THERMODYNAMICS

II B. Tech IV semester (Autonomous IARE R-16)

BY

Ms. C.H. RAGHA LEENA
Assistant Professor
Mr. S. R.SABARI VIHAR
Assistant Professor

DEPARTMENT OF AERONAUTICAL ENGINEERING
INSTITUTE OF AERONAUTICAL ENGINEERING
(Autonomous)
DUNDIGAL, HYDERABAD - 500 043

UNIT-I

INTRODUCTION

- Thermodynamics deals with stability of systems. It tells us ‘*what should happen?*’. ‘*Will it actually happen(?)’* is not the domain of thermodynamics and falls under the realm of kinetics.

- At –5°C at 1 atm pressure, ice is more stable then water. Suppose we cool water to –5°C. “Will this water freeze?” (& “how long will it take for it to freeze?”) is (are) not questions addressed by thermodynamics.

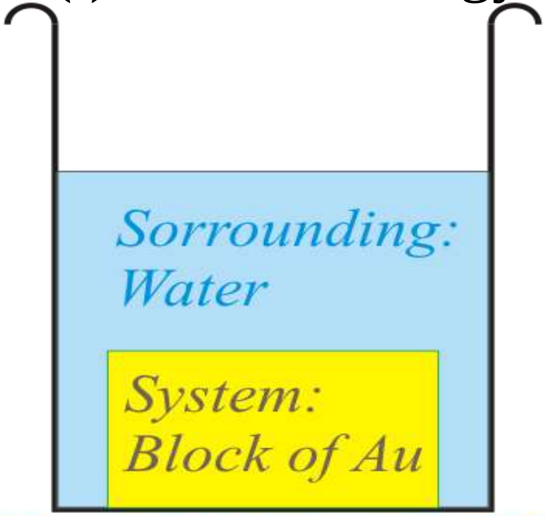
- One branch of knowledge that all engineers and scientists must have a grasp of *(to some extent or the other!)* is thermodynamics.

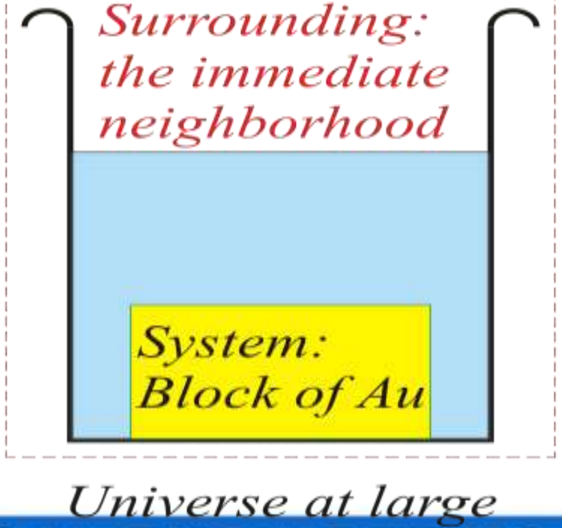
- Thermodynamics can be considered as a ‘system level’ science- i.e. it deals with descriptions of the whole system and *not with interactions (say) at the level of individual particles*.

- TD puts before us some fundamental laws which are universal in nature (and hence applicable to fields across disciplines).

- To understand the laws of thermodynamics and how they work, first we need to get the terminology right.
- System is region where we focus our attention *(Au block in figure).*
- Surrounding is the rest of the universe *(the water bath at constant 'temperature').*
- Universe = System + Surrounding (the part that is within the dotted line box in the figure below)

- More practically, we can consider the ‘Surrounding’ as the immediate neighbourhood of the system (the part of the universe at large, with which the system ‘effectively’ interacts).
- Things that matter for the surrounding: (i) T (ii) P (iii) ability to: do work, transfer heat, transfer matter, etc. Parameters for the system: (i) Internal energy, (ii) Enthapy, (iii) T, (iv) P, (v) mass, etc.





- Matter is easy to understand and includes atoms, ions, electrons, etc.
- Energy may be transferred (‘added’) to the system as heat, electromagnetic radiation etc.
- In TD the two modes of transfer of energy to the system considered are Heat and Work.

  Heat and work are modes of transfer of energy and not ‘energy’ itself.

- It is clear that, *bodies contain internal energy and not heat (nor work).*
- Matter when added to a system brings along with it some energy.
- The ‘energy density’ (energy per unit mass or energy per unit volume) in the incoming matter may be higher or lower than the matter already present in the system.

Macroscopic and microscopic approaches

Behavior of matter can be studied by these two approaches.

- In macroscopic approach, certain quantity of matter is considered, without a concern on the events occurring at the molecular level.

- These effects can be perceived by human senses or measured by instruments.

eg: pressure, temperature

In microscopic approach, the effect of molecular motion is considered.

eg: At microscopic level the pressure of a gas is not constant, the temperature of a gas is a function of the velocity of molecules.

Property

- It is some characteristic of the system to which some physically meaningful numbers can be assigned without knowing the history behind it.
- These are macroscopic in nature.
- Invariably the properties must enable us to identify the system.

Categories of Properties

Extensive property:

- Whose value depends on the size or extent of the system.

  eg: Volume, Mass (V,M).
- If mass is increased, the value of extensive property also increases.

Intensive property:

Whose value is independent of the size or extent of the system.

eg: pressure, temperature (p, T).

Specific property:

- It is the value of an extensive property per unit mass of system. (lower case letters as symbols) eg: specific volume, density (v, ρ).

- It is a special case of an intensive property.

- Most widely referred properties in thermodynamics:

Pressure; Volume; Temperature*; Entropy; Enthalpy;*

Internal energy

State:

- It is the condition of a system as defined by the values of all its properties.

- It gives a complete description of the system.

- Any operation in which one or more properties of a system change is called a change of state.

Phase:

- It is a quantity of mass that is homogeneous throughout in chemical composition and physical structure.

  e.g. solid, liquid, vapour, gas.

- Phase consisting of more than one phase is known as heterogenous system .

Path And Process:

The succession of states passed through during a change of state is called the *path of the system*. A system is said to go through a process if it goes through a series of changes in state.

- A system may undergo changes in some or all of its properties.
- A process can be construed to be the locus of changes of state
- Processes in thermodynamics are like streets in a city

  eg: we have north to south; east to west; roundabouts; crescents

Quasi-static Processes

The processes can be restrained or unrestrained

We need restrained processes in practice.

- A quasi-static process is one in which
- The deviation from thermodynamic equilibrium is infinitesimal.
- All states of the system passes through are equilibrium states.

Types of Equilibrium

Between the system and surroundings, if there is no difference in

❖ Pressure	Mechanical equilibrium
❖ Potential	Electrical equilibrium
❖ Concentration of species	Species equilibrium
❖ Temperature	Thermal equilibrium

- No interactions between them occur. They are said to be in equilibrium.

- Thermodynamic equilibrium implies all those together.

- A system in thermodynamic equilibrium does not deliver anything.

Zeroth Law of Thermodynamics

- If two systems (say A and B) are in thermal equilibrium with a third system (say C) separately (that is A and C are in thermal equilibrium; B and C are in thermal equilibrium).

- Then they are in thermal equilibrium themselves (that is A and B will be in thermal equilibrium

Heat And Work

Thermodynamic definition of work:

Positive work is done by a system when the sole effect external to the system could be reduced to the rise of a weight.

Thermodynamic definition of heat:

It is the energy in transition between the system and the surroundings by virtue of the difference in temperature.

- Work done BY the system is +ve Obviously work done ON the system is –ve .
- Heat given TO the system is +ve Obviously Heat rejected by the system is –ve

Types of Work Interaction

- Expansion and compression work (displacement work)
- Work of a reversible chemical cell
- Work in stretching of a liquid surface
- Work done on elastic solids

UNIT II

LIMITATIONS OF THE FIRST LAW

- There exists a law which determines the direction in which a spontaneous process proceeds.

- The law, known as the second law of thermodynamics, is a principle of wide generality and provides answer to the above questions.

- It is essential to understand the meaning of the following terms in order to discuss the second law of thermodynamics:

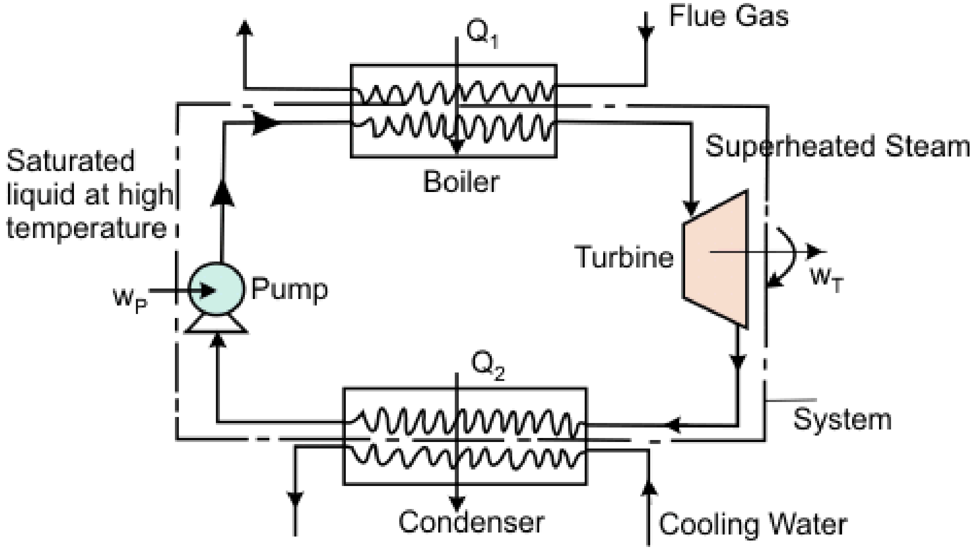
- Thermal reservoir is a large body from which a finite quantity of energy can be extracted or to which a finite quantity of energy can be added as heat without changing its temperature.

- A source is a thermal reservoir at high temperature from which a heat engine receives the energy as heat.

- A sink is a low temperature thermal reservoir to which a heat engine rejects energy as heat.

Heat Engine

- A heat engine is a device which converts the energy it receives at heat, into work. It is a cyclically operating device.
- It receives energy as heat form a high temperature body, converts part of it into work and rejects the rest to a low temperature body.
- A thermal power plant is an example of a heat engine.



Basic arrangement of thermal power plant

- In the boiler, the working fluid receives a certain amount of heat from the hot combustion products.

- The superheated steam enters a turbine where it undergoes expansion performing the shaft work .

- The low pressure steam enters a condenser where it exchange energy as heat at constant pressure with the cooling water and emerges as the condensate. The condensate rejects a certain amount of heat to the cooling water.

- The low pressure condensate from the condenser enters the pump. Work is done on the pump to elevate the condensate to the boiler pressure and return it to the boiler.

Finally, the thermal efficiency of a heat engine can be expressed as

$$\eta = \frac{(\text{Energy absorbed as heat} - \text{Energy rejected as heat})}{\text{Energy absorbed as heat}}$$

$$= \frac{\text{Net work done}}{\text{Energy absorbed as heat}}$$

$$= \frac{W_T - W_P}{Q_1}$$

HEAT PUMP

- Heat Pump is cyclically operating device which absorbs energy form a low temperature reservoir and reject energy as heat to a high temperature reservoir when work is performed on the device.

- Its objective is to reject energy as heat to a high temperature body (space heating in winter). The atmosphere acts as the low temperature reservoir.

Kelvin Plank Statement

It is impossible to construct a cyclically operating device such that it produces no other effect than the absorption of energy as heat from a single thermal reservoir and performs an equivalent amount of work.

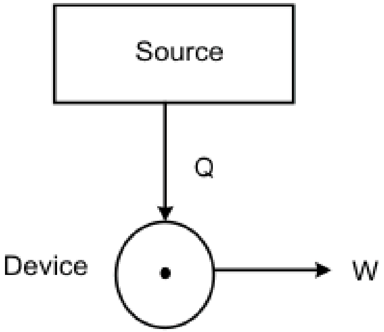
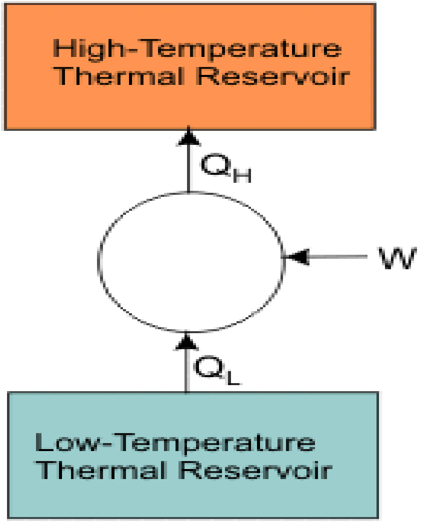


Figure 2.1 Kelvin Plank

Clausius Statement of the Second Law

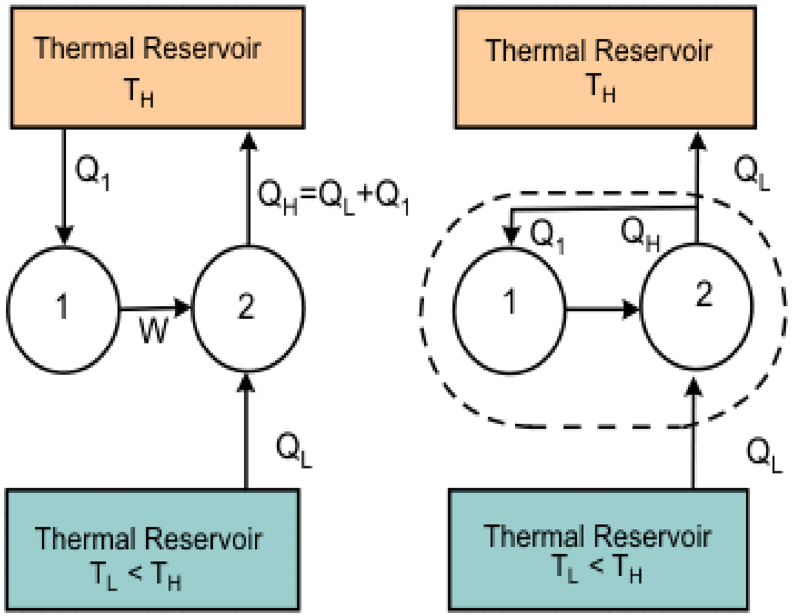
- Heat always flows from a body at higher temperature to a body at a lower temperature. The reverse process never occurs spontaneously.

- Clausius statement of the second law gives: It is impossible to construct a device which, operating in a cycle, will produce no effect other than the transfer of heat from a low-temperature body to a high temperature body.



Thermal reservoir

Clausius Statement of the Second Law



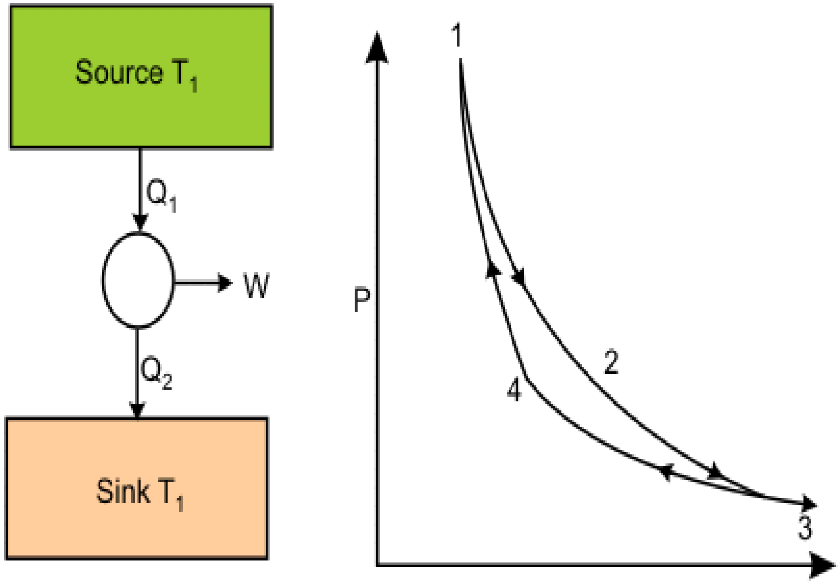
Clausius statement

$$W = Q_1,$$

$$Q_H = Q_L + W = Q_L + Q_1$$

Carnot Engine

Let us consider the operation of a hypothetical engine which employs the Carnot cycle. The Carnot engine consists of a **cylinder-piston assembly** in which a certain amount of gas(working fluid) is enclosed.



Carnot Cycle

The thermal efficiency,

$$\eta = \frac{W}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

Efficiency of Carnot Engine Using Ideal Gas

$$\eta = 1 + \frac{RT_2 \ \text{In}(v_4 / v_3)}{RT_1 \ \text{In}(v_2 / v_1)}$$

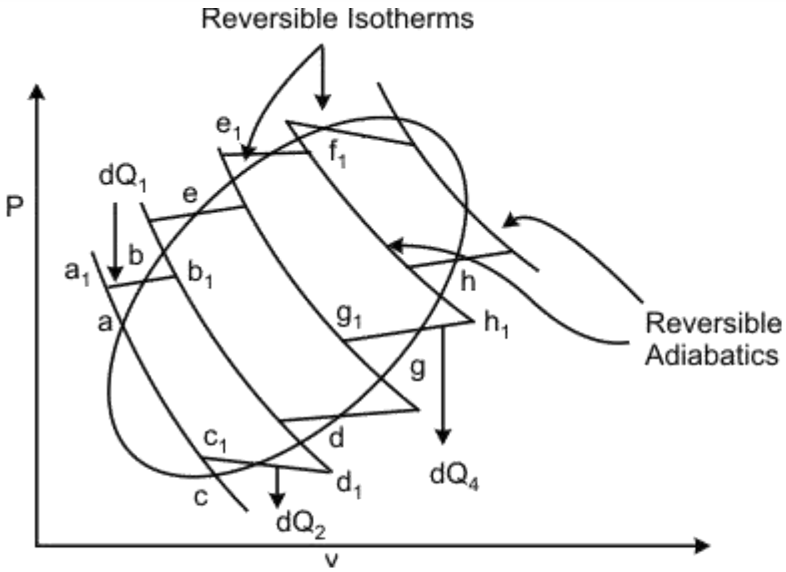
$$\eta = 1 - \frac{T_2 \ In(v_2 / v_1)}{T_1 \ In(v_2 / v_1)} = 1 - \frac{T_2}{T_1}$$

Thermodynamic Temperature Scale

A temperature scale, which does not depend on the thermodynamic property of the substance can be established by making use of the fact that the efficiency of a reversible heat engine does not depend on the nature of the nature of the working fluid but depends only upon the temperature of the reservoirs between which it operates.

Clausius Inequality

Consider a system undergoing a reversible cycle. The given cycle may be sub-divided by drawing a family of reversible adiabatic lines. Every two adjacent adiabatic lines may be joined by two reversible isotherms



$$\oint \frac{dQ}{T} \leq 0$$

- The equality holds good for a and the inequality holds good for an irreversible cycles.

- The complete expression ireversible cycle s known as Clausius Inequality.

Entropy

- Clausius inequality can be used to analyze the cyclic process in a quantitative manner.

