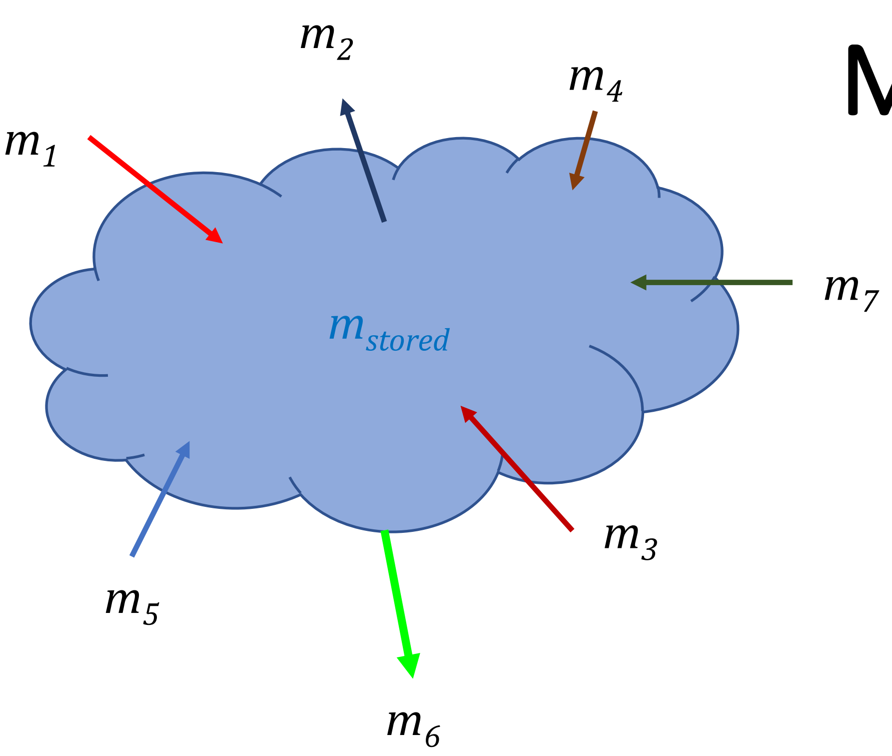
Superheated water

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)	v m³/kg	u kJ/kg	h kJ/kg	s kJ/(kg·K)
	P = 0.20 MPa (120.23°C)				P = 0.30 MPa (133.55°C)				P = 0.40 MPa (143.63°C)			
Sat.	0.8857	2529.5	2706.7	7.1272	0.6058	2543.6	2725.3	6.9919	0.4625	2553.6	2738.6	6.8959
150	0.9596	2576.9	2768.8	7.2795	0.6339	2570.8	2761.0	7.0778	0.4708	2564.5	2752.8	6.9299
200	1.0803	2654.4	2870.5	7.5066	0.7163	2650.7	2865.6	7.3115	0.5342	2646.8	2860.5	7.1706
250	1.1988	2731.2	2971.0	7.7086	0.7964	2728.7	2967.6	7.5166	0.5951	2726.1	2964.2	7.3789
300	1.3162	2808.6	3071.8	7.8926	0.8753	2806.7	3069.3	7.7022	0.6548	2804.8	3066.8	7.5662
400	1.5493	2966.7	3276.6	8.2218	1.0315	2965.6	3275.0	8.0330	0.7726	2964.4	3273.4	7.8985
500	1.7814	3130.8	3487.1	8.5133	1.1867	3130.0	3486.0	8.3251	0.8893	3129.2	3484.9	8.1913
600	2.013	3301.4	3704.0	8.7770	1.3414	3300.8	3703.2	8.5892	1.0055	3300.2	3702.4	8.4558
700	2.244	3478.8	3927.6	9.0194	1.4957	3478.4	3927.1	8.8319	1.1215	3477.9	3926.5	8.6987
800	2.475	3663.1	4158.2	9.2449	1.6499	3662.9	4157.8	9.0576	1.2372	3662.4	4157.3	8.9244
900	2.705	3854.5	4395.8	9.4566	1.8041	3854.2	4395.4	9.2692	1.3529	3853.9	4395.1	9.1362
1000	2.937	4052.5	4640.0	9.6563	1.9581	4052.3	4639.7	9.4690	1.4685	4052.0	4639.4	9.3360
1100	3.168	4257.0	4890.7	9.8458	2.1121	4256.8	4890.4	9.6585	1.5840	4256.5	4890.2	9.5256
1200	3.399	4467.5	5147.5	10.0262	2.2661	4467.2	5147.1	9.8389	1.6996	4467.0	5146.8	9.7060
1300	3.630	4683.2	5409.3	10.1982	2.4201	4683.0	5409.0	10.0110	1.8151	4682.8	5408.8	9.8780

Open systems



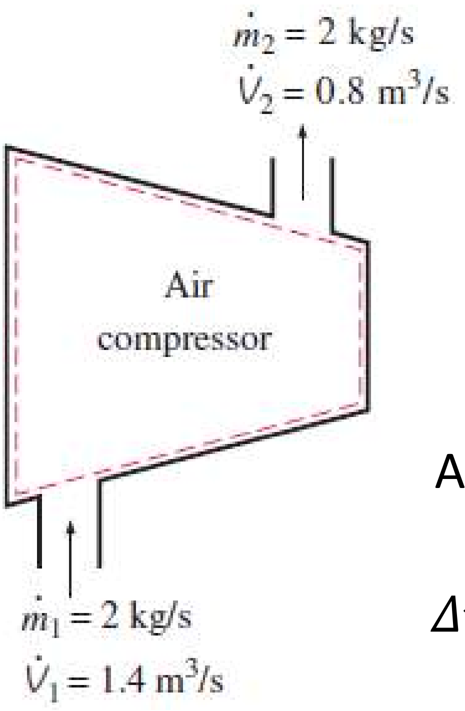
Mass interaction



$$m_{in} = m_1 + m_3 + m_4 + m_5 + m_7$$

$$m_{out} = m_2 + m_6$$

$$m_{in} - m_{out} = \Delta m_{stored}$$



In rate terms (per unit time)

$$\dot{m}_{in} = \dot{m}_1 + \dot{m}_3 + \dot{m}_4 + \dot{m}_5 + \dot{m}_7$$

$$\dot{m}_{out} = \dot{m}_2 + \dot{m}_6$$

$$\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{m}_{stored}$$

At steady state (no dependence on time)

$$\Delta \dot{m}_{stored} = 0 \quad \Rightarrow \quad \dot{m}_{in} = \dot{m}_{out}$$

Mass flow rate

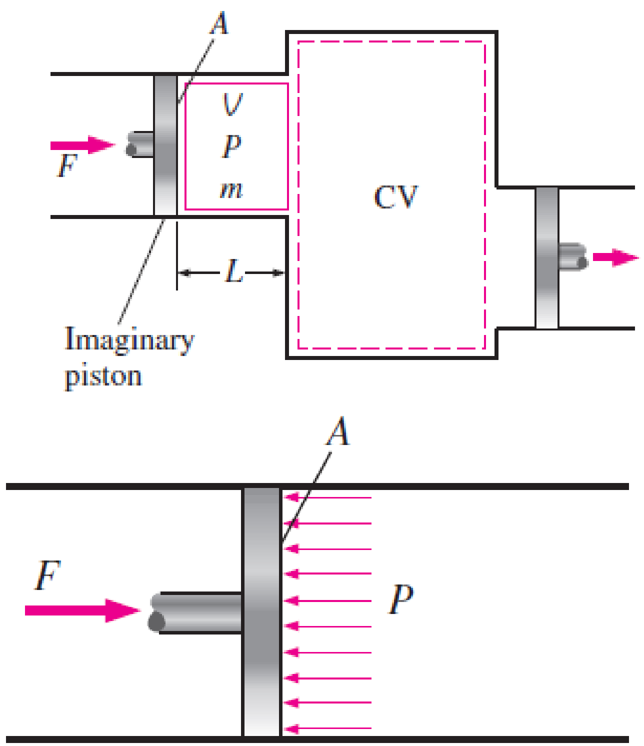
$$\dot{m} = \rho A c = \rho \dot{V}$$

Volume flow rate

$$\dot{V} = Ac$$

Energy Interaction – energy of a flowing fluid

- Energy of a flowing fluid



Force applied (N)

$$F = pA$$

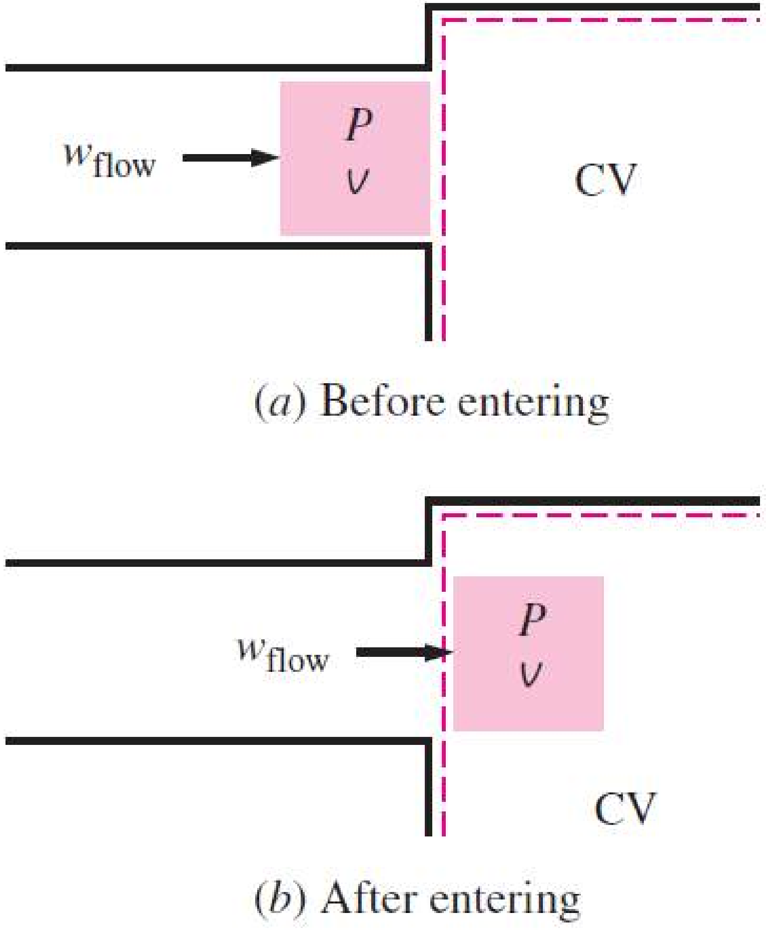
Flow work (J)

$$W_{flow} = FL$$

$$W_{flow} = pAL = pV$$

Specific flow work (J/kg)

$$w_{flow} = pv$$



Energy Interaction (contd.)

- Total energy of a flowing fluid per unit mass

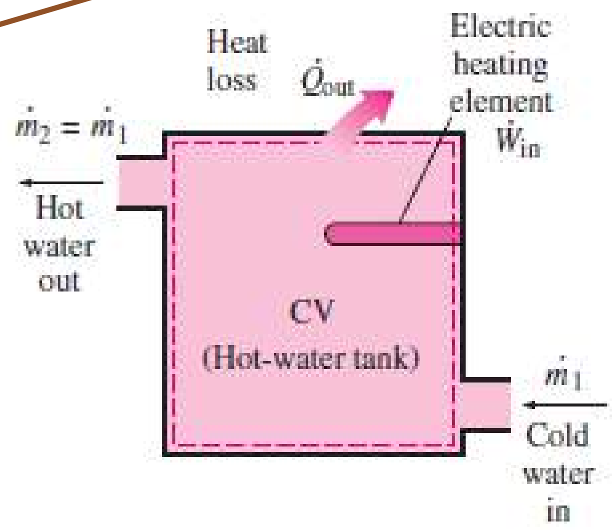
$$e = pe + ke + u$$

$$\theta = w_{flow} + e$$

$$\theta = pv + u + pe + ke$$

$$\theta = h + pe + ke$$

$$\theta = h + gz + \frac{1}{2}c^2$$



- Energy transport by mass

Amount of energy transport (J)

$$E = m\theta = m\left(h + gz + \frac{1}{2}c^2\right)$$

Rate of energy transport (W)

$$\dot{E} = \dot{m}\theta = \dot{m}\left(h + gz + \frac{1}{2}c^2\right)$$

- Steady flow analysis

$$\dot{m}_{in} = \dot{m}_{out} \qquad \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{in} = \dot{Q}_{out} + \dot{W}_{out} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{out}$$

The steady flow energy equation

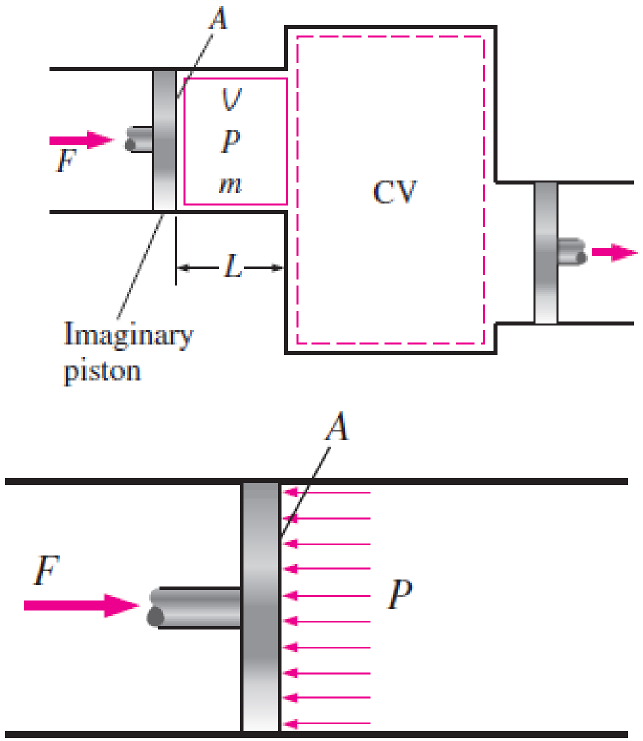
Engineering Thermodynamics
Lecture 13

I Law of TD for open systems (review)

Numerical Problems

Energy Interaction – energy of a flowing fluid

- Energy of a flowing fluid



Force applied (N)

$$F = pA$$

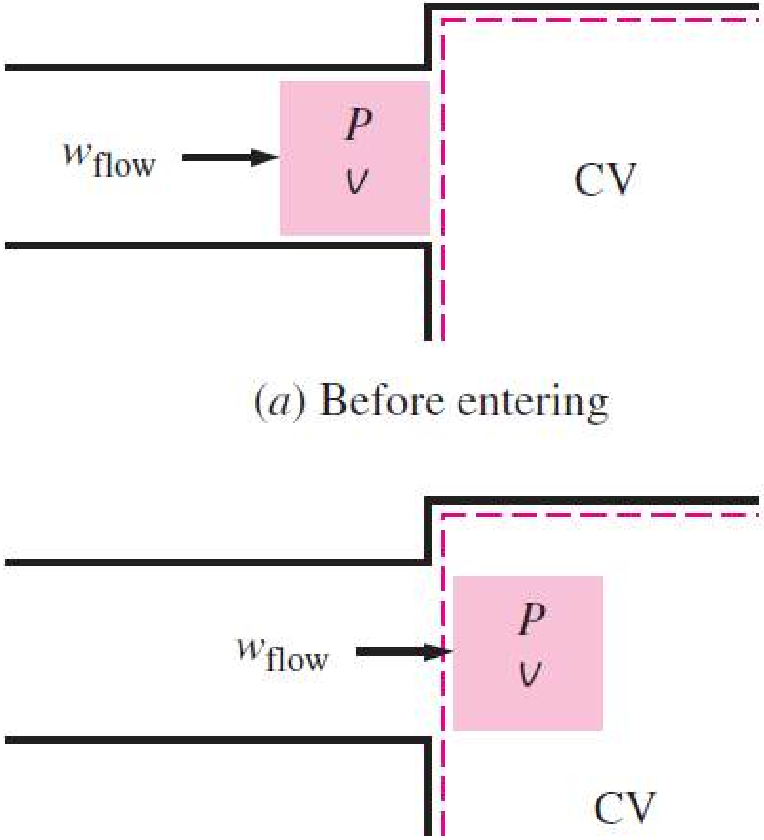
Flow work (J)

$$W_{flow} = FL$$

$$W_{flow} = pAL = pV$$

Specific flow work (J/kg)

$$w_{flow} = pv$$



(a) Before entering

(b) After entering

Energy Interaction (contd.)

- Total energy of a flowing fluid per unit mass

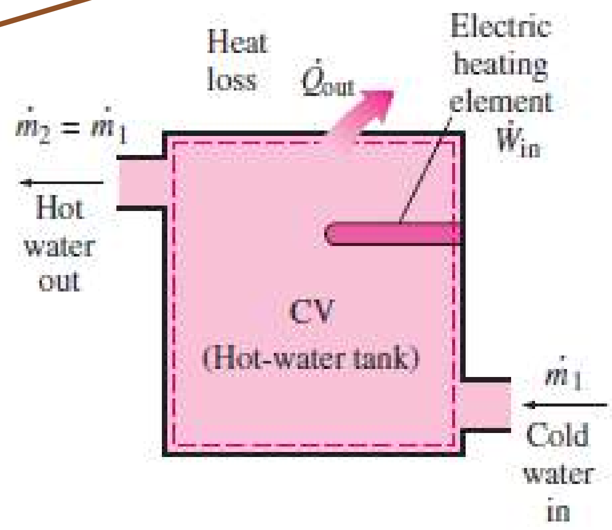
$$e = pe + ke + u$$

$$\theta = w_{flow} + e$$

$$\theta = pv + u + pe + ke$$

$$\theta = h + pe + ke$$

$$\theta = h + gz + \frac{1}{2}c^2$$



- Energy transport by mass

Amount of energy transport (J)

$$E = m\theta = m\left(h + gz + \frac{1}{2}c^2\right)$$

Rate of energy transport (W)

$$\dot{E} = \dot{m}\theta = \dot{m}\left(h + gz + \frac{1}{2}c^2\right)$$

- Steady flow analysis

$$\dot{m}_{in} = \dot{m}_{out} \qquad \dot{E}_{in} = \dot{E}_{out}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{in} = \dot{Q}_{out} + \dot{W}_{out} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{out}$$

The steady flow energy equation

Special forms of the SFEE

$$\dot{Q}_{in} + \dot{W}_{in} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{in} = \dot{Q}_{out} + \dot{W}_{out} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{out}$$

- No work & heat interaction

$$\left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{in} = \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{out}$$

- No changes in ke & pe

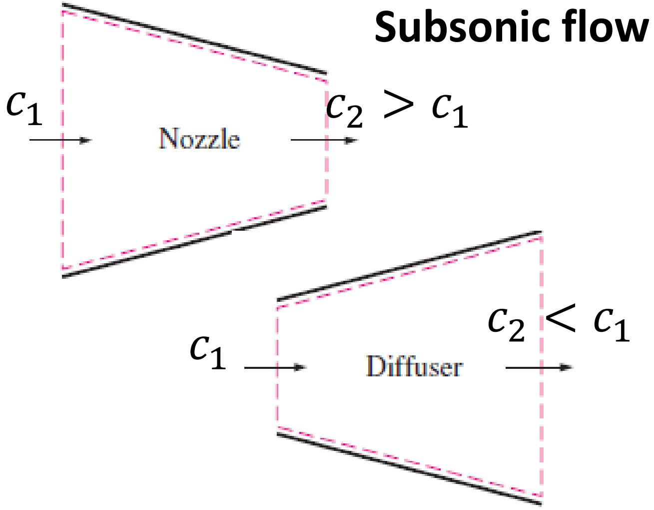
$$\dot{Q}_{in} + \dot{W}_{in} + (\dot{m}h)_{in} = \dot{Q}_{out} + \dot{W}_{out} + (\dot{m}h)_{out}$$

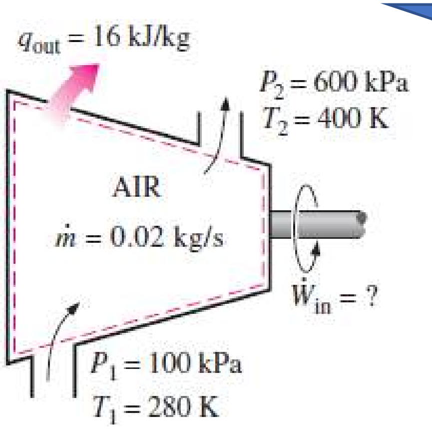
- No changes in potential energy

$$\dot{Q}_{in} + \dot{W}_{in} + \left[\dot{m}\left(h + \frac{1}{2}c^2\right)\right]_{in} = \dot{Q}_{out} + \dot{W}_{out} + \left[\dot{m}\left(h + \frac{1}{2}c^2\right)\right]_{out}$$

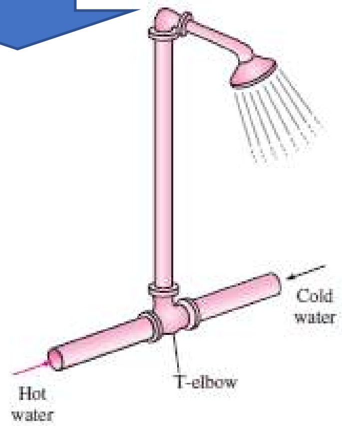
Some steady flow devices

Subsonic flow



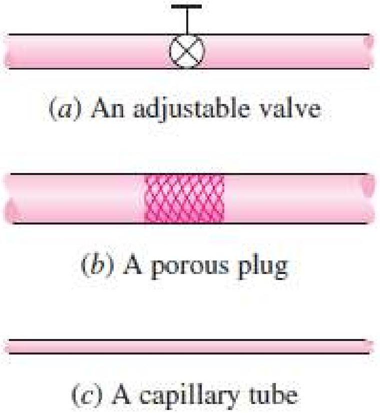


Compressor

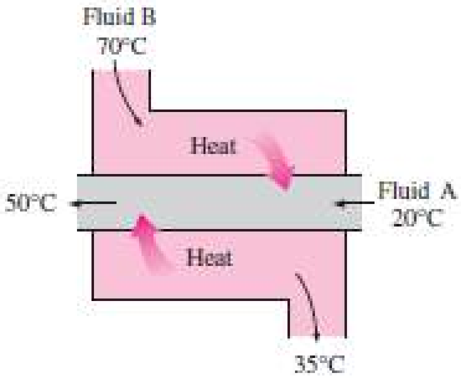


Mixing chambers

Throttling devices



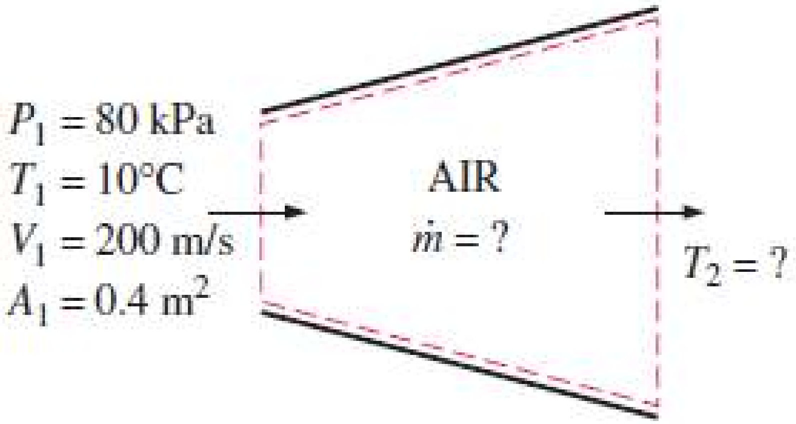
Heat exchangers



Steps in problem solving

Identify	the system & draw a sketch of it
List	the given information on the sketch
Check	for special processes
State	assumptions (if any)
Apply	the conservation equations
Draw	the process diagrams
Determine	the required properties & unknowns

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m². The air leaves the diffuser at a velocity that is much smaller than that at inlet. Determine the (a) mass flow rate & (b) temperature of air leaving the diffuser.



Assumptions

1. Steady flow process; no change in mass and energy stored within the CV.
2. Air is ideal gas; its at high temperature & low pressure compared to its critical point (-140°C & 37.86 bar)
3. HT & exit KE → Negligible
4. No change in PE
5. Constant sp. heat

$$\dot{Q}_{in} + \dot{W}_{in} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{in} = \dot{Q}_{out} + \dot{W}_{out} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{out}$$

Mass flow rate

$$\dot{m} = \rho A c$$

$$\rho = \frac{p}{RT}$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\left(h + \frac{1}{2}c^2\right)_{in} = h_{out}$$

$$h_{out} - h_{in} = \frac{1}{2}c_{in}^2 \Rightarrow c_p(T_{out} - T_{in}) = \frac{1}{2}c_{in}^2 \Rightarrow T_{out} = T_{in} + \frac{c_{in}^2}{2c_p}$$

The kinetic energy is converted to internal energy

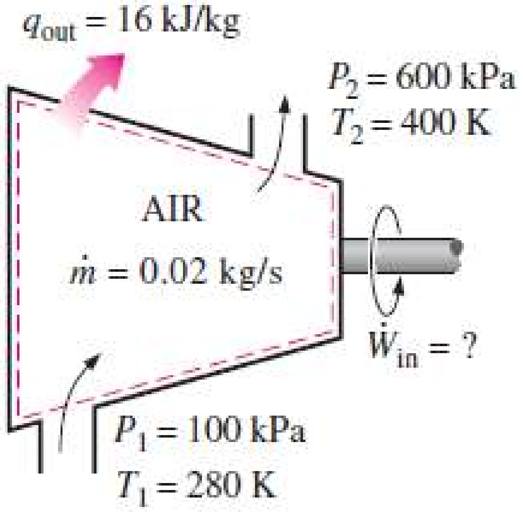
TABLE A-17

Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/(kg·K)	T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/(kg·K)
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	683.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
300	300.19	1.3860	214.07	621.2	1.70203	700	713.27	28.80	512.33	69.76	2.57277
305	305.22	1.4686	217.67	596.0	1.71865	710	724.04	30.38	520.23	67.07	2.58810
310	310.24	1.5546	221.25	572.3	1.73498	720	734.82	32.02	528.14	64.53	2.60319
315	315.27	1.6442	224.85	549.8	1.75106	730	745.62	33.72	536.07	62.13	2.61803
320	320.29	1.7375	228.42	528.6	1.76690	740	756.44	35.50	544.02	59.82	2.63280
325	325.31	1.8345	232.02	508.4	1.78249	750	767.29	37.35	551.99	57.63	2.64737
330	330.34	1.9352	235.61	489.4	1.79783	760	778.18	39.27	560.01	55.54	2.66176
340	340.42	2.149	242.82	454.1	1.82790	780	800.03	43.35	576.12	51.64	2.69013
350	350.49	2.379	250.02	422.2	1.85708	800	821.95	47.75	592.30	48.08	2.71787
360	360.58	2.626	257.24	393.4	1.88543	820	843.98	52.59	608.59	44.84	2.74504
370	370.67	2.892	264.46	367.2	1.91313	840	866.08	57.60	624.95	41.85	2.77170
380	380.77	3.176	271.69	343.4	1.94001	860	888.27	63.09	641.40	39.12	2.79783
390	390.88	3.481	278.93	321.5	1.96633	880	910.56	68.98	657.95	36.61	2.82344
400	400.98	3.806	286.16	301.6	1.99194	900	932.93	75.29	674.58	34.31	2.84856
410	411.12	4.153	293.43	283.3	2.01699	920	955.38	82.05	691.28	32.18	2.87324
420	421.26	4.522	300.69	266.6	2.04142	940	977.92	89.28	708.08	30.22	2.89748
430	431.43	4.915	307.99	251.1	2.06533	960	1000.55	97.00	725.02	28.40	2.92128
440	441.61	5.332	315.30	236.8	2.08870	980	1023.25	105.2	741.98	26.73	2.94468
450	451.80	5.775	322.62	223.6	2.11161	1000	1046.04	114.0	758.94	25.17	2.96770
460	462.02	6.245	329.97	211.4	2.13407	1020	1068.89	123.4	776.10	23.72	2.99034
470	472.24	6.742	337.32	200.1	2.15604	1040	1091.85	133.3	793.36	23.29	3.01260
480	482.49	7.268	344.70	189.5	2.17760	1060	1114.86	143.9	810.62	21.14	3.03449
490	492.74	7.824	352.08	179.7	2.19876	1080	1137.89	155.2	827.88	19.98	3.05608
500	503.02	8.411	359.49	170.6	2.21952	1100	1161.07	167.1	845.33	18.896	3.07732
510	513.32	9.031	366.92	162.1	2.23993	1120	1184.28	179.7	862.79	17.886	3.09825
520	523.63	9.684	374.36	154.1	2.25997	1140	1207.57	193.1	880.35	16.946	3.11883
530	533.98	10.37	381.84	146.7	2.27967	1160	1230.92	207.2	897.91	16.064	3.13916
540	544.35	11.10	389.34	139.7	2.29906	1180	1254.34	222.2	915.57	15.241	3.15916
550	555.74	11.86	396.86	133.1	2.31809	1200	1277.79	238.0	933.33	14.470	3.17888
560	565.17	12.66	404.42	127.0	2.33685	1220	1301.31	254.7	951.09	13.747	3.19834
570	575.59	13.50	411.97	121.2	2.35531	1240	1324.93	272.3	968.95	13.069	3.21751

Air

Air at 280K and 100 kPa is compressed steadily to 600 kPa and 400 K. The mass flow rate of air is 0.02 kg/s and a heat loss of 16 kJ/kg occurs during the process. Determine the necessary power input to the compressor.



Assumptions

1. KE & PE changes are negligible.
2. Air is ideal gas; its at high temperature & low pressure compared to its critical point (-140°C & 37.86 bar)
3. Constant sp. heat

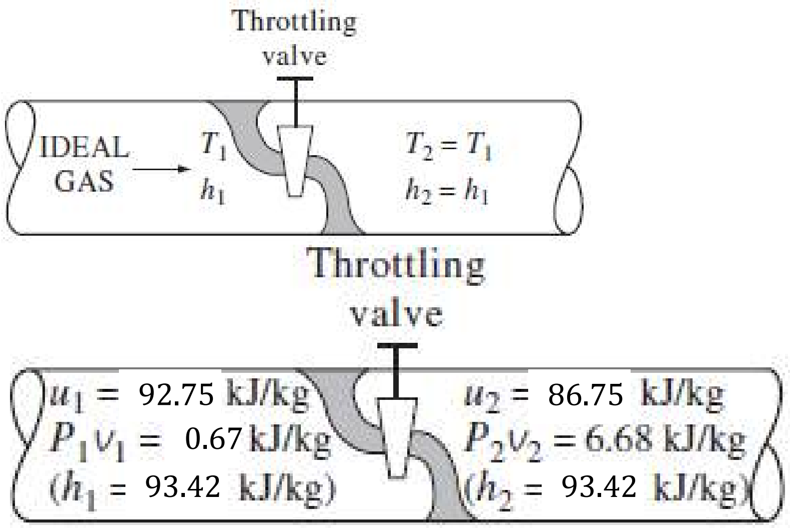
$$\dot{Q}_{in} + \dot{W}_{in} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{in} = \dot{Q}_{out} + \dot{W}_{out} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{out}$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{W}_{in} = \dot{Q}_{out} + \dot{m}(h_{out} - h_{in}) \Rightarrow \dot{W}_{in} = \dot{m}q_{out} + \dot{m}(h_{out} - h_{in}) \Rightarrow \dot{W}_{in} = \dot{m}[q_{out} + (h_{out} - h_{in})]$$

$$\dot{W}_{in} = \dot{m}[q_{out} + c_p(T_{out} - T_{in})]$$

Refrigerant 134a enters a capillary tube of a refrigerator as saturated liquid at 0.8 MPa and is throttled to a pressure of 0.12 MPa. Determine the quality of the refrigerant at the final state and the temperature drop during this process.



Assumptions

1. Steady flow process; no change in mass and energy stored within the CV.
2. HT, changes in KE & PE → Negligible
3. No work transfer

$$\dot{Q}_{in} + \dot{W}_{in} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{in} = \dot{Q}_{out} + \dot{W}_{out} + \left[\dot{m}\left(h + gz + \frac{1}{2}c^2\right)\right]_{out}$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$h_{in} = h_{out}$$

↓

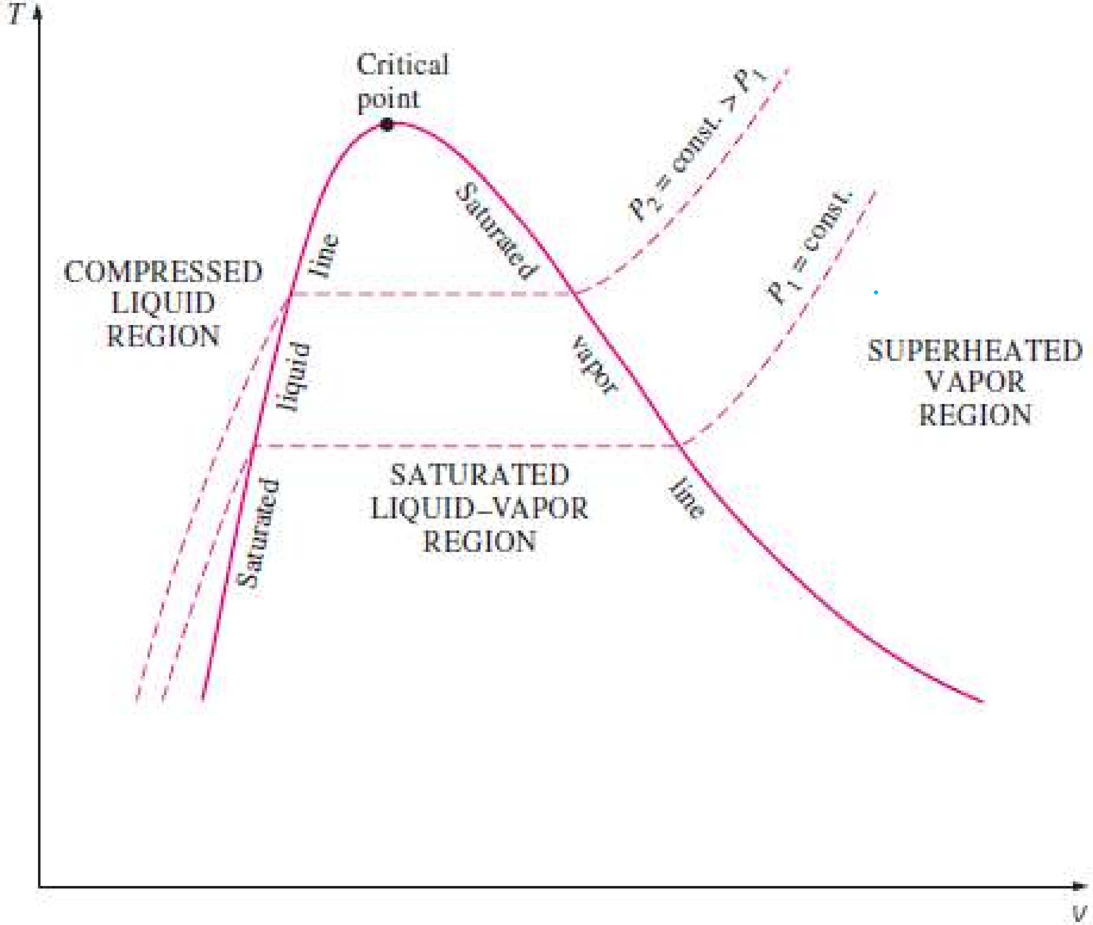
$$(u + pv)_{in} = (u + pv)_{out}$$

TABLE A-12

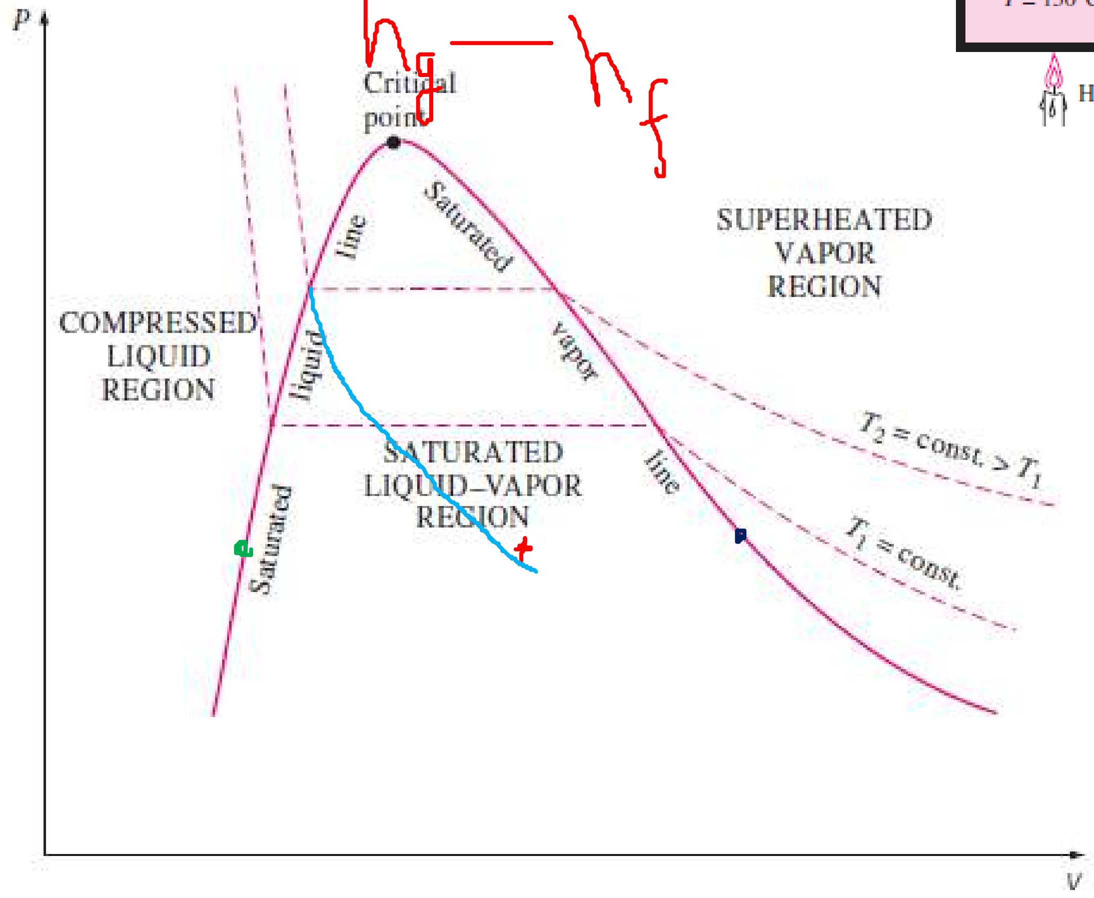
Saturated refrigerant-134a—Pressure table

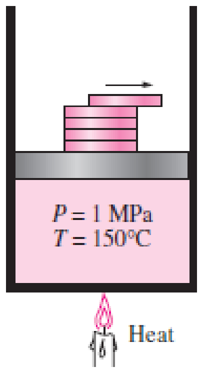
		Specific volume, m³/kg		Internal energy, kJ/kg		Enthalpy, kJ/kg			Entropy, kJ/(kg·K)	
Press., P MPa	Temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Sat. vapor, s_g
0.06	−37.07	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.7	26.72	0.0008328	0.0292	86.19	241.42	86.78	175.07	261.85	0.3242	0.9080
0.8	31.33	0.0008454	0.0255	92.75	243.78	93.42	170.73	264.15	0.3459	0.9066
0.9	35.53	0.0008576	0.0226	98.79	245.88	99.56	[illegible]	[illegible]	[illegible]	[illegible]

Pure substances – Tv & pV diagrams

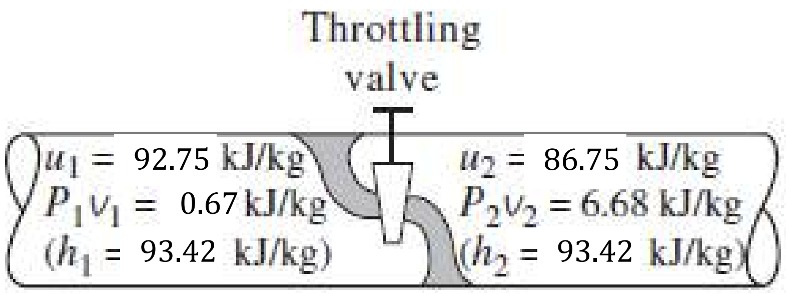


$$x = \frac{h - h_f}{h_g - h_f}$$





Throttling (contd.,)



- At inlet

$$p_{in} = 0.8\ MPa$$

$$T_{in} = T_{sat}\ @\ 0.8\ MPa = 31.33°C$$

$$u_{in} = u_f @\ 0.8\ MPa = 92.75\ kJ/kg$$

$$h_{in} = h_f @\ 0.8\ MPa = 93.42\ kJ/kg$$

- At exit

$$p_{out} = 0.12\ MPa$$

$$h_f\ @\ 0.12\ MPa = 21.32\ kJ/kg$$

$$h_g\ @\ 0.12\ MPa = 233.86\ kJ/kg$$

$$u_f\ @\ 0.12\ MPa = 21.23\ kJ/kg$$

$$u_g\ @\ 0.12\ MPa = 214.5\ kJ/kg$$

Dryness fraction

$$x_{out} = \frac{h_{out} - h_f}{h_{fg}} = \frac{93.42 - 21.32}{212.54} = \frac{72.1}{212.54} = 0.339$$

Saturated mixture

$$T_{out} = T_{sat}\ @\ 0.12\ MPa = -22.36°C$$

$$u_{out} = x_{out}(u_g - u_f) + u_f$$

$$u_{out} = 0.339(214.5 - 21.23) + 21.23 = 86.75\ kJ/kg$$

Drop in temperature = 31.33-(-22.36)=53.69 °C

TABLE A-12

Saturated refrigerant-134a—Pressure table

		Specific volume, m³/kg		Internal energy, kJ/kg		Enthalpy, kJ/kg			Entropy, kJ/(kg · K)	
Press., P MPa	Temp., T_{sat} °C	Sat. liquid, v_f	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
0.06	−37.07	0.0007097	0.3100	3.41	206.12	3.46	221.27	224.72	0.0147	0.9520
0.08	−31.21	0.0007184	0.2366	10.41	209.46	10.47	217.92	228.39	0.0440	0.9447
0.10	−26.43	0.0007258	0.1917	16.22	212.18	16.29	215.06	231.35	0.0678	0.9395
0.12	−22.36	0.0007323	0.1614	21.23	214.50	21.32	212.54	233.86	0.0879	0.9354
0.14	−18.80	0.0007381	0.1395	25.66	216.52	25.77	210.27	236.04	0.1055	0.9322
0.16	−15.62	0.0007435	0.1229	29.66	218.32	29.78	208.18	237.97	0.1211	0.9295
0.18	−12.73	0.0007485	0.1098	33.31	219.94	33.45	206.26	239.71	0.1352	0.9273
0.20	−10.09	0.0007532	0.0993	36.69	221.43	36.84	204.46	241.30	0.1481	0.9253
0.24	−5.37	0.0007618	0.0834	42.77	224.07	42.95	201.14	244.09	0.1710	0.9222
0.28	−1.23	0.0007697	0.0719	48.18	226.38	48.39	198.13	246.52	0.1911	0.9197
0.32	2.48	0.0007770	0.0632	53.06	228.43	53.31	195.35	248.66	0.2089	0.9177
0.36	5.84	0.0007839	0.0564	57.54	230.28	57.82	192.76	250.58	0.2251	0.9160
0.4	8.93	0.0007904	0.0509	61.69	231.97	62.00	190.32	252.32	0.2399	0.9145
0.5	15.74	0.0008056	0.0409	70.93	235.64	71.33	184.74	256.07	0.2723	0.9117
0.6	21.58	0.0008196	0.0341	78.99	238.74	79.48	179.71	259.19	0.2999	0.9097
0.7	26.72	0.0008328	0.0292	86.19	241.42	86.78	175.07	261.85	0.3242	0.9080
0.8	31.33	0.0008454	0.0255	92.75	243.78	93.42	170.73	264.15	0.3459	0.9066
0.9	35.53	0.0008576	0.0226	98.79	245.88	99.56	166.62	266.18	0.3656	0.9054
1.0	39.39	0.0008695	0.0202	104.42	247.77	105.29	162.68	267.97	0.3838	0.9043
1.2	46.32	0.0008928	0.0166	114.69	251.03	115.76	155.23	270.99	0.4164	0.9023
1.4	52.43	0.0009159	0.0140	123.98	253.74	125.26	148.14	273.40	0.4453	0.9003
1.6	57.92	0.0009392	0.0121	132.52	256.00	134.02	141.31	275.33	0.4714	0.8982
1.8	62.91	0.0009631	0.0105	140.49	257.88	142.22	134.60	276.83	0.4954	0.8959
2.0	67.49	0.0009878	0.0093	148.02	259.41	149.99	127.95	277.94	0.5178	0.8934
2.5	77.59	0.0010562	0.0069	165.48	261.84	168.12	111.06	279.17	0.5687	0.8854
3.0	86.22	0.0011416	0.0053	181.88	262.16	185.30	92.71	278.01	0.6156	0.8735

R-134a

TABLE A-12

Saturated refrigerant-134a—Pressure table

Press., P MPa	Temp., T_{sat} °C	Specific volume, m³/kg: Sat. liquid, v_f	Sat. vapor, v_g	Internal energy, kJ/kg: Sat. liquid, u_f	Sat. vapor, u_g	Enthalpy, kJ/kg: Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Entropy, kJ/(kg · K): Sat. liquid, s_f	Sat. vapor, s_g
0.06	−37.07	0.0007097	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
0.7	26.72	0.0008328	0.0292	86.19	241.42	86.78	175.07	261.85	0.3242	0.9080
0.8	31.33	0.0008454	0.0255	92.75	243.78	93.42	170.73	264.15	0.3459	0.9066
0.9	35.53	0.0008576	0.0226	98.79	245.88	99.56	[illegible]	[illegible]	[illegible]	[illegible]

References

1. Yunus A Cengel and Michael A Boles, "Thermodynamics – an Engineering Approach", 3rd Edition, Tata Mc Graw Hill, 2002.
2. Jones, J B and R E Dugan, "Engineering Thermodynamics", Pearson Education, 1996.
3. Richard J Feynnman, Lectures in Physics, 11th reprint, Narosa Publishing House, 2001.
4. Francis W Seers and Gerhard L Salinger, "Thermodynamics, Kinetic Theory and Statistical Thermodynamics", 3rd edition, Narosa Publishing House, 1998.
5. https://www.google.com/aclk?sa=L&ai=DChcSEwjN1uzm8b_rAhWKfSsKHSDlDUwYABAMGgJzZg&sig=AOD64_05Q13RTX43B2mfcOkF0_mEmVP8lA&adurl&ctype=5&ved=2ahUKEwio2uDm8b_rAhWeVX0KHVbUBxEQvhd6BAgBEGo

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19ME31 Engineering Thermodynamics (L14)

Dr A S Krishnan / Mr Sam Solomon
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Coimbatore Institute of Technology

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Second Law of Thermodynamics

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Thermodynamic Relations and Ideal Gas Mixtures

II Law of Thermodynamics

SNo	Topic	Hours
1	II Law – Statements of Kelvin Planck and Clausius; Equivalence	2
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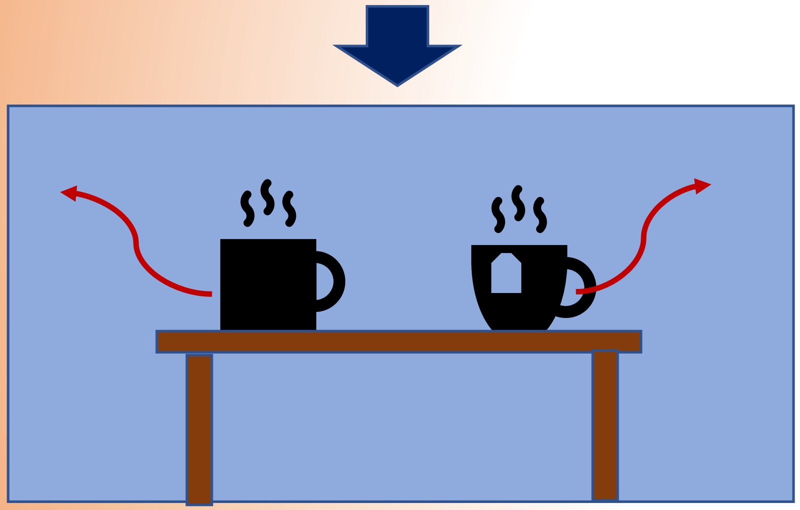
4	Carnot – Reversed Carnot cycle – Carnot's theorem – Absolute Thermodynamic temperature scale	2

Today's discussion

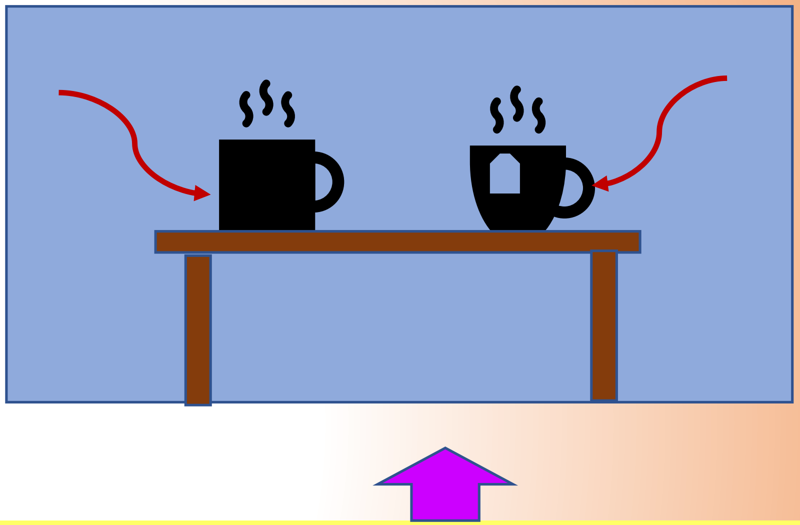
- Directionality of processes
- Need for a cycle
- Statements of II law of Thermodynamics
- Equivalence of the statements

Directionality of processes

- A hot cup of tea / coffee / milk / boost / bournvita / Horlicks etc. getting cooled in a room.



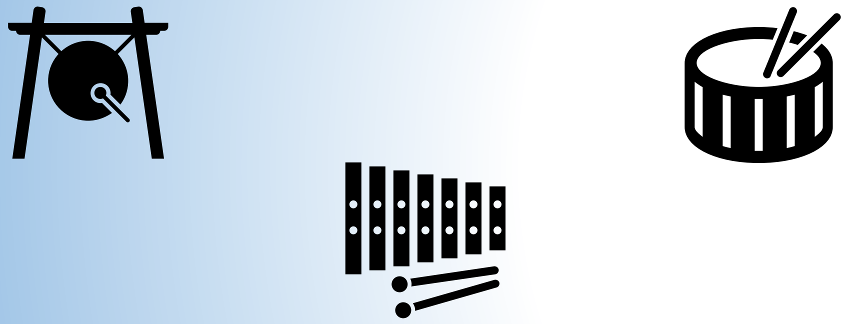
- I law is not violated, the total energy is constant



- I law is still not violated, but does this happen?

Directionality of processes (contd.)

- Music / sound being generated using instruments



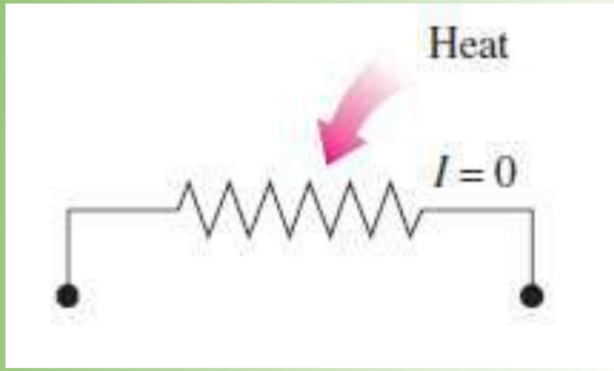
- I law is not violated; the total energy is constant - kinetic energy of the drum sticks (not drumstick) is converted to sound energy

- A recorded sound (exact replica) of the music is played in the room in which the instruments are kept
- Upon playing the recorded sound the sticks starts beating the drums by using the energy from the recorded sound!!!

- I law is still not violated, but does this happen?

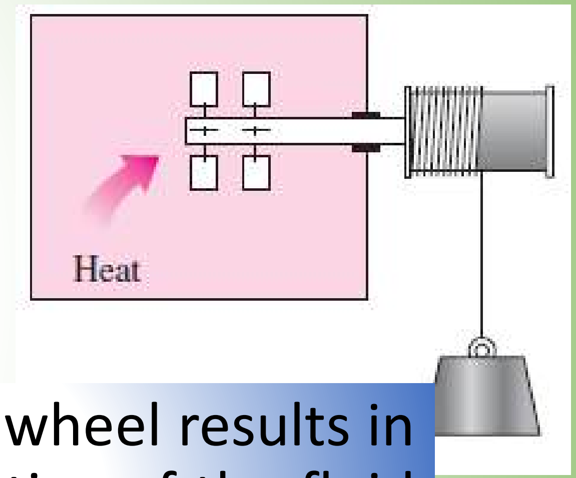
Directionality of processes (contd.)

Electrical heating coil



- Passing of current causes heating of coil; heating of coil result in an electric current generation !!

The paddle wheel

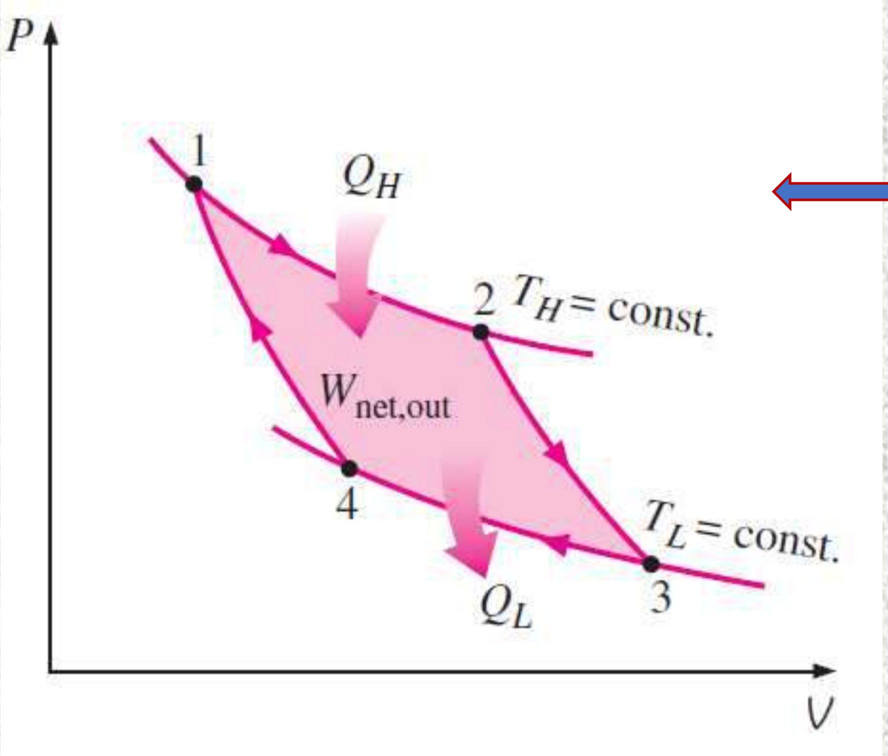


- Rotating the paddle wheel results in heating of fluid; heating of the fluid result in rotation of paddle wheel !!

I law is still not violated, but does this happen?

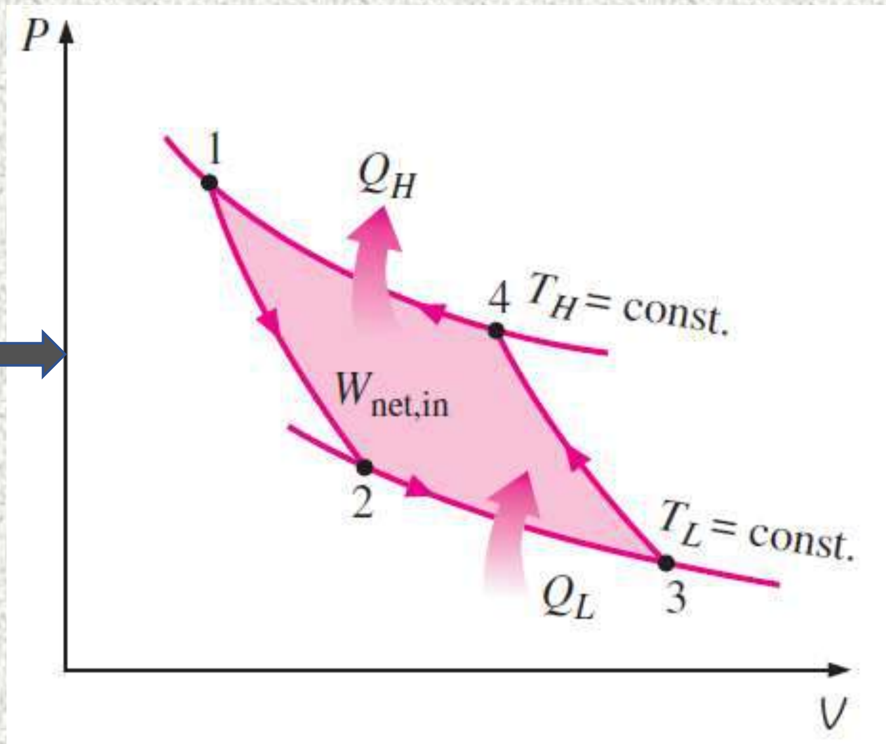
All process in nature have a natural direction

Need for a cycle



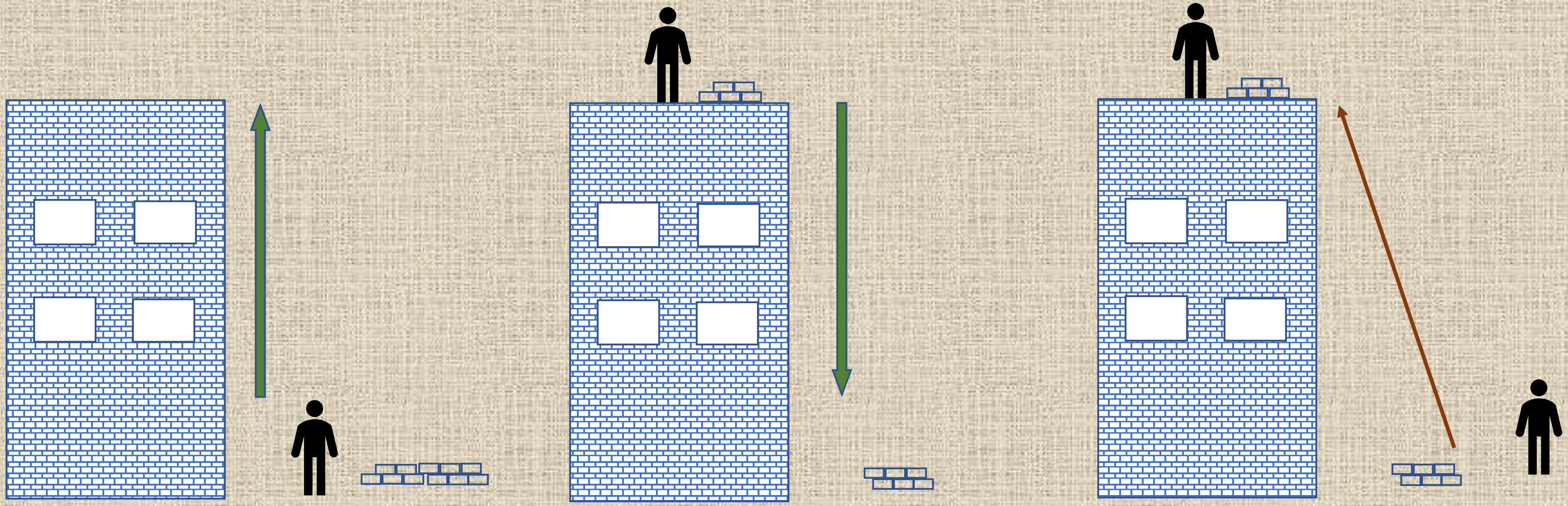
Work delivering

Work absorbing



A system needs to operate in a cycle if the work interaction needs to be continuous

Why a cycle is needed?



The person needs to come down if he /she must continuously transport bricks from the ground to the construction floor

II law of Thermodynamics

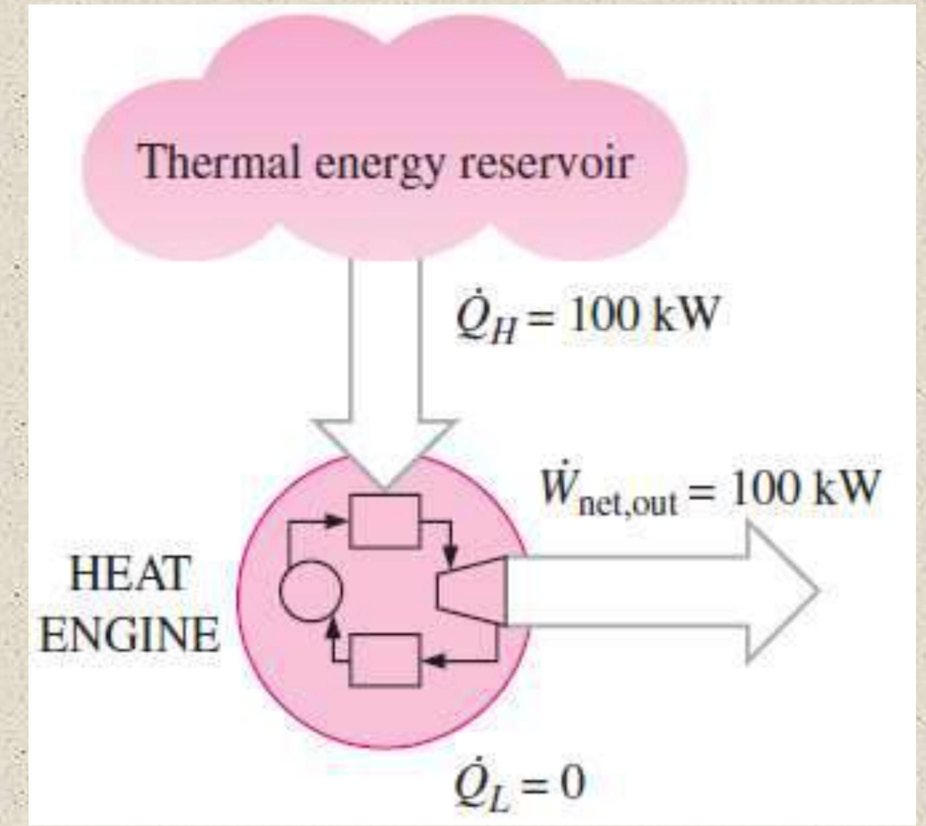
- Kelvin Planck's statement
  - It is impossible for any device that operates in a cycle to receive heat from a single reservoir and produce a net amount of work
- Clausius statement
  - It is impossible to construct a device that operates in a cycle and produces no other effect other than transfer of heat from a lower temperature body to a higher temperature body

Both the Kelvin-Planck and the Clausius statements of second law, are based on experimental observations. No experiment has so far violated the II law, and thus is a proof of the statements.

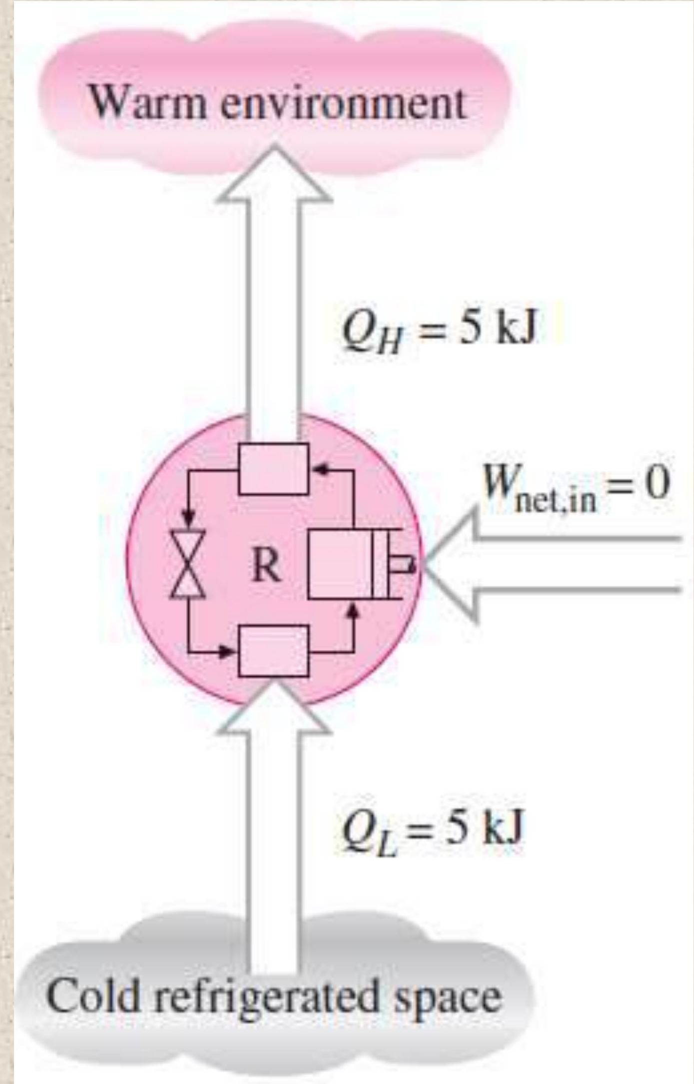
Reservoir – A body with a large thermal capacity; the temperature of the body does not change when heat is added or removed. E.g. Atmospheric air, ocean, etc.

Violation of the II law

Violation of the Kelvin-Planck's statement

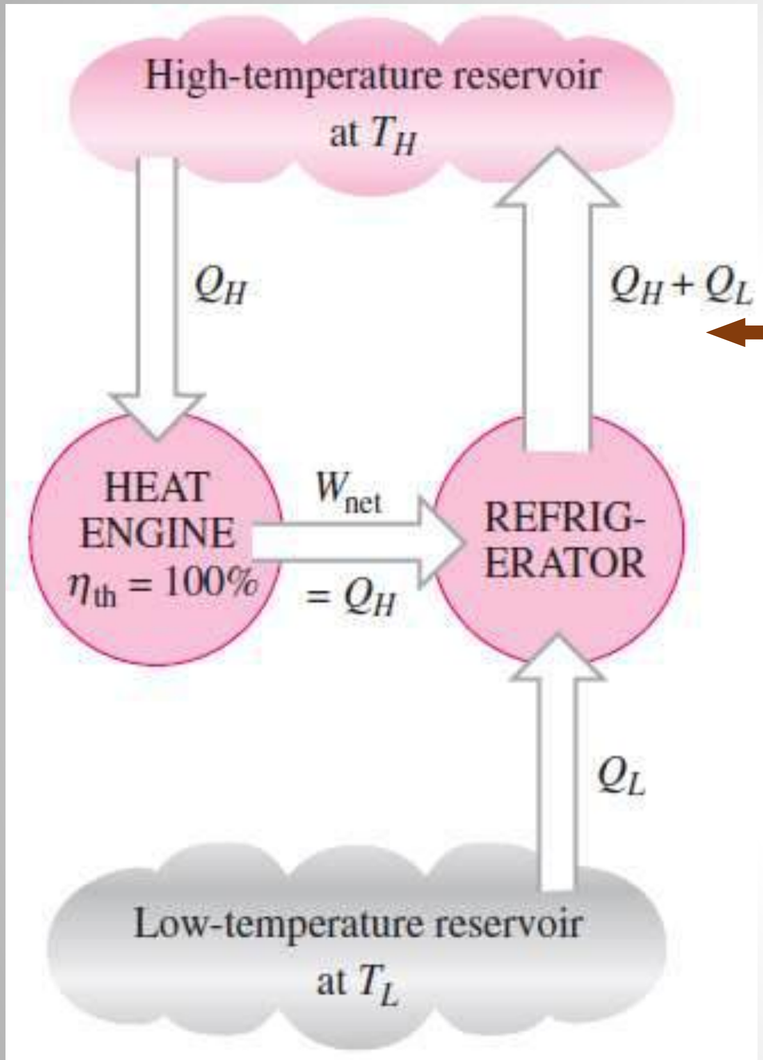


Not possible



Violation of the Clausius statement

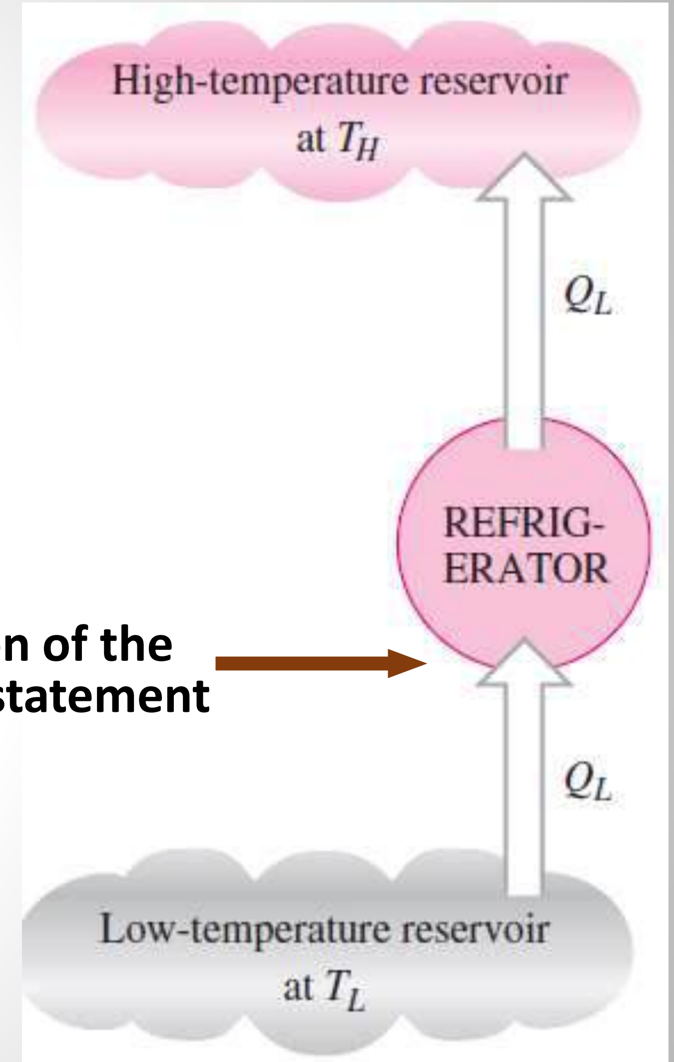
Equivalence of statements



(a) A refrigerator that is powered by a 100 percent efficient heat engine

Violation of the Kelvin-Planck's statement

Violation of the Clausius statement



(b) The equivalent refrigerator

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19ME31 Engineering Thermodynamics (L15)

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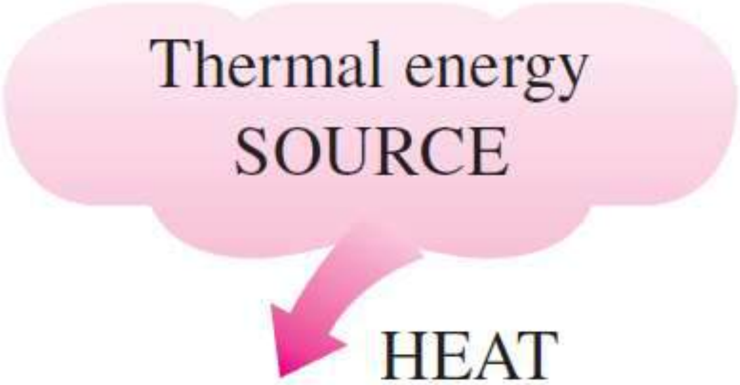
Today's discussion

- Thermal Energy Reservoirs (contd.)
- Heat engines
- Refrigerators & Heat Pumps
- Perpetual Motion Machine of 2nd kind

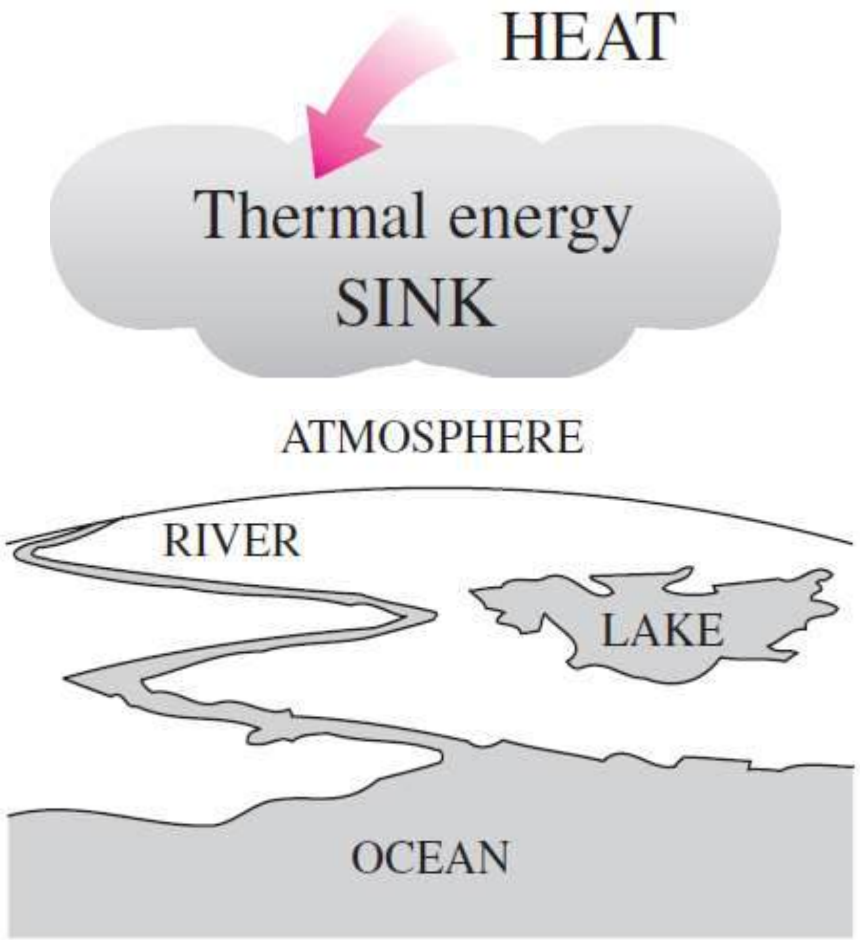
Thermal energy reservoirs

Heat source



https://www.inquisitive.com/lesson/322-here-comes-the-sun

Heat sink



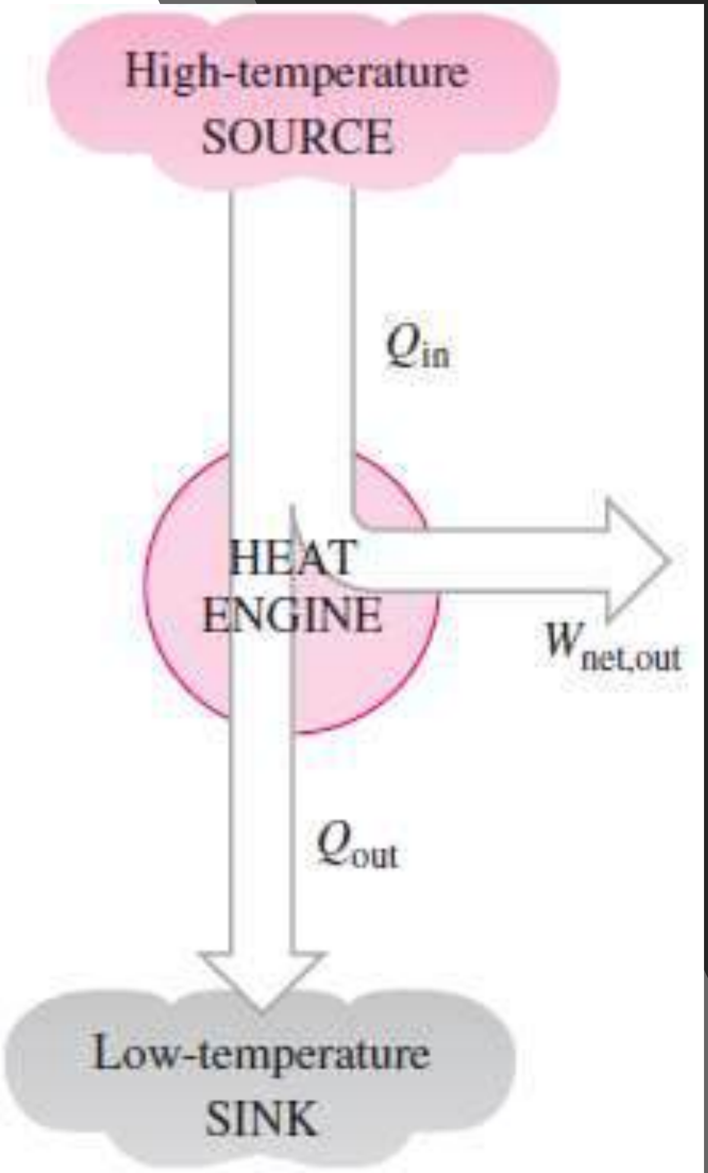
Heat Engines

WHAT ARE THEY?