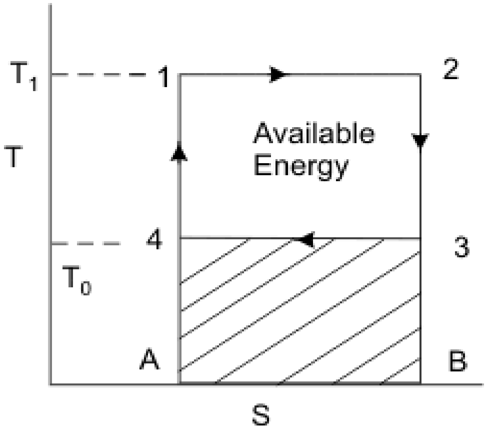
- The second law became a law of wider applicability when Clausius introduced the property called entropy.

- By evaluating the entropy change, one can explain as to why spontaneous processes occur only in one direction.

Available energy

- In order to determine that part of the energy which can be converted into work by an engine.

- We require consider a thermal reservoir at constant temperature T from which a quantity of energy Q is being absorbed as heat.



- The portion of energy is not available for conversion into work is called unavailable energy .

- Therefore, the available energy represents the portion of the energy supplied as heat which can be converted into work by means of a reversible engine. It is also known as EXERGY .

UNIT-III

PURE SUBSTANCES

Simple System

A simple system is one in which the effects of motion, viscosity, fluid shear, capillarity, anisotropic stress, and external force fields are absent.

Homogeneous Substance

A substance that has uniform thermodynamic properties throughout is said to be homogeneous.

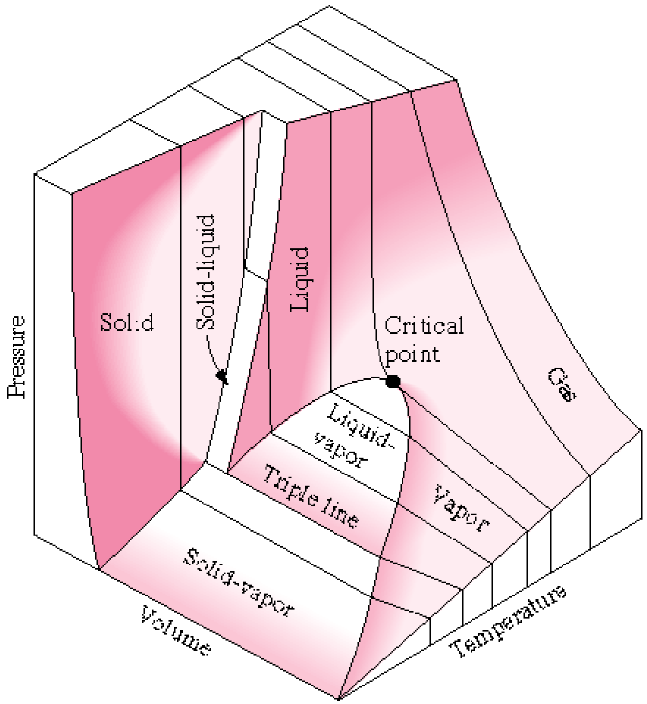
Pure Substance

A pure substance has a homogeneous and invariable chemical composition and may exist in more than one phase.

State Postulate

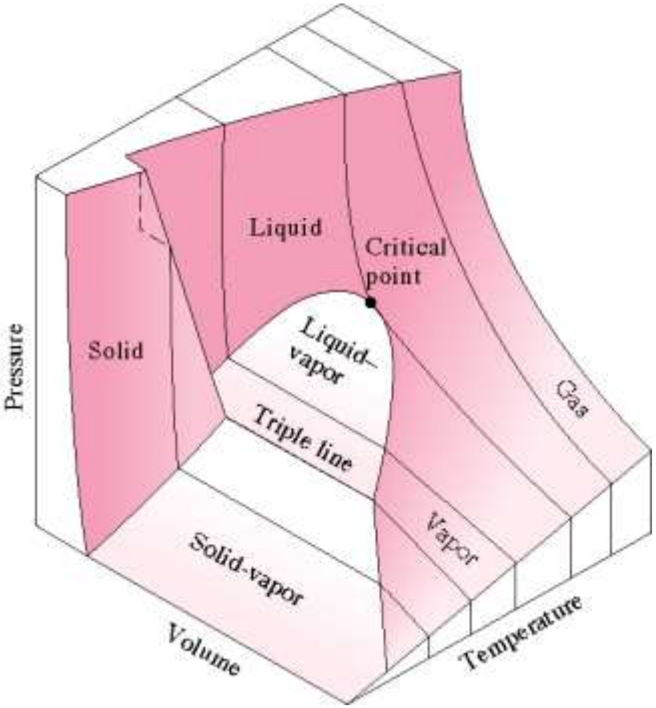
Again, the state postulate for a simple, pure substance states that the equilibrium state can be determined by specifying any two independent intensive properties.

_P-V-T_ Surface for a Substance that contracts upon freezing



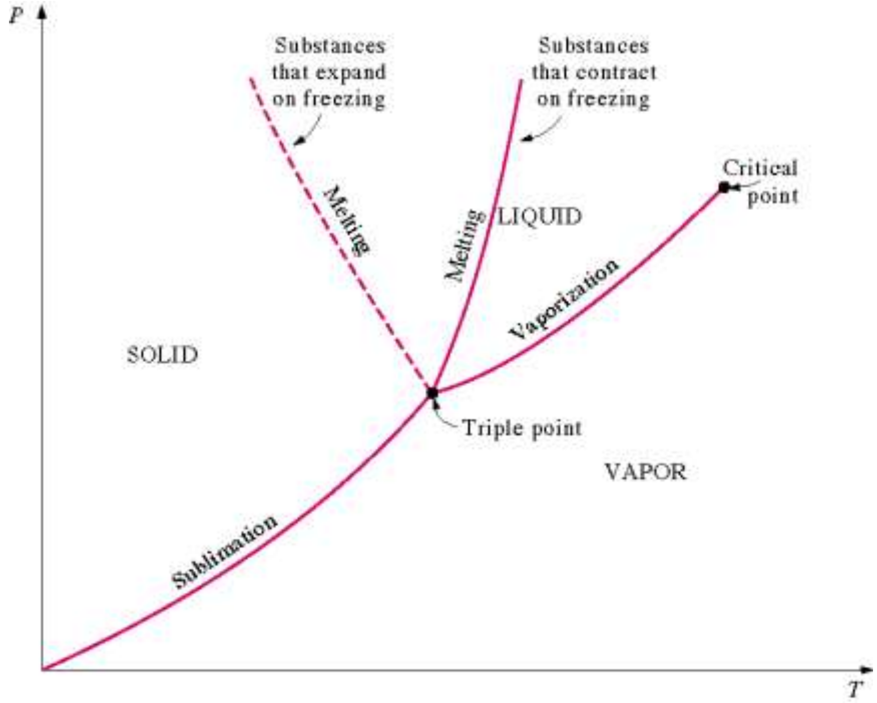
Temperature volume diagram

_P-V-T_ Surface for a Substance that expands upon freezing



Temperature volume diagram

The *P*-*T* diagram, often called the phase diagram, for pure substances that contract and expand upon freezing.



The triple point of water is 0.01°C, 0.6117 kPa.

The critical point of water is 373.95°C, 22.064 Mpa.

Property Tables

In addition to the temperature, pressure, and volume data, tables contain the data for the specific internal energy *u* the specific enthalpy *h* and the specific entropy *s*. The enthalpy is a convenient grouping of the internal energy, pressure, and volume and is given by

$$H = U + PV$$

The enthalpy per unit mass is

$$h = u + Pv$$

Saturation pressure is the pressure at which the liquid and vapor phases are in equilibrium at a given temperature.

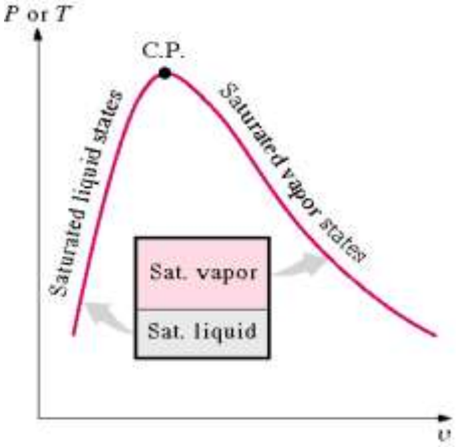
Saturation temperature is the temperature at which the liquid and vapor phases are in equilibrium at a given pressure.

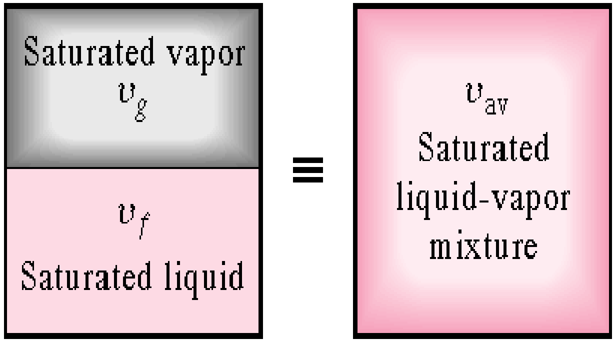
Quality and Saturated Liquid-Vapor Mixture

Now, let’s review the constant pressure heat addition process for water shown in Figure. Since state 3 is a mixture of saturated liquid and saturated vapor, how do we locate it on the T-v diagram? To establish the location of state 3 a new parameter called the quality *x* is defined as

$$x = \frac{mass_{saturated\ vapor}}{mass_{total}} = \frac{m_g}{m_f + m_g}$$

The quality is zero for the saturated liquid and one for the saturated vapor ($0 \leq x \leq 1$). The average specific volume at any state 3 is given in terms of the quality as follows. Consider a mixture of saturated liquid and saturated vapor. The liquid has a mass *mf* and occupies a volume V_f. The vapor has a mass *mg* and occupies a volume V_g.





We note

$$V = V_f + V_g$$

$$m = m_f + m_g$$

$$V = mv, \quad V_f = m_f v_f, \quad V_g = m_g v_g$$

$$mv = m_f v_f + m_g v_g$$

$$v = \frac{m_f v_f}{m} + \frac{m_g v_g}{m}$$

Recall the definition of quality x

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

$$\frac{m_f}{m} = \frac{m - m_g}{m} = 1 - x$$

Compressed Liquid Water Table

A substance is said to be a **compressed liquid** when the pressure is greater than the saturation pressure for the temperature.

Saturated Ice-Water Vapor Table

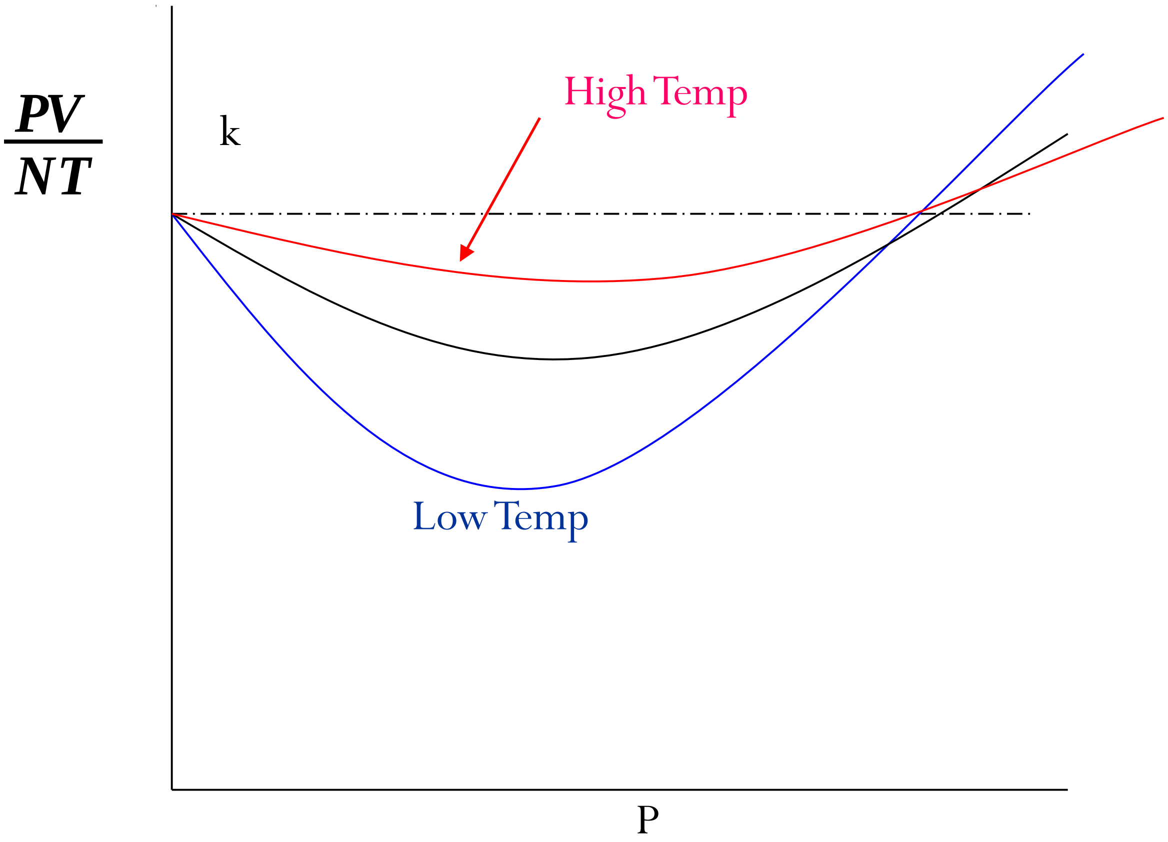
- When the temperature of a substance is below the triple point temperature, the saturated solid and liquid phases exist in equilibrium.
- Here we define the quality as the ratio of the mass that is vapor to the total mass of solid and vapor in the saturated solid-vapor mixture.
- The process of changing directly from the solid phase to the vapor phase is called sublimation.

Although thermodynamics applies to all forms of matter it is easiest to consider a gas or vapor. The equation of state is of the form f(P,V,T)=0.

The mechanical variables (P,V) occur as “canonically conjugate pairs”, the extensive variable V and the intensive variable P.

NOTE: The term “canonically conjugate” comes from Lagrangian mechanics. The close association of these variables will become clear as we develop the formalism.

Ideal Gas If P, V and T measurements are made on a sample of a real gas it is found that, if the results are plotted graphically, we obtain: (N=number of molecules)



As the pressure decreases approaches a fixed value. Furthermore this fixed value is found to be the same for all gases. This experimental no. is called Boltzmann’s Constant and the measured value is:

$$k = 1.3806504 \times 10^{-23} \, \tfrac{J}{K}$$

Thus, at low pressure, $\boldsymbol{\frac{PV}{NT} \approx k}$ $PV \approx N\,kT$

By definition, an **ideal gas**, obeys this **equation of state** exactly.

$$\boxed{\mathbf{PV = NkT}}$$

and a real gas behaves like an ideal gas when its pressure is low.

By definition, the universal gas constant R is

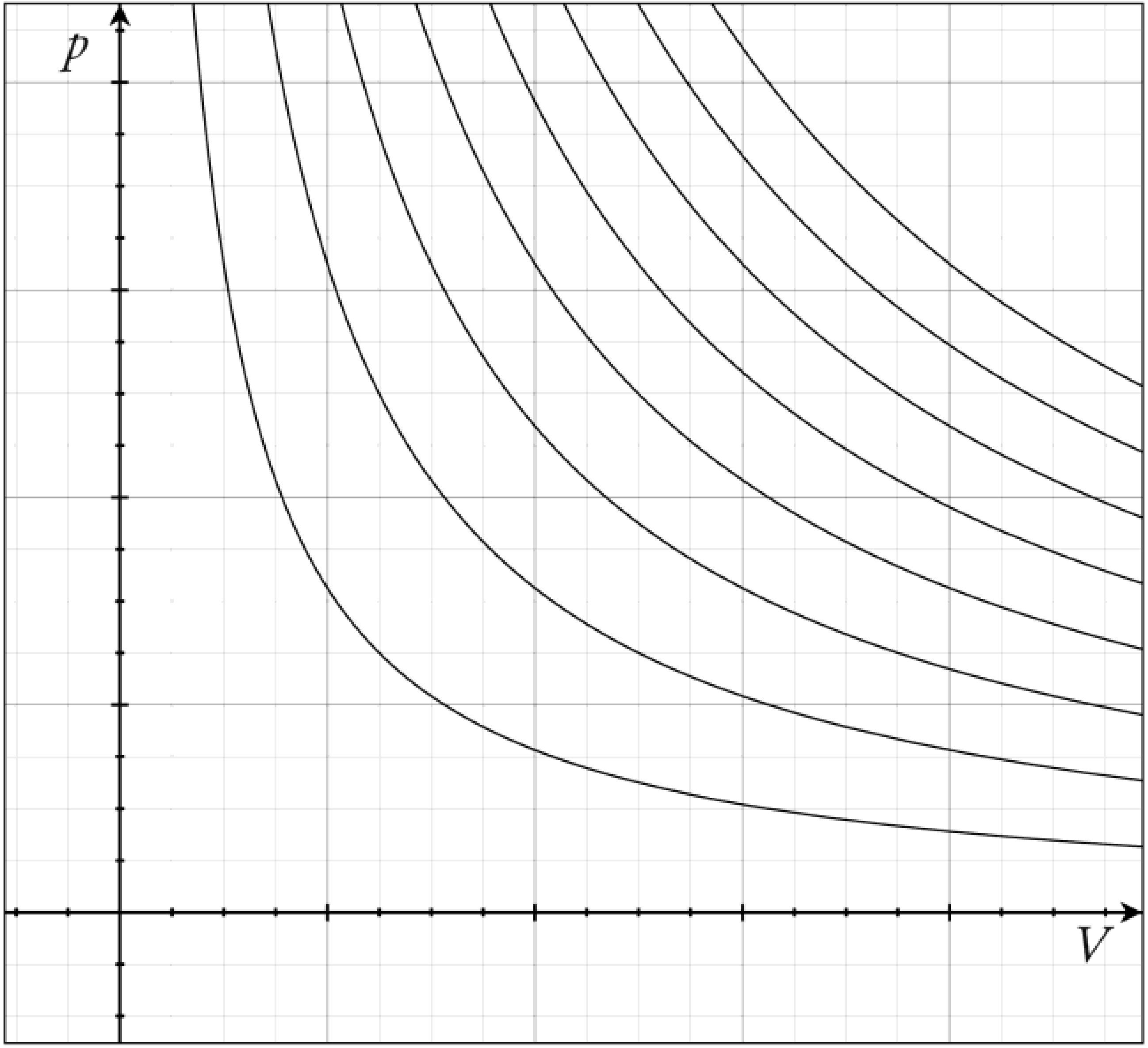
$$R \equiv N_A k = \left(6.02214179 \times 10^{23} \frac{molecules}{mole}\right)\left(1.3806504 \times 10^{-23} \frac{J}{K}\right)$$