SOME EXAMPLES

PERFORMANCE PARAMETER

NUMERICAL EXAMPLE



Heat Engines – what are they?

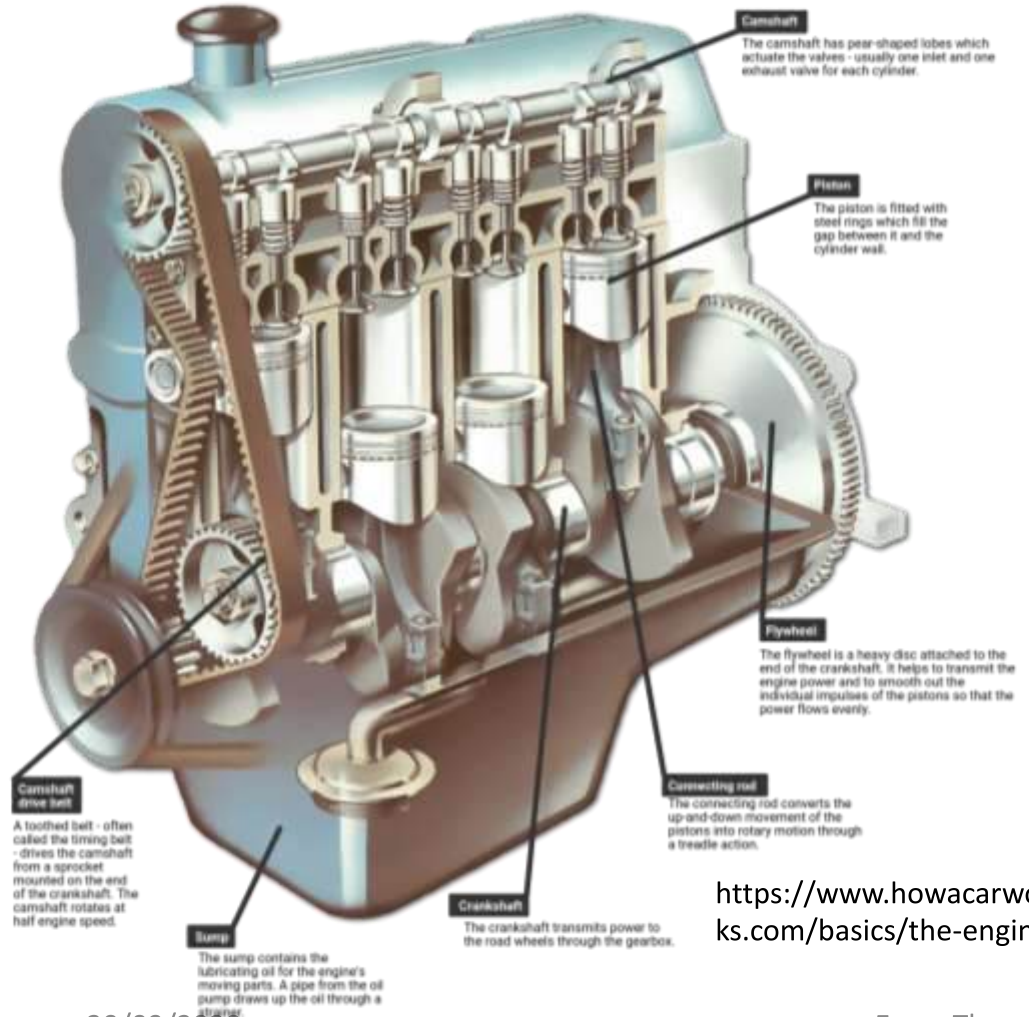
These are special devices that

1. Receive heat from a high-temperature source (solar energy, oil furnace, nuclear-reactor, boiler etc.)
2. Convert part of this heat to work (usually in the form of a rotating shaft)
3. Reject the remaining waste heat to a low-temperature sink (atmosphere, rivers, etc.)
4. Generally operate on a cycle
5. Generally use a fluid (working fluid) to & from which heat is transferred during the cycle

Heat Engines – Some examples

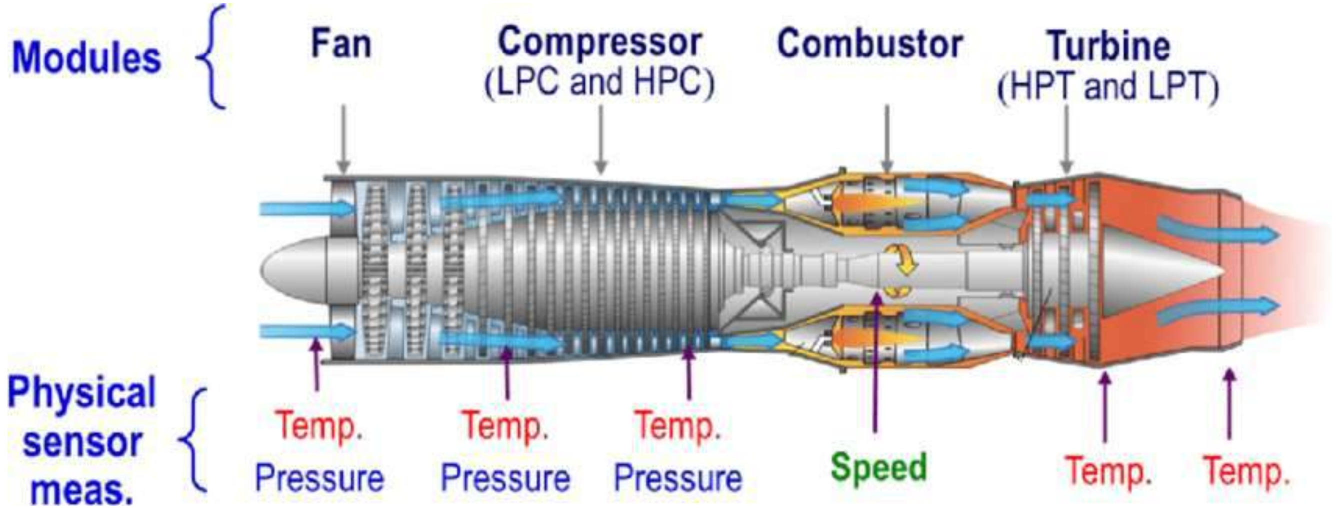
Those which do not operate on a cycle

Automobile engines

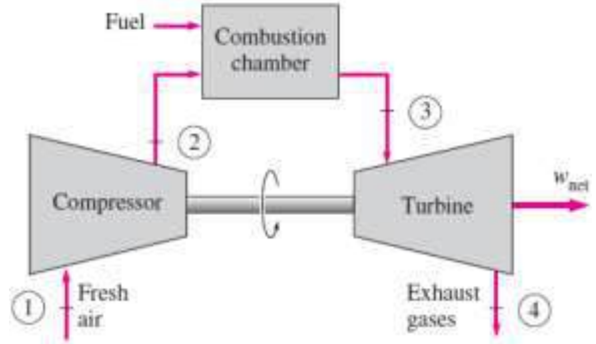


https://www.howacarworks.com/basics/the-engine

Aircraft engines

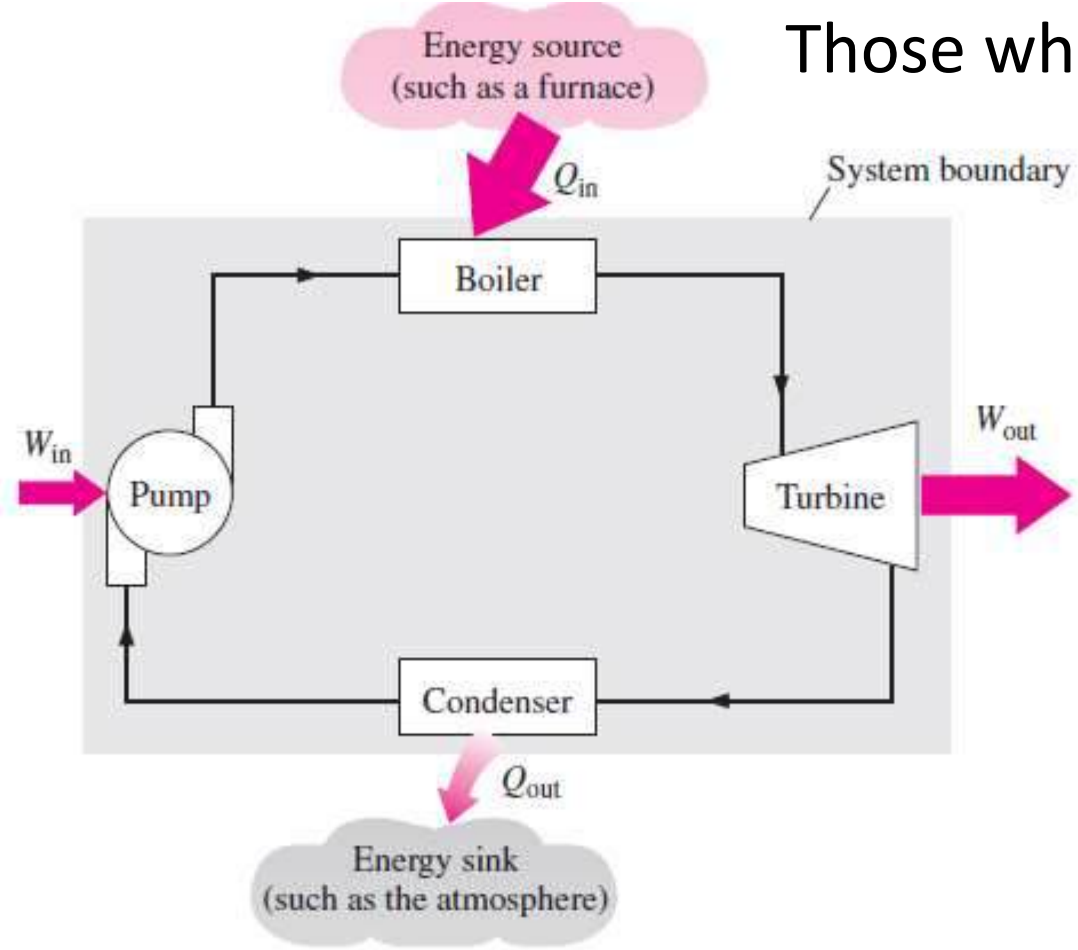


https://www.researchgate.net/figure/Diagram-of-aircraft-engine-modules-35_fig4_325564535

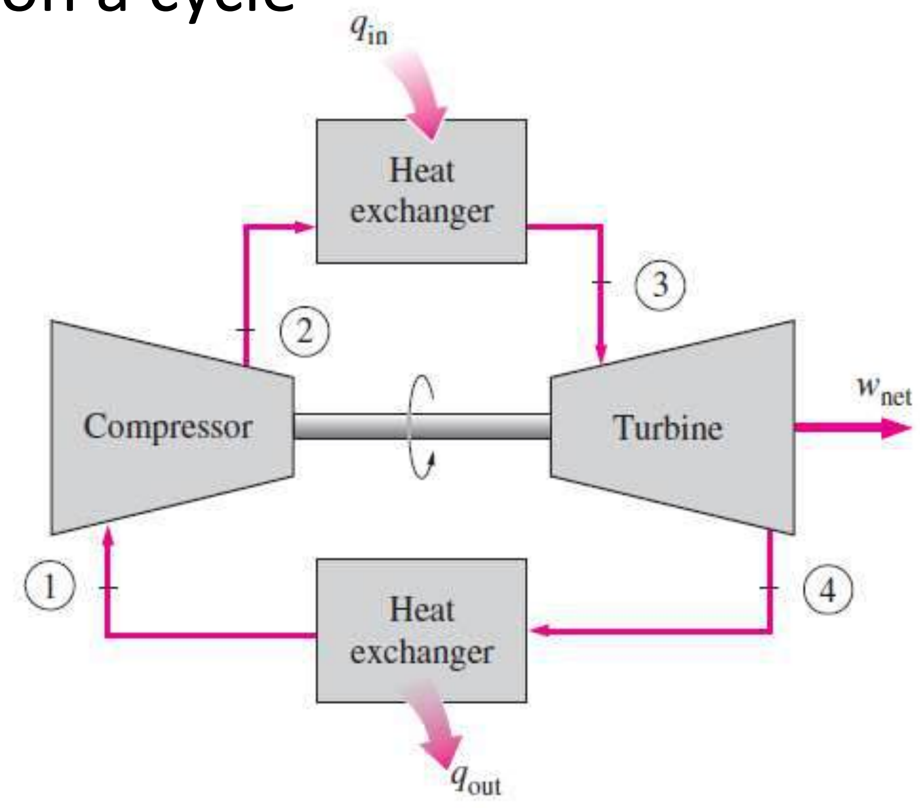


Heat Engines – Some examples

Those which operate on a cycle

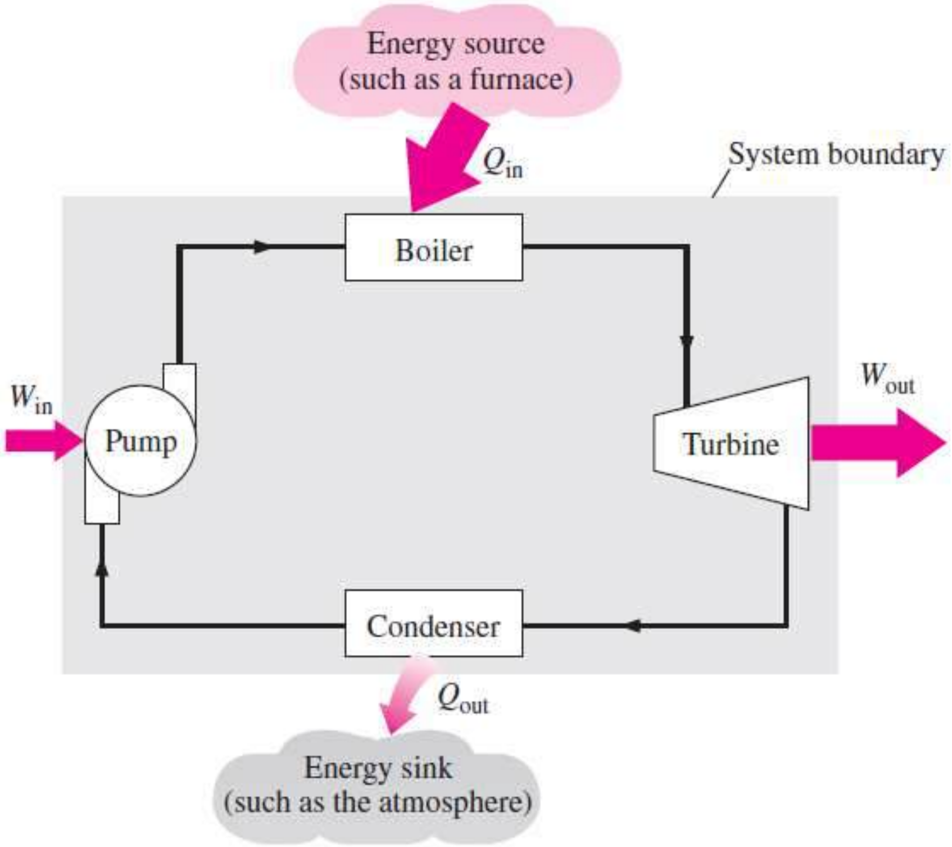


Operating principle of a Steam power plant



Operating principle of a Closed cycle gas turbine power plant

Heat Engines – Performance parameter



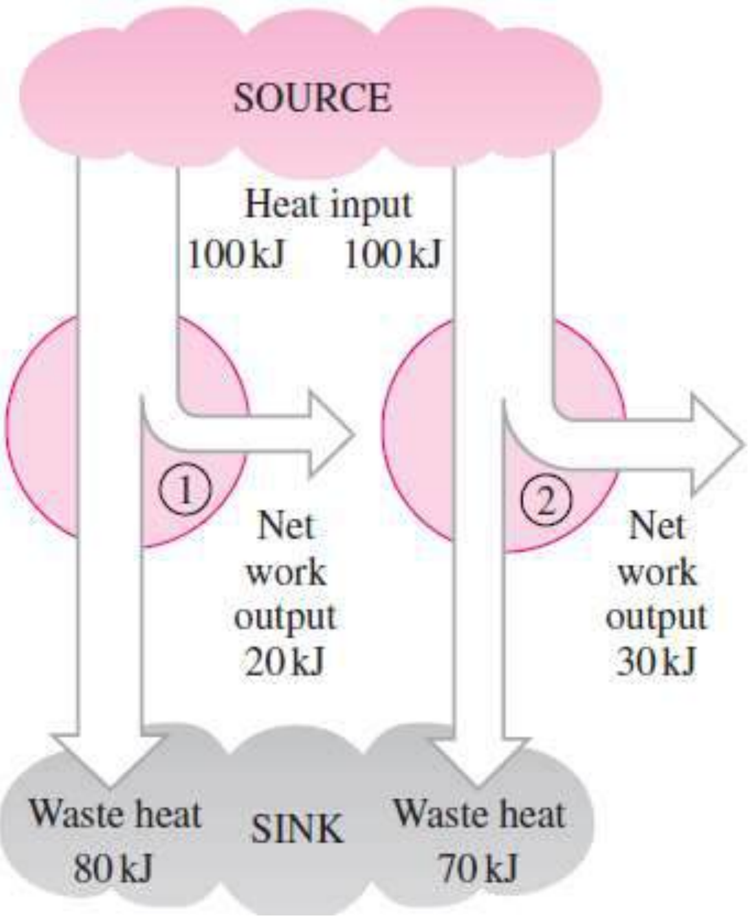
Thermal efficiency

$$\eta_{th} = \frac{Net\ work\ output}{Total\ heat\ input}$$

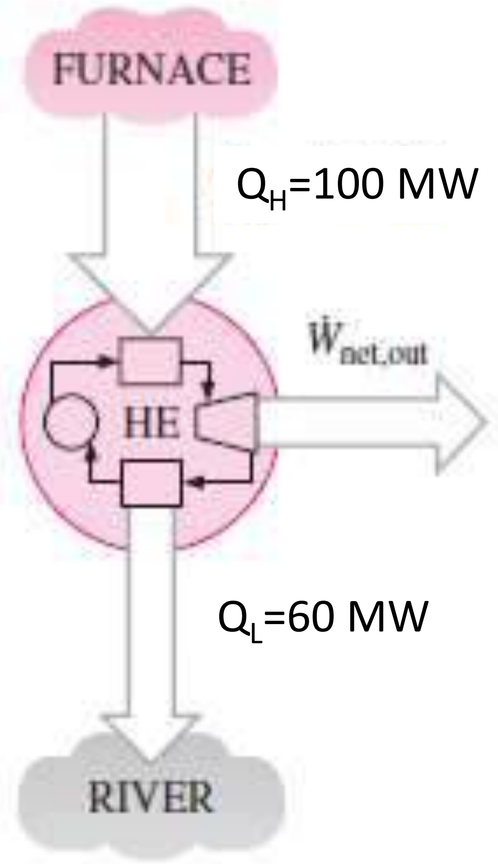
$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

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

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



Heat is transferred to a heat engine from a furnace at a rate of 100 MW. If the rate of waste heat rejection to a nearby river is 60 MW, calculate the net power output and the thermal efficiency of this heat engine.



- Net power output

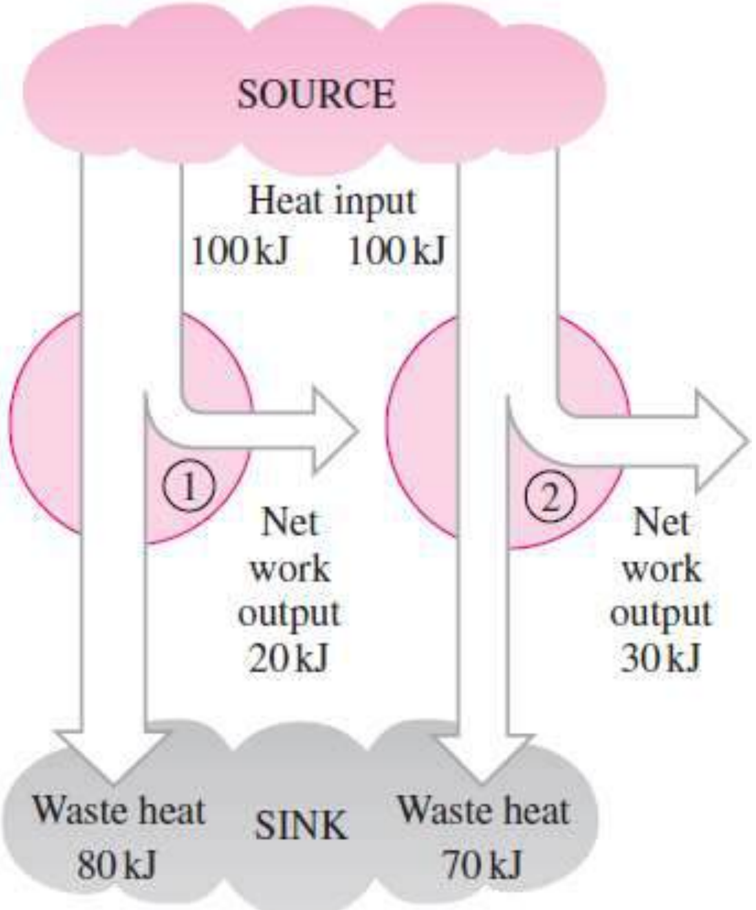
$$\dot{W}_{net,out} = \dot{Q}_{in} - \dot{Q}_{out}$$

$$\dot{W}_{net,out} = 40\ MW$$

- Thermal efficiency

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

$$\eta_{th} = \frac{40}{100} = 40\%$$

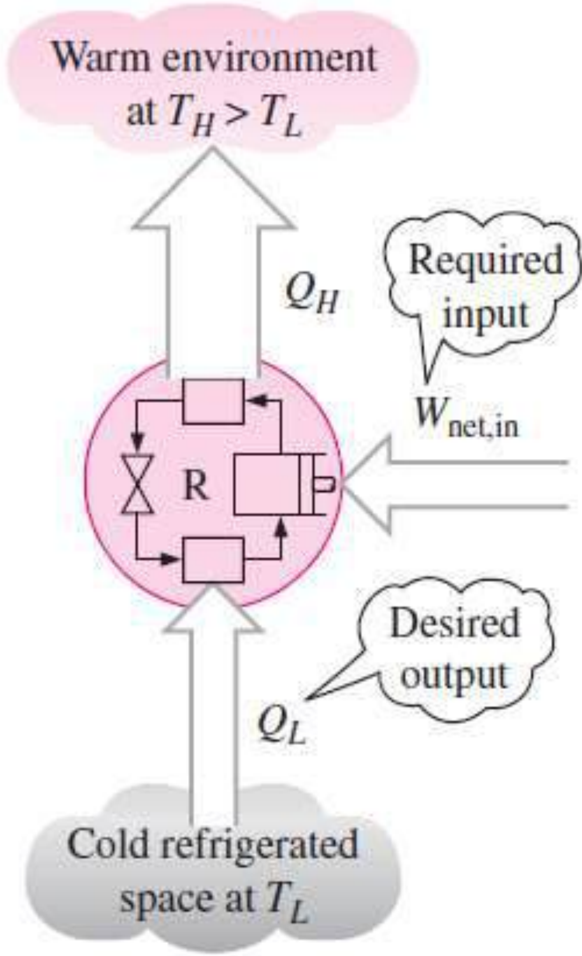


Refrigerators & Heat Pumps

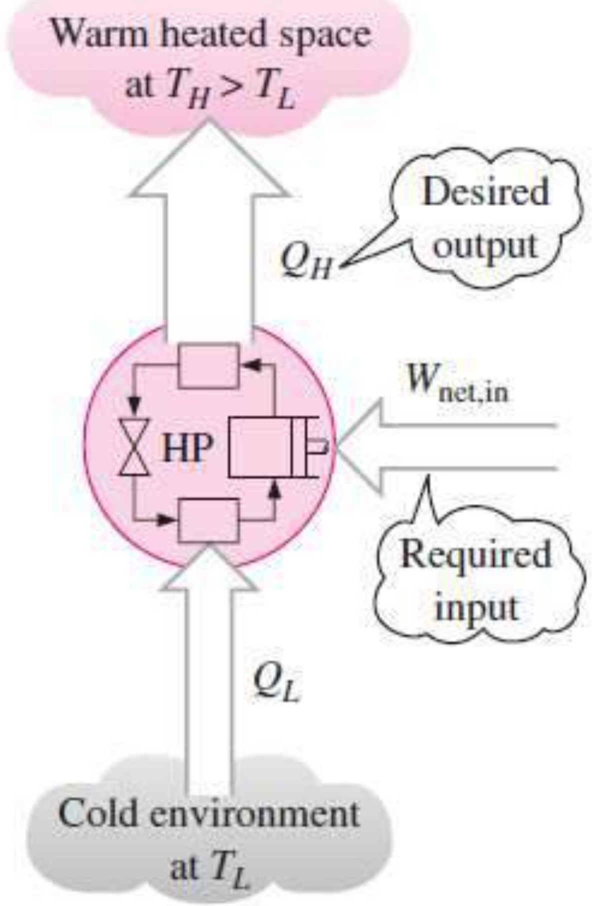
- What are they?
- Performance parameter
- Numerical example

Refrigerators & Heat Pumps – what are they?

Refrigerator

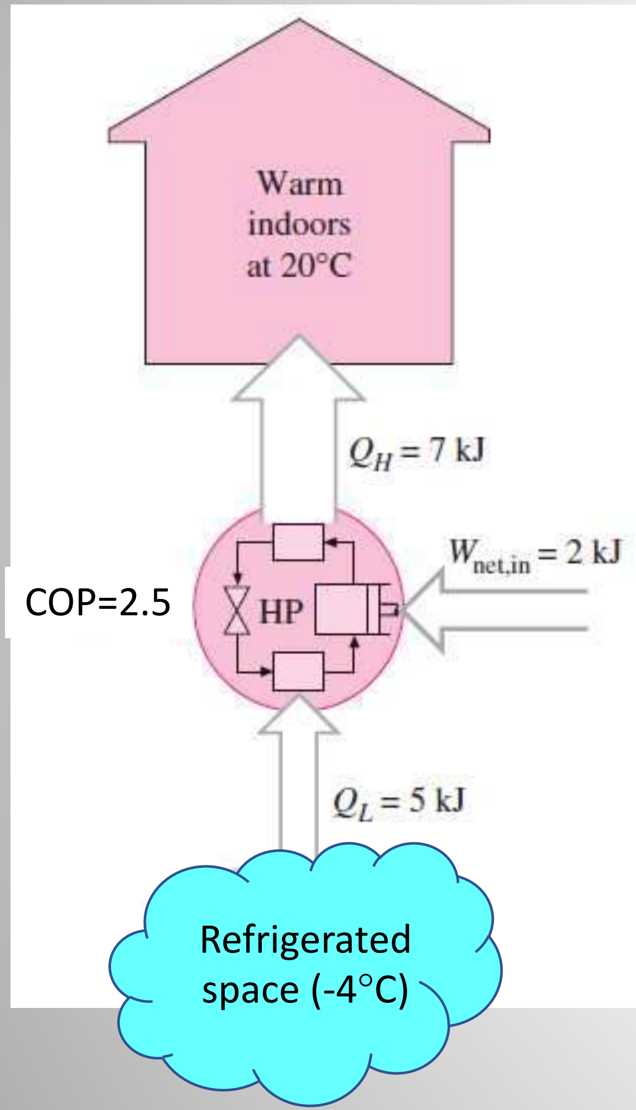


Heat Pump



Performance parameter – COP (Coeff. of Performance)

$$COP = \frac{Desired\ o/p}{Required\ i/p}$$



Refrigerator

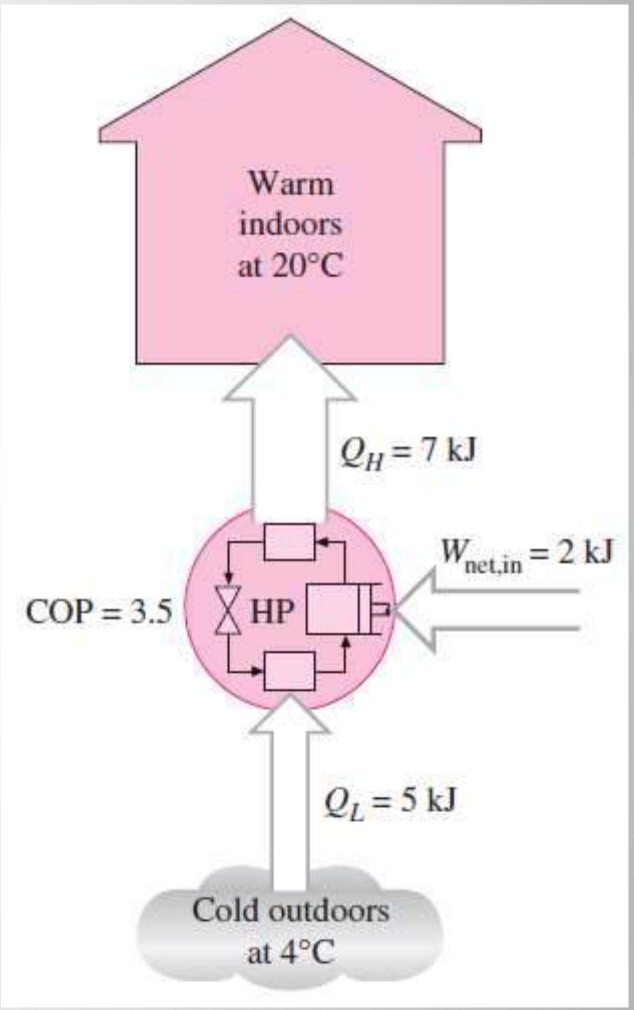
$$COP_R = \frac{Q_L}{W_{net,in}}$$

$$COP_R = \frac{5}{2} = 2.5$$

Heat Pump

$$COP_{HP} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{7}{2} = 3.5$$



$$COP_{HP} - COP_R = \frac{Q_H}{W_{net,in}} - \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} - COP_R = \frac{Q_H - Q_L}{W_{net,in}}$$

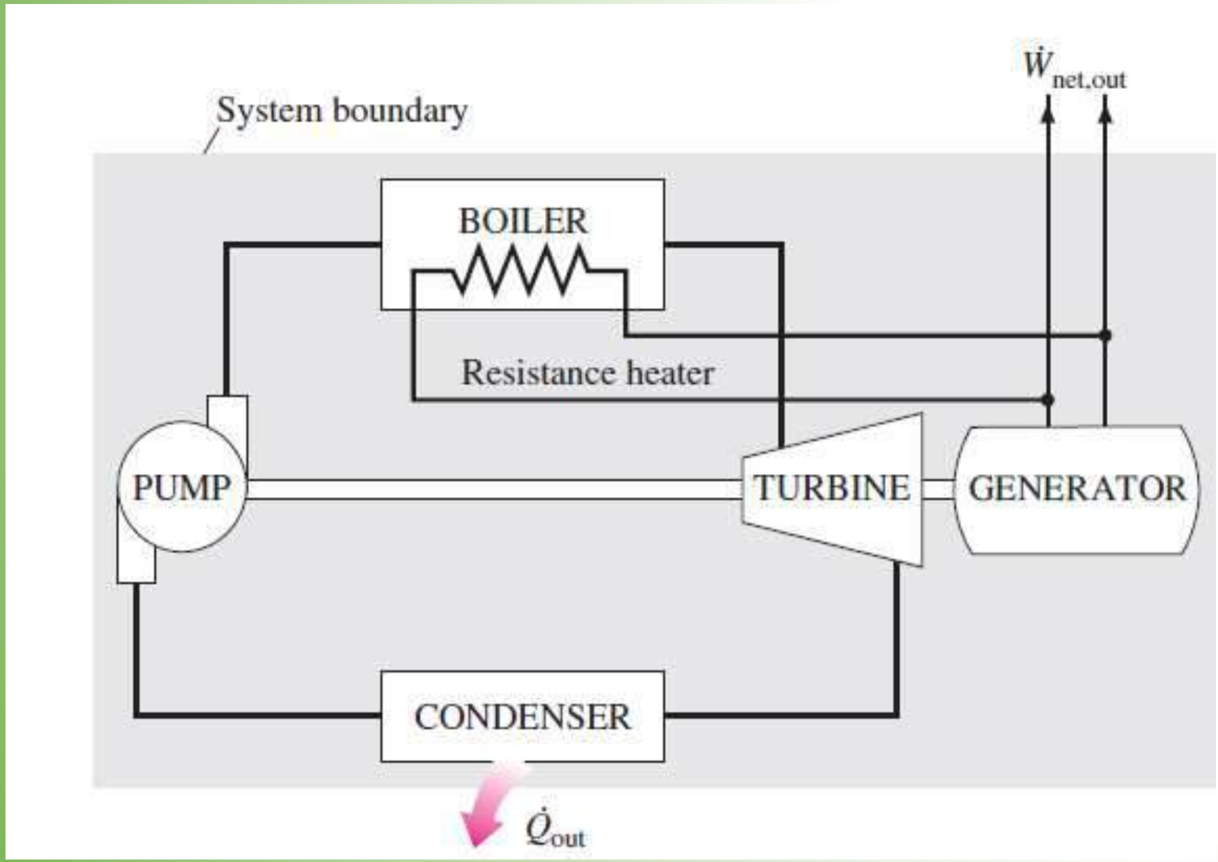
$$COP_{HP} - COP_R = \frac{W_{net,in}}{W_{net,in}} = 1$$

Refrigerators & Heat Pumps – Numerical examples

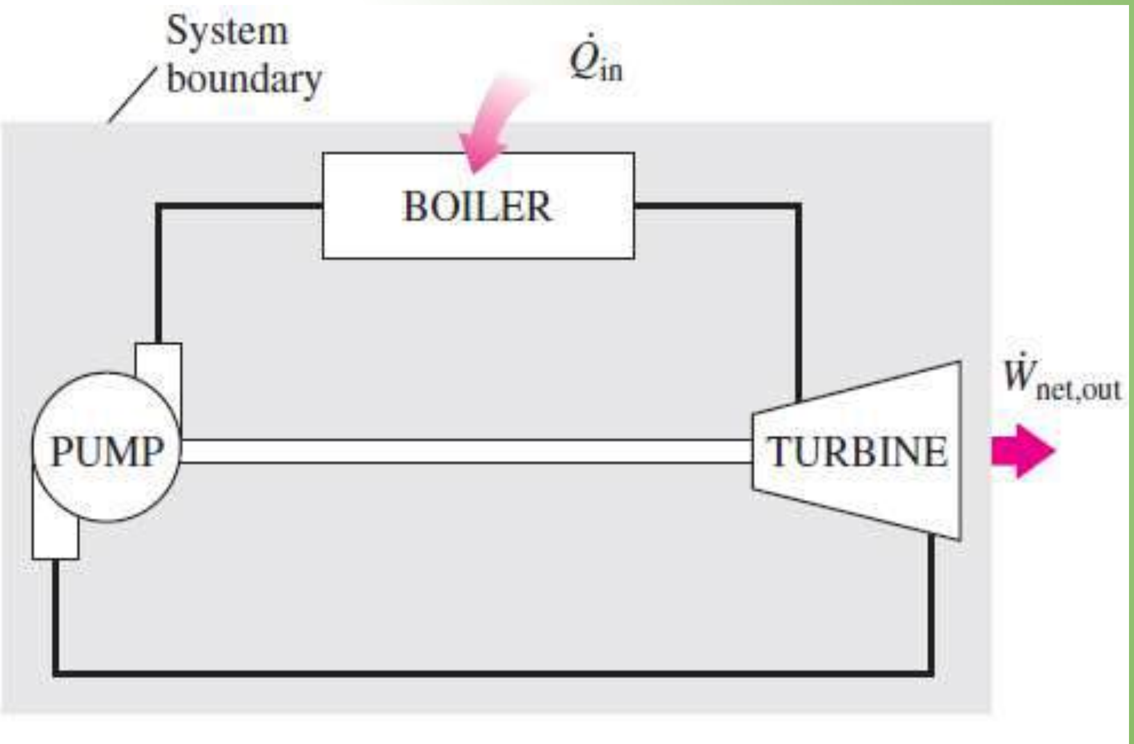
1. The food compartment of a refrigerator is maintained at 4°C by removing heat from it at a rate of 420 kJ/min. If the required power input to the refrigerator is 3 kW, determine (a) the COP and (b) the rate of het rejection into the room housing the refrigerator.
2. A heat pump is used to meet the heating requirements of a house to maintain it at 25 °C. On a day when the outdoor air temperature drops to – 4°C, the house is estimated to loose heat at a rate of 90 MJ/h. If the COP of the heat pump under these conditions is 2.5; determine the (a) power consumption of heat pump and (b) rate of absorption of heat from outside cold atmosphere.

Perpetual Motion Machines

- PMM 1



- PMM 2



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19ME31 Engineering Thermodynamics (L16)

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Today's discussion

- Reversibility & Irreversibility
- Causes & Types
- The Carnot & Reversed Carnot cycles

Directionality of processes

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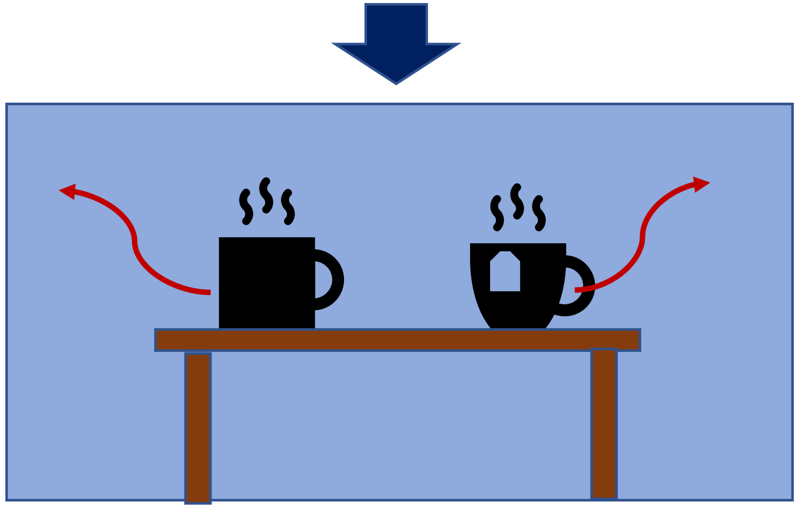
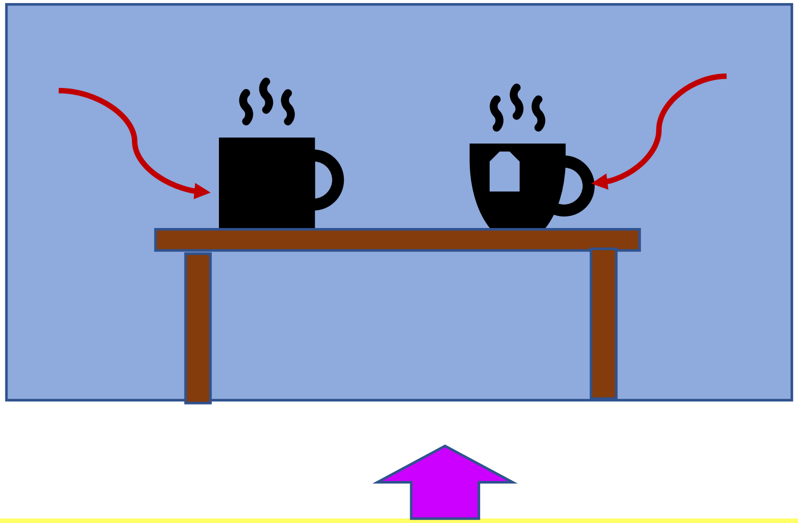




- I law is still not violated, but does this happen?

- I law is not violated, the total energy is constant

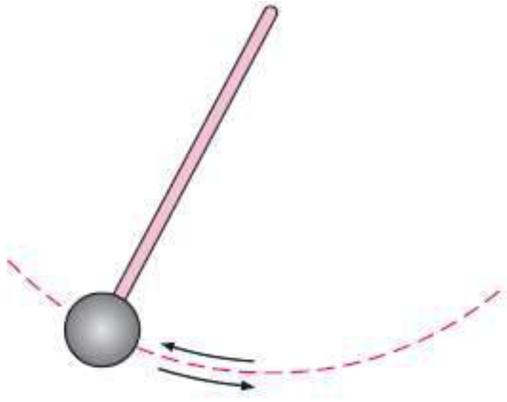
All process in nature have a natural direction

Reversible & Irreversible Process

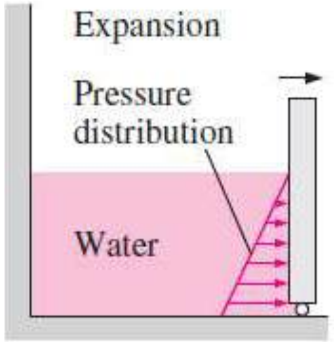
- Reversible process
  - A process is said to be reversible if the system can be restored to its initial state, without leaving any trace on the surroundings;
  - Both system & surroundings are restored to their initial states
  - Possible only when net heat interaction and net work interaction of the system with the surroundings is zero.
  - Deliver most work & consume least work; theoretical limit
  - Idealizations; do not occur in nature.
- Irreversible process
  - All processes that are not reversible
  - Eg. – all real processes

Examples

Reversible process

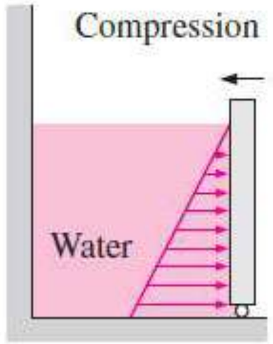


Frictionless pendulum



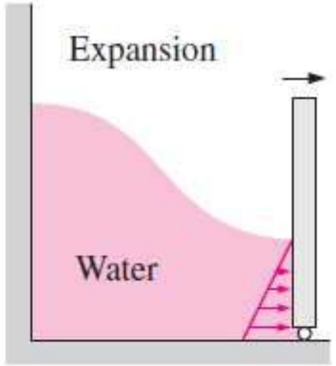
Slow expansion

Quasi-equilibrium expansion and compression of a gas

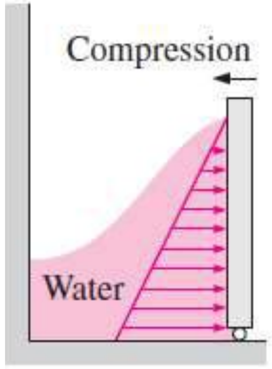


Slow compression

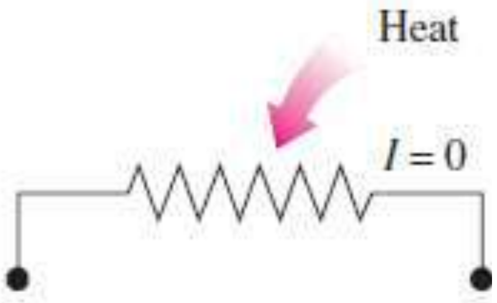
Irreversible process

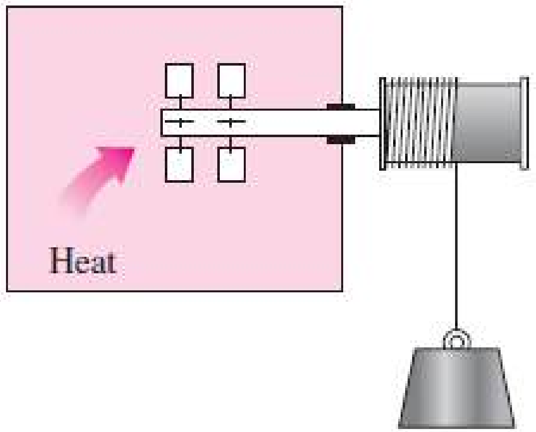


Fast expansion



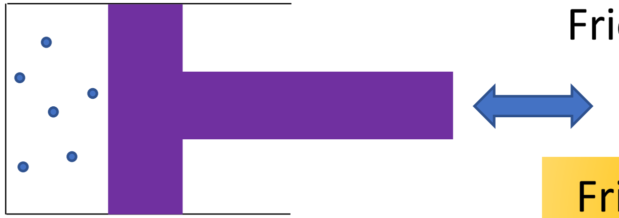
Fast compression





Causes of irreversibility

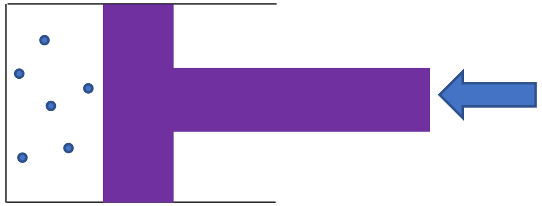
Friction



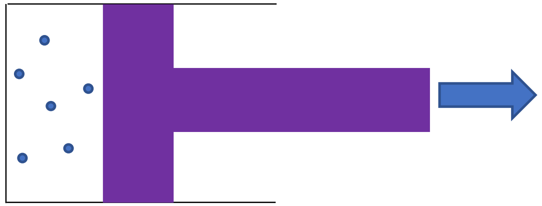
Friction includes fluid friction

Friction between two people also results in irreversibility !!

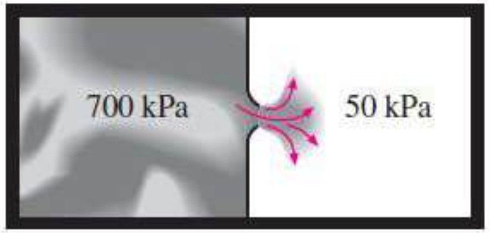
Non-quasi static expansion and compression



Fast compression

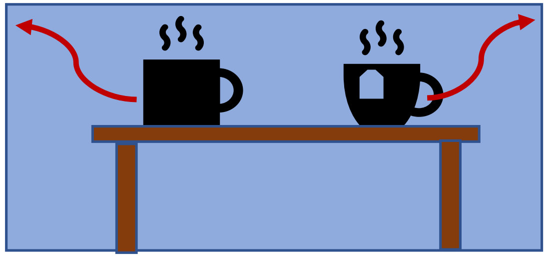


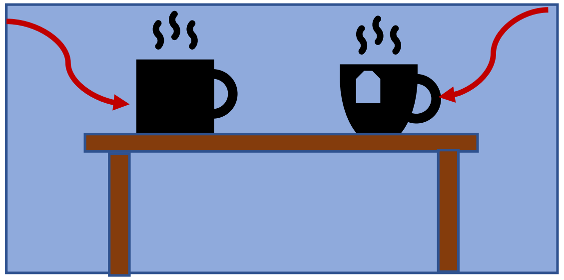
Fast expansion



Unrestrained expansion

Heat Transfer





Others – electric resistance, inelastic deformation of solids, chemical reactions, etc.

Types of reversible processes

Internally reversible

- no irreversibilities occur within the boundaries of the system during the process
- The system passes through exactly the same equilibrium states while returning to its initial state
- Forward & reverse processes coincide. Eg., a quasi-equilibrium process.

Externally reversible

- no irreversibilities occur outside the system boundaries during the process
- Eg., HT between a system & a reservoir wherein the surface of contact between the system & reservoir is at the same temperature as that of the reservoir.

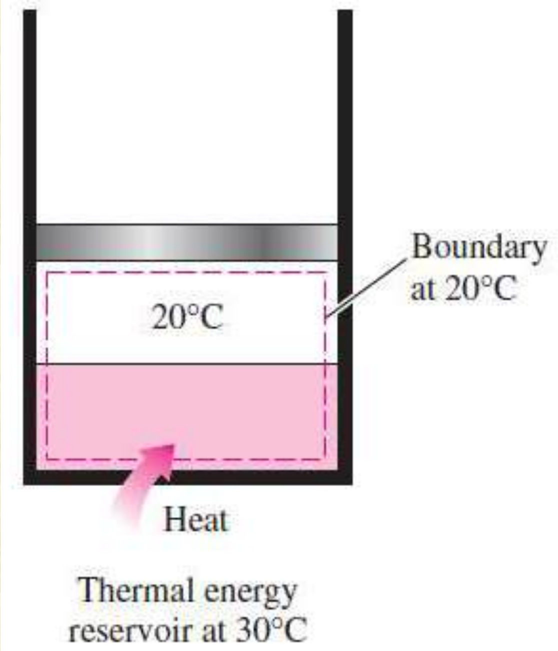
Totally reversible (or reversible)

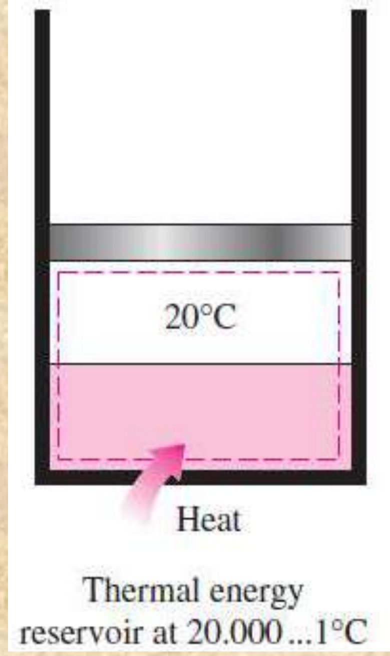
- Both internally and externally reversible.

Reversible or Irreversible Process?

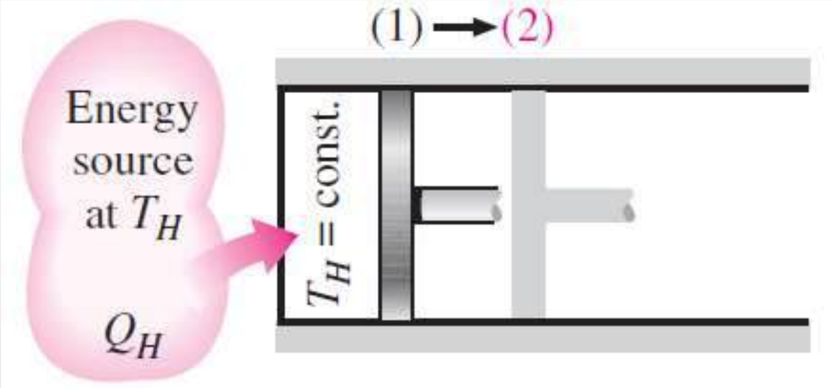
Internally Reversible	Externally Reversible	Resulting Process
Yes	Yes	Reversible
Yes	No	Irreversible
No	Yes	Irreversible
No	No	Irreversible

Classify the processes



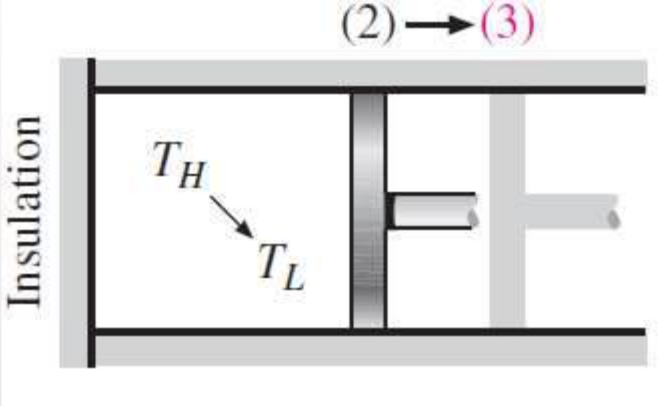


The Carnot Cycle



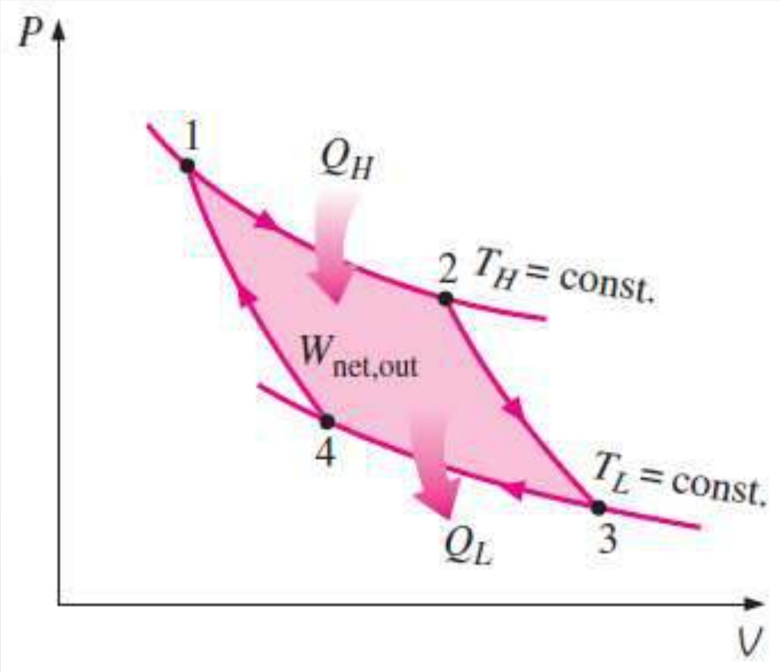
(*a*) Process 1-2

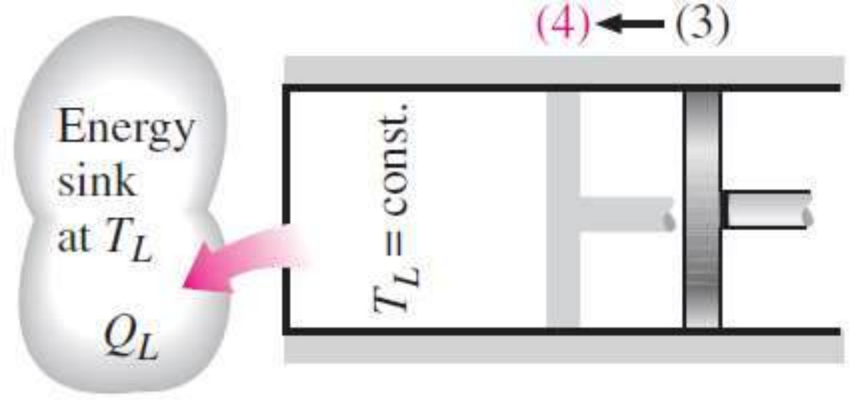
Reversible isothermal expansion



(*b*) Process 2-3

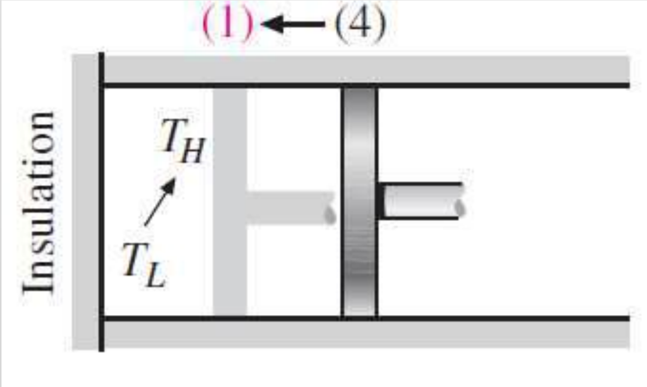
Reversible adiabatic expansion





(*c*) Process 3-4

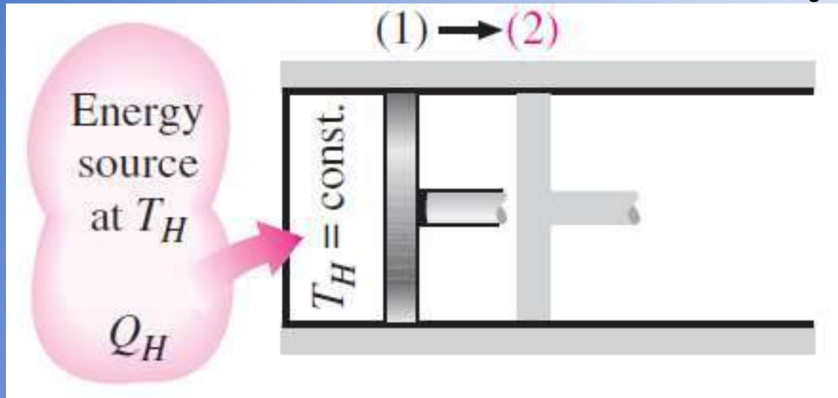
Reversible isothermal compression



(*d*) Process 4-1

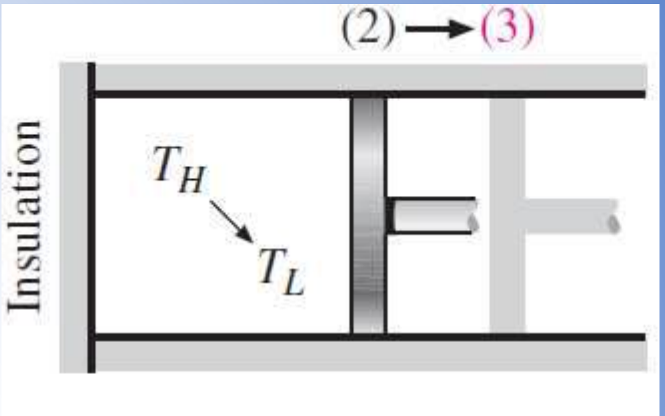
Reversible adiabatic compression

The reversed Carnot Cycle



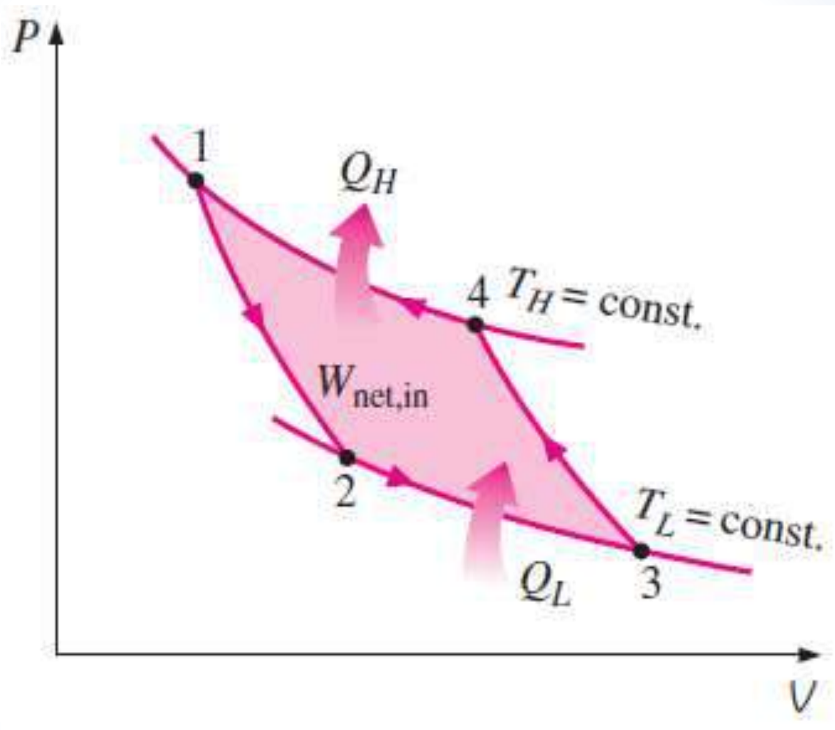
(*a*) Process 1-2

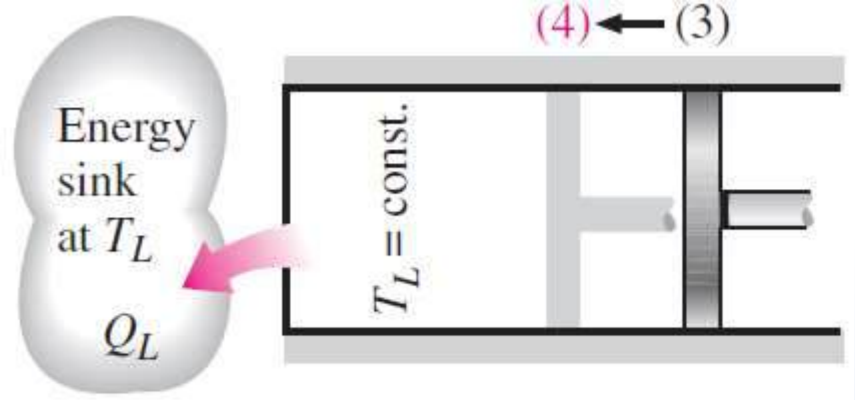
Reversible isothermal expansion



(*b*) Process 2-3

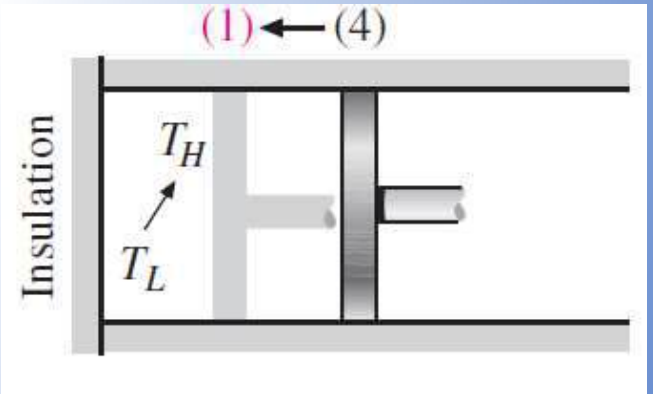
Reversible adiabatic expansion





(*c*) Process 3-4

Reversible isothermal compression



(*d*) Process 4-1

Reversible adiabatic compression

Assignment - Identify the mistakes

References

1. Yunus A Cengel and Michael A Boles, "Thermodynamics – an Engineering Approach", 3rd Edition, Tata Mc Graw Hill, 2002.
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19ME31 Engineering Thermodynamics (L17)

Dr A S Krishnan / Mr Sam Solomon

Faculty of Mechanical Engineering

Coimbatore Institute of Technology

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3. Depict various thermodynamic processes on property diagrams, estimate properties of mixtures and quantify deviation from ideal gas behavior.
4. Calculate changes in properties during different ideal gas processes

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- Second Law of Thermodynamics
- Entropy & Exergy
- Thermodynamic Relations and Ideal Gas Mixtures

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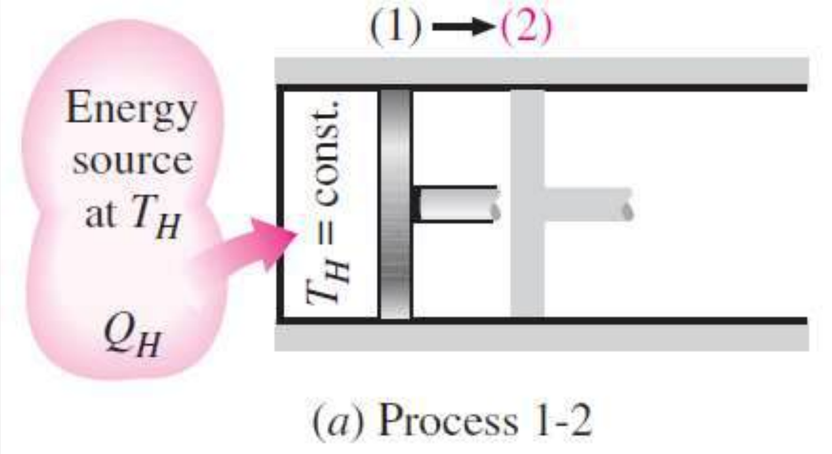
SNo	Topic	Hours
1	II Law – Statements of Kelvin Planck and Clausius; Equivalence	2
2	Thermal energy reservoirs, Heat engines, Refrigerators and Heat Pumps; PMM 2	2
3	Reversibility and Irreversibility – causes of irreversibility – types of irreversibility	2
4	Carnot – Reversed Carnot cycle – Carnot’s theorem – Absolute Thermodynamic temperature scale	2

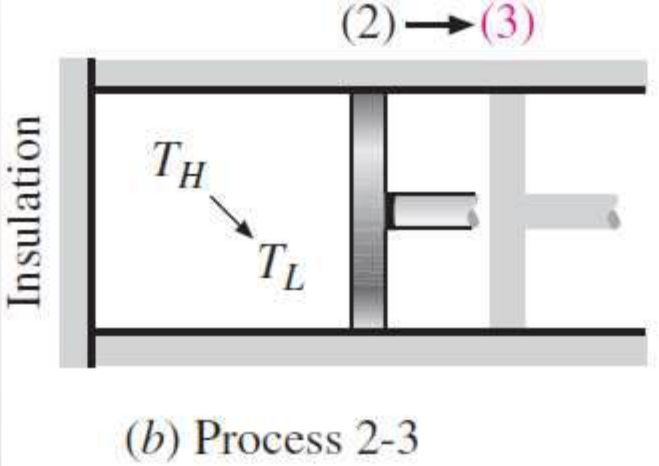
Today's discussion

- The Carnot & Reversed Carnot cycles
- Carnot Principles
- The Thermodynamic temperature scale

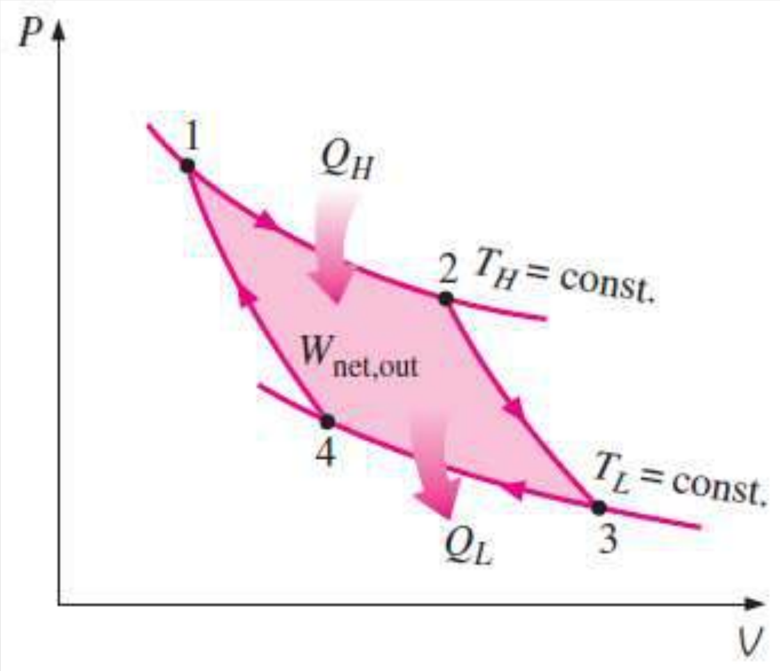
The Carnot Cycle

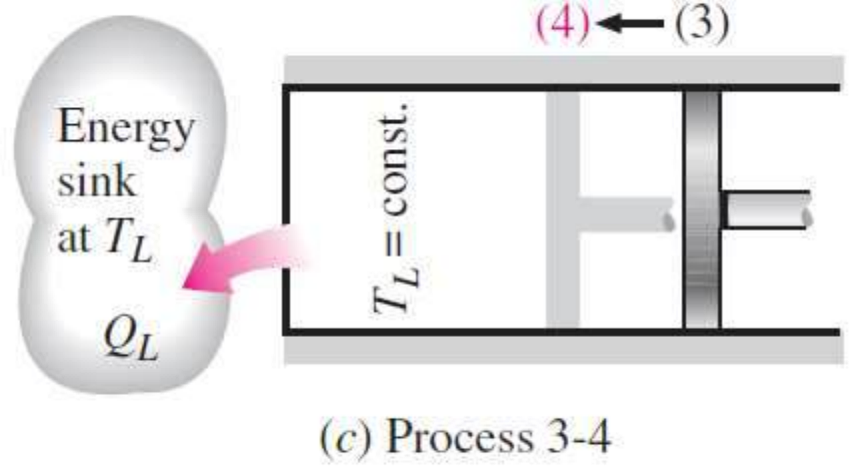


Reversible isothermal expansion

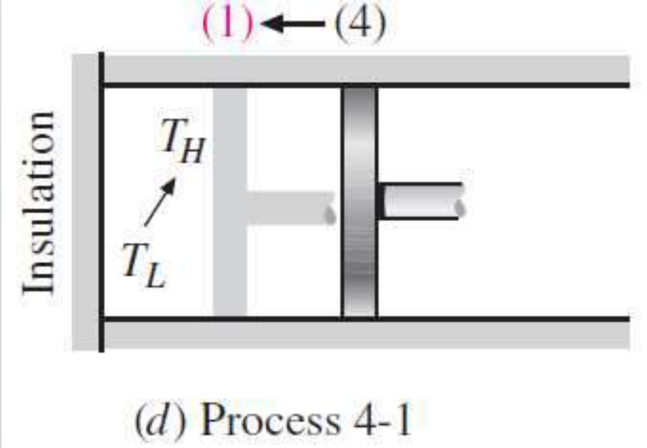


Reversible adiabatic expansion



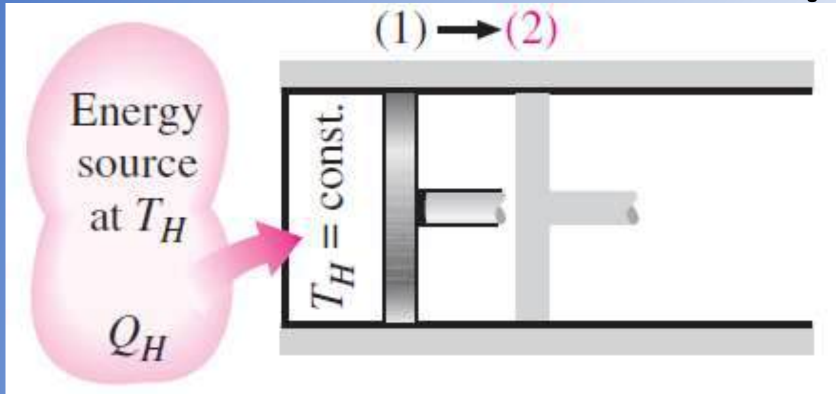


Reversible isothermal compression



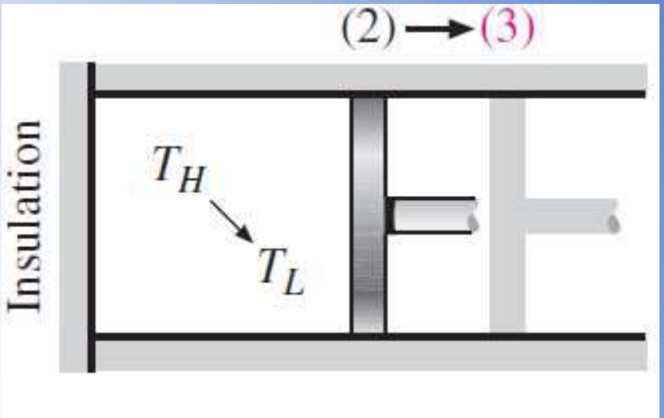
Reversible adiabatic compression

The reversed Carnot Cycle



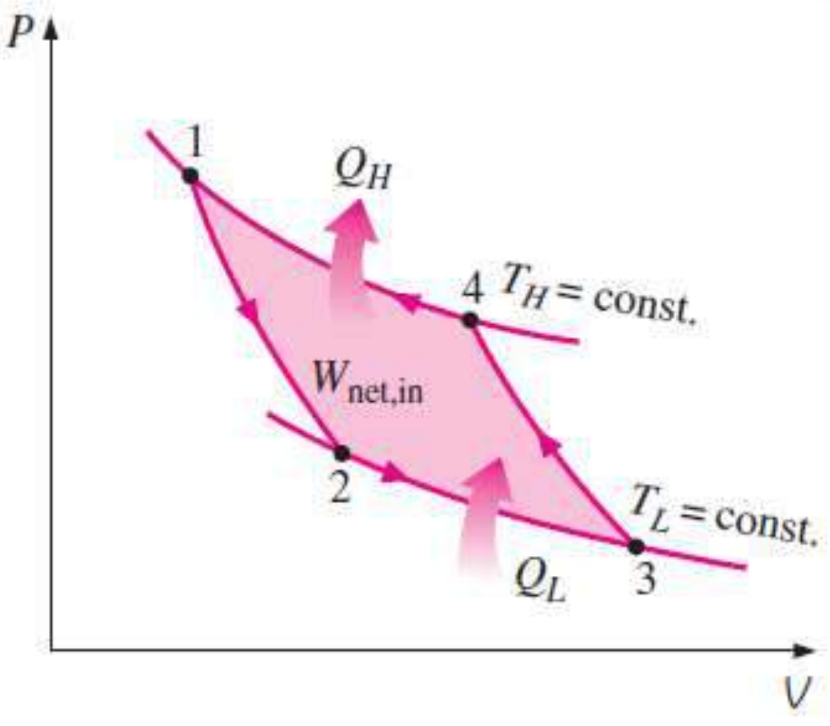
(*a*) Process 1-2

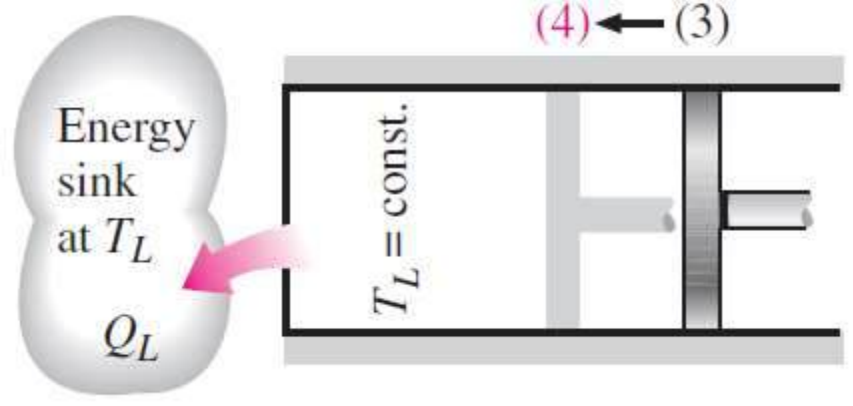
Reversible isothermal expansion



(*b*) Process 2-3

Reversible adiabatic expansion

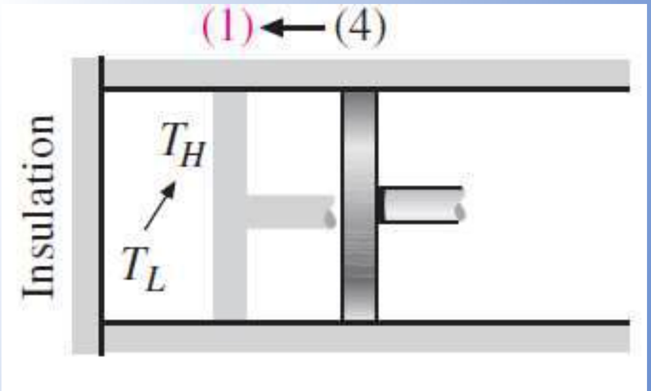




(*c*) Process 3-4

Reversible isothermal compression

Assignment - Identify the mistakes



(*d*) Process 4-1

Reversible adiabatic compression

Nicholas Leonard Sadi Carnot (1796-1832)

- Member of an illustrious family
- Studied at Ecole Polytechnique; Officer in the French Army Engineers
- An accomplished athlete
- Reflections on the Motive Power of Heat – only paper published; but a milestone of scientific thought
- Originated use of cycles in thermodynamic analysis
- Laid foundation for II law of thermodynamics

https://www.comsol.com/blogs/happy-birthday-nicolas-leonard-sadi-carnot/

Carnot Corollaries (or principles)

- Heat Engines
  1. No engine can be more efficient than a reversible heat engine *operating between the same reservoirs*.
  2. The efficiencies of all reversible engines operating *between the same reservoirs* are same.
- Refrigerators & Heat Pumps
  1. No refrigerator can have a higher COP than a reversible refrigerator operating *between the same reservoirs.*
  2. The COPs of all reversible refrigerators operating *between the same reservoirs are same*.

Same reservoirs means the same temperature limits

Proof of Carnot's corollary 1 for heat engines

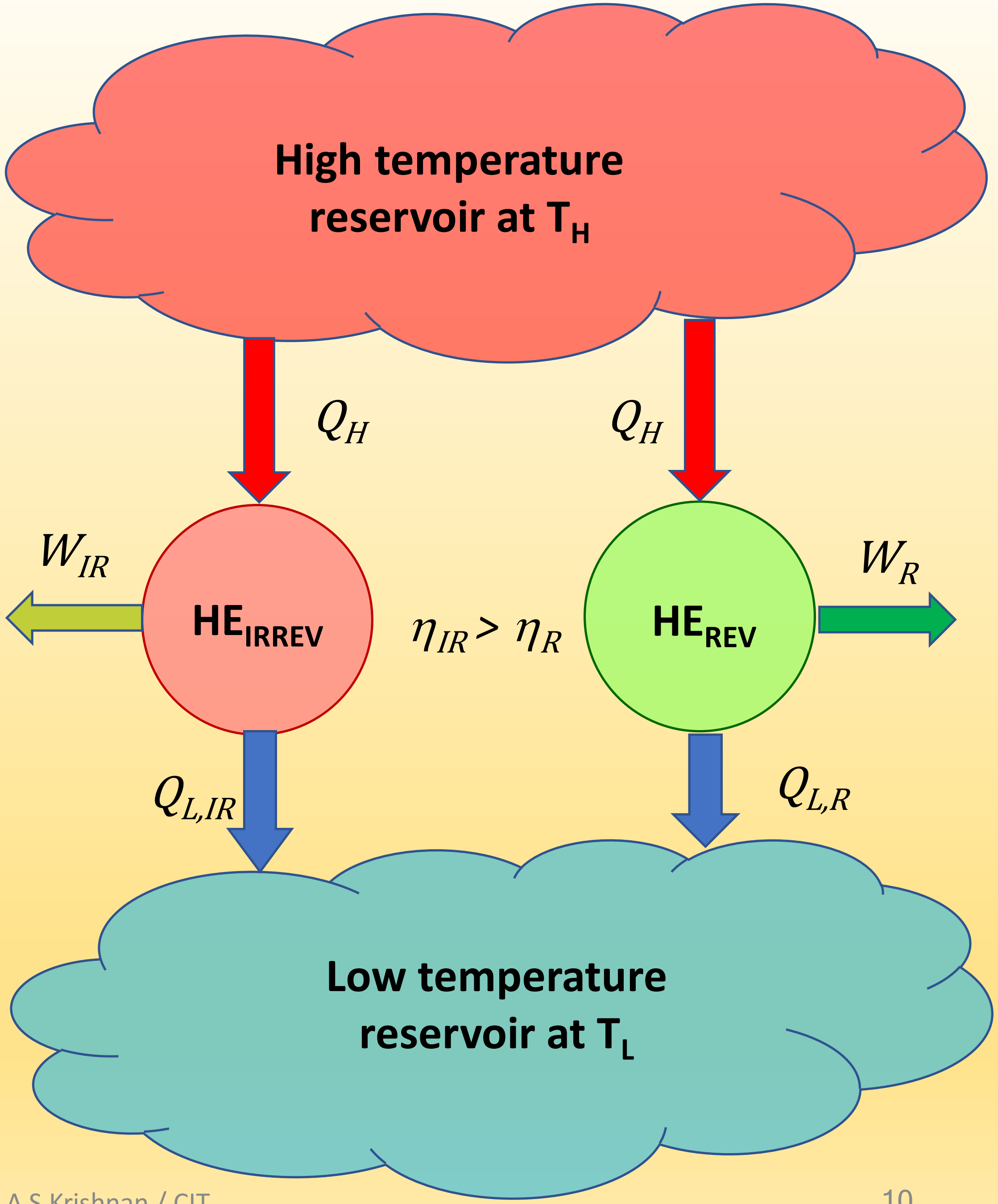
No engine can be more efficient than a reversible heat engine operating between the same reservoirs.