$$R = 8.314472 \frac{J}{moleK} \qquad n = number\ of\ moles$$

$$\boldsymbol{R = N_A k = \left(\frac{N}{n}\right)k \qquad nR = Nk\ so}$$

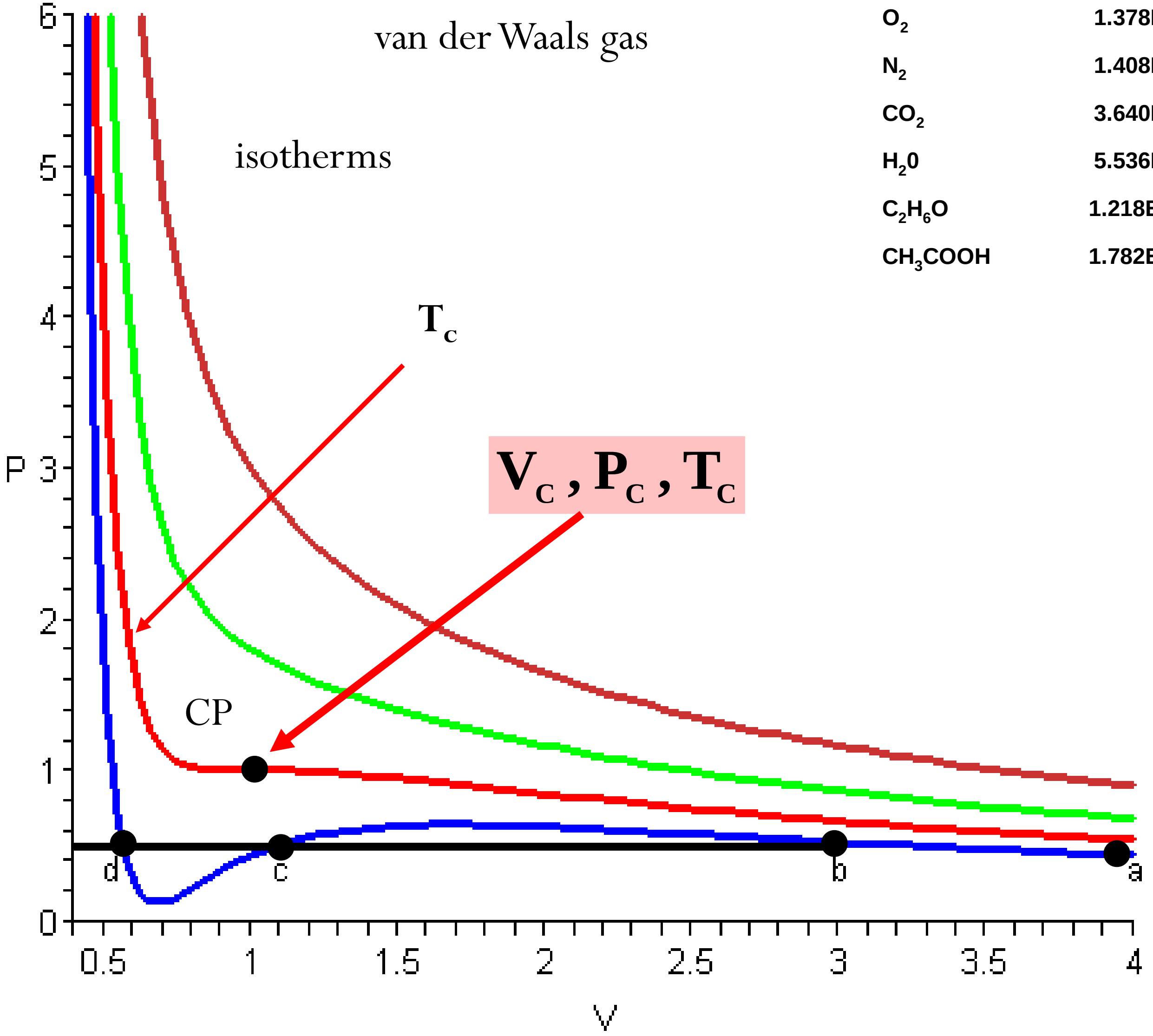
$$\boxed{\mathbf{PV = n\ RT}}$$

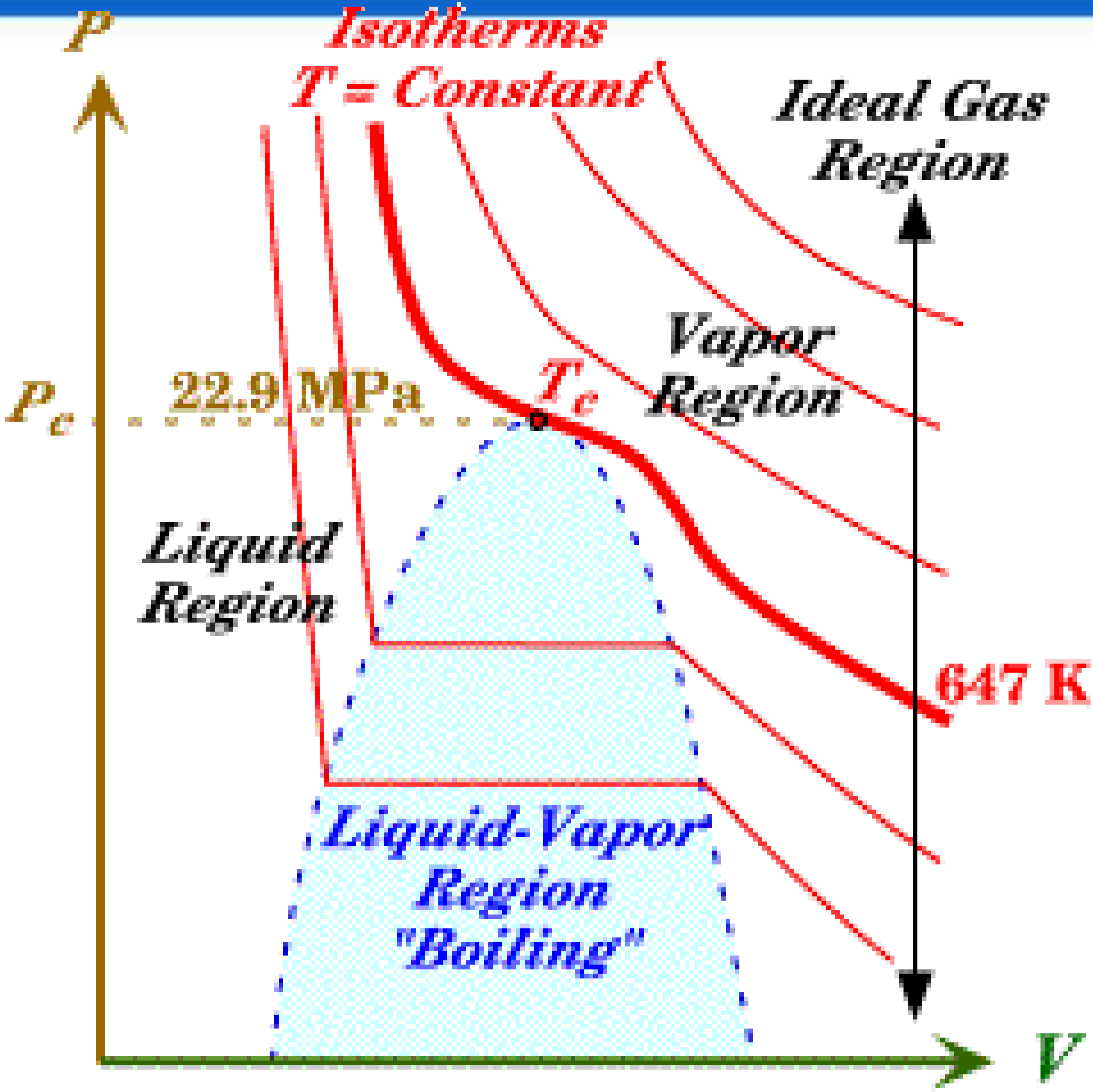
ideal gas



ideal gas isotherms
P = nRT/V
(hyperbolae)

vdW const.	a	b
He	3.457E-03	2.371E-05
Ne	2.135E-02	1.709E-05
H_2	2.476E-02	2.661E-05
Ar	1.363E-01	3.219E-05
O_2	1.378E-01	3.183E-05
N_2	1.408E-01	3.913E-05
CO_2	3.640E-01	4.267E-05
$H_2$0	5.536E-01	3.049E-05
C_2H_6O	1.218E+00	8.407E-05
CH_3COOH	1.782E+00	1.068E-04




P
Isotherms
T = Constant
Ideal Gas Region
Vapor Region
P_c
22.9 MPa
T_c
Liquid Region
647 K
Liquid-Vapor Region "Boiling"
V

One isotherm, has a point of inflection called the **critical point**. At the point of inflection:

$$\left(\frac{\partial \mathbf{P}}{\partial \mathbf{v}}\right)_{\mathbf{T}} = \mathbf{0} \qquad \left(\frac{\partial^2 \mathbf{P}}{\partial \mathbf{v}^2}\right)_{\mathbf{T}} = \mathbf{0}$$

$$T = T_C$$

Example: $T_C = 647.35\ K$ $\qquad P_C = 20.9\ MPa$

- Isotherms below the critical isotherm have a maximum. Consider an isothermal compression starting at point a. According to the vander Waals equation as v is decreased the path will be along the isotherm shown.

- However this does not happen. At point b a **change of phase** begins to take place. Liquid starts to form.

- At this point, as v is further decreased, P remains constant.

- At point d the substance has been completely converted to a liquid and as the volume continues to be decreased the pressure rises steeply.

- With a liquid, a small decrease in volume requires a large increase in pressure.

- Above the critical T there is no maximum on the isotherms. It is impossible to liquefy the gas regardless of the applied P.

Comment:

The van der Waals equation is a cubic equation in v so there are three possible roots for v. We can write

$$(\mathbf{v} - \mathbf{v}_1)(\mathbf{v} - \mathbf{v}_2)(\mathbf{v} - \mathbf{v}_3) = 0$$

in which the $\mathbf{v}_\mathbf{i}$ are the roots.

$$(\mathrm{v} - \mathrm{v}_C)^3 = 0$$

In the region **above** the critical isotherm, there is only one **real** root. In the region **below** the critical isotherm, are three **real** roots, all different. At the critical temperature there are three identical real roots and we have

Law of corresponding states:

- The equation of state when expressed in terms of the reduced variables is a universal equation valid for all substances.

- Since the van der Waals Equation is not exactly true, the law of corresponding states is only approximately true.

P-V-T surfaces for real gases:

- We consider a fixed amount of a real substance. The thermodynamic variables are P, V and T, two of which are independent.

- Equations, such as that for an ideal gas or the van der Waals equation, describe the system over a limited range of these variables, but no single equation is adequate for extended regions.

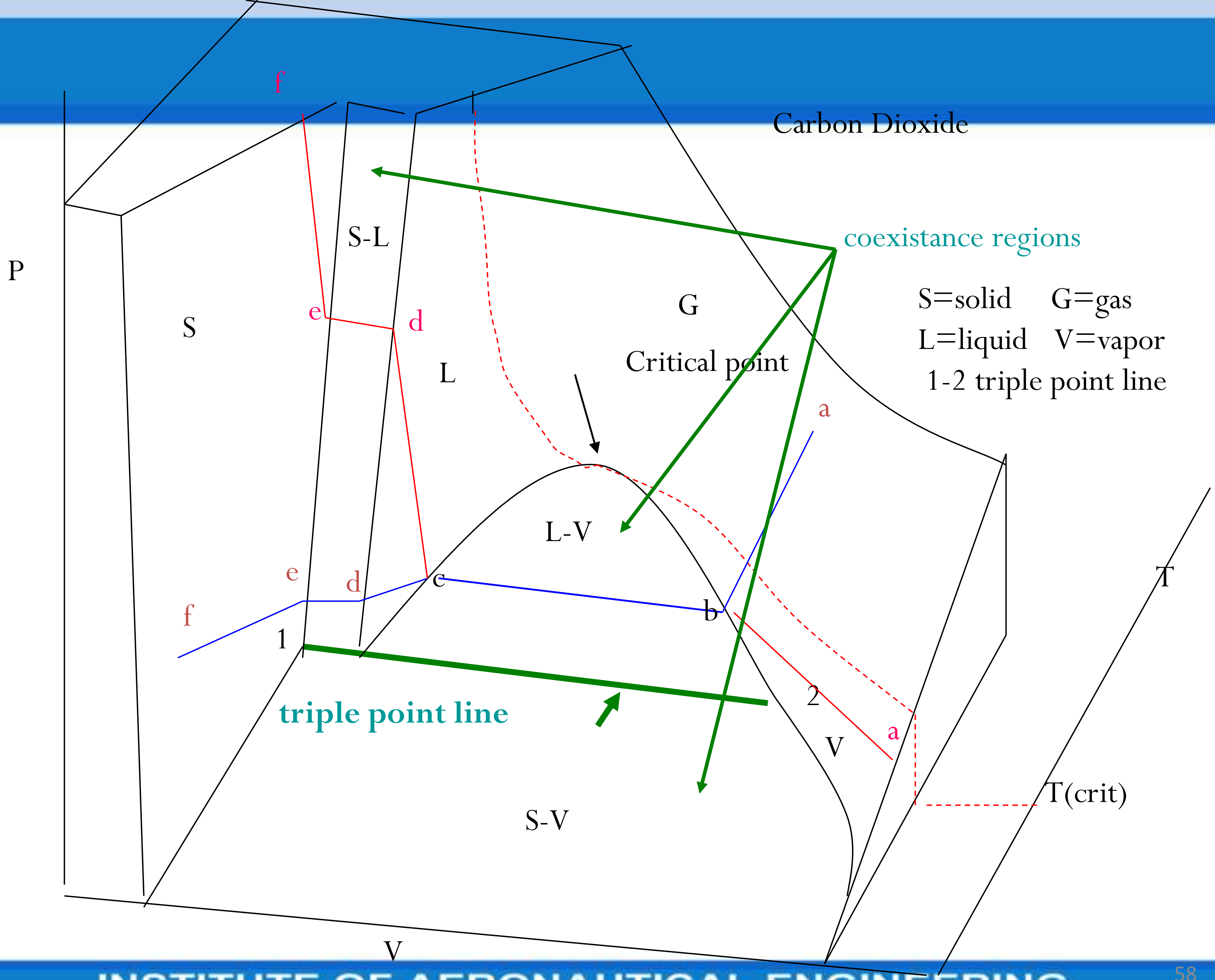
- Thus, P-V-T data are often given in tables. A convenient way to visualize the data is with a PVT surface.

- A cartesian coordinate system with P, V and T as the axes is used to represent the system. If we think as T and V as fixed, then P is determined.

- Changing T and V changes P and in this fashion a *surface* is generated. A quasistatic process may be represented by a path on this surface.

Let us consider the PVT surface of carbon dioxide, which is characteristic of many pure substances. The surface shown is qualitatively correct, but not quantitatively.

Carbon Dioxide



coexistance regions

triple point line

S=solid G=gas
L=liquid V=vapor
1-2 triple point line

The following are important aspects of the drawing:

- The coexistance regions are **ruled surfaces**. A line parallel to the V-axis which touches the surface at one point, touches it at all points.

- The line 1-2 is called the triple point line. At this unique temperature and pressure ($T = 216.6$ K, $P = 5.18\times10^5$ Pa for CO_2) the substance can exist in all three phases.

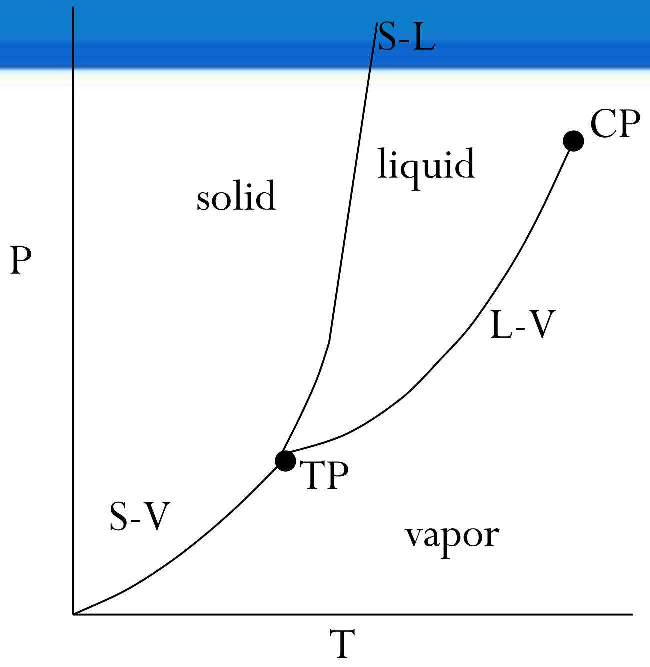
For carbon dioxide: $T_c = 304.2$ K, $P_c = 73.0\times10^5$Pa

- A line drawn on the surface such that T is constant is called an **isotherm**. The isotherm passing through the critical point is called the **critical isotherm**.

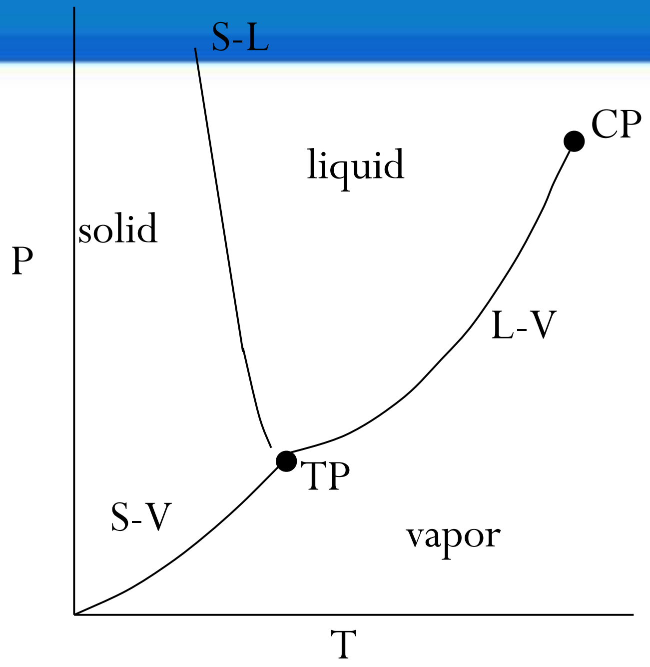
- When the system is in a fluid phase at a T greater than the critical temperature it is called a gas. The fluid phases at T'slower than critical are called liquid and vapor.

- Projections onto the P-T plane are useful (**phase diagram**). Two such diagrams are shown on the next slide.

- The one on the left is for a substance that contracts upon freezing and that on the right is for a substance that expands (rare) upon freezing. Note that the ruled surfaces become lines in this projection.



contracts on freezing



expands on freezing

L-V	saturated vapor or boiling point (or vapor pressure) curve
S-L	freezing point curve
S-V	sublimation curve

It should be emphasized that, with a change of phase, P and T remain constant, but V changes. Most substances contract on freezing. Water and a few other substances expand on freezing.

Expansivity and compressibility

We now consider a simple system that can be described by assigning P,V, and T.