- Consider 2 engines – 1 reversible and other irreversible operating between same two reservoirs.
- Assume the irreversible engine to be more efficient than a reversible engine
- Then,

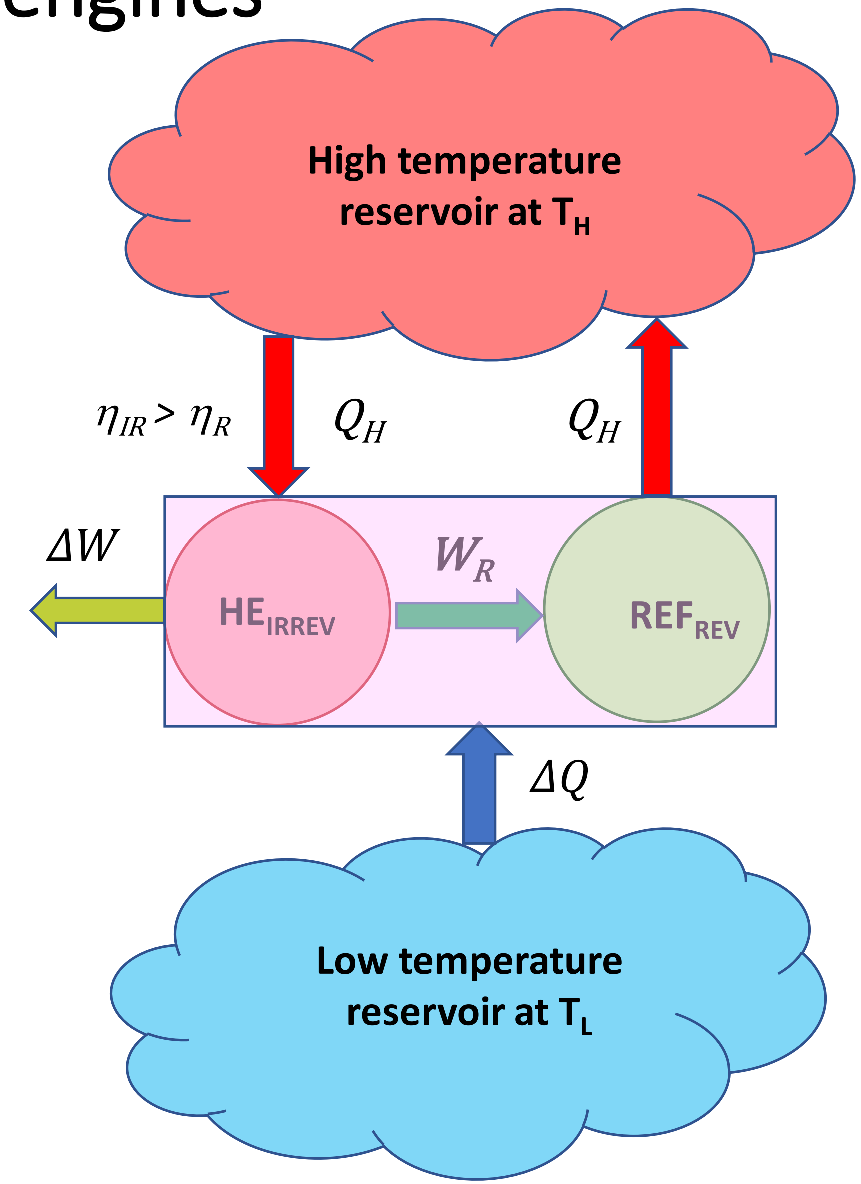
$$W_{IR} > W_R \quad \text{and} \quad Q_{L,IR} < Q_{L,R}$$

Let

$$\Delta W = W_{IR} - W_R \quad \text{and} \quad \Delta Q = Q_{L,R} - Q_{L,IR}$$

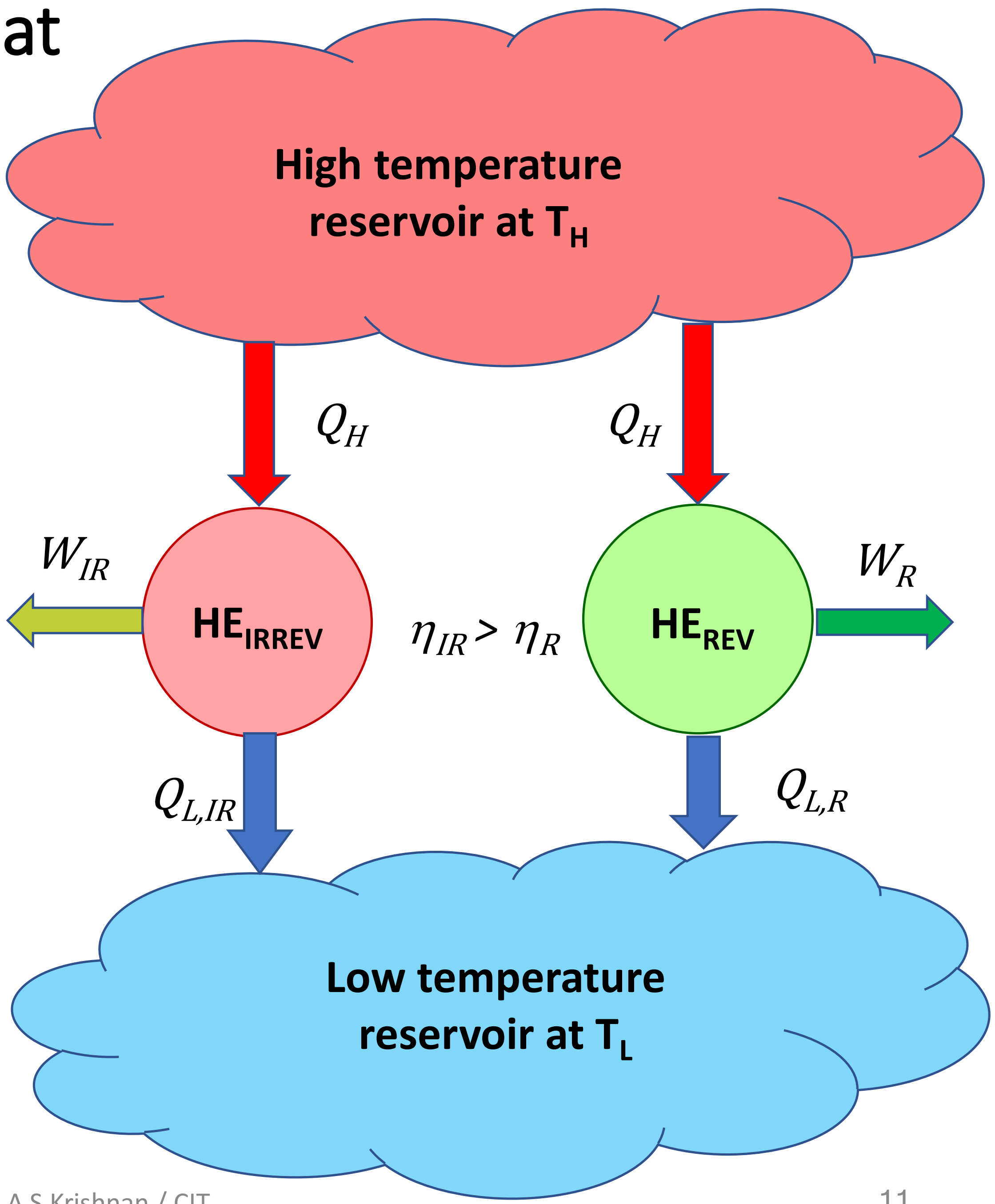


Proof of Carnot's corollary 1 for heat engines

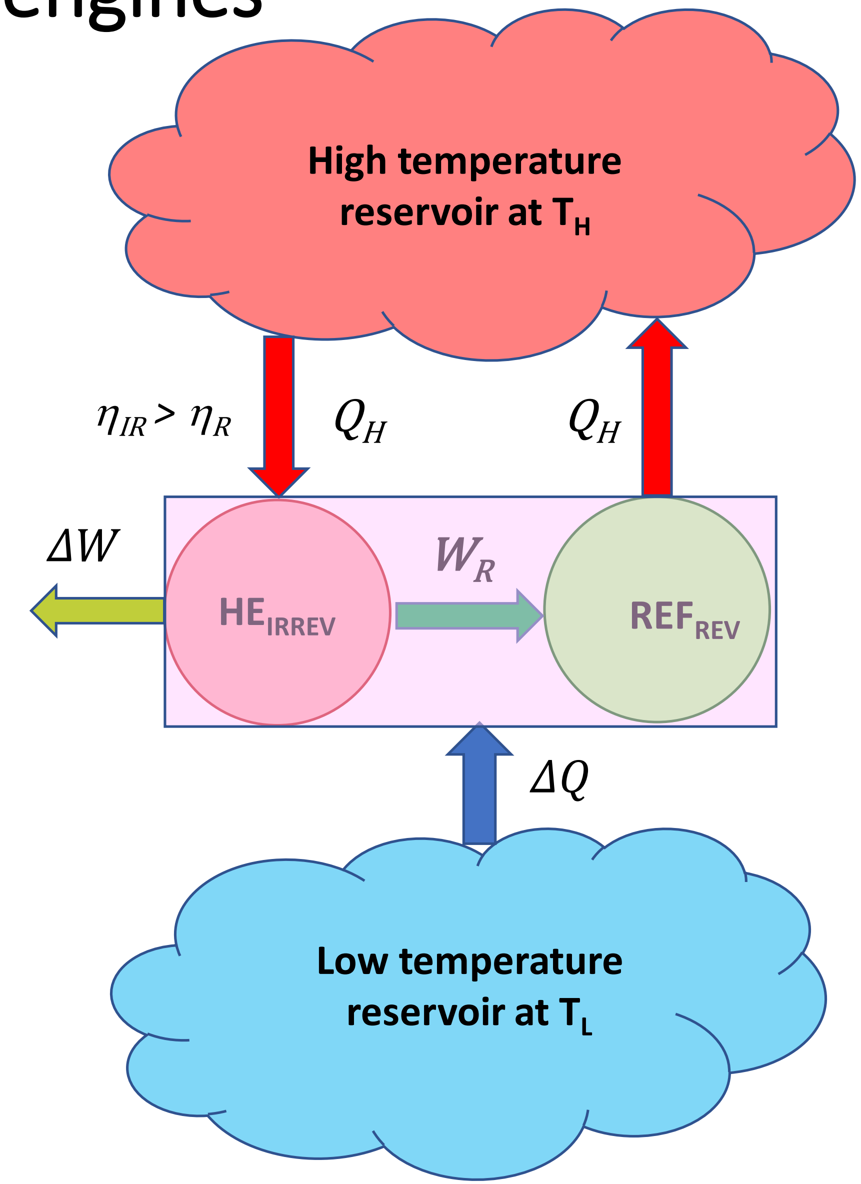


$$\Delta W = W_{IR} - W_R$$

$$\Delta Q = Q_{L,R} - Q_{L,IR}$$

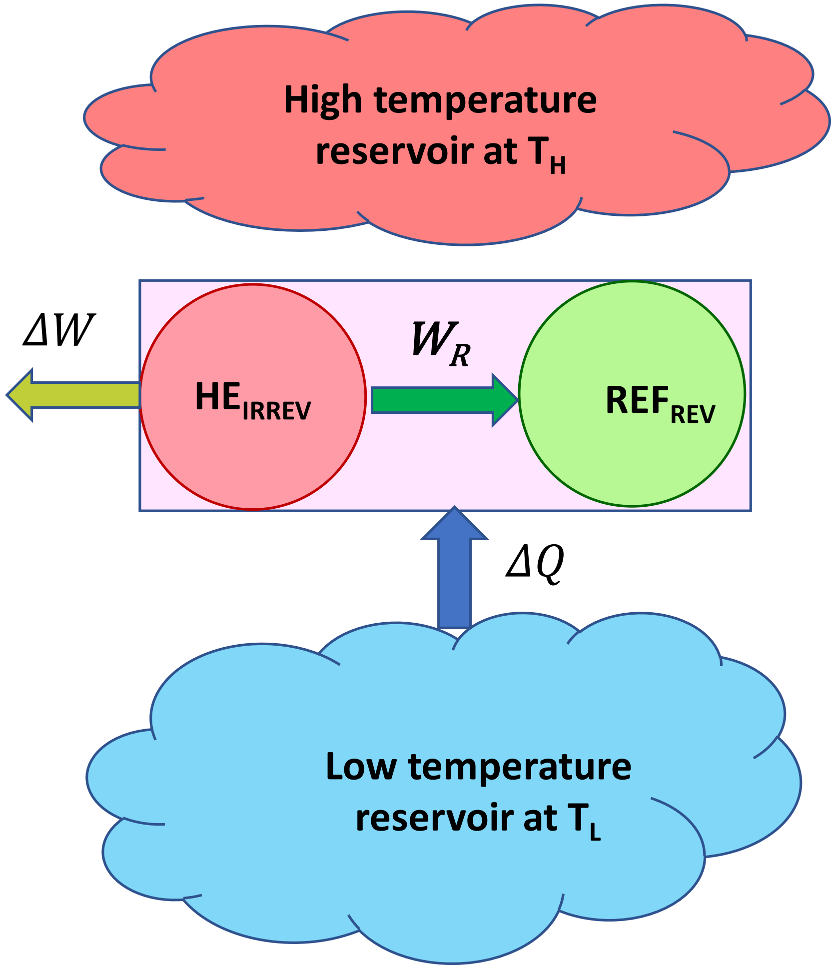


Proof of Carnot's corollary 1 for heat engines

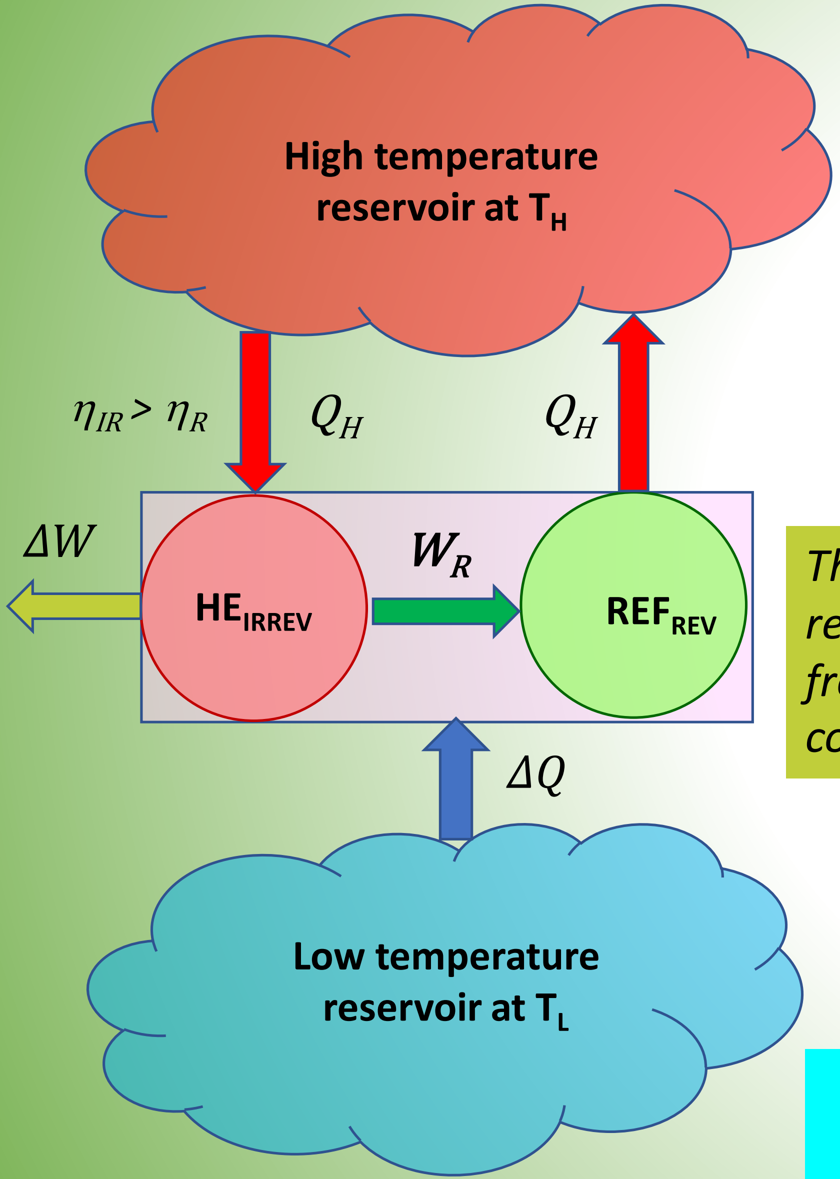


$$\Delta W = W_{IR} - W_R$$

$$\Delta Q = Q_{L,R} - Q_{L,IR}$$



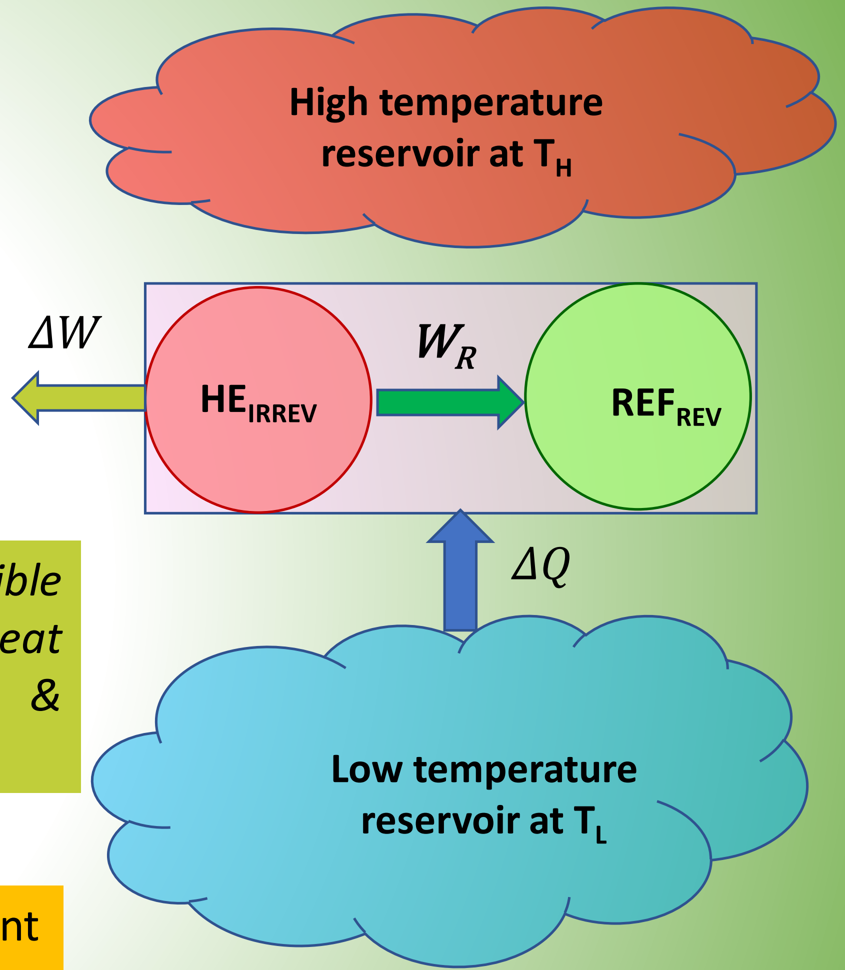
Proof of Carnot's corollary 1 for heat engines (contd.)



1. Reverse the operation of the reversible heat engine, i.e. operate it as a reversible refrigerator (or a heat pump)
2. Combine the irreversible heat engine & reversible refrigerator as a single device

The combined irreversible engine & reversible refrigerator is a device that receives heat from a lower temperature reservoir & convert to an equivalent work !

Violation of the Kelvin Planck's statement of II law of thermodynamics



A similar argument can be used to prove the 2nd corollary of Carnot for Heat Engines, and for the Carnot principles for the refrigerator & heat pump as well

The thermodynamic temperature scale

- Three reversible engines – A, B & C
- B operating @ intermediate temperature T_2
- The combined reversible engines A & B should be equivalent to the reversible engine C (2nd corollary of Carnot for heat engines)
- By 2nd corollary of Carnot for heat engines, $\eta_{th} = f(T_H, T_L)$

Also $\eta_{th} = 1 - \dfrac{Q_L}{Q_H}$ ➡ $\dfrac{Q_H}{Q_L} = g(T_H, T_L)$ Now

$$\frac{Q_1}{Q_2} = g(T_1, T_2) \qquad \frac{Q_2}{Q_3} = g(T_2, T_3) \qquad \frac{Q_1}{Q_3} = g(T_1, T_3) \qquad \frac{Q_1}{Q_3} = \frac{Q_1}{Q_2} \cdot \frac{Q_2}{Q_3}$$

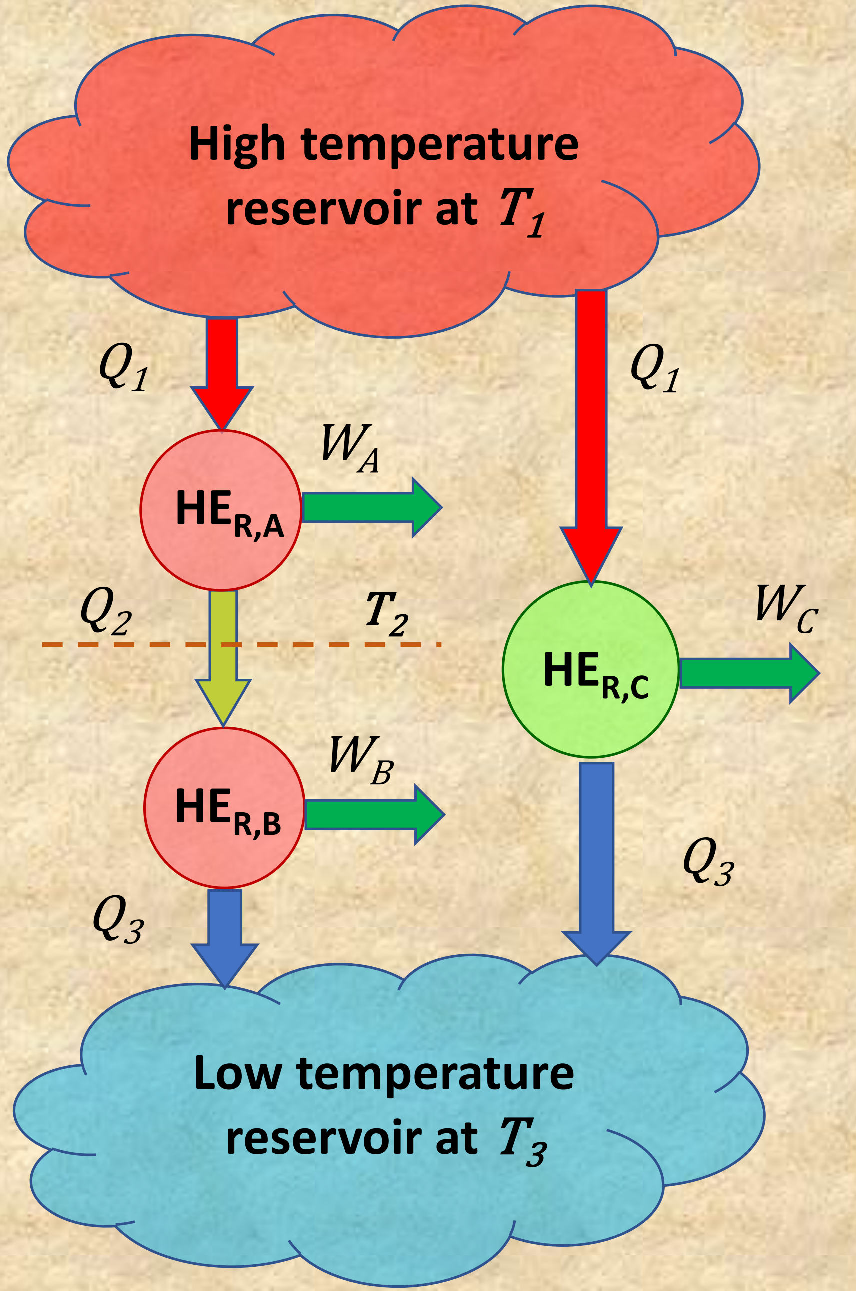
$$g(T_1, T_3) = g(T_1, T_2) \cdot g(T_2, T_3)$$

Possible only if

$$g(T_2, T_3) = \frac{\Psi(T_2)}{\Psi(T_3)} \quad \& \quad g(T_1, T_2) = \frac{\Psi(T_1)}{\Psi(T_2)}$$

$$g(T_1, T_3) = \frac{\Psi(T_1)}{\Psi(T_2)} \cdot \frac{\Psi(T_2)}{\Psi(T_3)} = \frac{\Psi(T_1)}{\Psi(T_3)} \Rightarrow \frac{Q_1}{Q_3} = \frac{\Psi(T_1)}{\Psi(T_3)} \Rightarrow \frac{Q_H}{Q_L} = \frac{\Psi(T_H)}{\Psi(T_L)} = \frac{T_H}{T_L}$$

Proposed by Lord Kelvin



Efficiency of a Carnot Engine

Working fluid – ideal gas

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} \qquad \eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} \qquad \eta_{th} = 1 - \frac{Q_L}{Q_H}$$

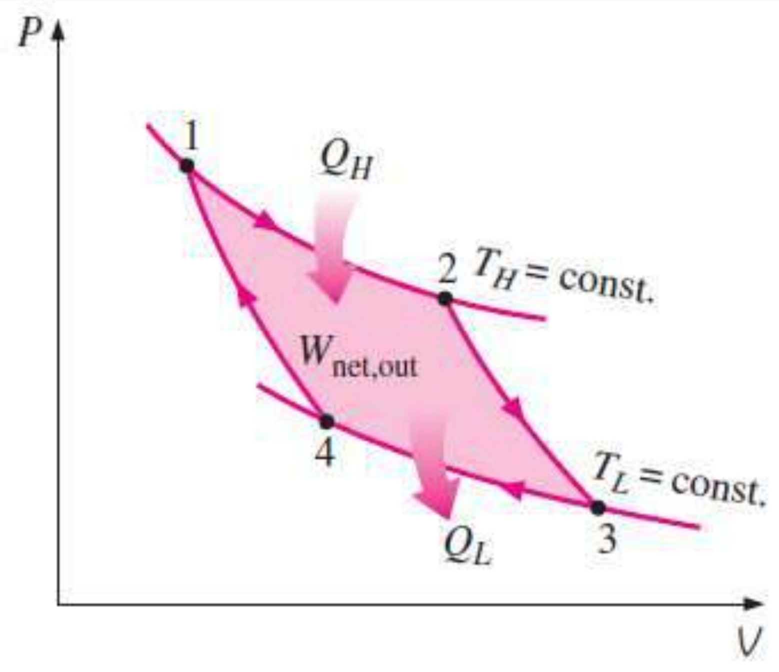
$$Q_H - W_{1-2} = \Delta U_{1-2} \quad (\Delta U_{1-2} \rightarrow 0) \qquad Q_H = \int_1^2 pdV = mRT_H \int_1^2 \frac{dV}{V} = mRT_H ln\frac{V_2}{V_1}$$

Likewise

$$-Q_L + W_{3-4} = \Delta U_{3-4} \quad (\Delta U_{3-4} \rightarrow 0) \Rightarrow Q_L = -W_{3-4}$$

Note the additional –ive sign

$$Q_L = -\int_3^4 pdV = -mRT_L \int_3^4 \frac{dV}{V} = -\,mRT_L ln\frac{V_4}{V_3} = mRT_L ln\frac{V_3}{V_4}$$



Processes (2-3) & (4-1) are adiabatic

$$\eta_{th} = 1 - \frac{T_L ln(V_3/V_4)}{T_H ln(V_2/V_1)} \Rightarrow \boldsymbol{\eta_{th} = 1 - \frac{T_L}{T_H}}$$

$$\frac{V_3}{V_4} = \frac{V_2}{V_1} \Leftarrow \frac{V_3}{V_2} = \frac{V_4}{V_1}$$

$$\frac{V_3}{V_2} = \left(\frac{T_2}{T_3}\right)^{\frac{1}{\gamma-1}} = \left(\frac{T_H}{T_L}\right)^{\frac{1}{\gamma-1}}$$

$$\frac{V_4}{V_1} = \left(\frac{T_1}{T_4}\right)^{\frac{1}{\gamma-1}} = \left(\frac{T_H}{T_L}\right)^{\frac{1}{\gamma-1}}$$

How?

Thermal efficiency of a Carnot engine is a function of ratio of the temperatures of the reservoirs

A similar argument can be used to prove the COP of a Carnot refrigerator (& heat pump) is a function of ratio of the temperatures of the reservoirs

References

1. Yunus A Cengel and Michael A Boles, "Thermodynamics – an Engineering Approach", 3rd Edition, Tata Mc Graw Hill, 2002.
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3. www.comsol.com

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19ME31 Engineering Thermodynamics (L18) 7th Oct 2020

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2	Thermal energy reservoirs, Heat engines, Refrigerators and Heat Pumps; PMM 2	2
3	Reversibility and Irreversibility – causes of irreversibility – types of irreversibility	2
4	Carnot – Reversed Carnot cycle – Carnot's theorem – Absolute Thermodynamic temperature scale	2

Today's discussion

Performance of Carnot HEs, Refs & HPs

Numerical Examples

Efficiency of a Carnot Engine

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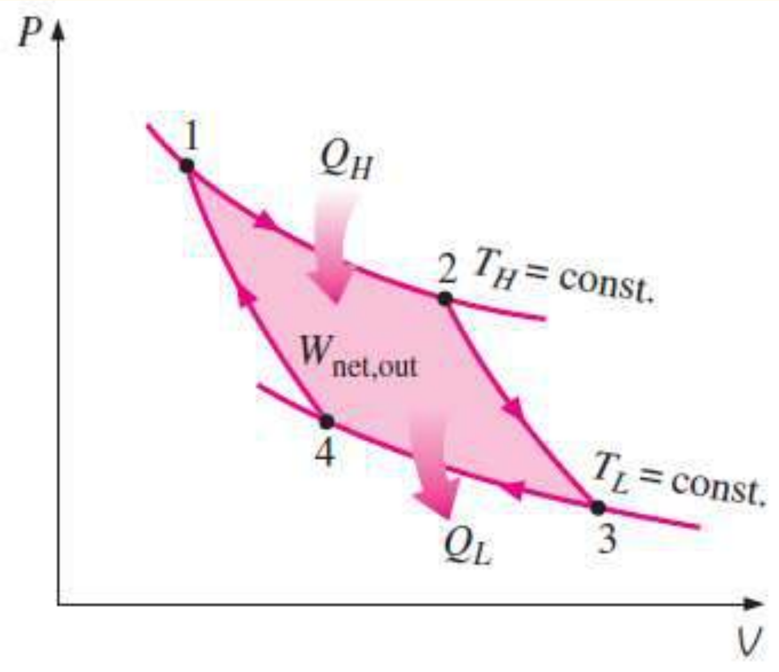

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$$\eta_{th} = 1 - \frac{T_L \ln(V_3/V_4)}{T_H \ln(V_2/V_1)} \Rightarrow \boldsymbol{\eta_{th} = 1 - \frac{T_L}{T_H}}$$

$$\frac{V_3}{V_4} = \frac{V_2}{V_1} \Leftarrow \frac{V_3}{V_2} = \frac{V_4}{V_1}$$

$$\frac{V_3}{V_2} = \left(\frac{T_2}{T_3}\right)^{\frac{1}{\gamma-1}} = \left(\frac{T_H}{T_L}\right)^{\frac{1}{\gamma-1}}$$

$$\frac{V_4}{V_1} = \left(\frac{T_1}{T_4}\right)^{\frac{1}{\gamma-1}} = \left(\frac{T_H}{T_L}\right)^{\frac{1}{\gamma-1}}$$

How?

Thermal efficiency of a Carnot engine is a function of ratio of the temperatures of the reservoirs

A similar argument can be used to prove the COP of a Carnot refrigerator (& heat pump) is a sole function of ratio of the temperatures of the reservoirs

Performance of Carnot devices

Heat engine

$$\eta_{th} = \frac{Net\ work\ output}{Total\ heat\ input}$$

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

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

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

$$\boldsymbol{\eta_{th} = 1 - \frac{T_L}{T_H}}$$

Refrigerator

$$COP = \frac{Heat\ absorbed}{Work\ input}$$

$$COP_R = \frac{Q_L}{Q_H - Q_L}$$

$$COP_R = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

$$COP_R = \frac{1}{\frac{T_H}{T_L} - 1}$$

$$\boldsymbol{COP_R = \frac{T_L}{T_H - T_L}}$$

Heat pump

$$COP = \frac{Heat\ rejected}{Work\ input}$$

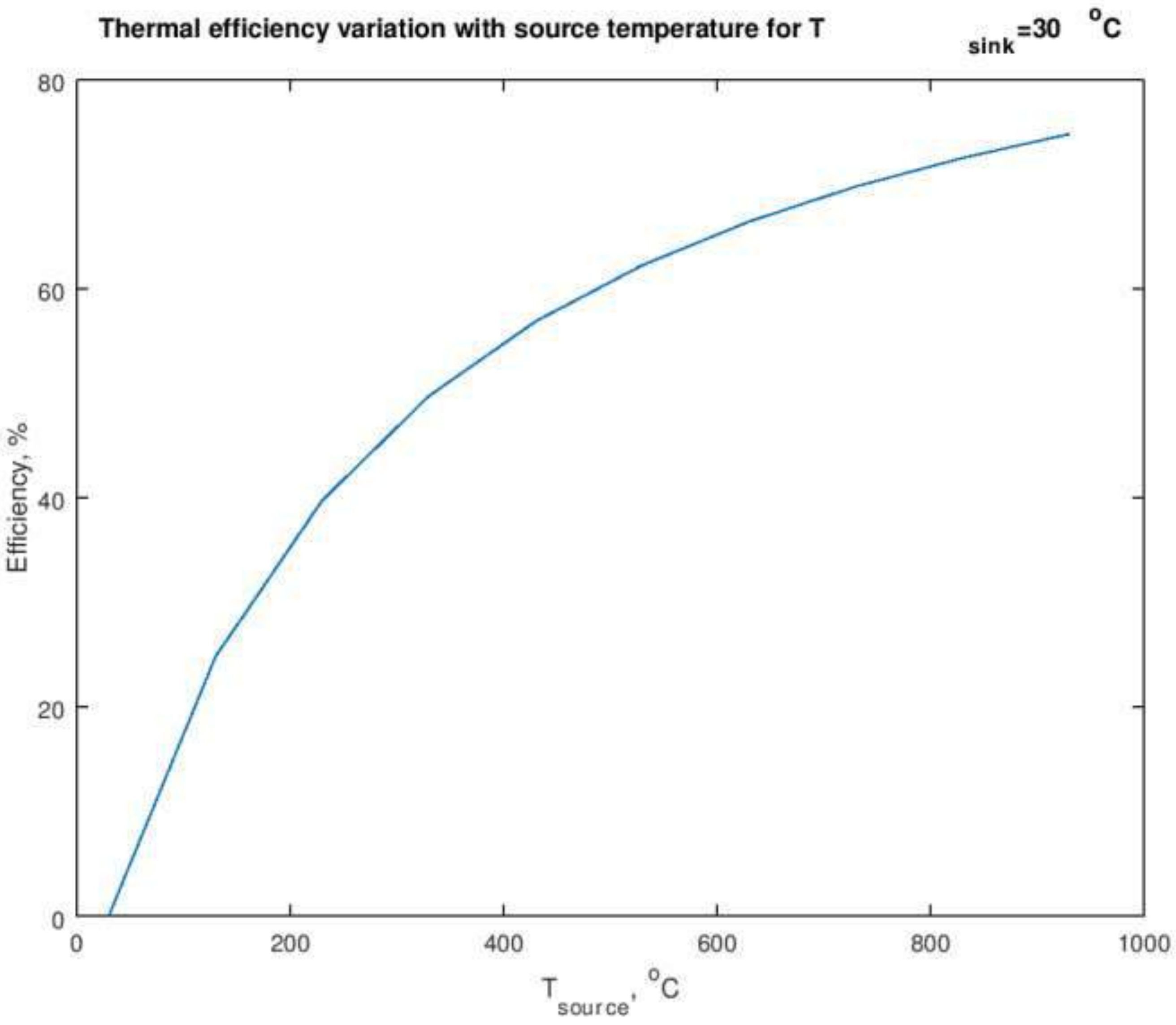
$$COP_{HP} = \frac{Q_H}{Q_H - Q_L}$$

$$COP_{HP} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

$$COP_{HP} = \frac{1}{1 - \frac{T_L}{T_H}}$$

$$\boldsymbol{COP_{HP} = \frac{T_H}{T_H - T_L}}$$

Temperature dependence of performance



Numerical examples

1. An automobile engine consumes fuel at a rate of 20 L/h and delivers 60 kW of power to the wheels. If the fuel has a heating value of 44 MJ/kg and a density of 800 kg/m^3, determine the efficiency of the engine.
2. A household refrigerator that consumes a power input of 450 W has a COP of 2.5. It is used to cool 5 large watermelons, 10 kg each from a temperature of 20°C to 8°C. Treating the water melon as water whose specific heat is 4.2 kJ/kgK, determine how long it would take for the refrigerator to cool them. Is your answer realistic (or) optimistic? Explain
3. A heat pump is used to maintain a house at a constant temperature of 23 ° C. The house looses heat to the outside air through the walls, roof and windows at a rate of 60 MJ/h, while the energy generated within the house from the people, lights and appliances amount to 4 MJ/h. If the COP of the heat pump is 2.5, determine the power required for the heat pump.
4. A Carnot heat engine operates between a source at 1000 K and a sink at 300 K. If the heat engine is supplied with heat at a rate of 800 kJ/min, determine the (a) thermal efficiency and (b) power output of the engine.

Numerical examples

5. A Carnot heat engine receives 500 kJ of heat from a source of unknown temperature and rejects 200 kJ of it to a sink at 17°C. Determine the (a) temperature of the source and (b) thermal efficiency of the heat engine.

6. An inventor claims to have developed a heat engine that receives 800 kJ of heat from a source at 400 K and produces 250 kJ of net work while rejecting the waste heat to a sink at 300 K. Is the claim reasonable? Justify.

7. During an experiment conducted in a room at 25°C, a laboratory assistant measures that a refrigerator draws 2kW of power has removed a heat of 30 MJ of heat in 20 minutes from a refrigerated space at -30°C. Determine if these measurements are reasonable.

8. A Carnot heat engine receives heat from a reservoir at 900 C at a rate of 800 kJ/min and rejects waste heat to the ambient air at 27°C. The entire work output of the engine is used to drive a refrigerator that removes heat from the refrigerated space at -5°C and transfers it to the same ambient air at 27°C. Determine the (a) maximum rate of heat removal from the refrigerated space and (b) total rate of heat rejection to the ambient air.

References

1. Yunus A Cengel and Michael A Boles, “Thermodynamics – an Engineering Approach”, 3rd Edition, Tata Mc Graw Hill, 2002.

Textbooks

1. Yunus A. Cengel, Introduction to Thermodynamics and Heat Transfer, McGraw-Hill Companies, Inc., 2nd Edition, 2017.
2. Nag P K., Engineering Thermodynamics, Tata McGraw Hill, 2019.
3. www.comsol.com

Suggested readings

1. Van Wylen, Fundamentals of Thermodynamics, John Wiley and Sons, 9th Edition, 2018.
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3. Mahesh M. Rathore, Thermal Engineering, Tata McGraw Hill, 2018.
4. C. P. Kothandaraman and Domkundwar, A Course in Thermodynamics (Thermal Engineering), DhanpatRai and Co. Ltd., 2018.

19ME31 Engineering Thermodynamics (L18)
8th Oct 2020

Dr A S Krishnan / Mr Sam Solomon
Faculty of Mechanical Engineering
Coimbatore Institute of Technology

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4. Calculate changes in properties during different ideal gas processes

Overview of the topics

- Basic Concepts of Thermodynamics
- First Law of Thermodynamics
- Second Law of Thermodynamics
- Entropy & Exergy
- Thermodynamic Relations and Ideal Gas Mixtures

Entropy & Exergy

SNo	Topic	Hours
1	Entropy – Clausius Theorem, Clausius Inequality	2
2	Entropy of Isolated system	1
3	Entropy change of liquids, solids & ideal gases	2
4	Exergy – Reversible work and Irreversibility - II law efficiency	2
5	Exergy change for non flow system & flow streams	2
6	III law of Thermodynamics	1

Today's discussion

Entropy

Performance of Carnot devices

Heat engine

$$\eta_{th} = \frac{Net\ work\ output}{Total\ heat\ input}$$

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

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

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

$$\boldsymbol{\eta_{th} = 1 - \frac{T_L}{T_H}}$$

Refrigerator

$$COP = \frac{Heat\ absorbed}{Work\ input}$$

$$COP_R = \frac{Q_L}{Q_H - Q_L}$$

$$COP_R = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

$$COP_R = \frac{1}{\frac{T_H}{T_L} - 1}$$

$$\boldsymbol{COP_R = \frac{T_L}{T_H - T_L}}$$

Heat pump

$$COP = \frac{Heat\ rejected}{Work\ input}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L}$$

$$COP_{HP} = \frac{1}{1 - \frac{Q_L}{Q_H}}$$

$$COP_{HP} = \frac{1}{1 - \frac{T_L}{T_H}}$$

$$\boldsymbol{COP_{HP} = \frac{T_H}{T_H - T_L}}$$

Sub-dividing a reversible process

Work done $W_{1-2} = W_{1-b-c-2}$

By I law of thermodynamics

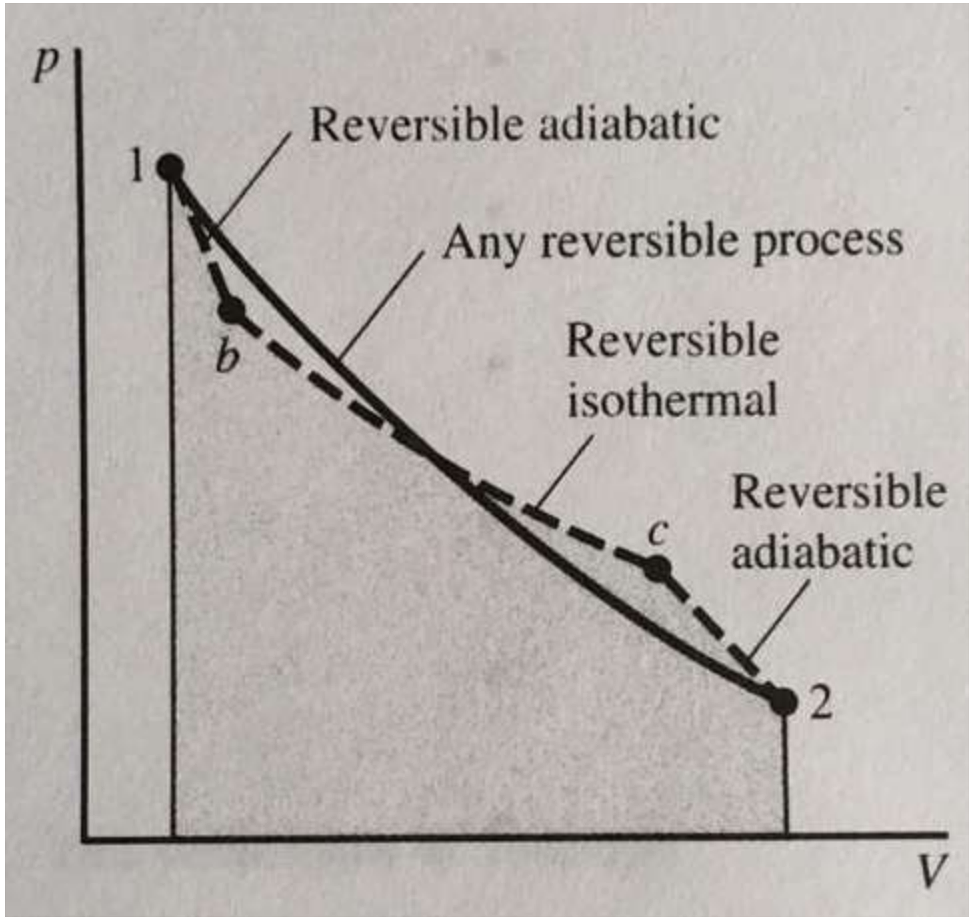
$$Q_{1-2} = U_2 - U_1 + W_{1-2}$$

$$Q_{1-2} = U_2 - U_1 + W_{1-b-c-2}$$

$$Q_{1-b-c-2} = U_2 - U_1 + W_{1-b-c-2}$$

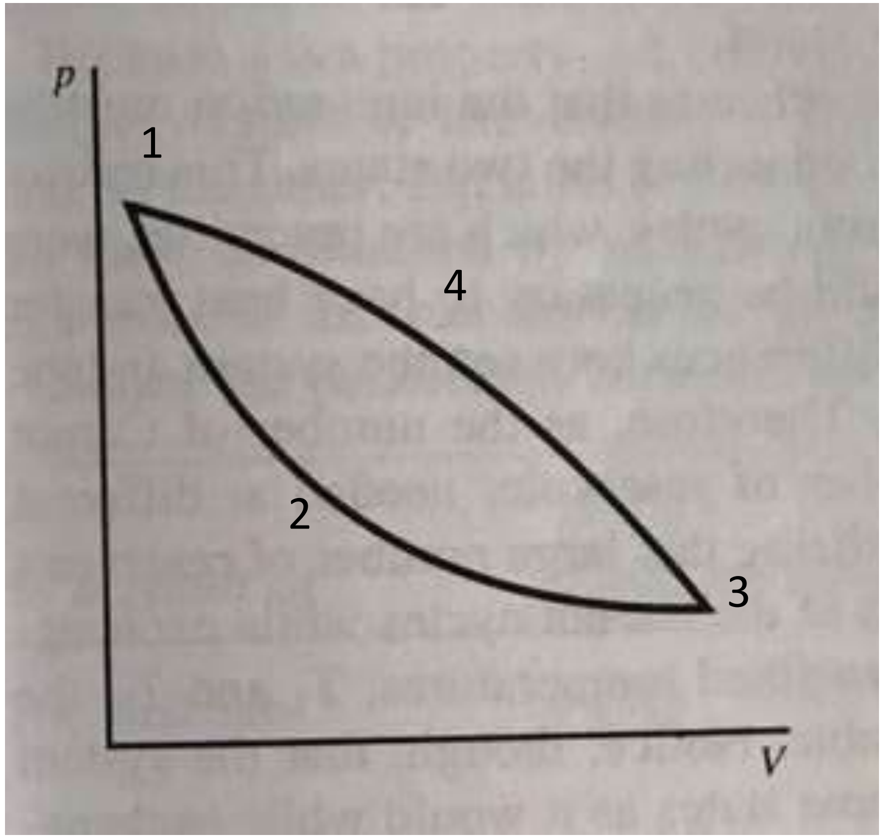
Now $Q_{1-b} = Q_{c-2} = 0$ ➡ $Q_{1-b-c-2} = Q_{b-c}$

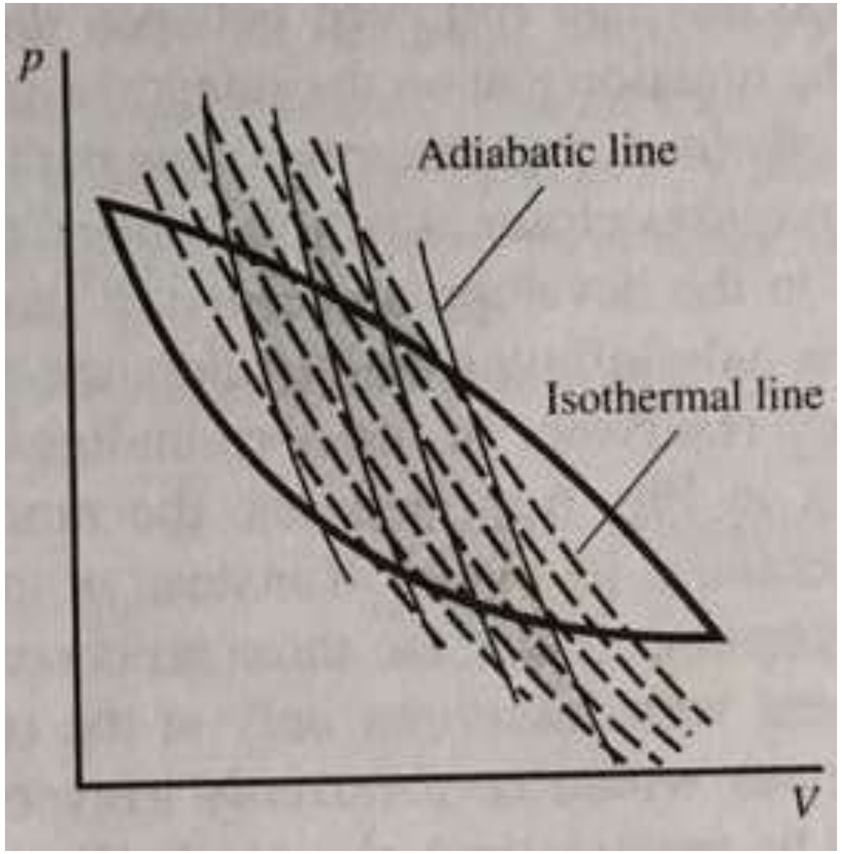
It is always possible to replace a reversible process by a series of reversible adiabatic and isothermal processes so that the internal energy change, the heat transferred, and the work done are the same.

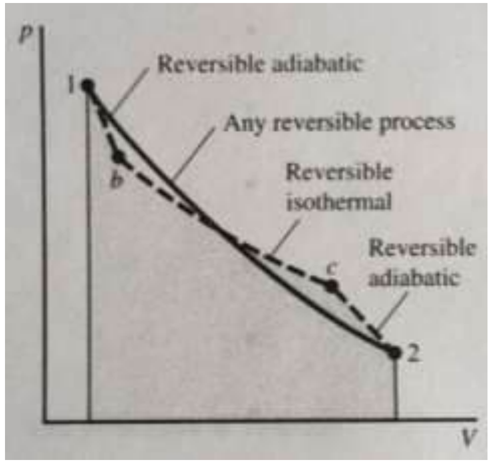


Reversible cycle

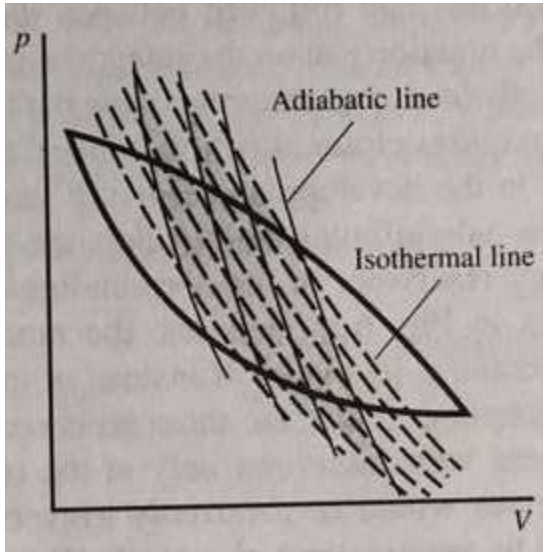
- Reversible cycle ~ series of reversible adiabatic & isothermal processes







Reversible cycles - Application of II law

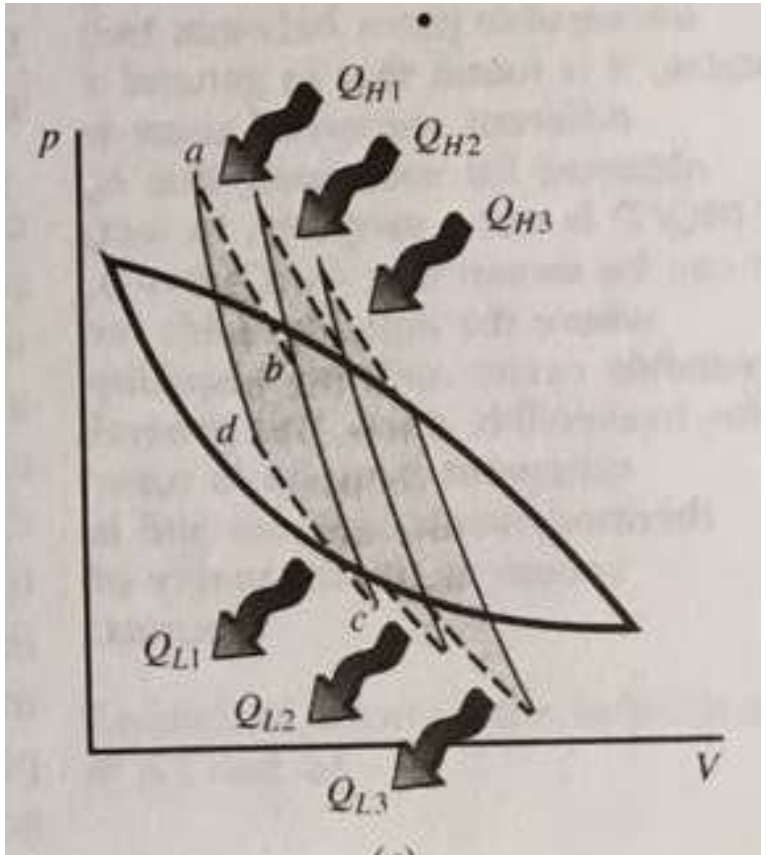


By II law, for the Carnot cycle a-b-c-d-a

$$\frac{|Q_{H,a-b}|}{|T_{H,a-b}|} = \frac{|Q_{L,c-d}|}{|T_{L,c-d}|} \rightarrow \frac{Q_{H,a-b}}{T_{H,a-b}} + \frac{Q_{L,c-d}}{T_{L,c-d}} = 0$$

By II law, for the Carnot cycle e-f-g-h-e

$$\frac{|Q_{H,e-f}|}{|T_{H,e-f}|} = \frac{|Q_{L,g-h}|}{|T_{L,g-h}|} \rightarrow \frac{Q_{H,e-f}}{T_{H,e-f}} + \frac{Q_{L,g-h}}{T_{L,g-h}} = 0$$



(c)

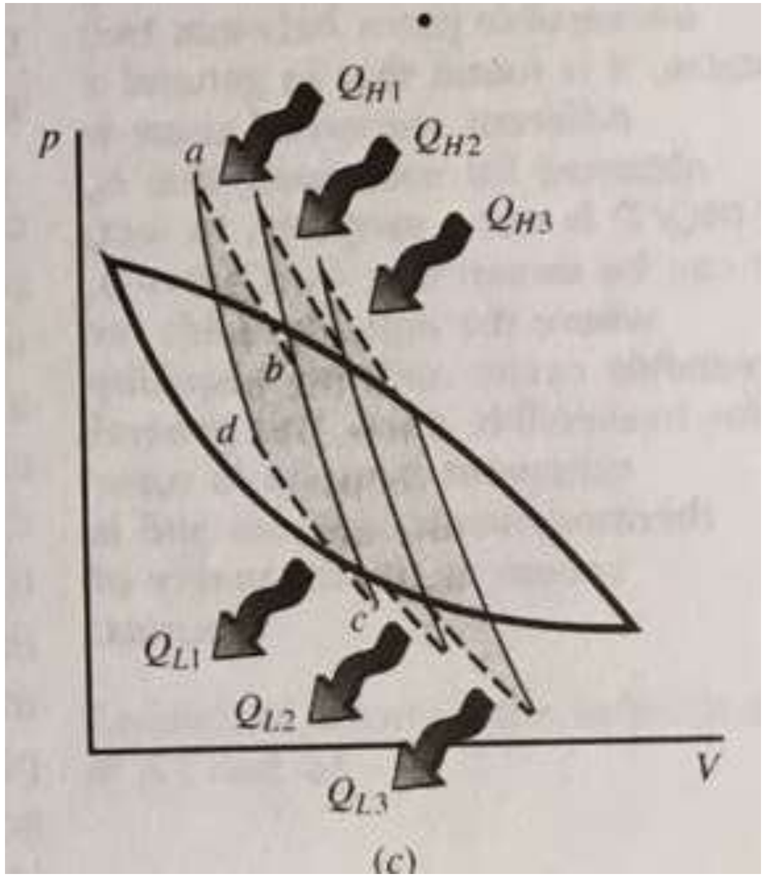
Reversible cycle ~ series of reversible adiabatic & isothermal processes (contd.)

$$\frac{Q_{H,a-b}}{T_{H,a-b}} + \frac{Q_{L,c-d}}{T_{L,c-d}} = 0 \qquad \text{and} \qquad \frac{Q_{H,e-f}}{T_{H,e-f}} + \frac{Q_{L,g-h}}{T_{L,g-h}} = 0$$

Therefore

$$\left(\frac{Q_{H,a-b}}{T_{H,a-b}} + \frac{Q_{L,c-d}}{T_{L,c-d}}\right) + \left(\frac{Q_{H,e-f}}{T_{H,e-f}} + \frac{Q_{L,g-h}}{T_{L,g-h}}\right) + and\ so\ on\ \ldots = 0$$

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



Change in *Entropy* → $\Delta S = \int \left(\frac{\delta Q}{T}\right)_{rev}$

References

1. Jones and Dugan, Engineering Thermodynamics, Prentice Hall of India, 2018.
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19ME31 Engineering Thermodynamics (L20) 9th Oct 2020

Dr A S Krishnan / Mr Sam Solomon
Faculty of Mechanical Engineering
Coimbatore Institute of Technology

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Overview of the topics

Basic Concepts of Thermodynamics

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Second Law of Thermodynamics

Entropy & Exergy

Thermodynamic Relations and Ideal Gas Mixtures

Entropy & Exergy

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1	Entropy – Clausius Theorem, Clausius Inequality	2
2	Entropy of Isolated system	1
3	Entropy change of liquids, solids & ideal gases	2
4	Exergy – Reversible work and Irreversibility - II law efficiency	2
5	Exergy change for non flow system & flow streams	2
6	III law of Thermodynamics	1

Today's discussion

Entropy (review) & Clausius theorem

Clausius inequality

Reversible cycle ~ series of reversible adiabatic & isothermal processes (contd.)

$$\frac{Q_{H,a-b}}{T_{H,a-b}} + \frac{Q_{L,c-d}}{T_{L,c-d}} = 0 \quad \text{and} \quad \frac{Q_{H,e-f}}{T_{H,e-f}} + \frac{Q_{L,g-h}}{T_{L,g-h}} = 0$$

Therefore

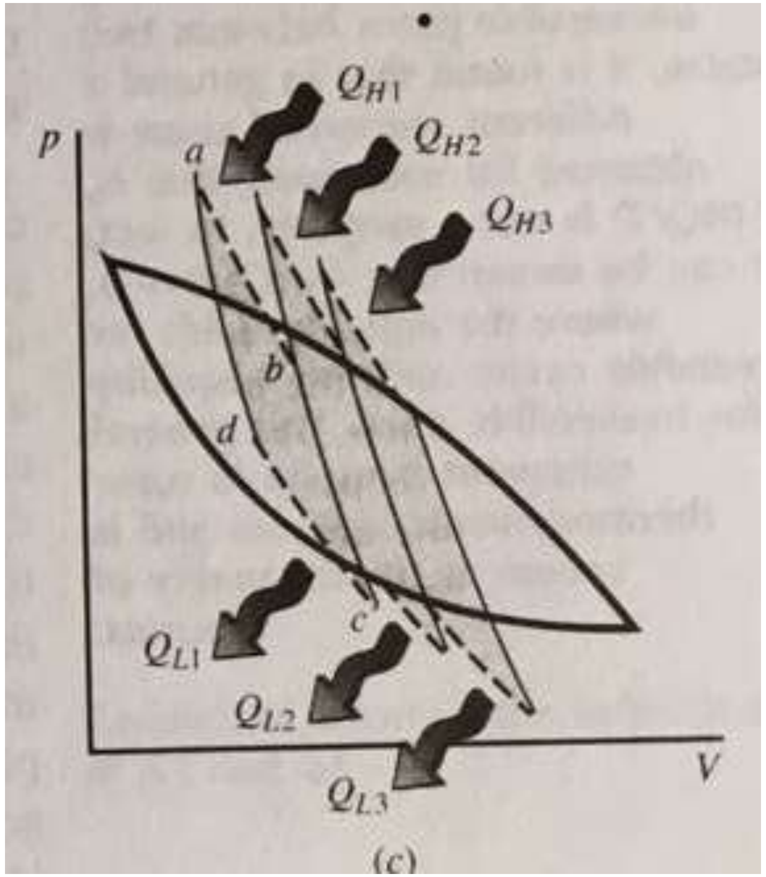
$$\left(\frac{Q_{H,a-b}}{T_{H,a-b}} + \frac{Q_{L,c-d}}{T_{L,c-d}}\right) + \left(\frac{Q_{H,e-f}}{T_{H,e-f}} + \frac{Q_{L,g-h}}{T_{L,g-h}}\right) + and\ so\ on\ \ldots = 0$$

$$\sum \frac{Q}{T} = 0$$

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

Clausius theorem

Change in ***Entropy*** → $\Delta S = \int \left(\frac{\delta Q}{T}\right)_{rev}$



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

Clausius inequality

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

To be specific $\oint \left(\frac{\delta Q}{T}\right)_{int,rev} = 0$

So, if the process is not internally reversible ?

By I Law of TD $\delta W_C = \delta Q_R - dE_C$

Where $\delta W_C = \delta W_{rev} + \delta W_{sys}$

For the cyclic device

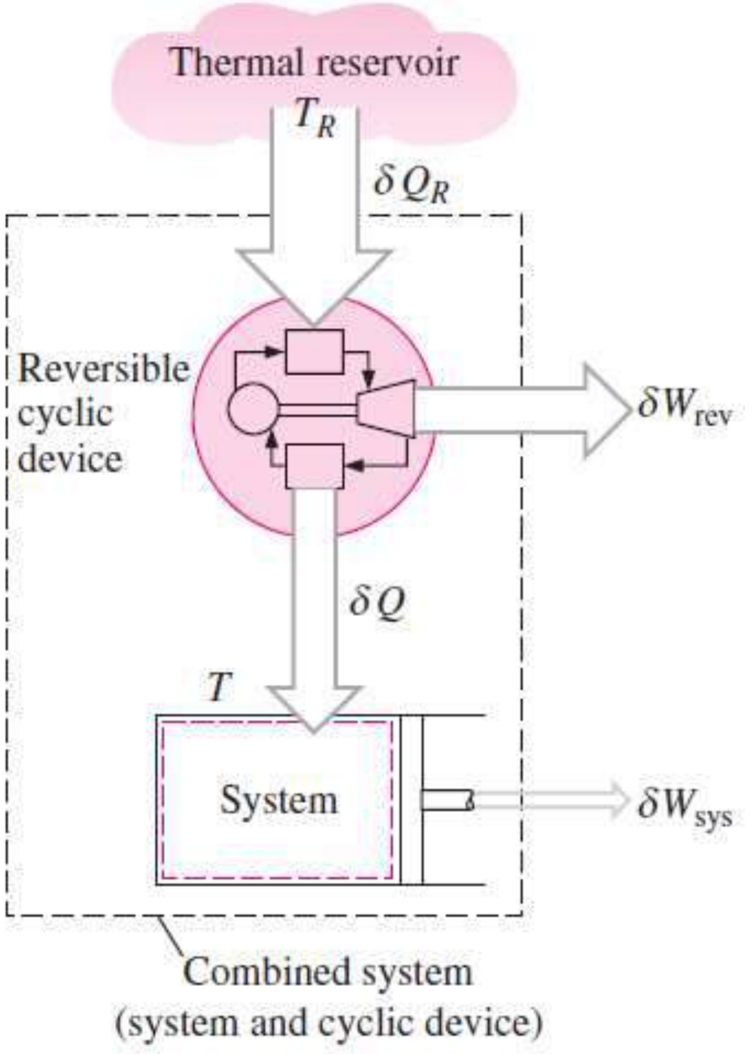
$$\frac{\delta Q_R}{T_R} = \frac{\delta Q}{T} \qquad \delta Q_R = T_R \frac{\delta Q}{T}$$

$$\delta W_C = T_R \frac{\delta Q}{T} - dE_C$$

$$W_C = T_R \oint \frac{\delta Q}{T}$$

$\oint \frac{\delta Q}{T}$: *cannot be positive*

$$\oint \frac{\delta Q}{T} \leq 0$$



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19ME31 Engineering Thermodynamics (L21)
12th Oct 2020

Dr A S Krishnan / Mr Sam Solomon
Faculty of Mechanical Engineering
Coimbatore Institute of Technology

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Today's discussion

- Review – entropy & Clausius inequality
- Entropy change of Isolated systems
- Numerical illustrations

Reversible cycle ~ series of reversible adiabatic & isothermal processes (contd.)

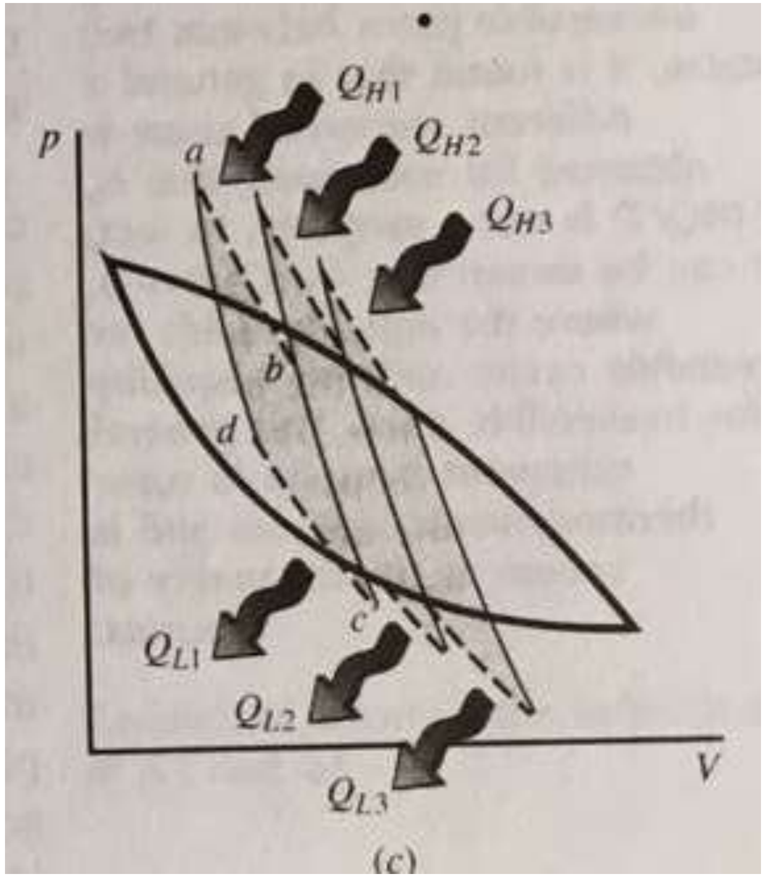
$$\frac{Q_{H,a-b}}{T_{H,a-b}} + \frac{Q_{L,c-d}}{T_{L,c-d}} = 0 \quad \text{and} \quad \frac{Q_{H,e-f}}{T_{H,e-f}} + \frac{Q_{L,g-h}}{T_{L,g-h}} = 0$$

Therefore

$$\left(\frac{Q_{H,a-b}}{T_{H,a-b}} + \frac{Q_{L,c-d}}{T_{L,c-d}}\right) + \left(\frac{Q_{H,e-f}}{T_{H,e-f}} + \frac{Q_{L,g-h}}{T_{L,g-h}}\right) + and\ so\ on\ \ldots = 0$$

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

Change in ***Entropy*** → $\Delta S = \int \left(\frac{\delta Q}{T}\right)_{rev}$



Clausius inequality

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

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

To be specific $\oint \left(\frac{\delta Q}{T}\right)_{int,rev} = 0$

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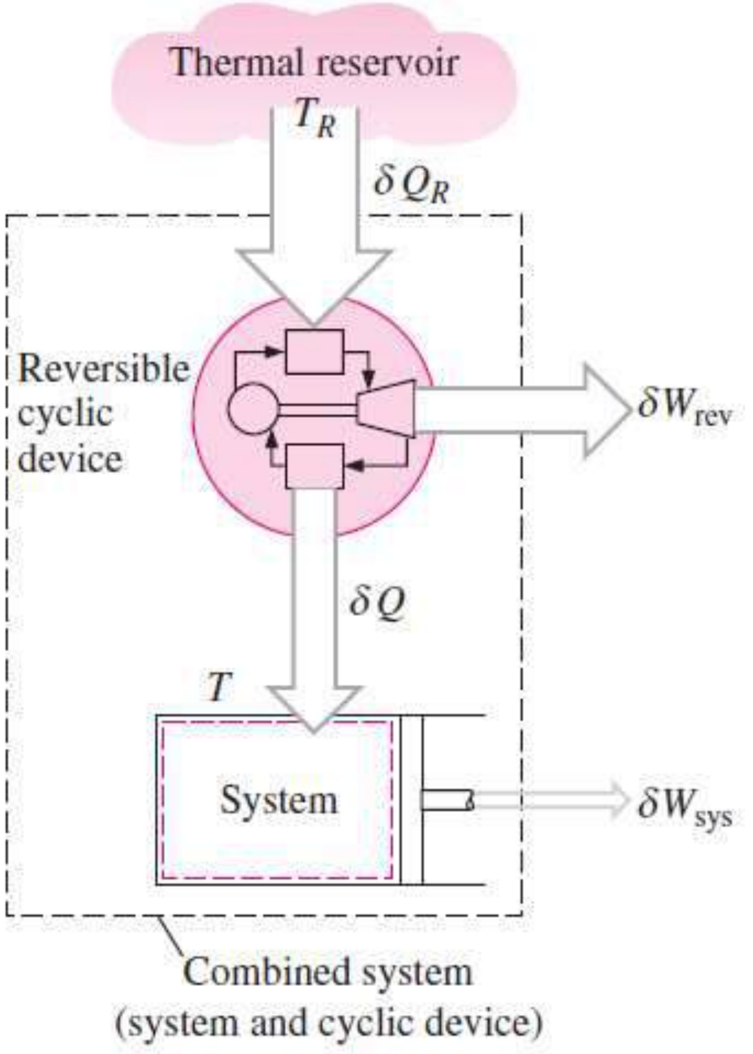
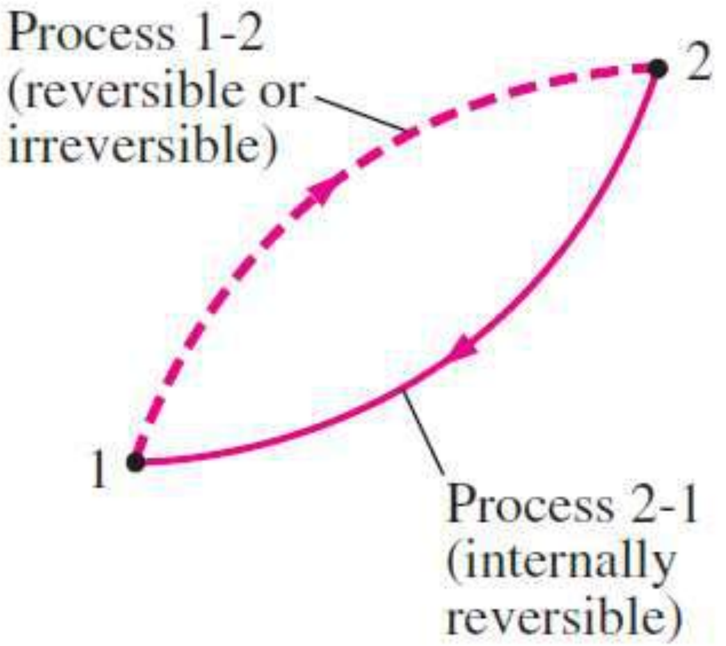
$$W_C = T_R \oint \frac{\delta Q}{T}$$

$$\oint \frac{\delta Q}{T} : cannot\ be\ positive$$

$$\oint \frac{\delta Q}{T} \leq 0$$



Entropy change of an isolated system



- A cycle with 2 processes
  - Onward (irreversible or reversible)
  - Return (reversible)
- Recalling Clausius inequality

$$\oint \frac{\delta Q}{T} \leq 0 \Rightarrow \int_1^2 \frac{\delta Q}{T} + \int_2^1 \left(\frac{\delta Q}{T}\right)_{rev} \leq 0$$

Also

$$\Delta S = \int \left(\frac{\delta Q}{T}\right)_{rev}$$

$$\Delta S = S_1 - S_2 \rightarrow \int_1^2 \frac{\delta Q}{T} + \Delta S \leq 0 \Rightarrow \Delta S \geq \int_1^2 \frac{\delta Q}{T}$$

(or) $dS \geq \frac{\delta Q}{T}$ ⇐ In differential form

For an isolated system, since there is no heat transfer

$$\int_1^2 \frac{\delta Q}{T} = 0$$

For process 1-2

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

Always > 0 ← Entropy generated

$$\Delta S_{isolated\ sys} \geq 0$$

Principle of increase of entropy

Principle of increase of entropy

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

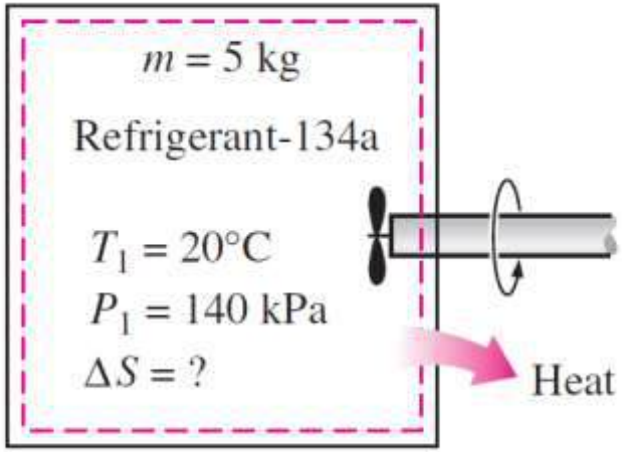
$$S_{gen} \begin{cases} > 0 & \text{Irreversible process} \\ = 0 & \text{Reversible process} \\ < 0 & \text{Impossible process} \end{cases}$$

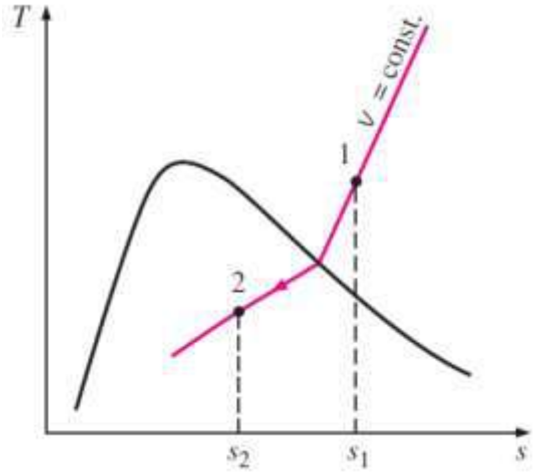
1. A piston-cylinder device contains a liquid-vapor mixture of water at 300K. During a constant pressure process, 750 kJ of heat is transferred to the water. As a result, part of the liquid in the cylinder vaporizes. Determine the entropy change of water during the process.

2. A heat source at 800 K looses 2000 kJ to a sink at (a) 500 K and (b) 750 K. Determine which heat transfer process is more irreversible.

3. A rigid tank contains 5 kg of refrigerant (R-134a) initially at 20 °C and 140 kPa. The refrigerant is now cooled while being stirred until its pressure drops to 100 kPa. Determine the entropy change during this process.