- The equation of state is $f(P,V,T) = 0$
- Two quantities are found to be independent. We can, for example, solve the equation of state for V.

$$V = V(T,P)$$

Consider an infinitesimal change from one equilibrium state to another equilibrium state. The temperature and pressure, the two variables chosen to be independent, will generally change and we can then write, for the infinitesimal change in V.

$$dV = \left(\frac{\partial V}{\partial T}\right)_p dT + \left(\frac{\partial V}{\partial P}\right)_T dP \quad \_\ \_\ \_\ \_\ \_(1)$$

Each partial can be a function of P and T.

- We cannot integrate this equation to obtain the change in volume when there are temperature and pressure changes because the partial derivatives are unknown.

- One way to proceed is to try to obtain expressions for the partials by creating a model of the system.

- However the approach in macroscopic thermodynamics is to appeal to experimental measurements.

We define two quantities which can be measured and are often tabulated:

Volume expansivity:

$$\boxed{\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P}$$

Isothermal compressibility

$$\boxed{\kappa = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T}$$

$$\beta = \beta(P, V, T) \qquad \kappa = \kappa(P, V, T)$$

UNIT-IV

MIXTURES OF PERFECT GASES

Ideal Gas Mixtures and Liquid Solutions

- We next explore the development of a quantitative definition of the chemical potential in terms of the volumetric properties and composition of mixtures.

- We have observed earlier that just as ideal gas state is a reference for real gas properties, ideal gas mixtures play the same role with respect to real gas mixtures.

- Therefore, it is instructive to establish the property relations for ideal gas mixture first.

- Consider the constitution of an ideal gas mixture (containing *N* species) at a given temperature (T) and pressure (P).

- To obtain *n* moles of the total mixture we need to bring together n_i moles of each species at temperature T but at a pressure p_i which corresponds to the *partial pressure* that each species would exert in the final mixture. If V^t is the total volume of the mixture, the following set of relations hold.

- The result indicates that the molar volume for a species does not change between its pure state and in an ideal gas mixture at the same T & P.

- Itmay then be concluded that for an ideal gas mixture the properties of each species are independent of that of the other ones.

- This may be easy to appreciate as the concept of an ideal gas is premised on the idea that the intermolecular interaction is non-existent in such a state. This conclusion leads to the well-known *Gibbs theorem***.**

- *“Except for volume all other partial molar property of a species in an ideal-gas mixture is equal to the corresponding molar property of the species as a pure ideal gas at a temperature same as that of the mixture, but at a pressure equal to its partial pressure in the mixture.”*

Avogadro's Law

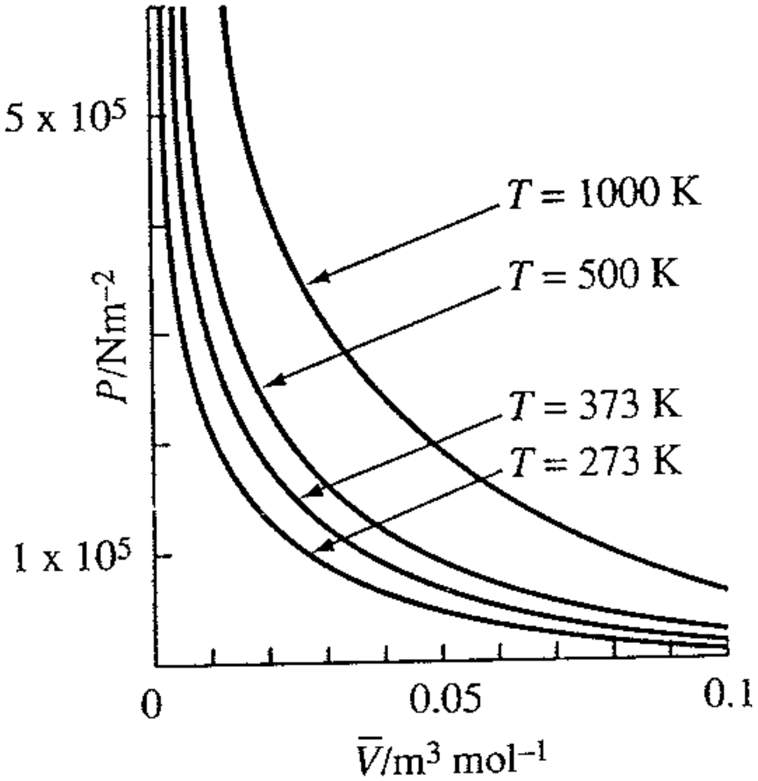
- At constant temperature and pressure
  - Volume of gas proportionate to amount of gas
  - i.e. $V \propto n$

- Independent of gas' identity

- Approximate molar volumes of gas
  - 24.0 dm^3 at 298K
  - 22.4 dm^3 at 273K

Boyle’s Law

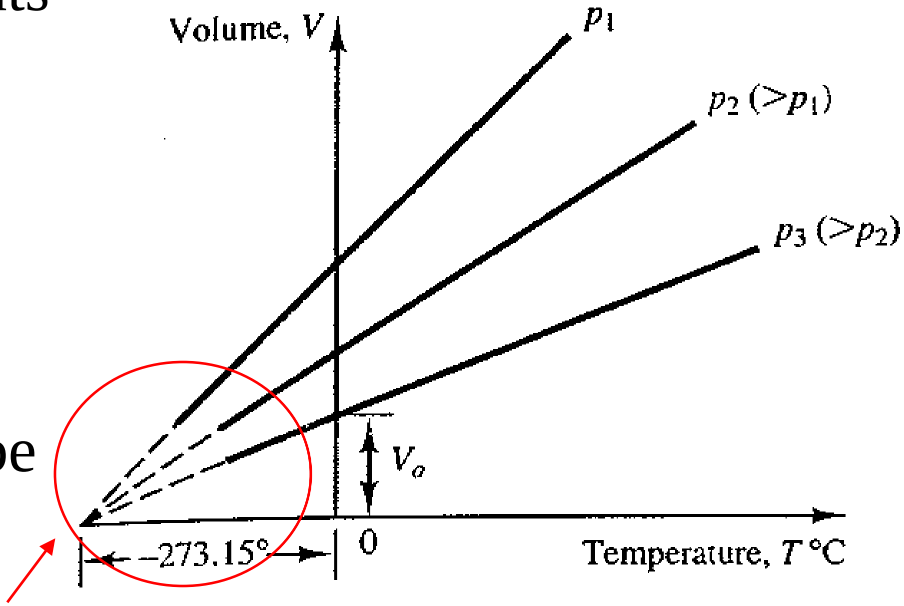
- At constant temperature and amounts
  - Gas’ volume inversely proportionate to pressure, i.e. V ∝ 1/p
  - The product of V & p, which is constant, increases with temperature



Charles' Law

- At constant pressure and amounts
  - Volume proportionate to temperature, i.e. V ∝ T
  - T is in Kelvins

- Note the extrapolated lines (to be explained later)



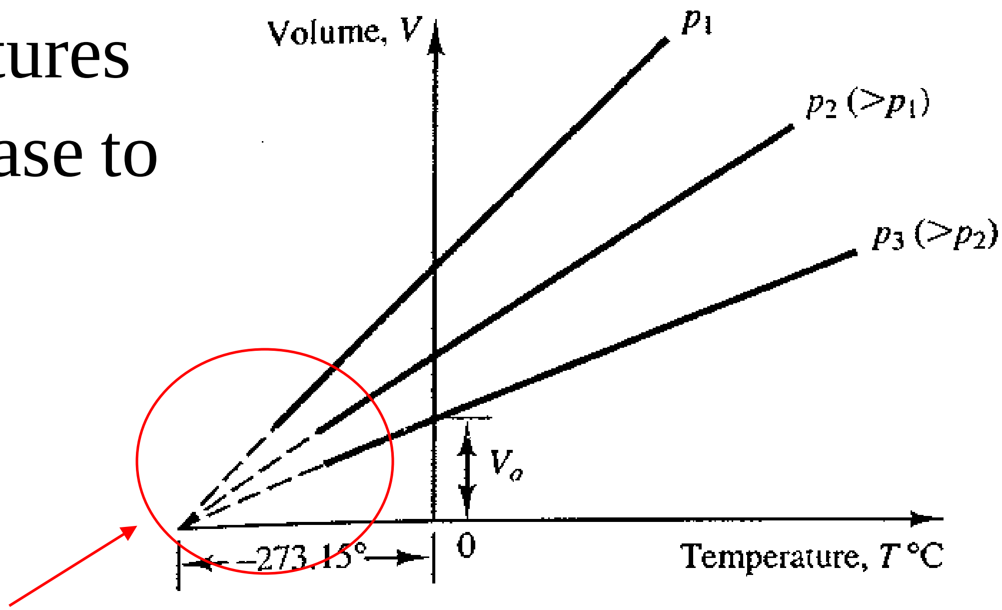
Combining all 3 laws…

- $V \propto (1/p)(T)(n)$
- $V \propto nT/p$
- Rearranging, $pV = (\text{constant})nT$
- Thus we get the ideal gas equation:

$$\mathbf{pV = nRT}$$

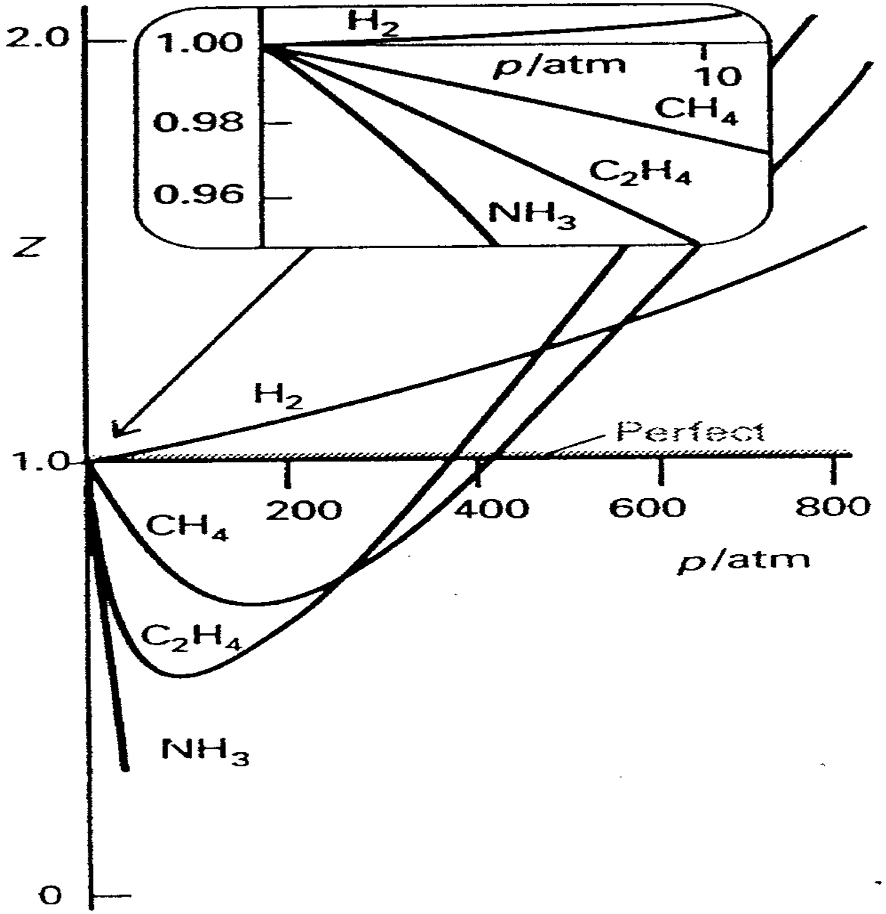
Failures of ideal gas equation

- Failure of Charles' Law
  - At very low temperatures
  - Volume do not decrease to zero
  - Gas liquefies instead
  - Remember the extrapolated lines?

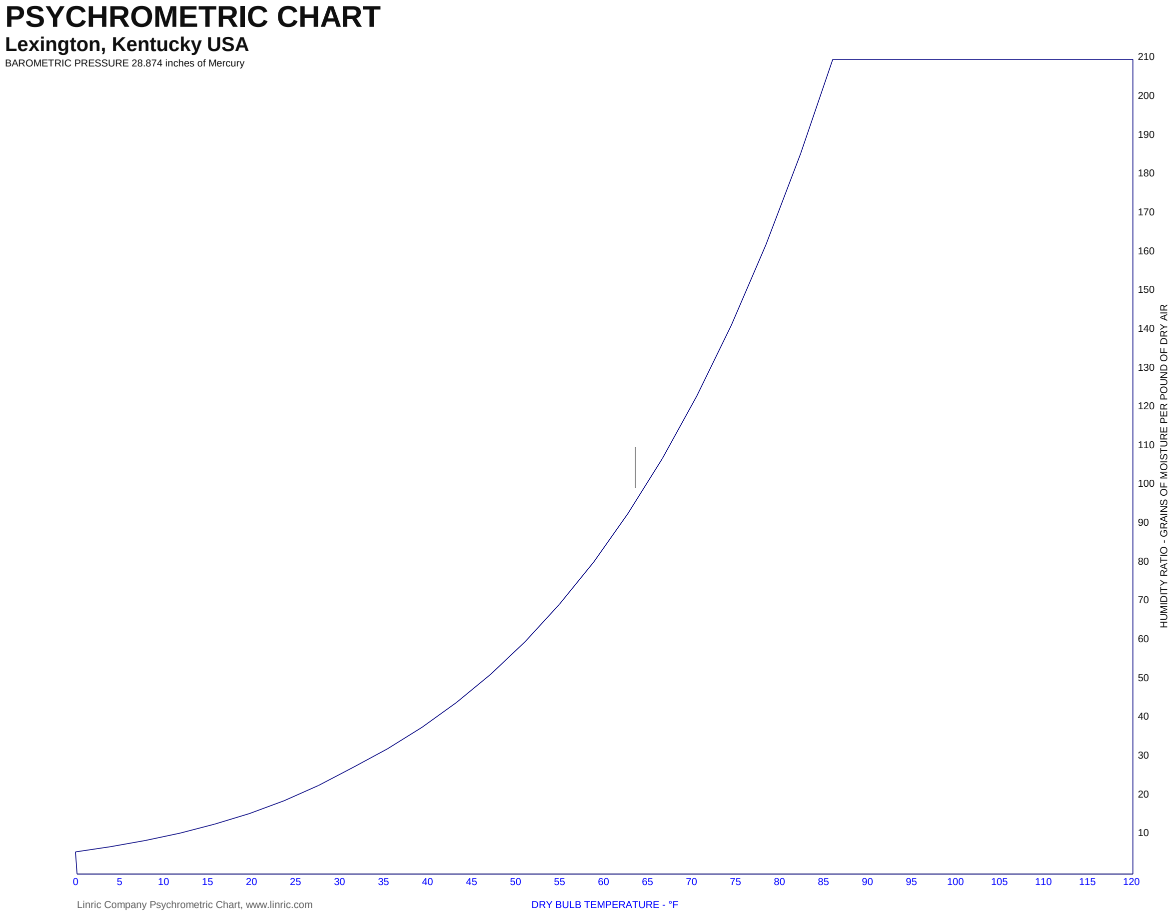


Failures of ideal gas equation

- Looking at Z plot of real gases.
- Obvious deviation from the line Z=1
- Failure of ideal gas equation to account for these deviations

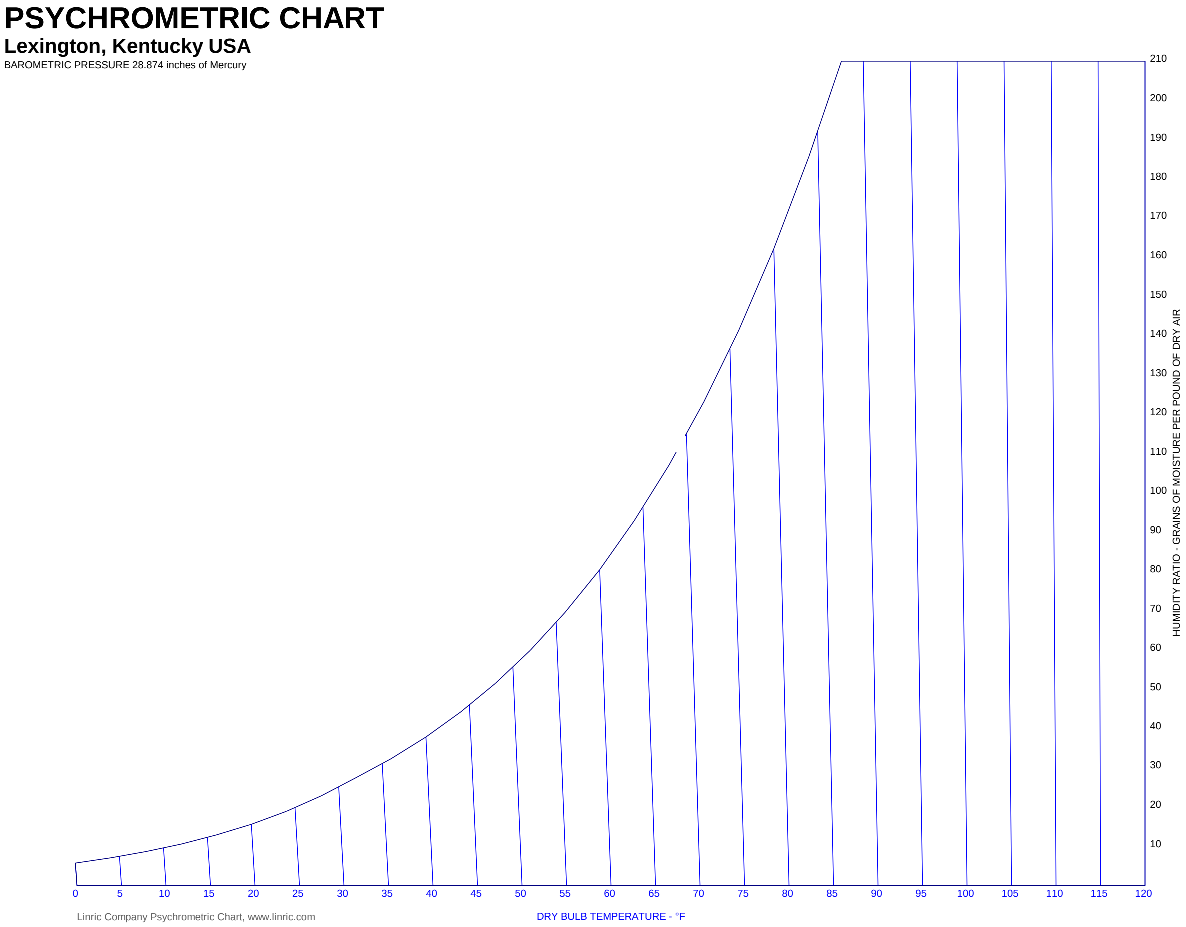


Saturation Line

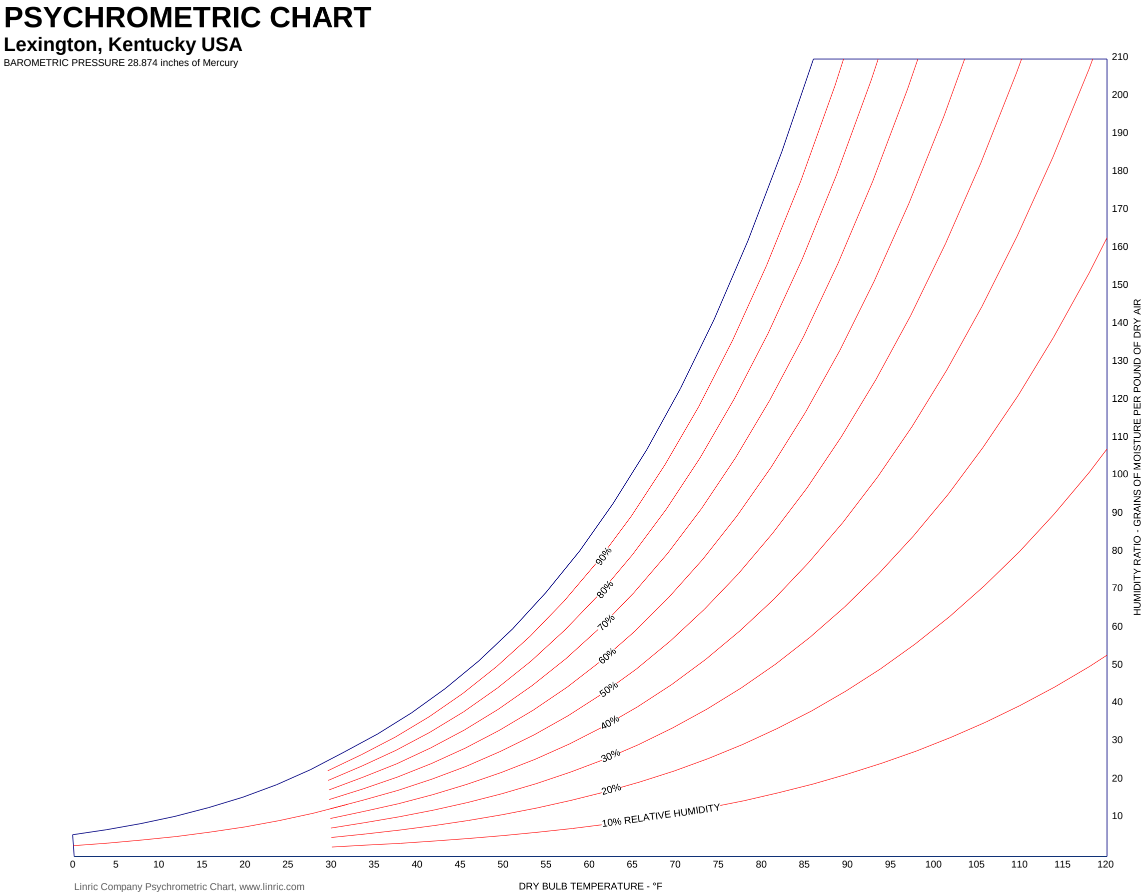


Linric Company Psychrometric Chart, www.linric.com

Constant Dry Bulb Temperature



Constant Relative Humidity

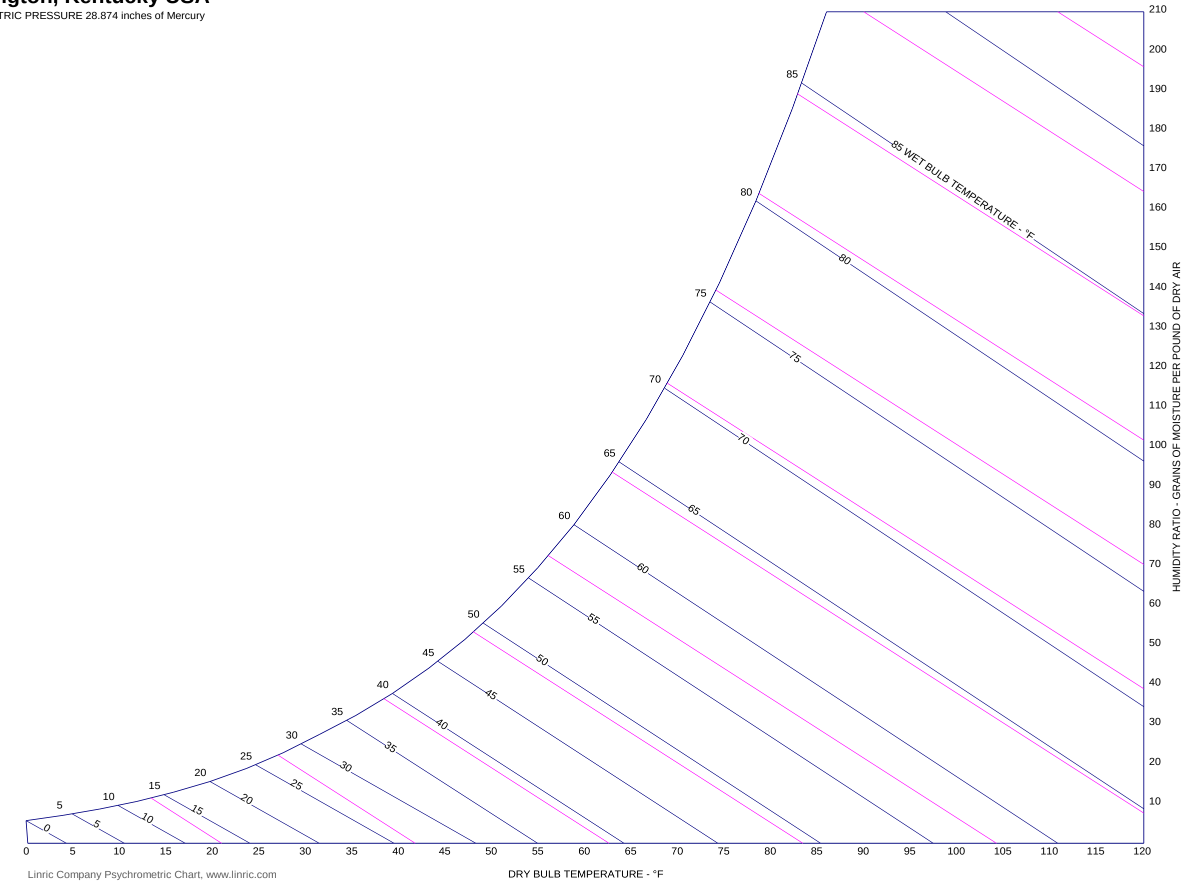

PSYCHROMETRIC CHART
Lexington, Kentucky USA
BAROMETRIC PRESSURE 28.874 inches of Mercury

Constant Enthalpy and Web Bulb

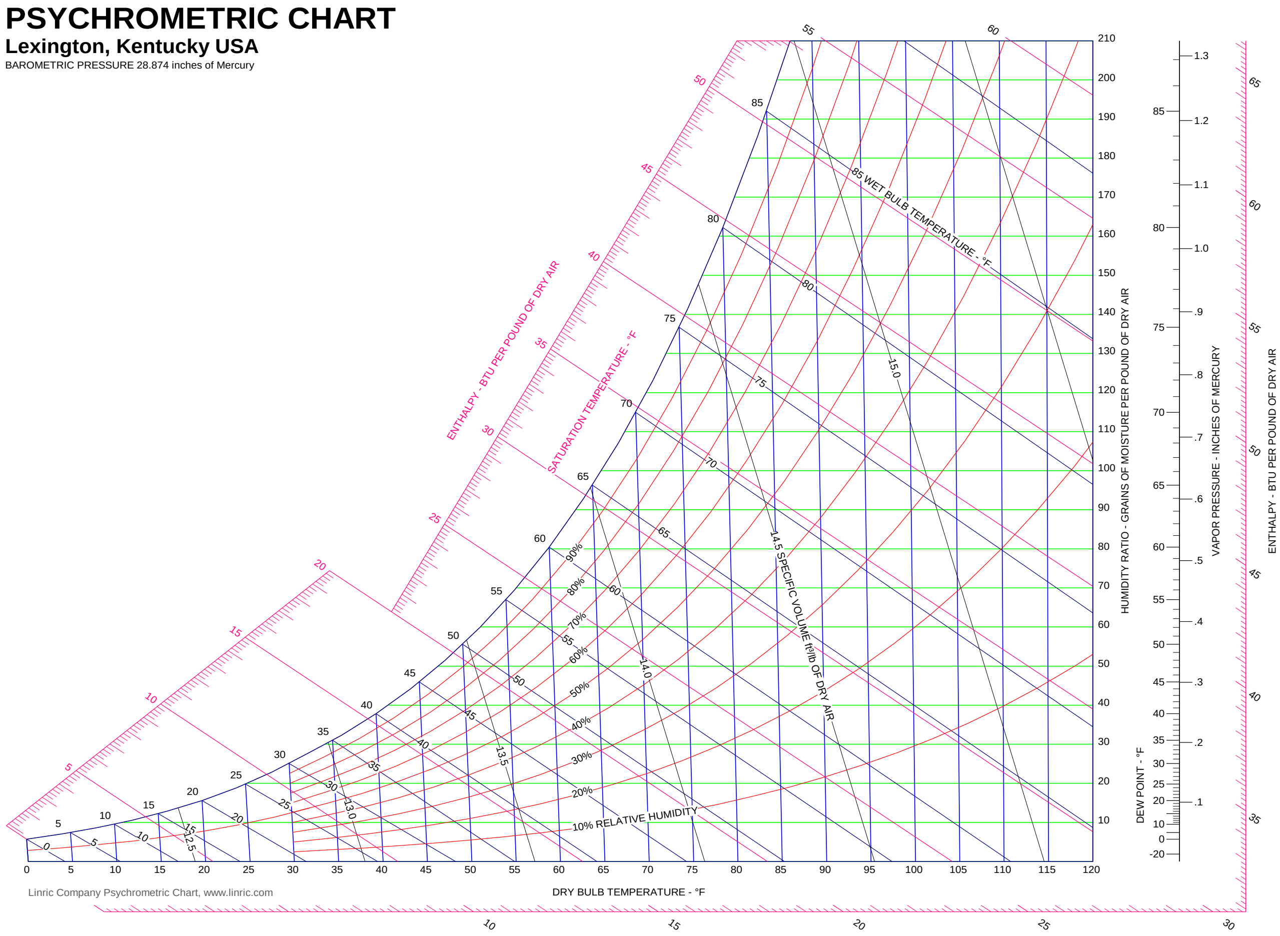
PSYCHROMETRIC CHART

Lexington, Kentucky USA

BAROMETRIC PRESSURE 28.874 inches of Mercury



Typical Chart With Enthalpy Lines



Humidity Ratio

Sea Level Chart
Dry-bulb temperature = 70 F
Relative humidity = 60%

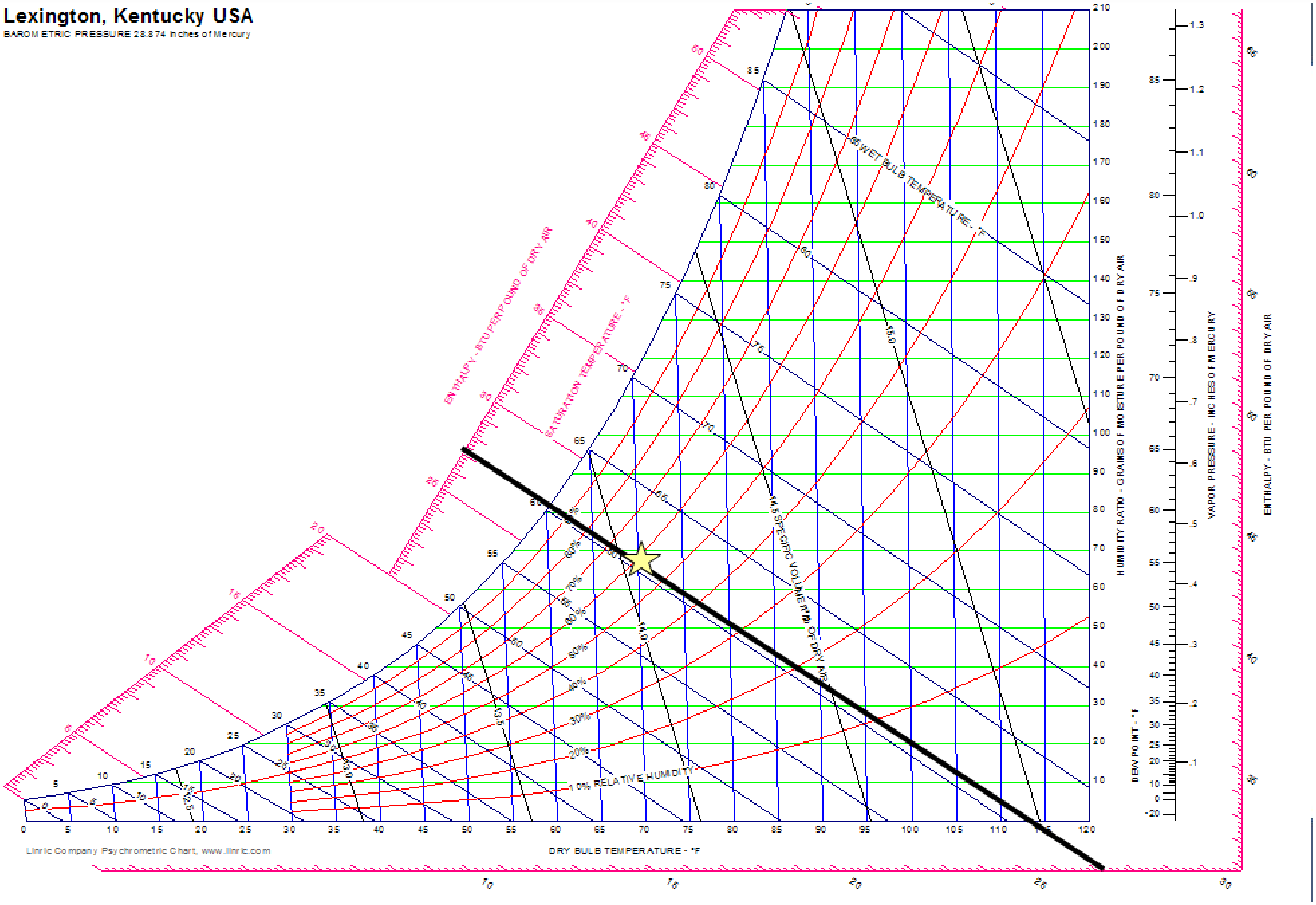
Humidity ratio = 0.0094 lb water / lb dry air
or
7000 grains = 1 lb water
7000 x 0.0094 = 65.8

Enthalpy

Sea Level Chart
Dry-bulb temperature = 70 F
Relative humidity = 60%

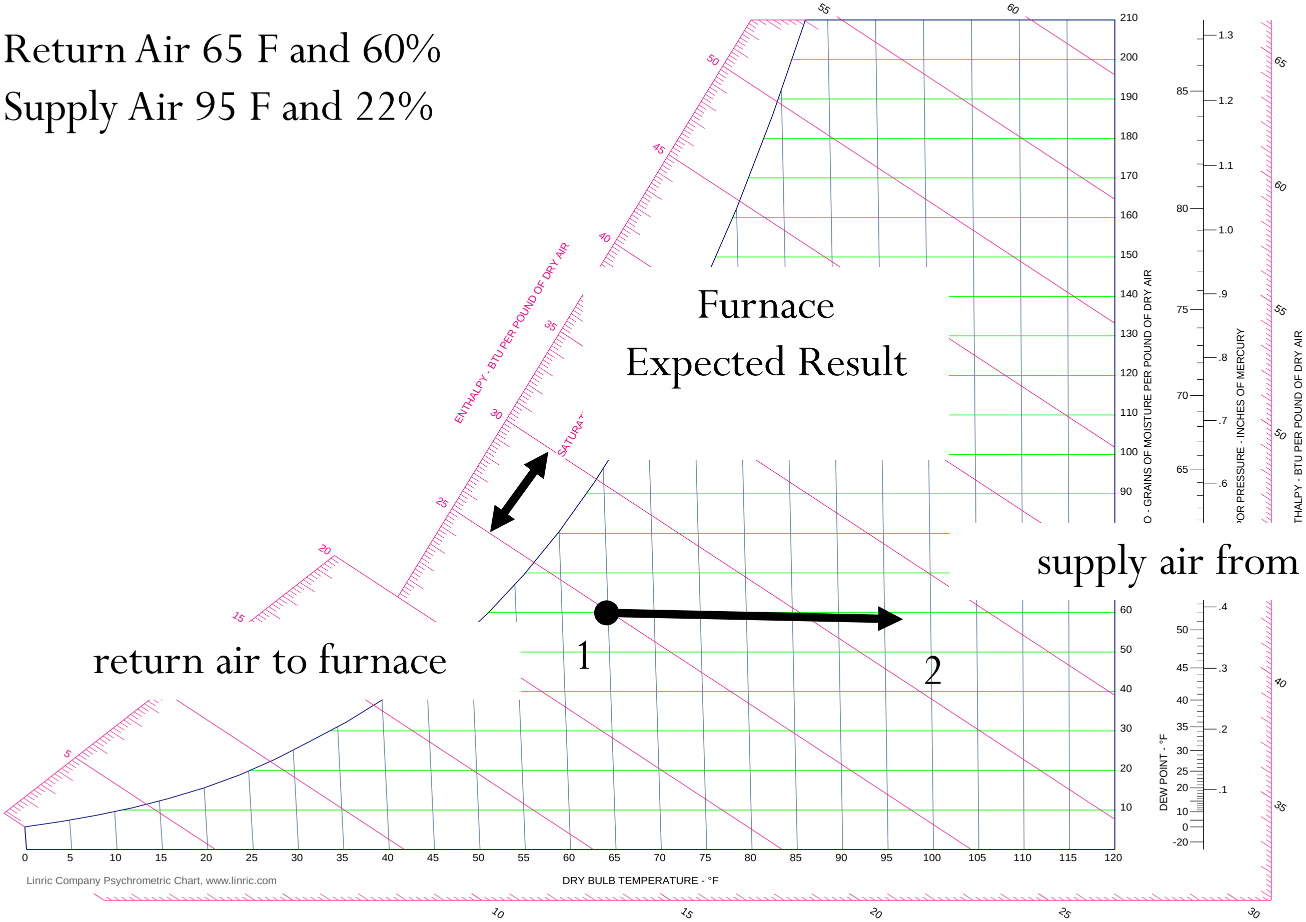
Enthalpy = ?