A rigid tank contains 5 kg of refrigerant (R-134a) initially at 20 °C and 140 kPa. The refrigerant is now cooled while being stirred until its pressure drops to 100 kPa. Determine the entropy change during this process.





State 1: $\left.\begin{array}{l} P_1 = 140 \text{ kPa} \\ T_1 = 20°\text{C} \end{array}\right\}$ $\begin{array}{l} s_1 = 1.0624 \text{ kJ/kg}\cdot\text{K} \\ v_1 = 0.16544 \text{ m}^3/\text{kg} \end{array}$

State 2: $\left.\begin{array}{l} P_2 = 100 \text{ kPa} \\ (v_2 = v_1) \end{array}\right\}$ $\begin{array}{l} v_f = 0.0007259 \text{ m}^3/\text{kg} \\ v_g = 0.19254 \text{ m}^3/\text{kg} \end{array}$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.16544 - 0.0007259}{0.19254 - 0.0007259} = 0.859$$

$$s_2 = s_f + x_2 s_{fg} = 0.07188 + (0.859)(0.87995) = 0.8278 \text{ kJ/kg}\cdot\text{K}$$

$$\Delta S = m(s_2 - s_1) = (5 \text{ kg})(0.8278 - 1.0624) \text{ kJ/kg}\cdot\text{K}$$
$$= \mathbf{-1.173 \text{ kJ/K}}$$

References

1. Yunus A Cengel and Michael A Boles, “Thermodynamics – an Engineering Approach”, 3rd Edition, Tata Mc Graw Hill, 2002.
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19ME31 Engineering Thermodynamics (L22) 14th Oct 2020

Dr A S Krishnan / Mr Sam Solomon
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4. Calculate changes in properties during different ideal gas processes

Overview of the topics

- Basic Concepts of Thermodynamics
- First Law of Thermodynamics
- Second Law of Thermodynamics
- Entropy & Exergy
- Thermodynamic Relations and Ideal Gas Mixtures

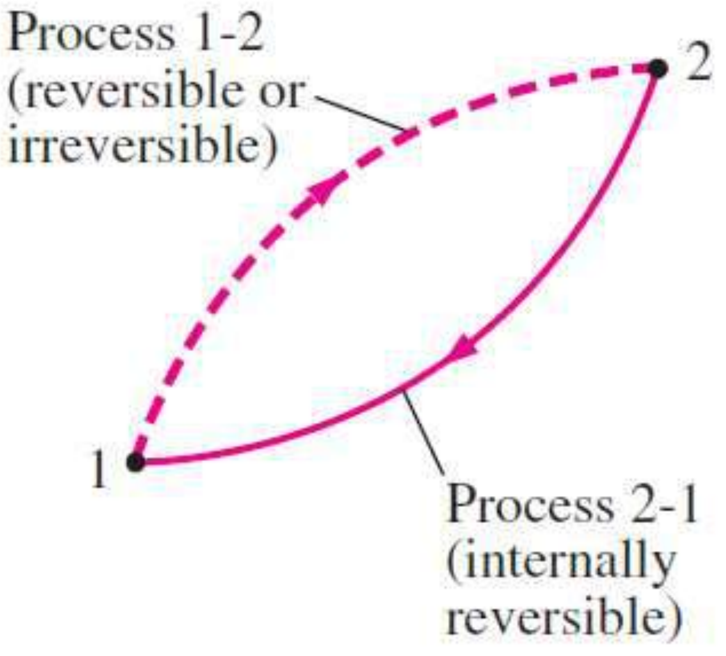
Entropy & Exergy

SNo	Topic	Hours
1	Entropy – Clausius Theorem, Clausius Inequality	2
2	Entropy of Isolated system	1
3	Entropy change of liquids, solids & ideal gases	2
4	Exergy – Reversible work and Irreversibility - II law efficiency	2
5	Exergy change for non flow system & flow streams	2
6	III law of Thermodynamics	1

Today's discussion

- Review
- The TdS equations
- Entropy changes – Liquids & Solids
- Entropy changes – Ideal gases
- Numerical illustrations

Entropy change of an isolated system



- A cycle with 2 processes
  - Onward (irreversible or reversible)
  - Return (reversible)
- Recalling Clausius inequality

$$\oint \frac{\delta Q}{T} \le 0 \Rightarrow \int_1^2 \frac{\delta Q}{T} + \int_2^1 \left(\frac{\delta Q}{T}\right)_{rev} \le 0$$

Also

$$\Delta S = \int \left(\frac{\delta Q}{T}\right)_{rev}$$

$$\Delta S = S_1 - S_2 \rightarrow \int_1^2 \frac{\delta Q}{T} + \Delta S \le 0 \Rightarrow \Delta S \ge \int_1^2 \frac{\delta Q}{T} \quad \text{(or)} \quad dS \ge \frac{\delta Q}{T}$$

In differential form

For an isolated system, since there is no heat transfer

$$\int_1^2 \frac{\delta Q}{T} = 0$$

$$\Delta S_{isolated\ sys} \ge 0$$

Principle of increase of entropy

For process 1-2

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

Always > 0 ← Entropy generated

Principle of increase of entropy

$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \Delta S_{sur}$$

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

The *Tds* equations

- Differential form of energy conservation equation, as applied to
  - A closed stationary system
  - Simple compressible substance
  - Internally reversible process

$$\delta Q_{int\ rev,in} - \delta W_{int\ rev,out} = dU$$

$$\delta Q_{int\ rev,in} = TdS \qquad \delta W_{int\ rev,out} = pdV$$

$$TdS = dU + pdV$$

$$Tds = du + pdv$$

1st *Tds* equation or Gibbs equation

$$Tds = du + d(pv) - vdp$$

$$Tds = dh - vdp$$

2nd *Tds* equation

(OR)

$$TdS = dH - Vdp$$

$$Tds = du + pdv \longrightarrow ds = \frac{du}{T} + \frac{pdv}{T}$$

$$Tds = dh - vdp \longrightarrow ds = \frac{dh}{T} - \frac{vdp}{T}$$

Entropy changes – liquids & solids

- Liquids & solids
  - approximated as incompressible substances($dv = 0$)

Entropy change during a process

$$ds = \frac{du}{T} = \frac{cdT}{T}$$

Where $c = c_p = c_v$

$$s_2 - s_1 = \int_1^2 c(T)\frac{dT}{T} = c_{avg} ln\frac{T_2}{T_1}$$

Where $c_{avg} = \dfrac{c(T_1) + c(T_2)}{2}$

If the process is isentropic $s_2 = s_1$

As a special case $T_2 = T_1$ The process is isothermal too !

Entropy changes – ideal gases

$$ds = \frac{du}{T} + \frac{pdv}{T} \Rightarrow ds = c_v \frac{dT}{T} + \frac{RTdv}{vT} \Rightarrow ds = c_v \frac{dT}{T} + R\frac{dv}{v} \Rightarrow s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\, ln \frac{v_2}{v_1}$$

All the quantities on the right hand side are measurable

$$ds = \frac{dh}{T} - \frac{vdp}{T} \Rightarrow ds = c_p \frac{dT}{T} - \frac{RTdp}{pT} \Rightarrow ds = c_p \frac{dT}{T} - R\frac{dp}{p} \Rightarrow s_2 - s_1 = \int_1^2 c_p(T)\frac{dT}{T} - R\, ln \frac{p_2}{p_1}$$

The III law of Thermodynamics

The entropy of a pure crystalline substance at absolute zero temperature is zero

Note: ***The entropy of a substance that is not pure crystalline substance at absolute temperature is not zero.***

Entropy changes – ideal gases

- Constant specific heats (Approximate analysis)

$$s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\,ln\frac{v_2}{v_1} \Rightarrow s_2 - s_1 = c_{v,avg}\int_1^2 \frac{dT}{T} + R\,ln\frac{v_2}{v_1}$$

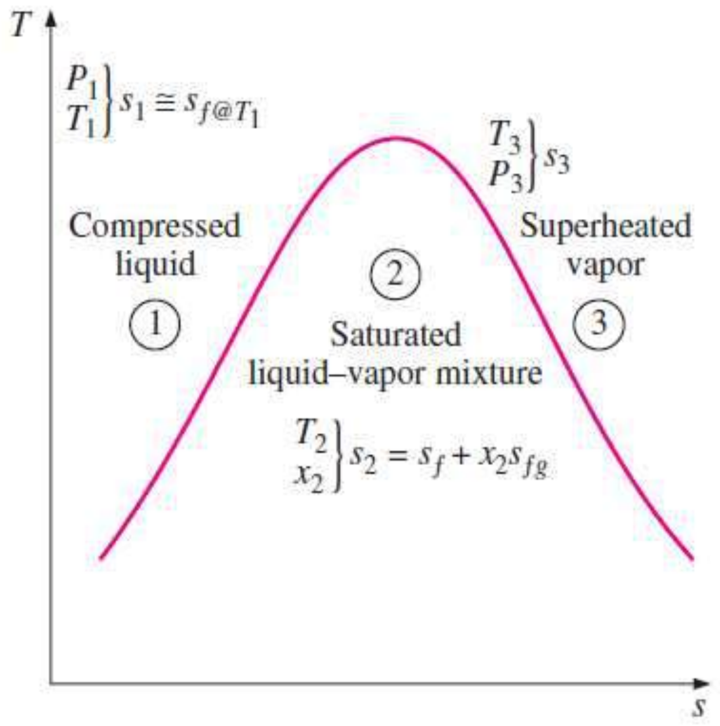
$$s_2 - s_1 = \int_1^2 c_p(T)\frac{dT}{T} - R\,ln\frac{p_2}{p_1} \Rightarrow s_2 - s_1 = c_{p,avg}\int_1^2 \frac{dT}{T} - R\,ln\frac{p_2}{p_1}$$

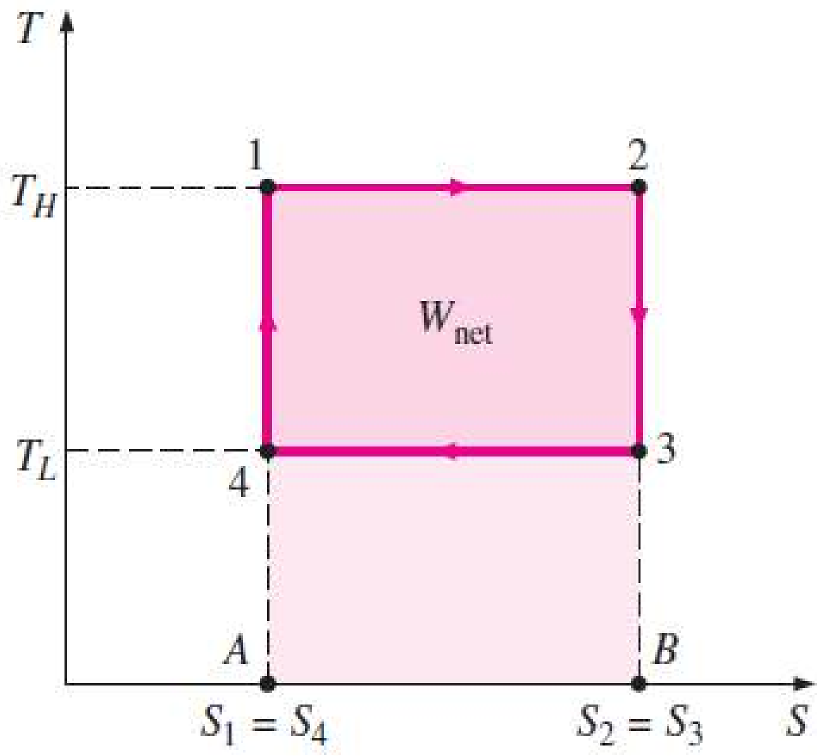
- Exact analysis

$$s_v^0 = \int_0^T c_v(T)\frac{dT}{T} \Rightarrow \int_1^2 c_v(T)\frac{dT}{T} = s_v^2 - s_v^1 \Rightarrow s_2 - s_1 = s_v^2 - s_v^1 + R\,ln\frac{v_2}{v_1}$$

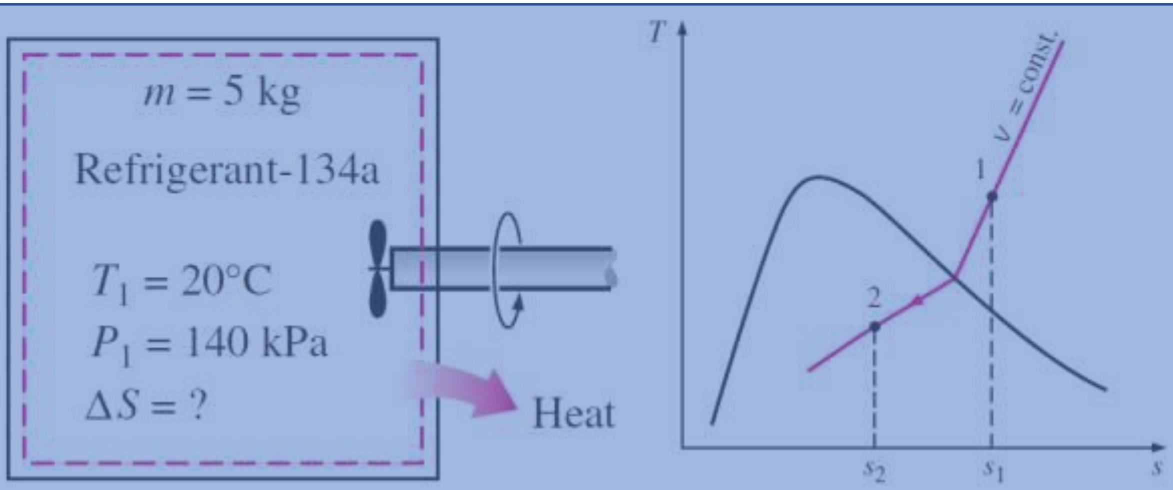
The superscripts on the 1st two terms on the RHS are not powers !

$$s_p^0 = \int_0^T c_p(T)\frac{dT}{T} \Rightarrow \int_1^2 c_p(T)\frac{dT}{T} = s_p^2 - s_p^1 \Rightarrow s_2 - s_1 = s_p^2 - s_p^1 - R\,ln\frac{p_2}{p_1}$$


T
P1
T1
s1 ≅ sf@T1
T3
P3
s3
Compressed
liquid
Superheated
vapor
2
1
3
Saturated
liquid–vapor mixture
T2
x2
s2 = sf + x2sfg
s


T
TH
TL
1
2
3
4
Wnet
A
B
S1 = S4
S2 = S3
S

A rigid tank contains 5 kg of refrigerant (R-134a) initially at 20 °C and 140 kPa. The refrigerant is now cooled while being stirred until its pressure drops to 100 kPa. Determine the entropy change during this process.



State 1: $\left.\begin{aligned} P_1 &= 140 \text{ kPa} \\ T_1 &= 20°\text{C} \end{aligned}\right\}$ $\begin{aligned} s_1 &= 1.0624 \text{ kJ/kg} \cdot \text{K} \\ v_1 &= 0.16544 \text{ m}^3\text{/kg} \end{aligned}$

State 2: $\left.\begin{aligned} P_2 &= 100 \text{ kPa} \\ (v_2 &= v_1) \end{aligned}\right\}$ $\begin{aligned} v_f &= 0.0007259 \text{ m}^3\text{/kg} \\ v_g &= 0.19254 \text{ m}^3\text{/kg} \end{aligned}$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.16544 - 0.0007259}{0.19254 - 0.0007259} = 0.859$$

$$s_2 = s_f + x_2 s_{fg} = 0.07188 + (0.859)(0.87995) = 0.8278 \text{ kJ/kg} \cdot \text{K}$$

$$\Delta S = m(s_2 - s_1) = (5 \text{ kg})(0.8278 - 1.0624) \text{ kJ/kg} \cdot \text{K}$$
$$= \mathbf{-1.173 \text{ kJ/K}}$$

Liquid methane is commonly used in many cryogenic applications. The critical temperature of methane is 191 K & hence methane must be maintained below 191 K to keep it in liquid phase. Determine the change in entropy of liquid methane as it undergoes a process from 110 K and 1 MPa to 120 K and 5 MPa using (a) actual data from table below and (b) approximating liquid methane as an incompressible substance. What is the % error involved in case (b)?

10/14/2020

TABLE 7–1

Properties of liquid methane

Temp., T, K	Pressure, P, MPa	Density, ρ, kg/m^3	Enthalpy, h, kJ/kg	Entropy, s, kJ/kg · K	Specific heat, c_p, kJ/kg · K
110	0.5	425.3	208.3	4.878	3.476
	1.0	425.8	209.0	4.875	3.471
	2.0	426.6	210.5	4.867	3.460
	5.0	429.1	215.0	4.844	3.432
120	0.5	410.4	243.4	5.185	3.551
	1.0	411.0	244.1	5.180	3.543
	2.0	412.0	245.4	5.171	3.528
	5.0	415.2	249.6	5.145	3.486

References

1. Yunus A Cengel and Michael A Boles, “Thermodynamics – an Engineering Approach”, 3rd Edition, Tata Mc Graw Hill, 2002.
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19ME31 Engineering Thermodynamics (L23) 17th Oct 2020

Dr A S Krishnan / Mr Sam Solomon

Faculty of Mechanical Engineering

Coimbatore Institute of Technology

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Entropy & Exergy

SNo	Topic	Hours
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Today's discussion

- Review & Numerical illustrations
- Exergy, Reversible Work, Irreversible Work

Entropy changes – liquids & solids

- Liquids & solids
  - approximated as incompressible substances($dv = 0$)

Entropy change during a process

$$ds = \frac{du}{T} = \frac{cdT}{T}$$

Where $c = c_p = c_v$

$$s_2 - s_1 = \int_1^2 c(T)\frac{dT}{T} = c_{avg} ln\frac{T_2}{T_1}$$

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The process is isothermal too !

Entropy changes – ideal gases

- Constant specific heats (Approximate analysis)

$$s_2 - s_1 = \int_1^2 c_v(T)\frac{dT}{T} + R\, ln\frac{v_2}{v_1} \Rightarrow s_2 - s_1 = c_{v,avg}\int_1^2 \frac{dT}{T} + R\, ln\frac{v_2}{v_1}$$

$$s_2 - s_1 = \int_1^2 c_p(T)\frac{dT}{T} - R\, ln\frac{p_2}{p_1} \Rightarrow s_2 - s_1 = c_{p,avg}\int_1^2 \frac{dT}{T} - R\, ln\frac{p_2}{p_1}$$

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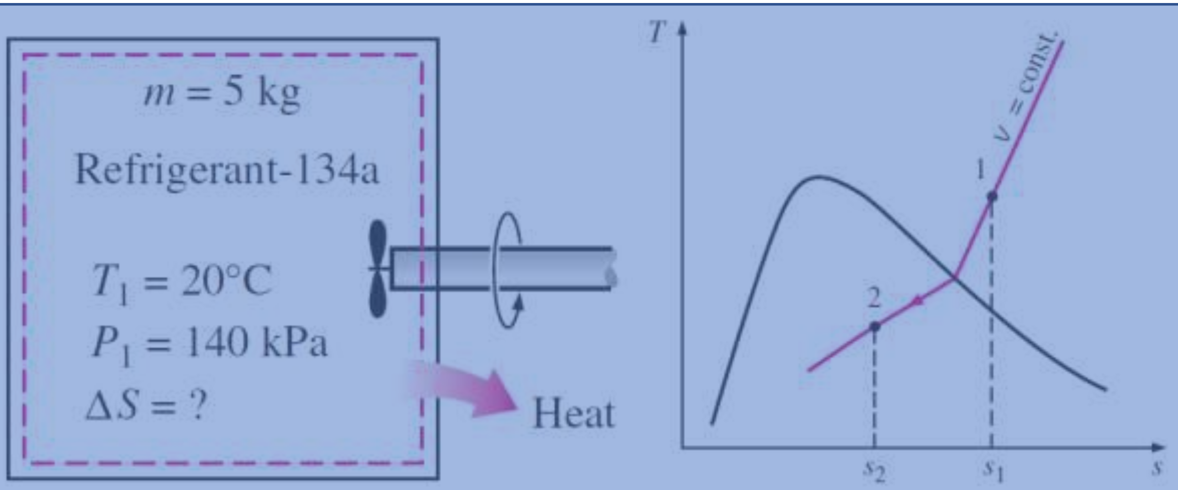

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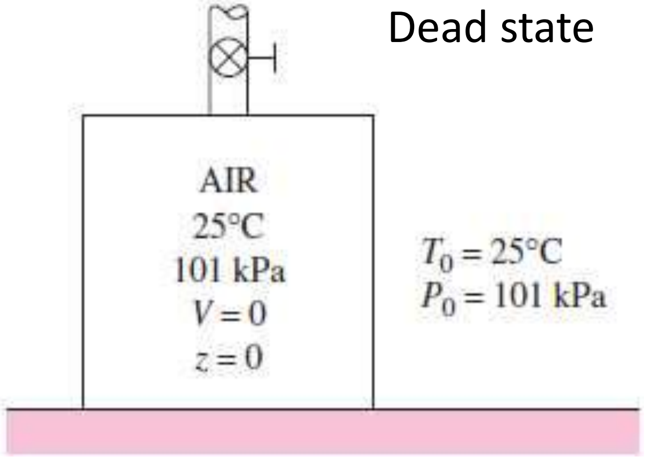
$$= \mathbf{-1.173 \text{ kJ/K}}$$

Exergy – work potential of energy

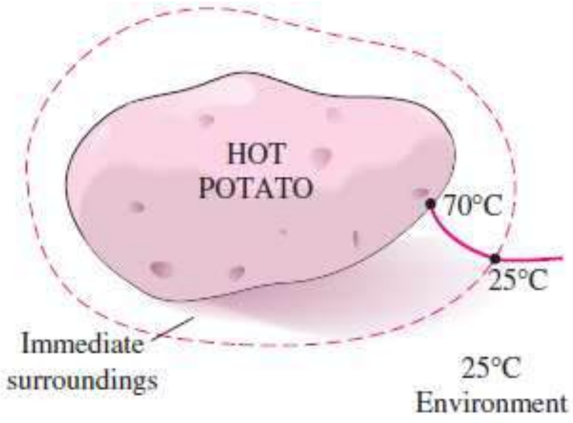


Dead state

- Also called as availability or available energy
- Work potential of energy in a system

  Work=*f*(initial state, process path, final state)

- All irreversibilities are disregarded in calculating the exergy
- System must be in dead state (thermodynamic equilibrium with surrounding) at the end of the process to maximize work output



Surroundings =

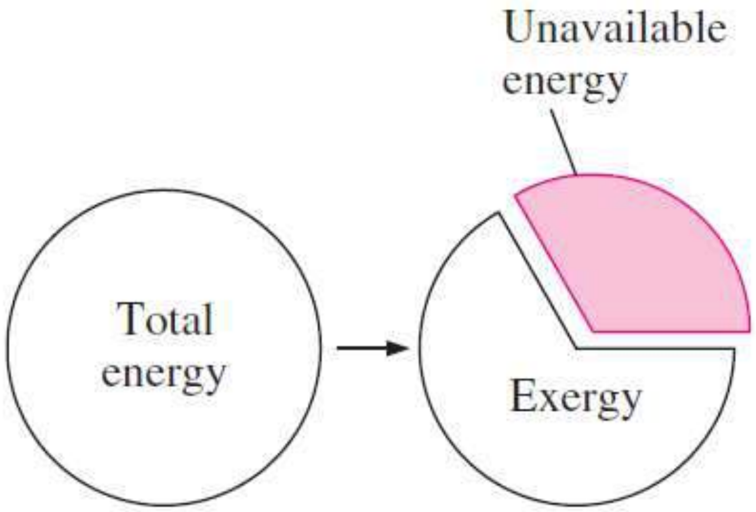
Immediate Surroundings + Environment

- Surroundings – everything outside system boundary
- Immediate surroundings – portion of surroundings that is affected by the process
- Environment – region beyond the immediate surroundings whose properties are not affected by the process at any point

A system will deliver the maximum possible work as it undergoes a reversible process from a specified initial state to the state of its environment, i.e. dead state. → Exergy

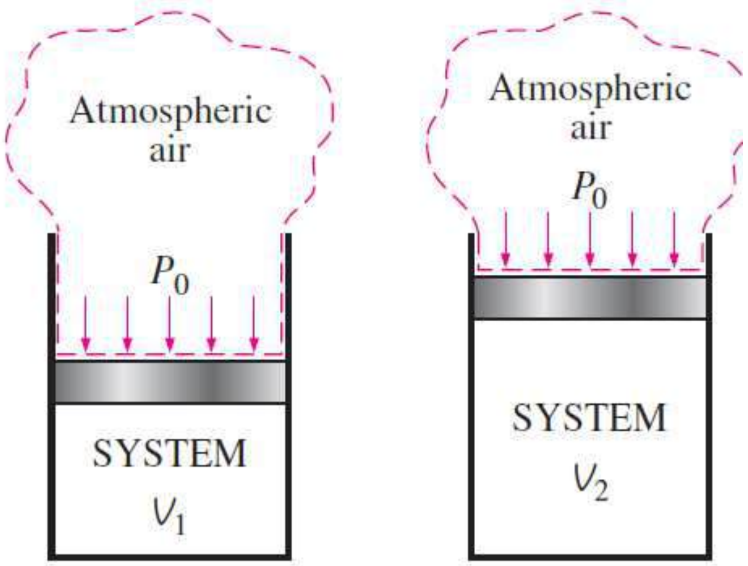
Exergy (contd.)

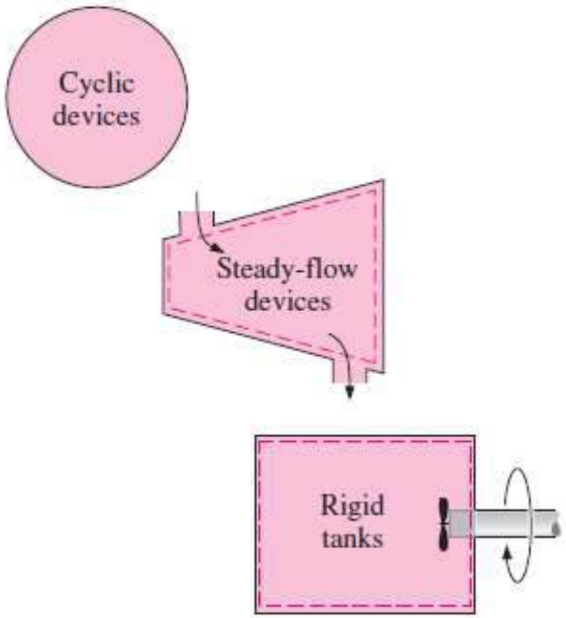
- Upper limit on the amount of work a device can deliver (or lower limit on the amount of work a device will consume) without violating any laws of thermodynamics
- Not the actual work delivered or consumed
- Property of system-environment combination



A windmill with a diameter of 12-m rotor is to be installed in a location where the wind is blowing steadily at an average velocity of 12 m/s. Determine the maximum power that can be generated by the wind mill

Reversible work & irreversibility





$$W_{surr} = p_{atm}(V_2 - V_1)$$

$$W_u = W_{act} - W_{surr}$$

$$I = W_{rev,out} - W_{act,out}$$

(OR)

$$I = W_{act,in} - W_{rev,in}$$

No surrounding work for constant volume & cyclic devices

Reversible work & irreversibility (contd.)

- Reversible work
  - maximum amount of useful work that can be produced (or the minimum work that needs to be supplied) as a system undergoes a process between the specified initial and final states.
  - Equal to exergy, if the final state is dead state
- Irreversibility
  - Difference between reversible work and useful work
  - Equivalent to exergy destroyed
  - Wasted work potential or lost opportunity to do work

A heat engine receives heat from a source at 1000 K at a rate of 750 kW and rejects waste heat to a medium at 300 K. If the power output of the engine is 200 kW, determine the reversible power and the irreversibility rate for this process.

References

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19ME31 Engineering Thermodynamics (L24)
19th Oct 2020

Dr A S Krishnan / Mr Sam Solomon
Faculty of Mechanical Engineering
Coimbatore Institute of Technology

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Second Law of Thermodynamics

Entropy & Exergy

Thermodynamic Relations and Ideal Gas Mixtures

Entropy & Exergy

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6	III law of Thermodynamics	1

Today’s discussion

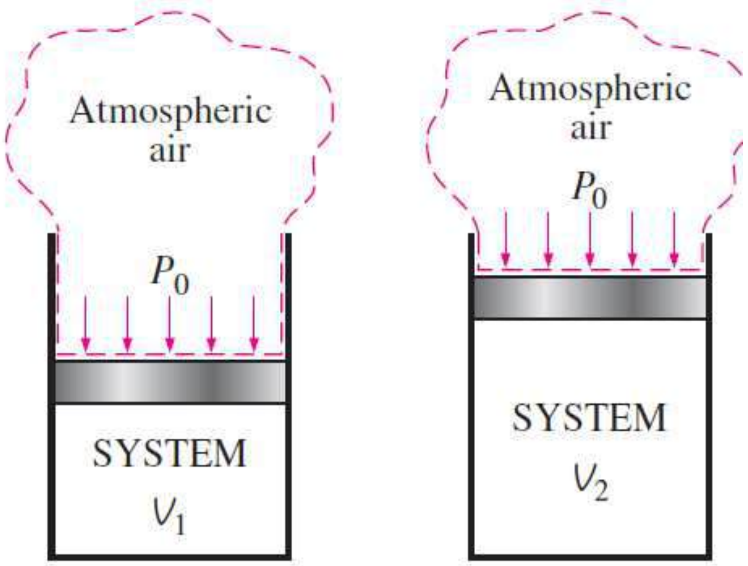
Review – Exergy, Reversible work & Irreversibility

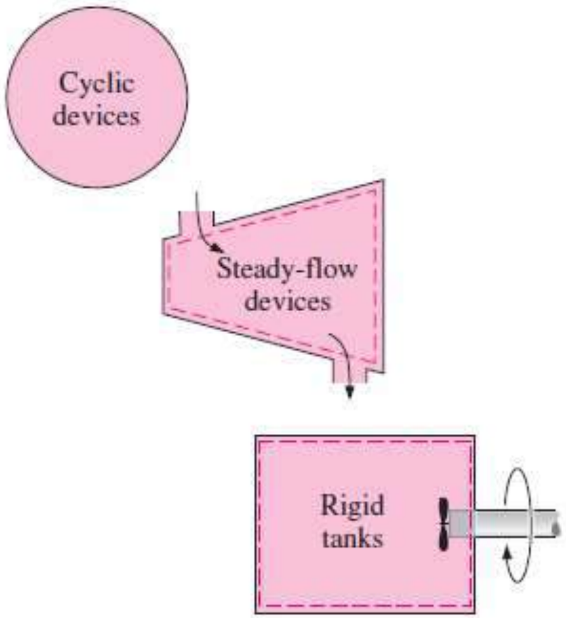
Numerical Examples

EXERGY, REVERSIBLE WORK & IRREVERSIBILITY

- Exergy
  - Maximum possible work delivered by a system as it undergoes a reversible process from a specified initial state to the state of its environment.
- Reversible Work
  - Maximum amount of useful work produced (or the minimum work that needs to be supplied) as a system undergoes a process between the specified initial and final states.
- Irreversibility
  - Difference between useful work and reversible work

Reversible work & irreversibility





$$W_{surr} = p_{atm}(V_2 - V_1)$$

$$W_u = W_{act} - W_{surr}$$

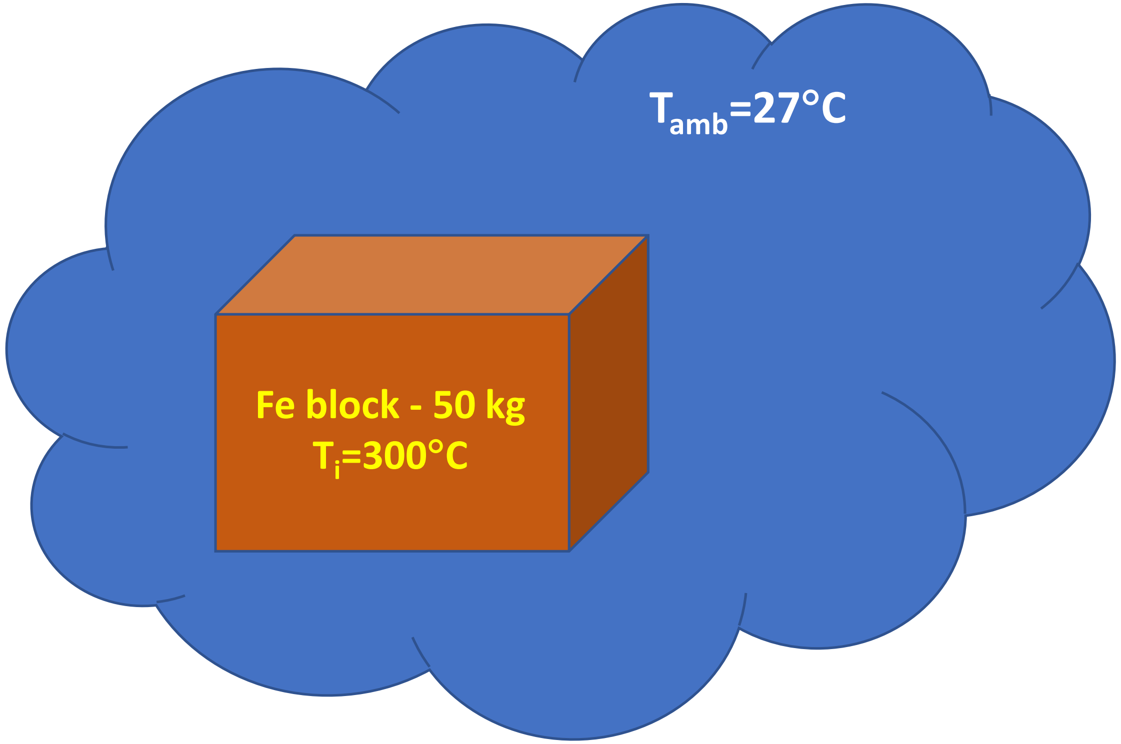
$$I = W_{rev,out} - W_{act,out}$$

(OR)

$$I = W_{act,in} - W_{rev,in}$$

No surrounding work for constant volume & cyclic devices

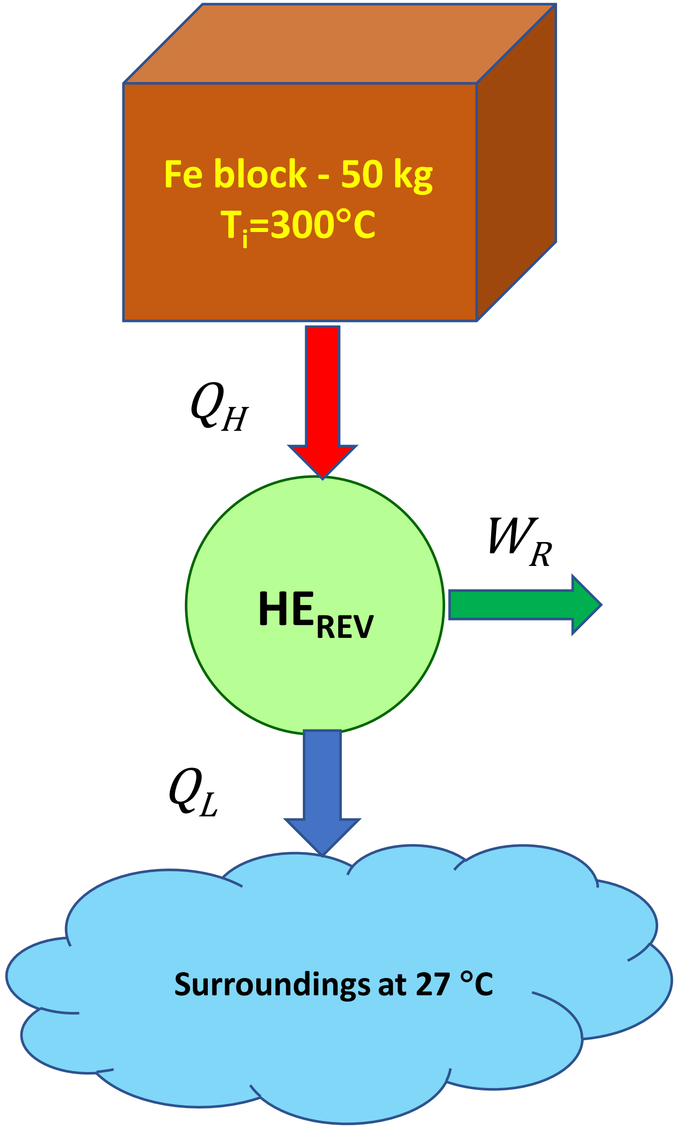
An 50 kg iron block, initially at a temperature of 300 °C is allowed to cool to 27 °C by transferring heat to the surrounding at 27 °C. Determine the reversible work and irreversibility for this process.