Enthalpy

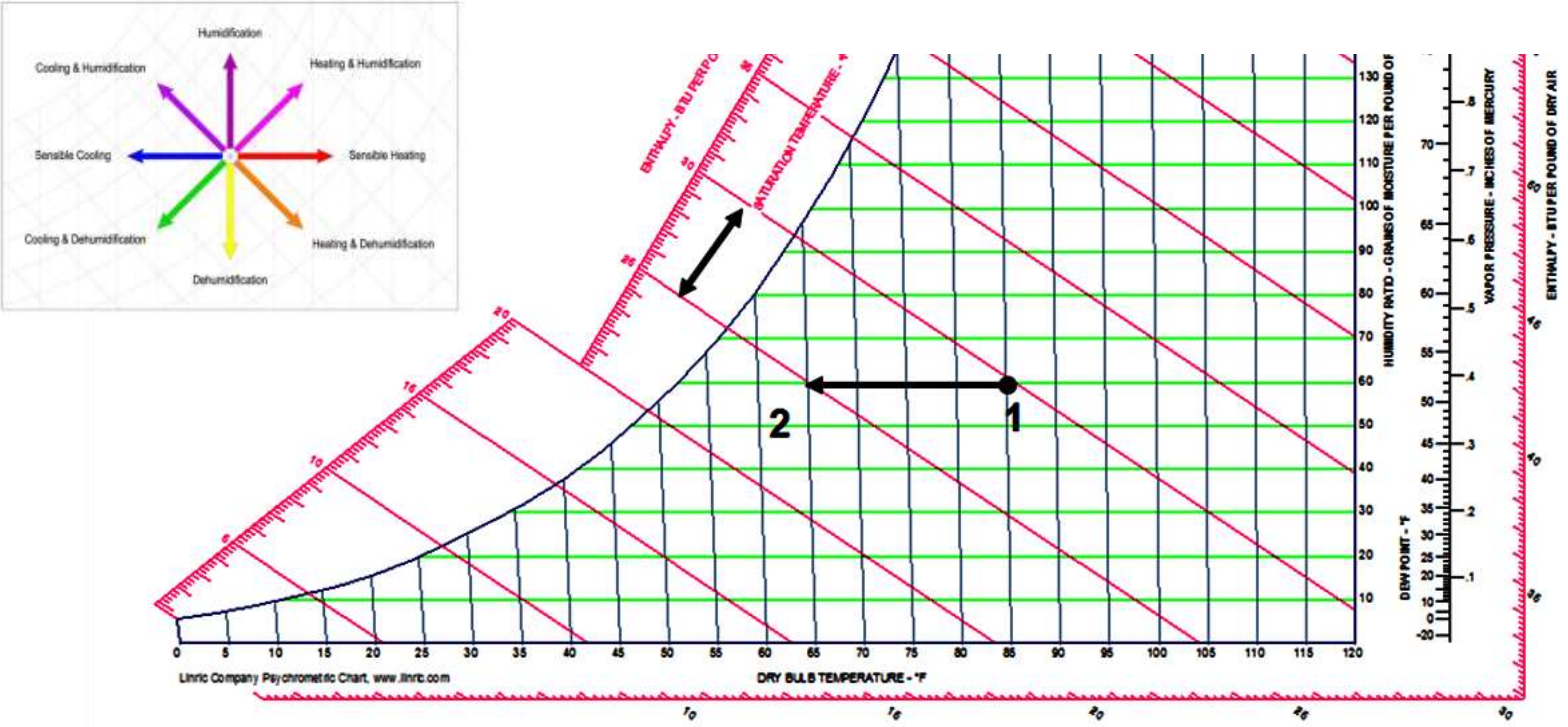

Lexington, Kentucky USA
BAROMETRIC PRESSURE 28.874 inches of Mercury
ENTHALPY - BTU PER POUND OF DRY AIR
SATURATION TEMPERATURE - °F
WET BULB TEMPERATURE - °F
14.5 SPECIFIC VOLUME ft³/lb OF DRY AIR
10% RELATIVE HUMIDITY
20%
30%
40%
50%
60%
70%
80%
90%
HUMIDITY RATIO - GRAINS OF MOISTURE PER POUND OF DRY AIR
DEW POINT - °F
VAPOR PRESSURE - INCHES OF MERCURY
ENTHALPY - BTU PER POUND OF DRY AIR
DRY BULB TEMPERATURE - °F
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
Linric Company Psychrometric Chart, www.linric.com

Heating System Example

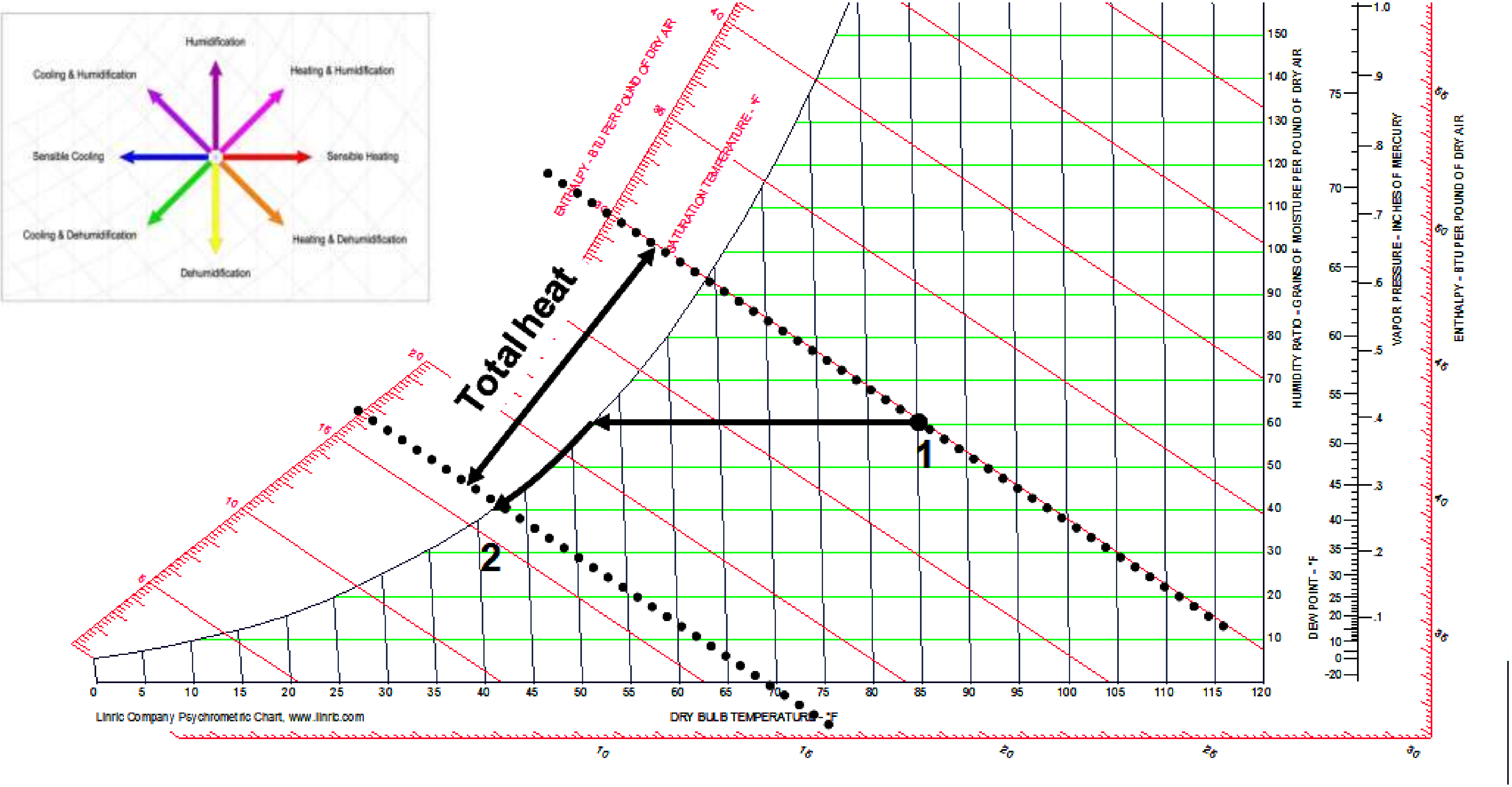
1) Return Air 65 F and 60%
2) Supply Air 95 F and 22%



Cooling


Humidification
Cooling & Humidification
Heating & Humidification
Sensible Cooling
Sensible Heating
Cooling & Dehumidification
Heating & Dehumidification
Dehumidification
ENTHALPY - BTU PER POUND OF DRY AIR
SATURATION TEMPERATURE - °F
HUMIDITY RATIO - GRAINS OF MOISTURE PER POUND OF DRY AIR
DEW POINT - °F
VAPOR PRESSURE - INCHES OF MERCURY
DRY BULB TEMPERATURE - °F
Linric Company Psychrometric Chart, www.linric.com
1
2
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120
10 20 30 40 50 60 70 80 90 100 110 120 130
-20 0 10 20 25 30 35 40 45 50 55 60 65 70
.1 .2 .3 .4 .5 .6 .7 .8
10 15 20 25 30
5 10 15 20 25 30 35

Cooling Systems



Standard Operation of an Air Conditioner

Total Heat

$$q = (\text{cfm})\ (4.5)\ (\Delta h)$$

$$12{,}000 = (400)\ (4.5)\ (\Delta h)$$

$$(\Delta h) = 27.3 \text{ Btu / lb dry air}$$

Sensible Heat

$$q = (\text{cfm})\ (1.08)\ (\Delta t)$$

$$12{,}000\ (0.7) = (400)\ (1.08)\ (\Delta t)$$

$$(\Delta t) = 19 \text{ F}$$

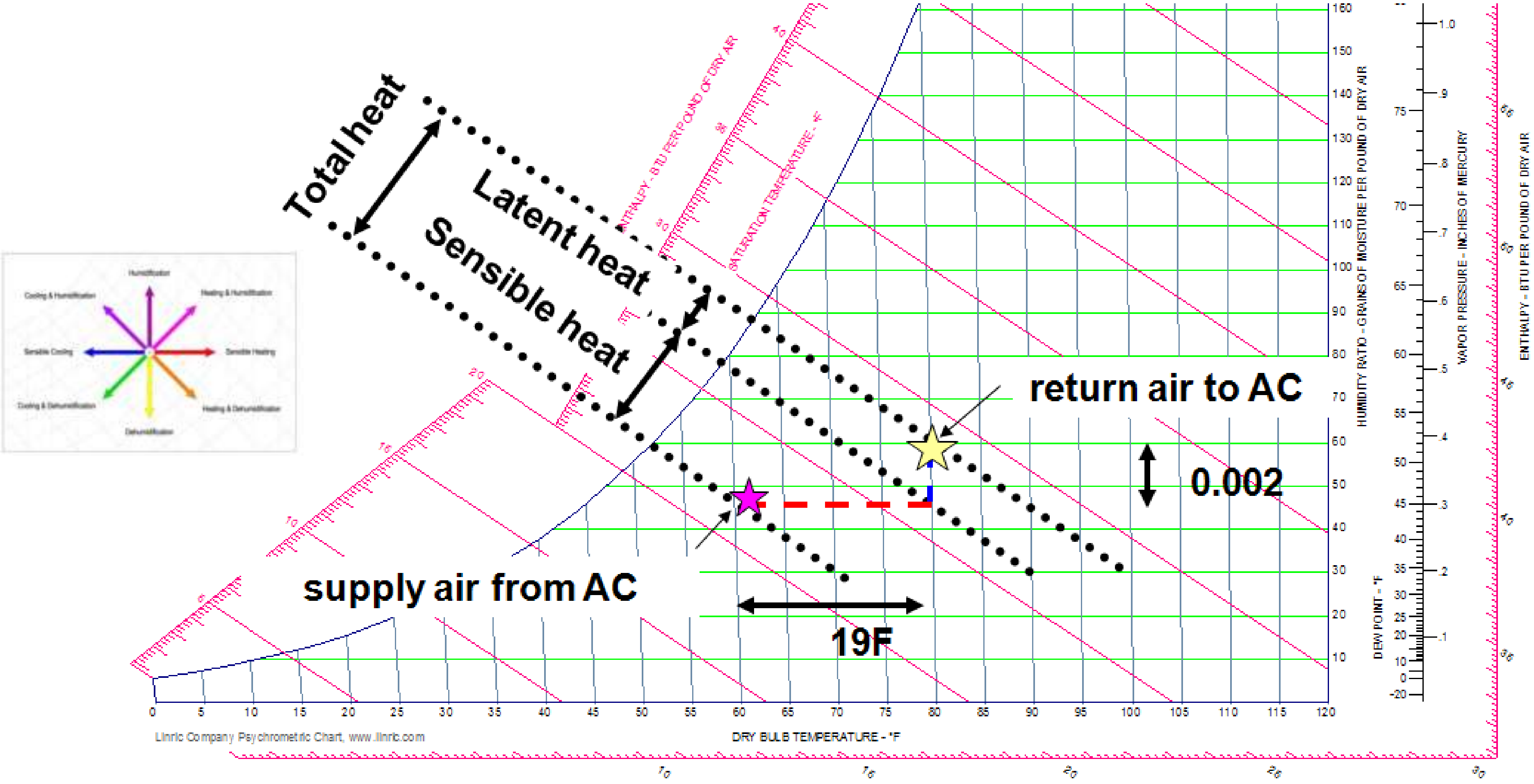
Latent Heat

$$q = (\text{cfm})\ (4840)\ (\Delta w)$$

$$12{,}000\ (.3) = (400)\ (4840)\ (\Delta w)$$

$$(\Delta w) = 0.002 \text{ lb water / lb dry air}$$

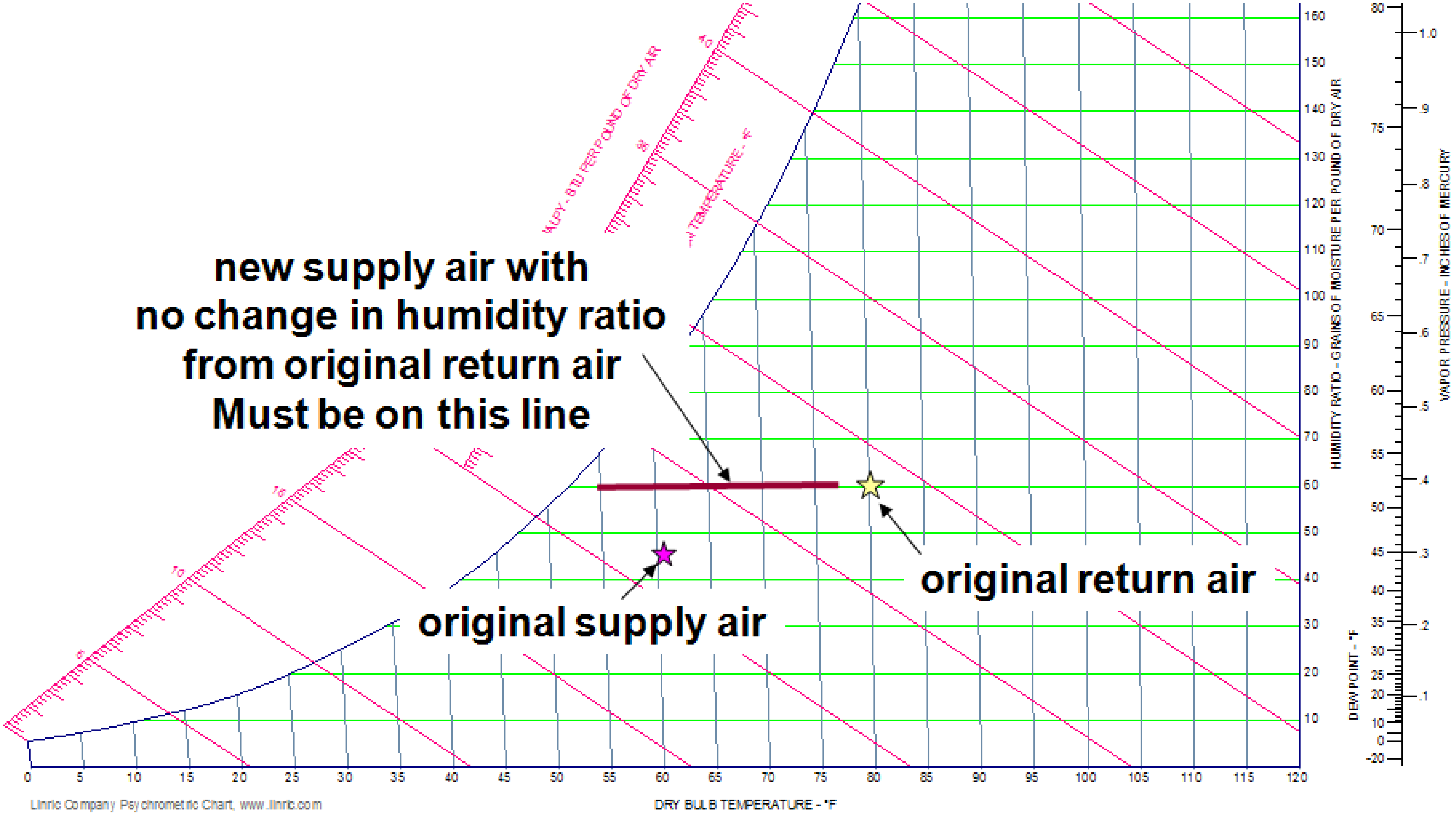
Standard Operation of an Air Conditioner



Operation of an Air Conditioner

What if humidity ratio of return air equals the humidity ratio of the supply air?

Air Conditioner Example



new supply air with
no change in humidity ratio
from original return air
Must be on this line

original return air

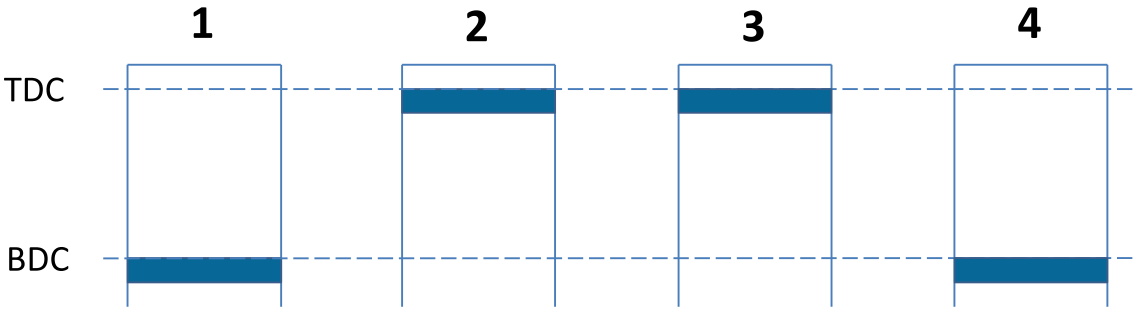
original supply air

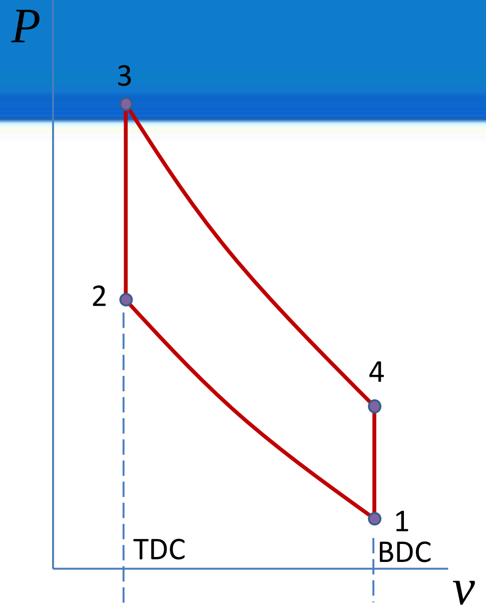
Linric Company Psychrometric Chart, www.linric.com

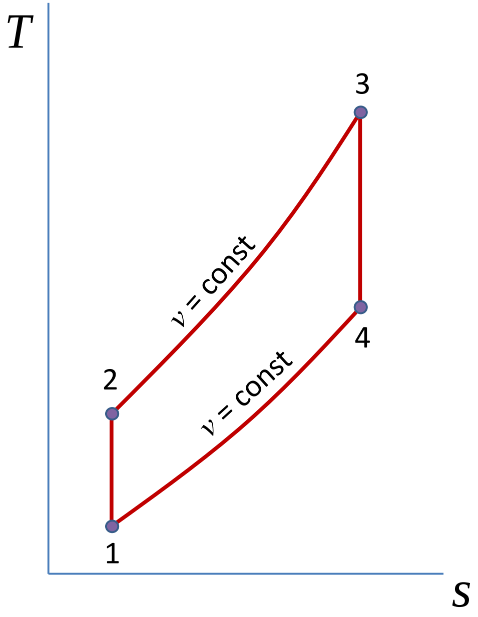
UNIT-V

POWER CYCLES

SI Engine - Otto Cycle







- **1-2** Isentropic compression from BDC to TDC

$$W_{12} = m\left(u_2 - u_1\right)$$

- **2-3** Isochoric heat input (combustion)

$$Q_{23} = m\left(u_3 - u_2\right)$$

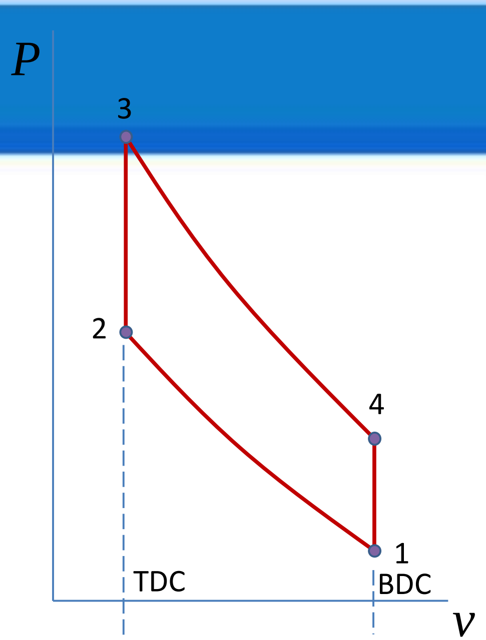
- **3-4** Isentropic expansion (power stroke)

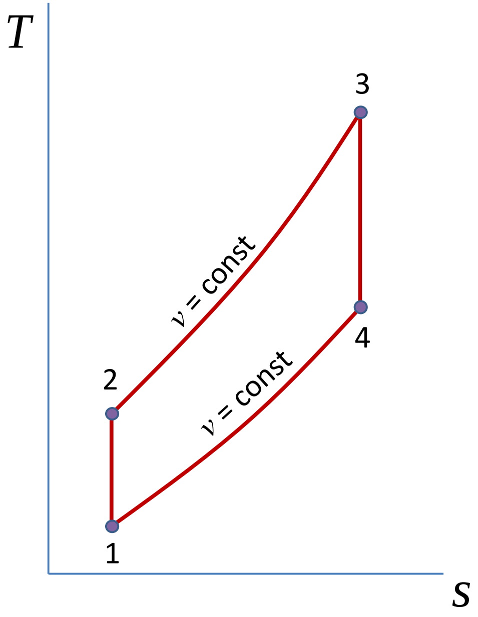
$$W_{34} = m\left(u_3 - u_4\right)$$

- **4-1** Isochoric heat rejection (exhaust)

$$Q_{41} = m\left(u_4 - u_1\right)$$

Otto Cycle Performance





Compression Ratio

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

Thermal Efficiency

$$\eta_{th,\mathrm{ASC}} = \frac{W_{net}}{Q_{in}} = \frac{W_{34} - W_{12}}{Q_{23}} = 1 - \frac{u_4 - u_1}{u_3 - u_2}$$

$$\eta_{th,\mathrm{cold\ ASC}} = 1 - \frac{T_1}{T_2} = 1 - CR^{1-k}$$

Otto Cycle Performance

Mean Effective Pressure

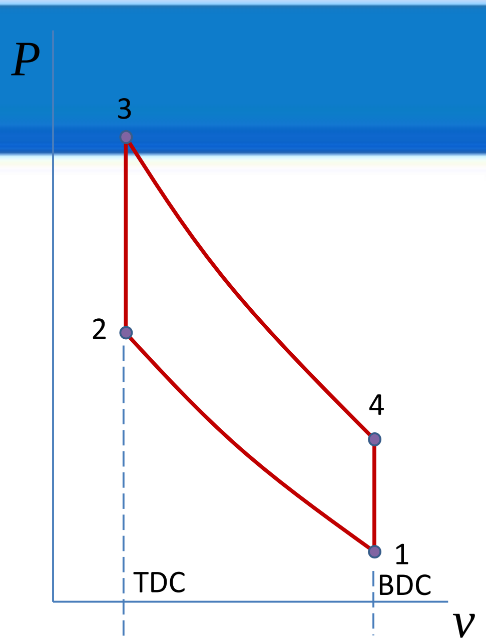
$$\text{mep} = \frac{W_{net}}{\cancel{V}_{disp}} = \frac{W_{34} - W_{12}}{\cancel{V}_{disp}} = \frac{(u_3 - u_4) - (u_2 - u_1)}{(v_1 - v_2)}$$

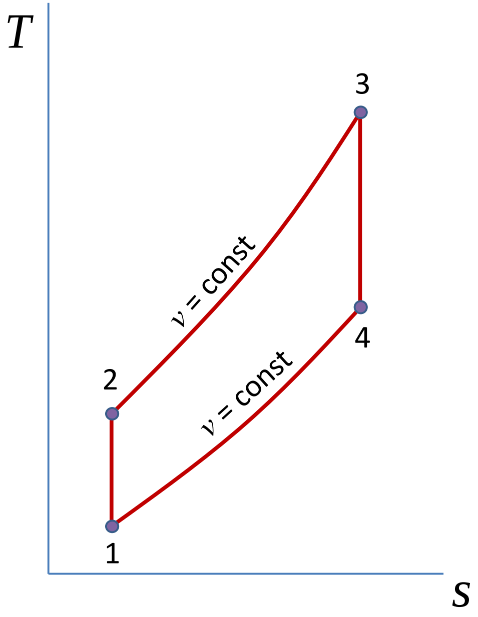
$$\text{mep}_{\text{cold ASC}} = \frac{c_v\left[(T_3 - T_4) - (T_2 - T_1)\right]}{(v_1 - v_2)}$$

Cold ASC values (Table C.13a) ...

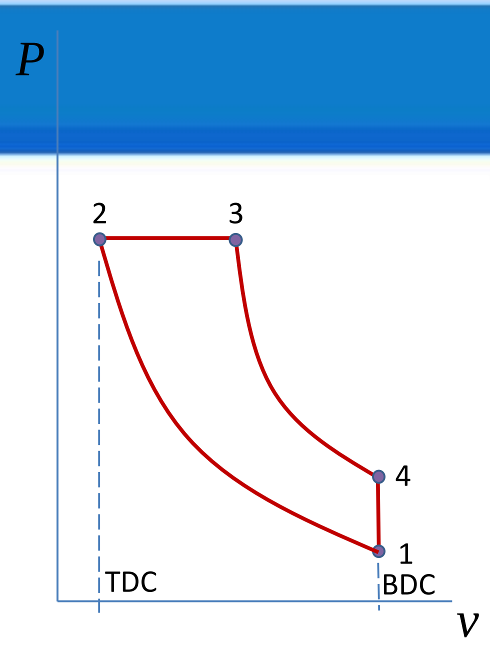
$$c_p = 0.24\,\frac{\text{Btu}}{\text{lbm-R}} \qquad c_v = 0.172\,\frac{\text{Btu}}{\text{lbm-R}}$$

$$k = \frac{c_p}{c_v} = 1.4$$





Diesel Cycle Performance



Compression Ratio

$$CR = \frac{v_1}{v_2}$$

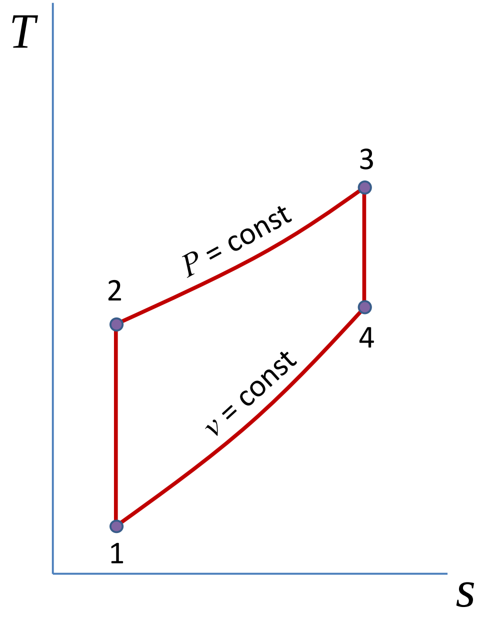
Cutoff Ratio

$$CO = \frac{v_3}{v_2}$$

Thermal Efficiency

$$\eta_{th,\mathrm{ASC}} = \frac{W_{net}}{Q_{in}} = \frac{W_{23} + W_{34} - W_{12}}{Q_{23}} = 1 - \frac{u_4 - u_1}{h_3 - h_2}$$

$$\eta_{th,\mathrm{cold\ ASC}} = 1 - \frac{CR^{1-k}\left(CO^k - 1\right)}{k\left(CO - 1\right)}$$



Diesel Cycle Performance

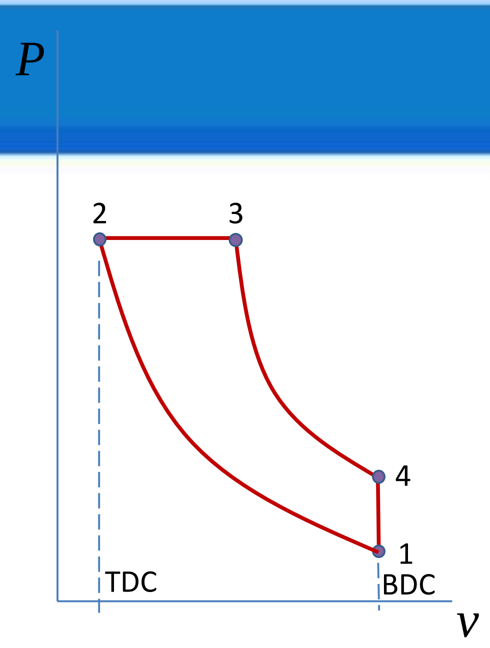
Mean Effective Pressure

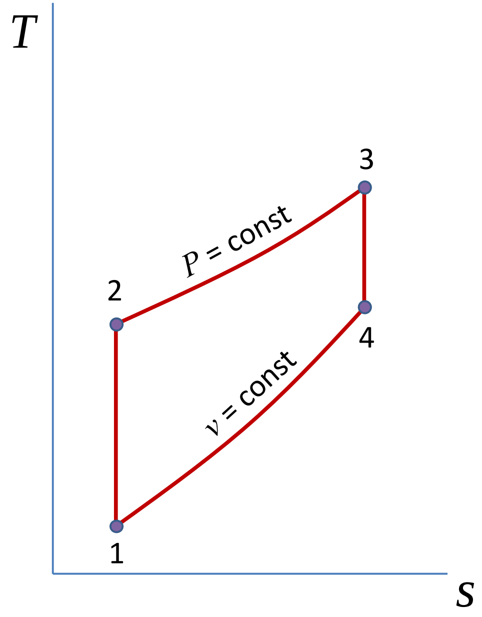
$$\text{mep} = \frac{W_{net}}{\cancel{V}_{disp}} = \frac{W_{23} + W_{34} - W_{12}}{\cancel{V}_{disp}} = \frac{\left(h_3 - h_2\right) - \left(u_4 - u_1\right)}{\left(v_1 - v_2\right)}$$

$$\text{mep}_{\text{cold ASC}} = \frac{c_p\left(T_3 - T_2\right) - c_v\left(T_4 - T_1\right)}{\left(v_1 - v_2\right)}$$

$$c_p = 0.24\,\frac{\text{Btu}}{\text{lbm-R}} \qquad c_v = 0.172\,\frac{\text{Btu}}{\text{lbm-R}}$$

$$k = \frac{c_p}{c_v} = 1.4$$





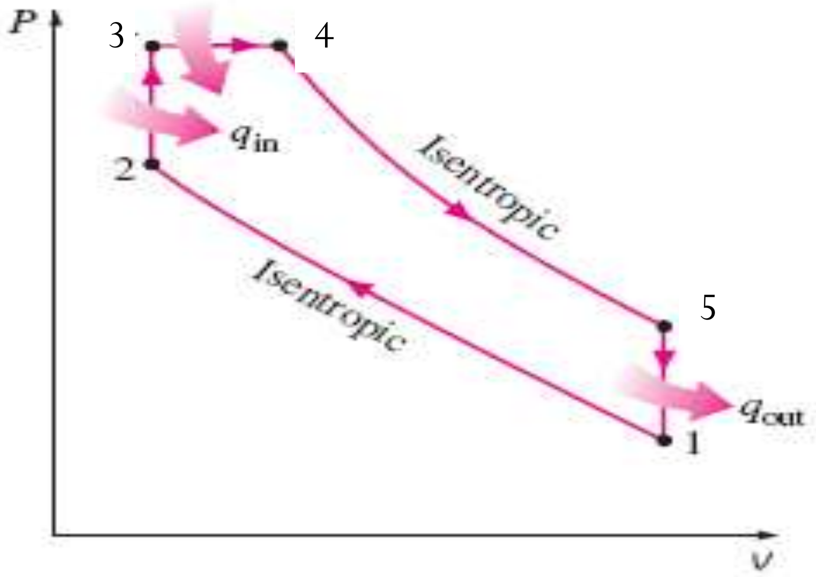
Dual combustion or Limited pressure or Mixed cycle:

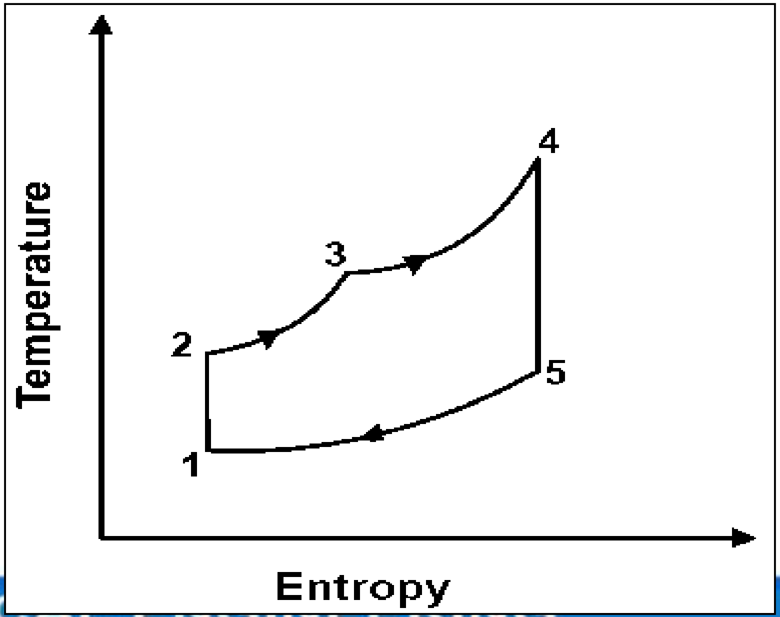
This cycle is a combination of Otto and Diesel cycles.

It is also called semi-diesel cycle because semi-diesel engines work on this cycle.

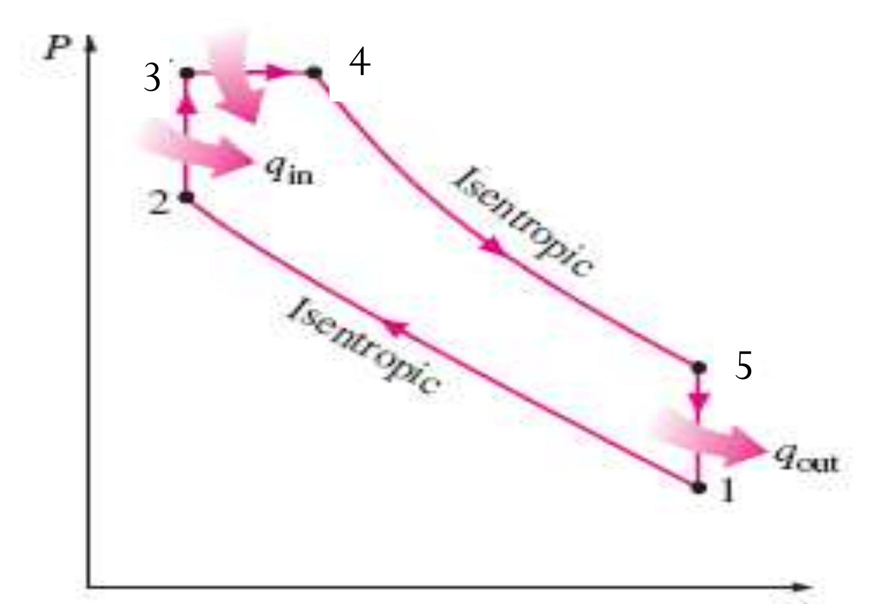
In this cycle heat is absorbed partly at constant volume and partly at constant pressure.

It consists of two reversible adiabatic or isentropic, two constant volume and a constant pressure processes as shown in P-v and T-s diagrams.





Dual combustion or Limited pressure or Mixedcycle:



Process 1-2:

The air is compressed reversibly and adiabatically from temperature T_1 to T_2 .

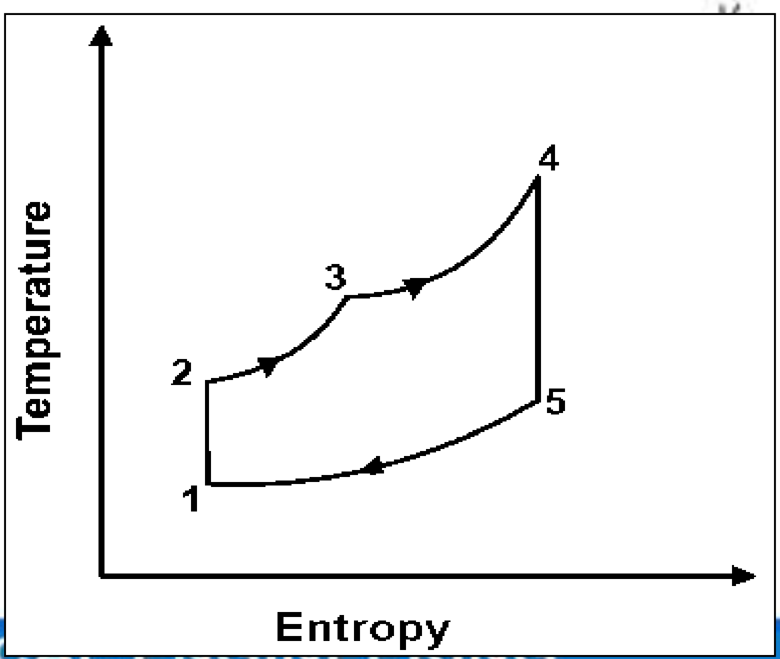
No heat is rejected or absorbed by the air.