Assumptions

1. KE & PE changes are negligible
2. No work interactions during the process
3. Sp. Heat variations are negligible

Iron block loosing heat to reversible HE



- Let the iron block be connected to a reversible HE, to which it looses heat, then

$$\delta W_{rev} = \eta_{th,rev}\delta Q_{in} \Rightarrow \delta W_{rev} = \left(1 - \frac{T_L}{T_H}\right)\delta Q_{in} \Rightarrow \delta W_{rev} = \left(1 - \frac{T_{amb}}{T_{iron}}\right)\delta Q_{in}$$

$$W_{rev} = \int_{T_i}^{T_f}\left(1 - \frac{T_{amb}}{T}\right)\delta Q_{in}$$

$$\delta E_{in} - \delta E_{out} = dE_{system}$$

$$-\delta Q_{out,sys} = dU = mc_{v,av}dT$$

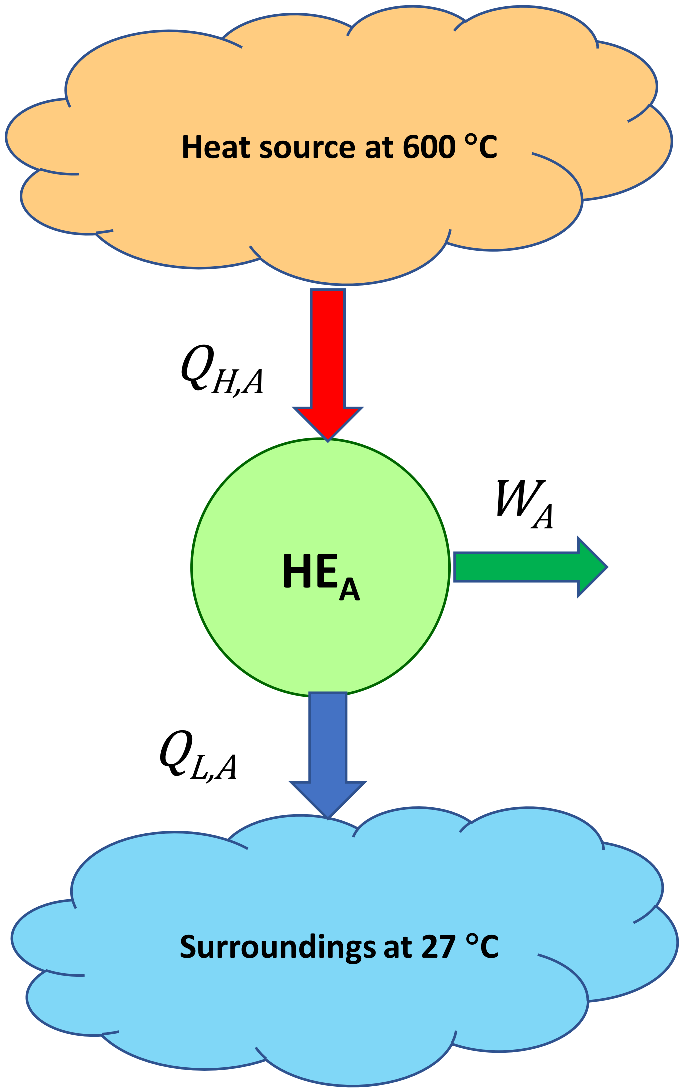
$$\delta Q_{in,HE} = \delta Q_{out,sys} = -mc_{v,av}dT$$

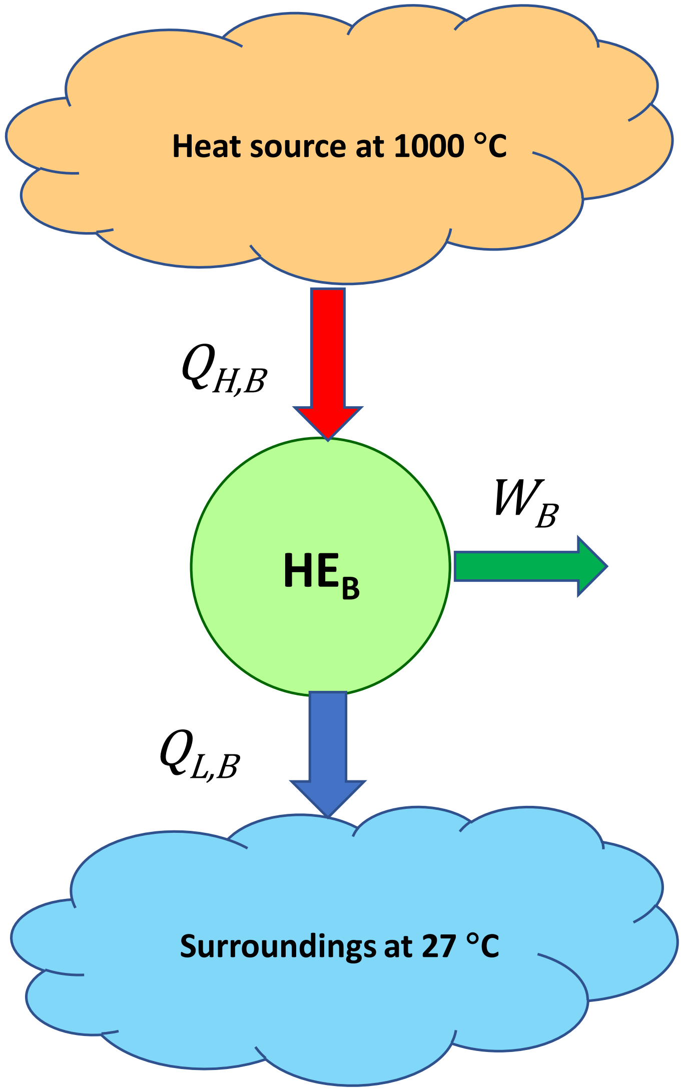
$$W_{rev} = \int_{T_i}^{T_f}\left(1 - \frac{T_{amb}}{T}\right)(-mc_{v,av}dT)$$

$$W_{rev} = mc_{v,av}(T_i - T_f) + T_{amb}mc_{v,av}ln\frac{T_f}{T_i}$$

$$W_{rev} = mc_{v,av}\left((T_i - T_f) + T_{amb}ln\frac{T_f}{T_i}\right)$$

Two heat engines, both 30% efficient are connected between a source and sink as shown in figure. Comment on the performances of these.





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19ME31 Engineering Thermodynamics (L25) 21st Oct 2020

Dr A S Krishnan / Mr Sam Solomon

Faculty of Mechanical Engineering

Coimbatore Institute of Technology

Course Objective

To enable undergraduate students of Mechanical Engineering to apply concepts of energy, entropy and exergy to simple systems with justifiable assumptions through theoretical concepts and illustrations

Course Outcomes* – At the end of the course, the student will be able to

1. Apply concepts of energy conservation to open and closed systems
2. Arrive at benchmark performances of heat engines and refrigerator / heat pump and compute entropy changes.
3. Depict various thermodynamic processes on property diagrams, estimate properties of mixtures and quantify deviation from ideal gas behavior.
4. Calculate changes in properties during different ideal gas processes

Overview of the topics

- Basic Concepts of Thermodynamics
- First Law of Thermodynamics
- Second Law of Thermodynamics
- Entropy & Exergy
- Thermodynamic Relations and Ideal Gas Mixtures

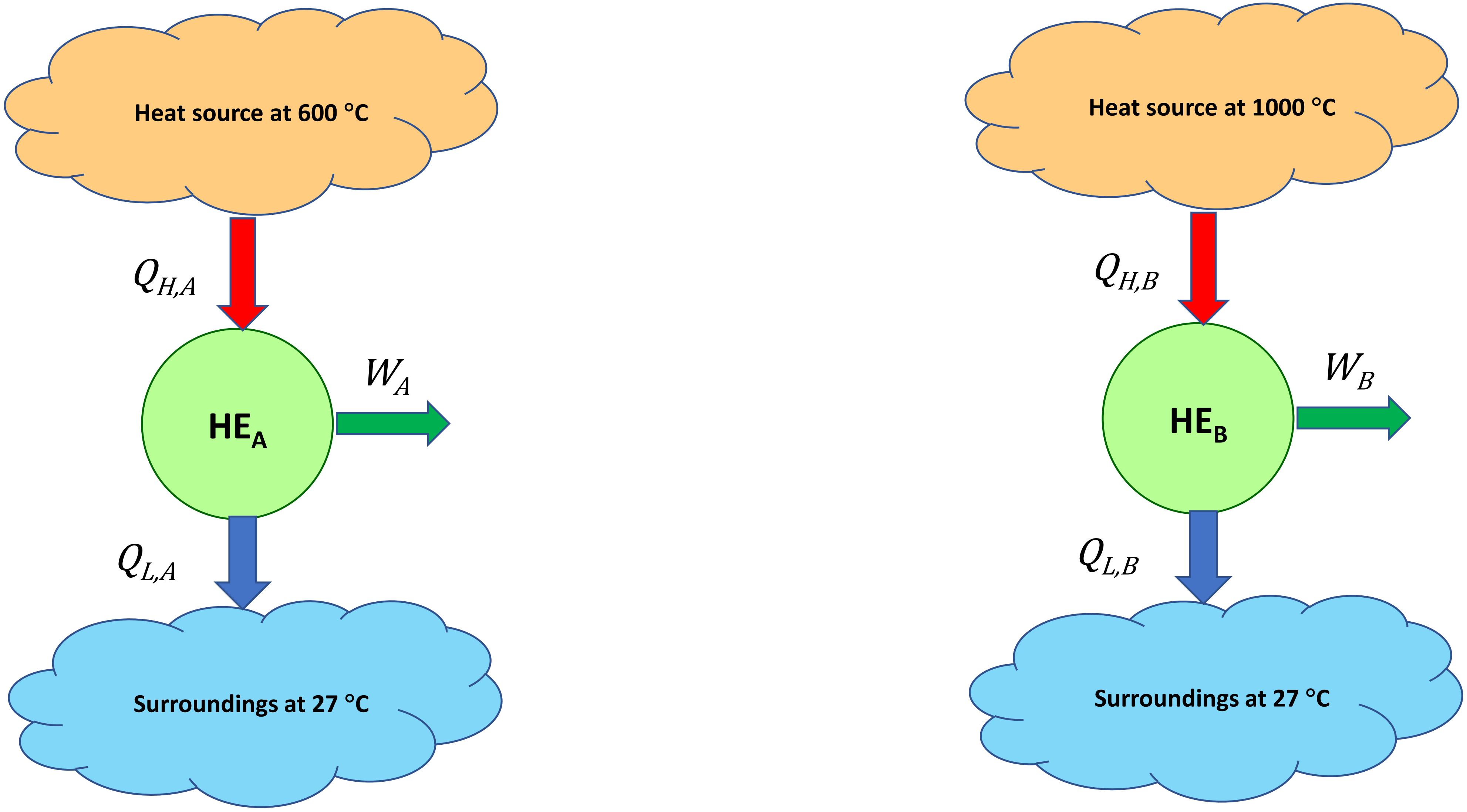
Entropy & Exergy

SNo	Topic	Hours
1	Entropy – Clausius Theorem, Clausius Inequality	2
2	Entropy of Isolated system	1
3	Entropy change of liquids, solids & ideal gases	2
4	Exergy – Reversible work and Irreversibility - II law efficiency	2
5	Exergy change for non flow system & flow streams	2
6	III law of Thermodynamics	1

Today's discussion

- Review
- II law efficiency
- Numerical example
- Exergy for non-flow systems
- Exergy for flow streams

Two heat engines, both 30% efficient are connected between a source and sink as shown in figure. Comment on the performances of these.



The II law efficiency

Heat engines → $\eta_{II} = \frac{\eta_{th}}{\eta_{th,rev}}$

$\eta_{II} = \frac{W_{u,out}}{W_{rev,out}}$ ← Work producing devices

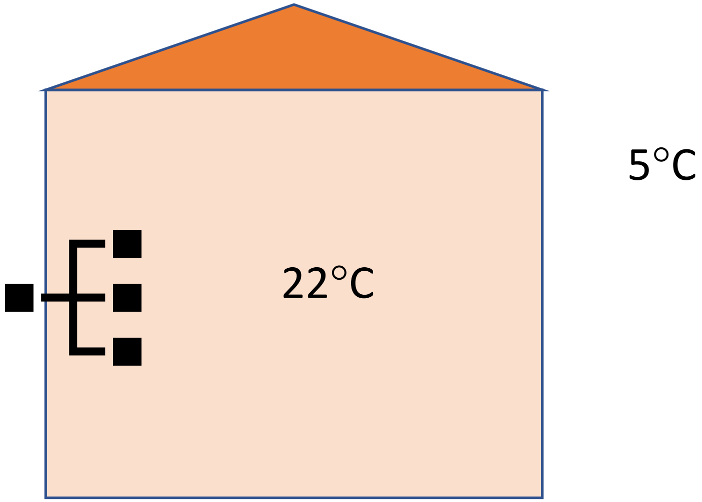
Work consuming devices → $\eta_{II} = \frac{W_{rev,in}}{W_{u,in}}$

$\eta_{II} = \frac{COP}{COP_{rev}}$ ← Refrigerators and heat pumps

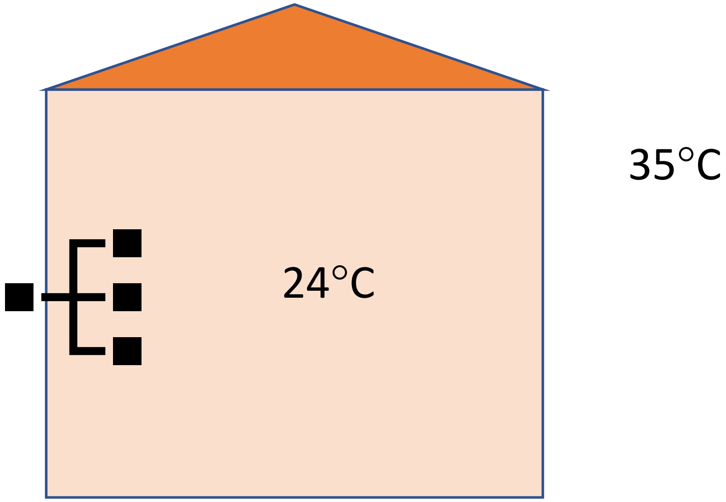
Based on exergy → $\eta_{II} = \frac{Exergy\ recovered}{Exergy\ supplied}$

$\eta_{II} = 1 - \frac{Exergy\ destroyed}{Exergy\ supplied}$ ← Based on exergy

A dealer advertises that he has received a shipment of room heaters that are 100% efficient. Assuming indoor and outdoor temperatures of 22°C and 5°C, determine the second law efficiency of the room heaters.

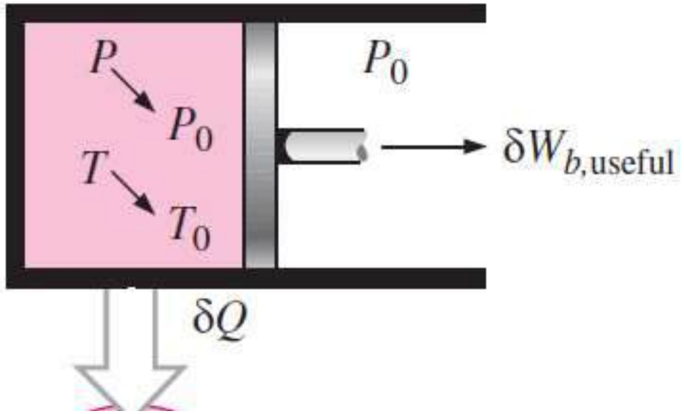


A dealer advertises that he has received a shipment of air conditioner that is 80% efficient. Assuming indoor and outdoor temperatures of 24°C and 35°C, determine the second law efficiency of the air conditioner.



Exergy of a fixed mass (non-flow) system

- A piston cylinder arrangement with a fixed mass, m of a fluid



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

$$-\delta Q - \delta W = dU$$

Energy balance
- Both heat & work transfer out of the system

$$\delta W = P\, dV$$

$$\delta W = P\, dV = (P - P_0)\, dV + P_0\, dV = \delta W_{b,useful} + P_0\, dV$$

Includes surrounding work too !!

Exergy of a fixed mass (non-flow) system

$$\underbrace{\delta E_{in} - \delta E_{out}}_{\substack{\text{Net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}}_{\substack{\text{Change in internal, kinetic,}\\ \text{potential, etc., energies}}}$$

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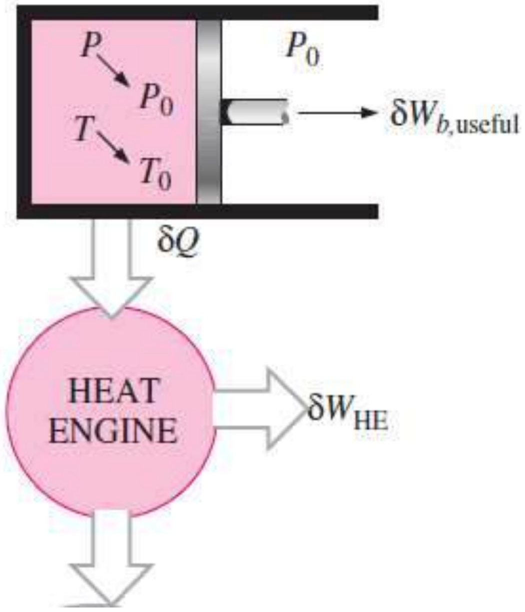

$$\delta W_{HE} = \left(1 - \frac{T_0}{T}\right)\delta Q = \delta Q - \frac{T_0}{T}\delta Q = \delta Q - (-T_0\,dS)$$

$$\delta Q = \delta W_{HE} - T_0\,dS$$

$$\delta W_{\text{total useful}} = \delta W_{HE} + \delta W_{b,\text{useful}} = -dU - P_0\,dV + T_0\,dS$$

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

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

$$dS = \delta Q/T$$

$$\eta_{th} = 1 - T_0/T,$$

$$\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

$$= (e - e_0) + P_0(v - v_0) - T_0(s - s_0)$$

Exergy of a fixed mass (non-flow) system

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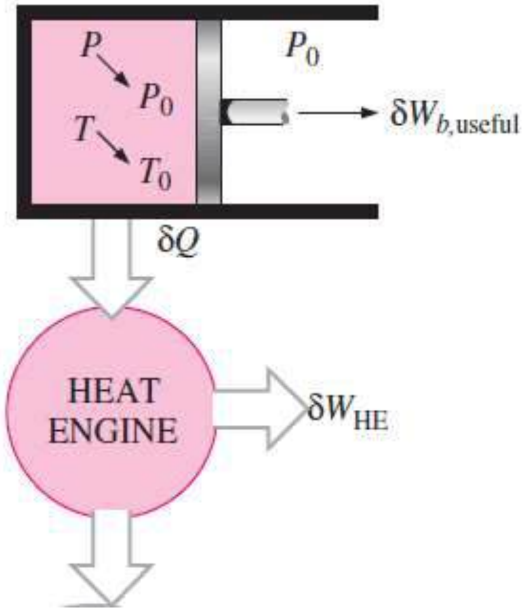


$$X = (U - U_0) + P_0(V - V_0) - T_0(S - S_0) + m\frac{V^2}{2} + mgz$$

$$\phi = (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

$$= (e - e_0) + P_0(v - v_0) - T_0(s - s_0)$$

From a state 1 to state 2

$$\Delta X = X_2 - X_1 = m(\phi_2 - \phi_1) = (E_2 - E_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1)$$

$$= (U_2 - U_1) + P_0(V_2 - V_1) - T_0(S_2 - S_1) + m\frac{V_2^2 - V_1^2}{2} + mg(z_2 - z_1)$$

On unit mass basis

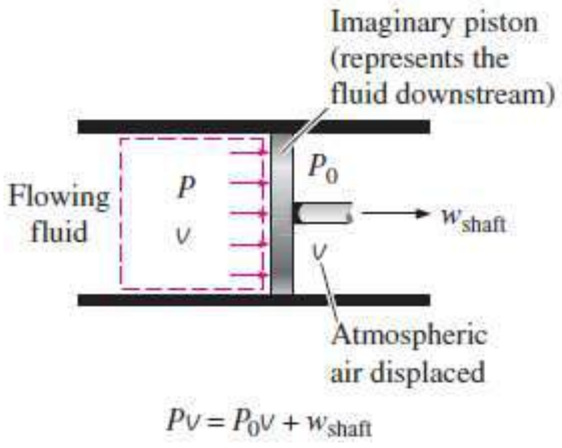
$$dS = \delta Q/T$$

$$\eta_{th} = 1 - T_0/T,$$

$$\Delta\phi = \phi_2 - \phi_1 = (u_2 - u_1) + P_0(v_2 - v_1) - T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$= (e_2 - e_1) + P_0(v_2 - v_1) - T_0(s_2 - s_1)$$

Exergy of flow stream



$$x_{flow} = Pv - P_0v = (P - P_0)v$$

$$x_{flowing\ fluid} = x_{nonflowing\ fluid} + x_{flow}$$

$$= (u - u_0) + P_0(v - v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz + (P - P_0)v$$

$$= (u + Pv) - (u_0 + P_0v_0) - T_0(s - s_0) + \frac{V^2}{2} + gz$$

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

Flow exergy

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

From a state 1 to state 2

$$\Delta\psi = \psi_2 - \psi_1 = (h_2 - h_1) + T_0(s_2 - s_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

References

1. Yunus A Cengel and Michael A Boles, "Thermodynamics – an Engineering Approach", 3rd Edition, Tata Mc Graw Hill, 2002.
2. Jones and Dugan, Engineering Thermodynamics, Prentice Hall of India, 2018.

Textbooks

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3. Mahesh M. Rathore, Thermal Engineering, Tata McGraw Hill, 2018.
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19ME31 Engineering Thermodynamics (L27) 2nd Nov 2020

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Thermodynamic Relations & Ideal Gas Mixtures

SNo	Topic	Hours
1	Thermodynamic potentials, Gibbs & Helmholtz functions	2
2	Maxwell Relations – T dS equations	2
3	Joule Kelvin effect & Clausius Clapeyron Equation	2
4	Ideal Gas Mixtures – Mass & Mole Fractions, Dalton's Law and Amagat-Leduc law	1
5	Properties of Ideal Gas mixture.	2

Today's discussion

- Review
- Clapeyron Equation
- Clausius – Clapeyron equation
- The Joule –Thompson (Joule – Kelvin) experiment

Application – Arriving at the Maxwell relations

- For a closed system, undergoing an incremental reversible change

$$dU = TdS - pdV$$

- Further

Enthalpy $H = U + pV$ → $dH = TdS + Vdp$

Helmholtz function $A = U - TS$ → $dA = -SdT - pdV$

Gibbs function $G = H - TS$ → $dG = -SdT + Vdp$

$$dz = Mdx + Ndy$$

The results – Maxwell relations

$$dU = TdS - pdV$$

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial p}{\partial S}\right)_V$$

$$dA = -SdT - pdV$$

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial p}{\partial T}\right)_V$$

$$dz = Mdx + Ndy$$

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y$$

$$dH = TdS + Vdp$$

$$\left(\frac{\partial T}{\partial p}\right)_S = \left(\frac{\partial V}{\partial S}\right)_p$$

$$dG = -SdT + Vdp$$

$$\left(\frac{\partial S}{\partial p}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_p$$

Relates rates of changes of immeasurable and measurable quantities

The Clapeyron Equation

- Enthalpy change associated with a phase change
- During phase change, pressure is a function of temperature alone (& independent of sp. Volume)

By integrating $\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial p}{\partial T}\right)_V$ at saturated conditions

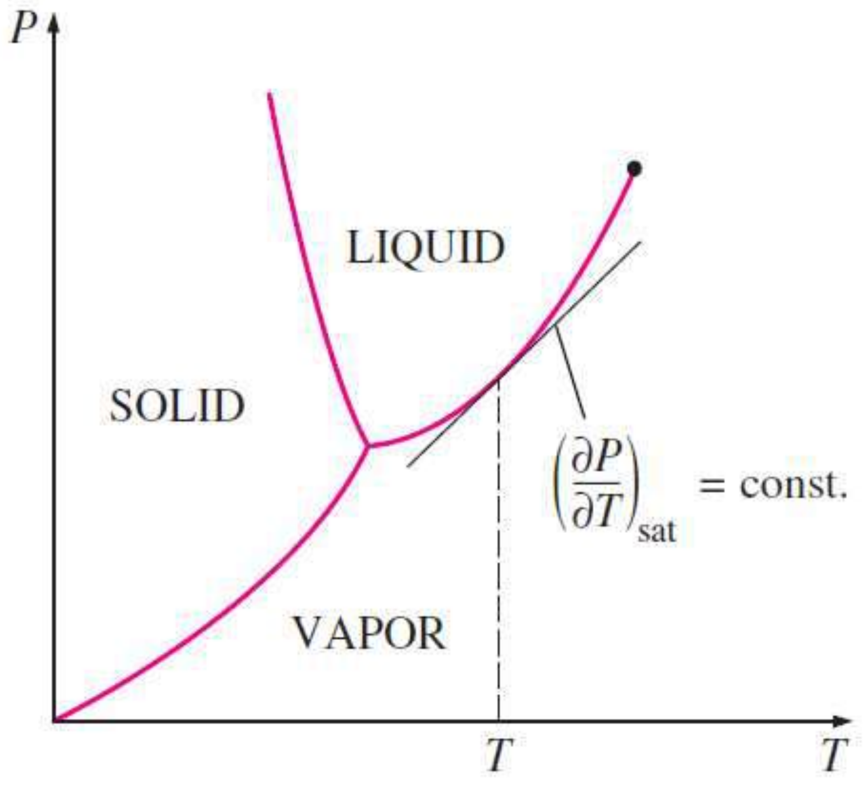
$$s_g - s_f = \left(\frac{dP}{dT}\right)_{sat}(v_g - v_f) \rightarrow \left(\frac{dP}{dT}\right)_{sat} = \frac{s_{fg}}{v_{fg}}$$

$$dh = T\,ds + v\,dP^{\nearrow 0} \rightarrow \int_f^g dh = \int_f^g T\,ds \rightarrow h_{fg} = Ts_{fg}$$

p = constant during phase change

The general form $\leftarrow$ $\left(\frac{\partial p}{\partial T}\right)_{sat} = \frac{h_{12}}{Tv_{12}}$

1 & 2 are phases



$$\left(\frac{\partial p}{\partial T}\right)_{sat} = \frac{h_{fg}}{Tv_{fg}}$$

Clapeyron equation

The Clausius Clapeyron equation

$$\left(\frac{\partial p}{\partial T}\right)_{sat} = \frac{h_{12}}{T v_{12}}$$

- General form can be simplified
- At low pressures, $v_g >> v_f \rightarrow v_{fg} \cong v_g$
- $v_g = RT/p$ @saturation (using ideal gas relationship)

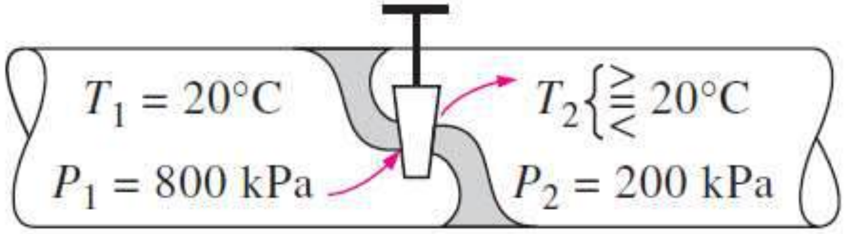
$$\left(\frac{\partial p}{\partial T}\right)_{sat} = \frac{p h_{fg}}{R T^2} \Rightarrow \left(\frac{\partial p}{p}\right)_{sat} = \frac{h_{fg}}{R}\left(\frac{\partial T}{T^2}\right)_{sat}$$

- Between small temperature intervals, h_{fg} be a assumed to be a constant
- Integrating between two phases, we get

$$\ln\left(\frac{p_2}{p_1}\right)_{sat} \cong \frac{h_{fg}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)_{sat}$$

⇐ **The Clausius - Clapeyron equation**

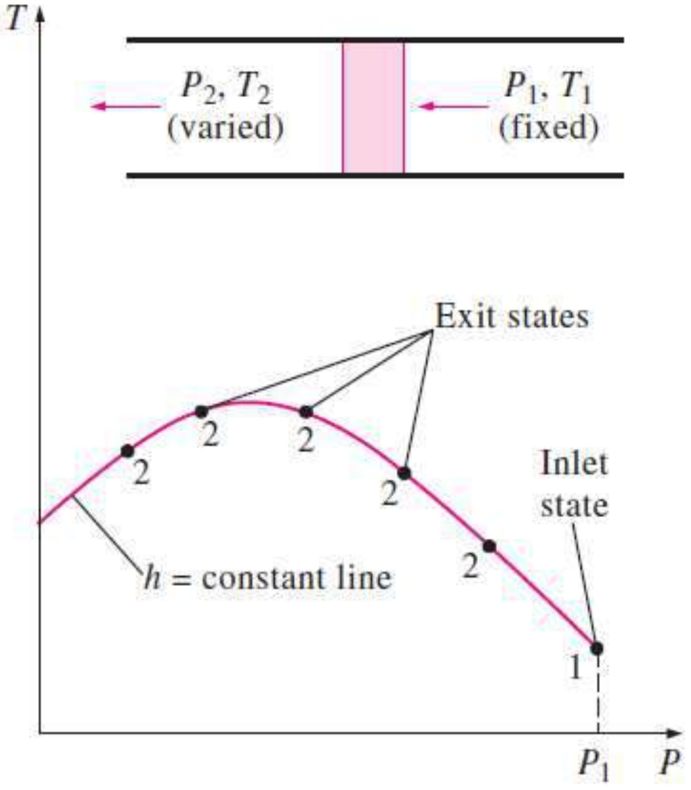
Joule-Thomson effect

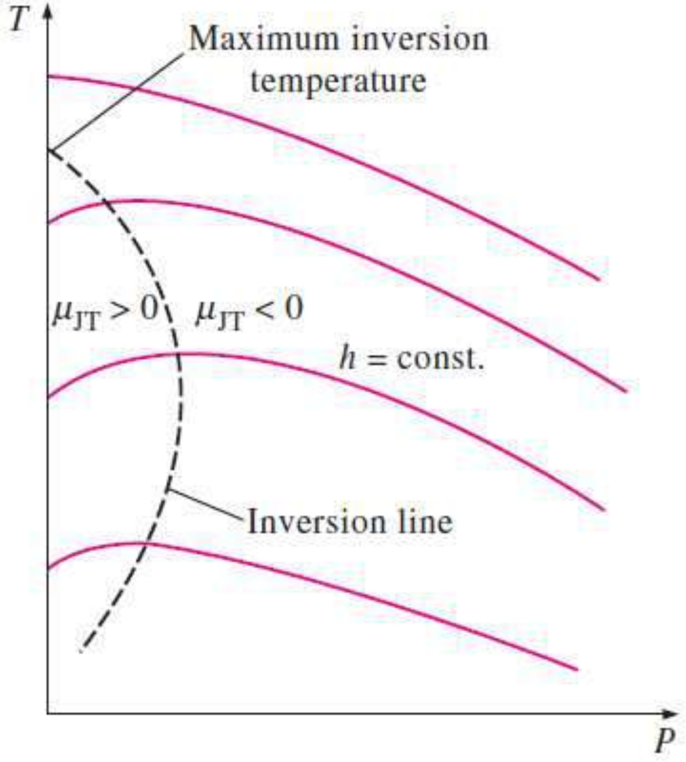


Joule Thomson coefficient

$$\mu = \left(\frac{\partial T}{\partial P}\right)_h$$

$$\mu_{JT} \begin{cases} < 0 & \text{temperature increases} \\ = 0 & \text{temperature remains constant} \\ > 0 & \text{temperature decreases} \end{cases}$$





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3. http://www.physics.rutgers.edu/~gersh/351/Lecture%2013.pdf

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19ME31 Engineering Thermodynamics (L28)
4th Nov 2020

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Second Law of Thermodynamics

Entropy & Exergy

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5	Properties of Ideal Gas mixture.	2

Today's discussion

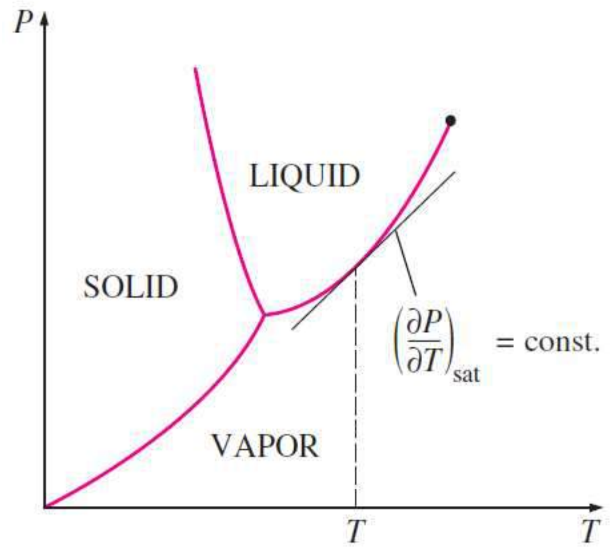
Review

Ideal Gas Mixtures – Mass & Mole Fraction

Dalton's law and Amagat-Leduc's law

Enthalpy change associated with a phase change

Joule-Thomson effect

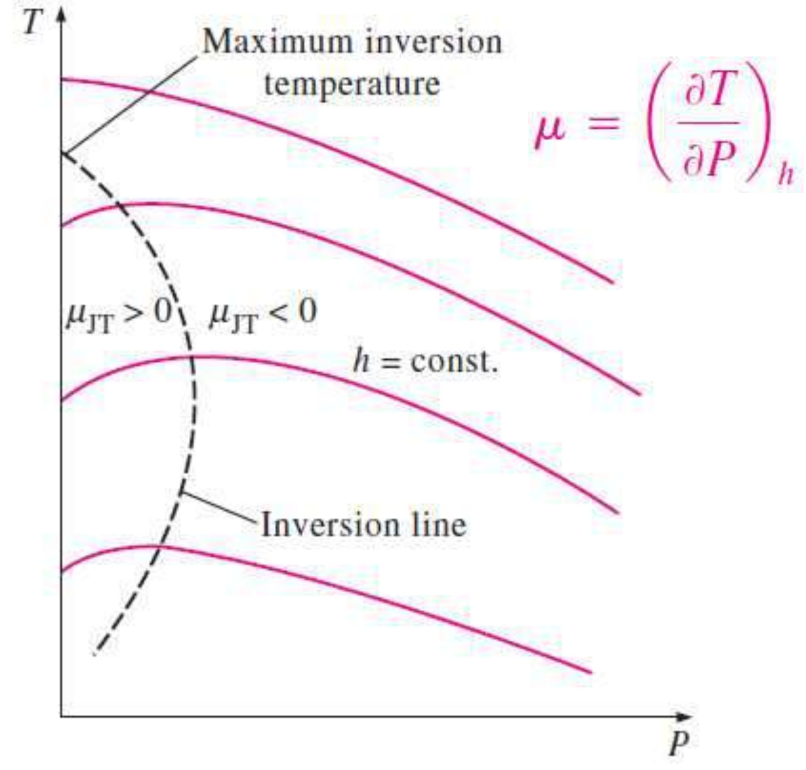


The Clapeyron Equation

$$\left(\frac{\partial p}{\partial T}\right)_{sat} = \frac{h_{fg}}{T v_{fg}}$$

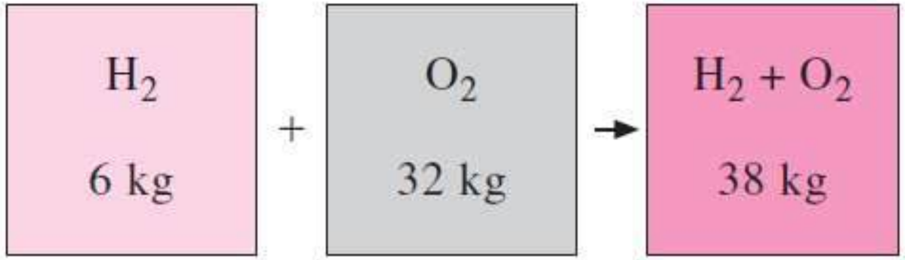
The Clausius Clapeyron equation

$$\ln\left(\frac{p_2}{p_1}\right)_{sat} \cong \frac{h_{fg}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)_{sat}$$



Ideal gas mixtures

Mass



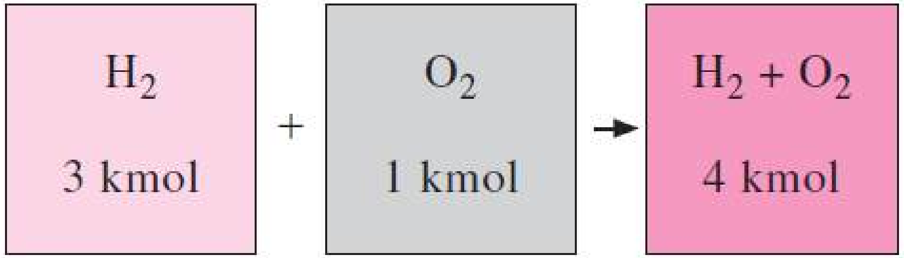
Mass of mixture → $m_m = \sum_{i=1}^{k} m_i$

Mass fraction of i[th] component → $mf_i = \dfrac{m_i}{m_m}$

$$\sum_{i=1}^{k} mf_i = 1$$

Gravimetric analysis

Moles



$N_m = \sum_{i=1}^{k} N_i$ ← Mole number of mixture

$y_i = \dfrac{N_i}{N_m}$ ← Mole fraction of i[th] component

$$\sum_{i=1}^{k} y_i = 1$$

Molar analysis

$$m = NM$$

Ideal gas mixtures (contd.)

Molar mass of mixtures

$$M_m = \frac{m_m}{N_m} = \frac{\sum_{i=1}^{k} m_i}{N_m} \rightarrow M_m = \frac{\sum_{i=1}^{k} N_i M_i}{N_m} = \sum_{i=1}^{k} y_i M_i$$

$$M_m = \frac{m_m}{N_m} = \frac{m_m}{\sum_{i=1}^{k} N_i} \rightarrow M_m = \frac{m_m}{\sum_{i=1}^{k} m_i/M_i} = \frac{1}{\sum_{i=1}^{k} \frac{mf_i}{M_i}}$$

Relation between mass fraction and mole fraction

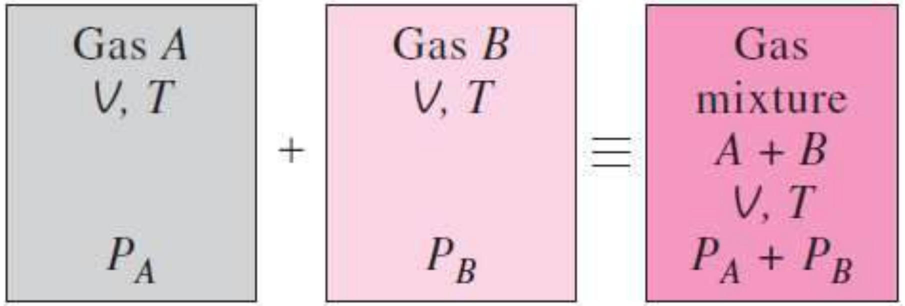
$$mf_i = \frac{m_i}{m_m} = \frac{N_i M_i}{N_m M_m} = y_i \frac{M_i}{M_m}$$

Gas constant of mixtures

$$R_m = \frac{\bar{R}}{M_m}$$

pVT behaviour of mixture of gases predicted by

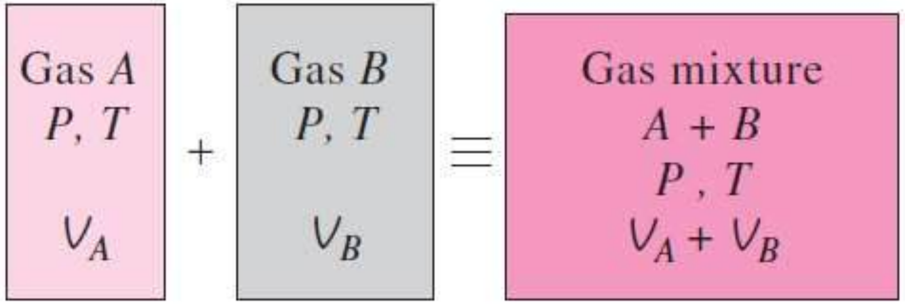
Dalton's law and Amagat-Leduc law



Dalton's law of additive pressures

$$P_m = \sum_{i=1}^{k} P_i(T_m, V_m)$$

The pressure of a gas mixture is equal to the sum of the pressures each gas would exert, if it existed alone at the same mixture temperature and volume



Amagat's law of additive volumes

$$V_m = \sum_{i=1}^{k} V_i(T_m, P_m)$$

The volume of a gas mixture is equal to the sum of the volume each gas would occupy, if it existed alone at the same mixture temperature and pressure

- The above laws hold good exactly for ideal gases
- They are valid only approximately for real gases, owing to intermolecular forces

References

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