Process 2-3:

The air is heated at constant volume from T_2 to T_3.

Heat absorbed by the air is given by,

$$q_{in} = mC_v(T_3 - T_2)$$

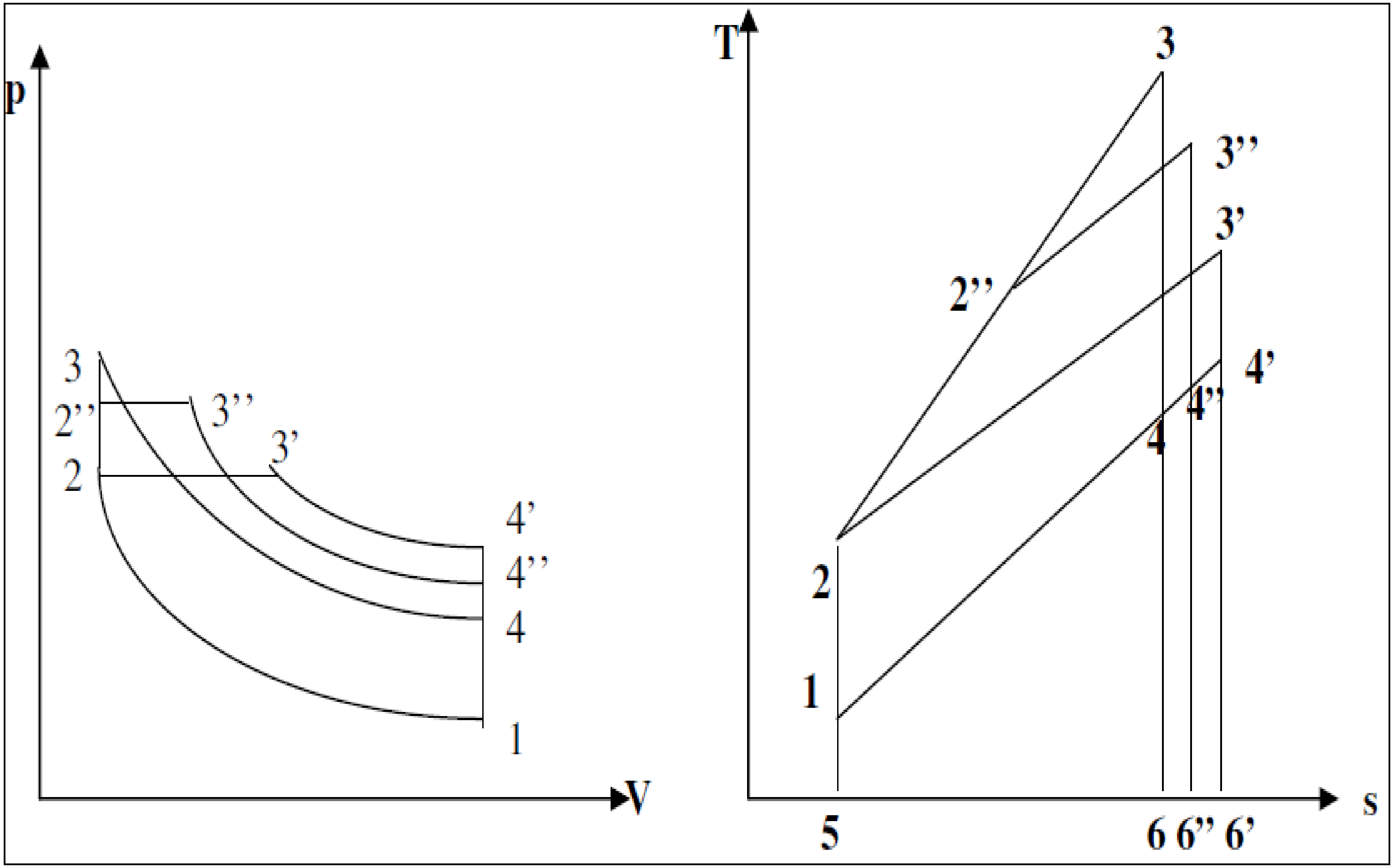


Comparison between Otto, Diesel and Dual combustion cycles

The important variables which are used as the basis for comparison of the cycles are compression ratio, peak pressure, heat supplied, heat rejected and the net work output.

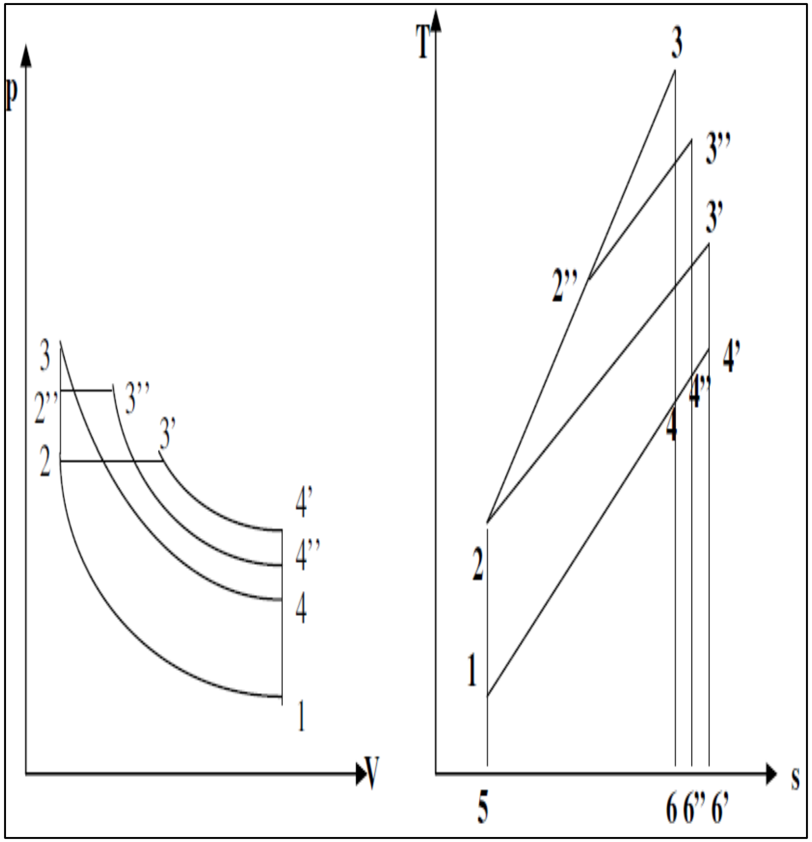
In order to compare the performance of the Otto, Diesel and Dual combustion cycles some of these variables have to be fixed.

Comparison with same compression ratio and heat supply:



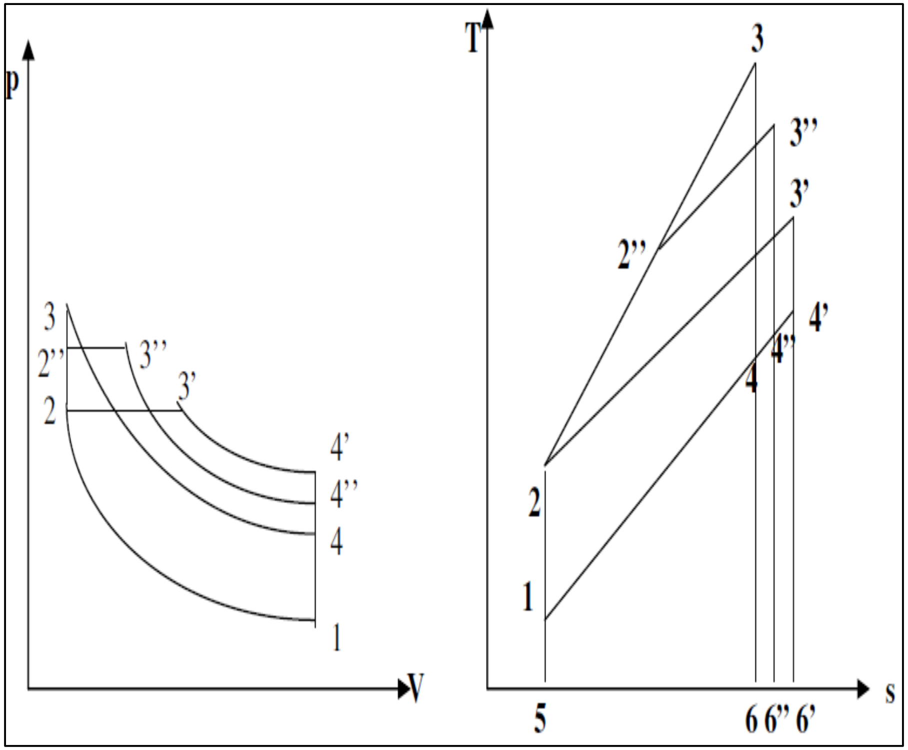
The comparison of these cycles for the same compression ratio and same heat supply are shown in on both p – V and T – S diagrams.

In these diagrams, cycle 1-2-3-4-1 represents Otto Cycle, cycle 1-2-3’-4’-1 represents diesel cycle and cycle 1-2”-3”-4”-1 represents the dual combustion cycle for the same compression ratio and heat supply.

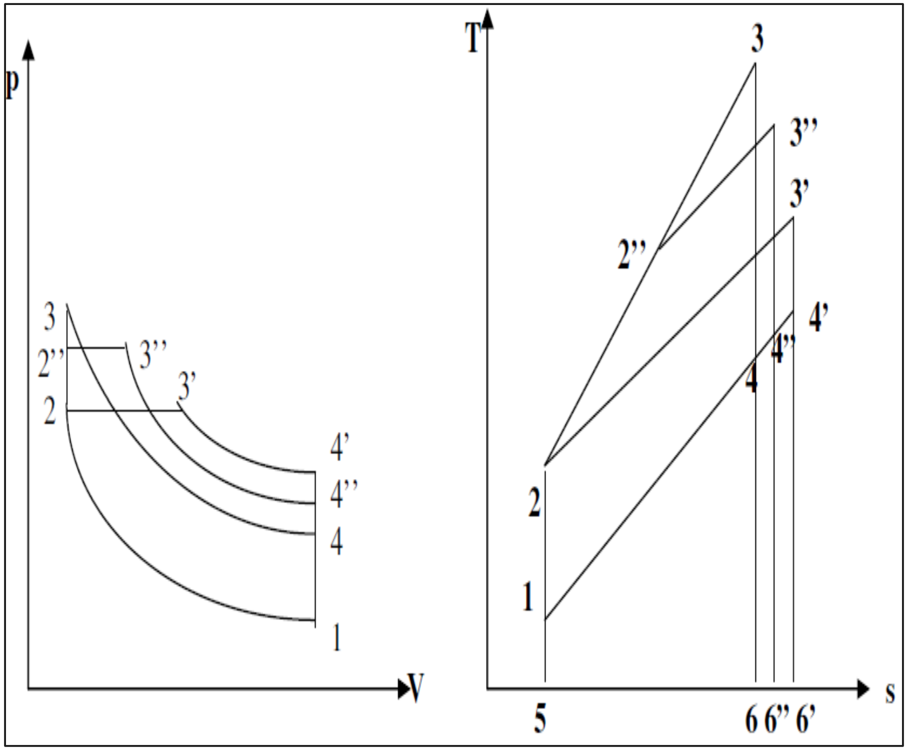


From the T-S diagram, it can be seen that area 5236 = area 522”3”6” = area 523’6’ as this area represents the heat supply which is same for all the cycles.

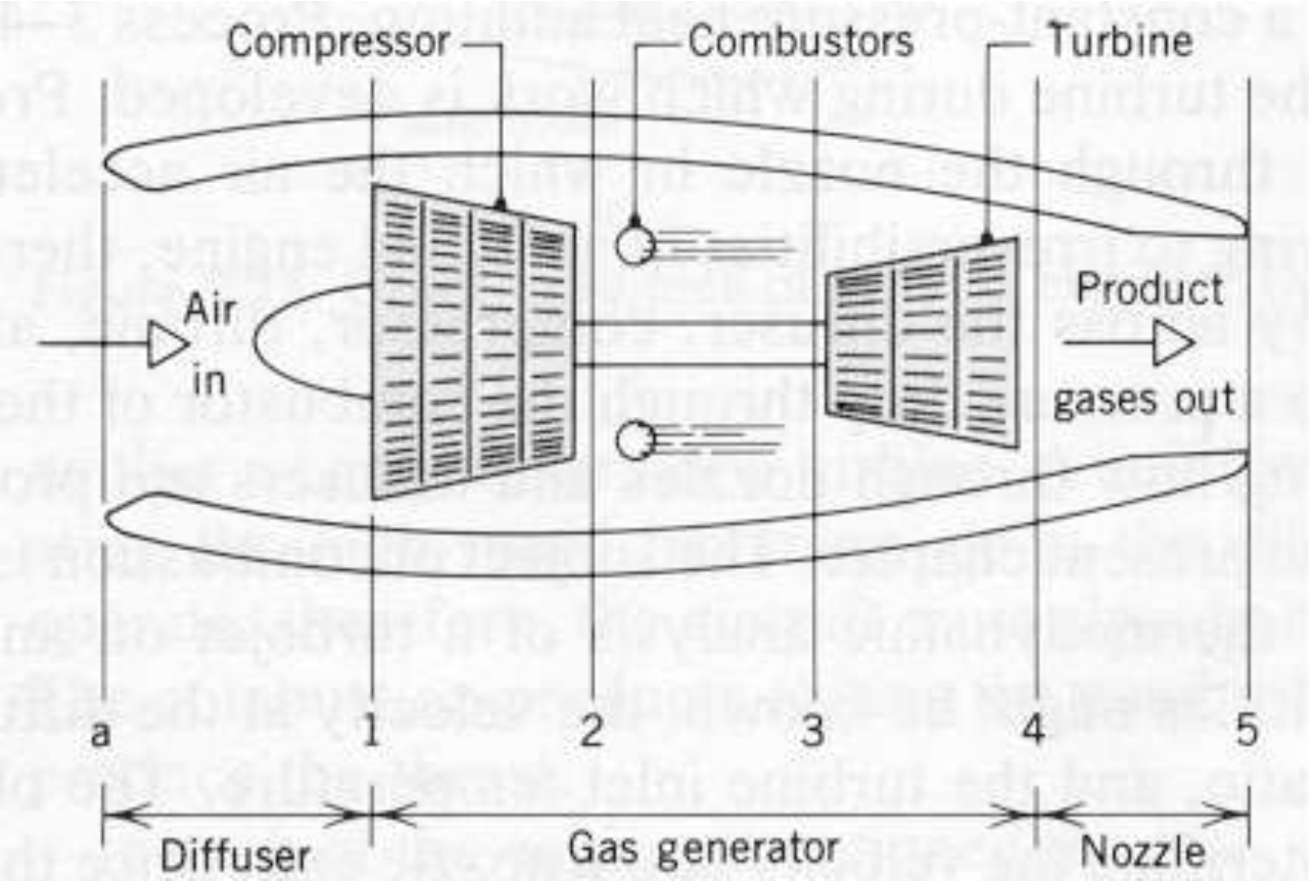
All the cycles start from the same initial point 1 and the air is compressed from state 1 to state 2 as the compression ratio is same.



It is seen from the T-s diagram, that for the same heat supply, the heat rejection in Otto cycle (area 5146) is minimum and heat rejection in Diesel cycle (area 514’6’) is maximum. Consequently Otto cycle has the highest work output and efficiency. Diesel cycle has the least efficiency and dual cycle has the efficiency between the two.



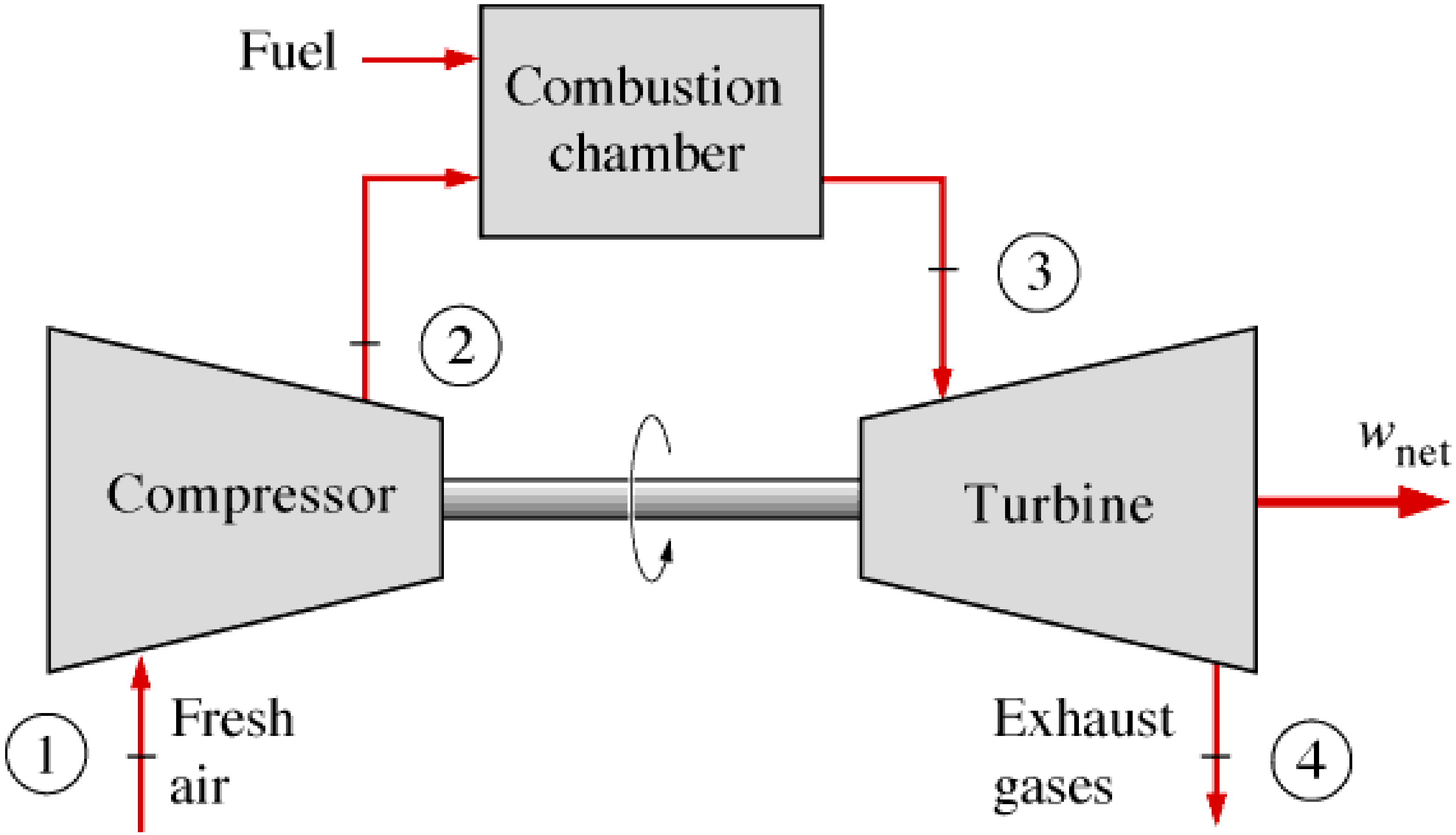
Brayton Cycle



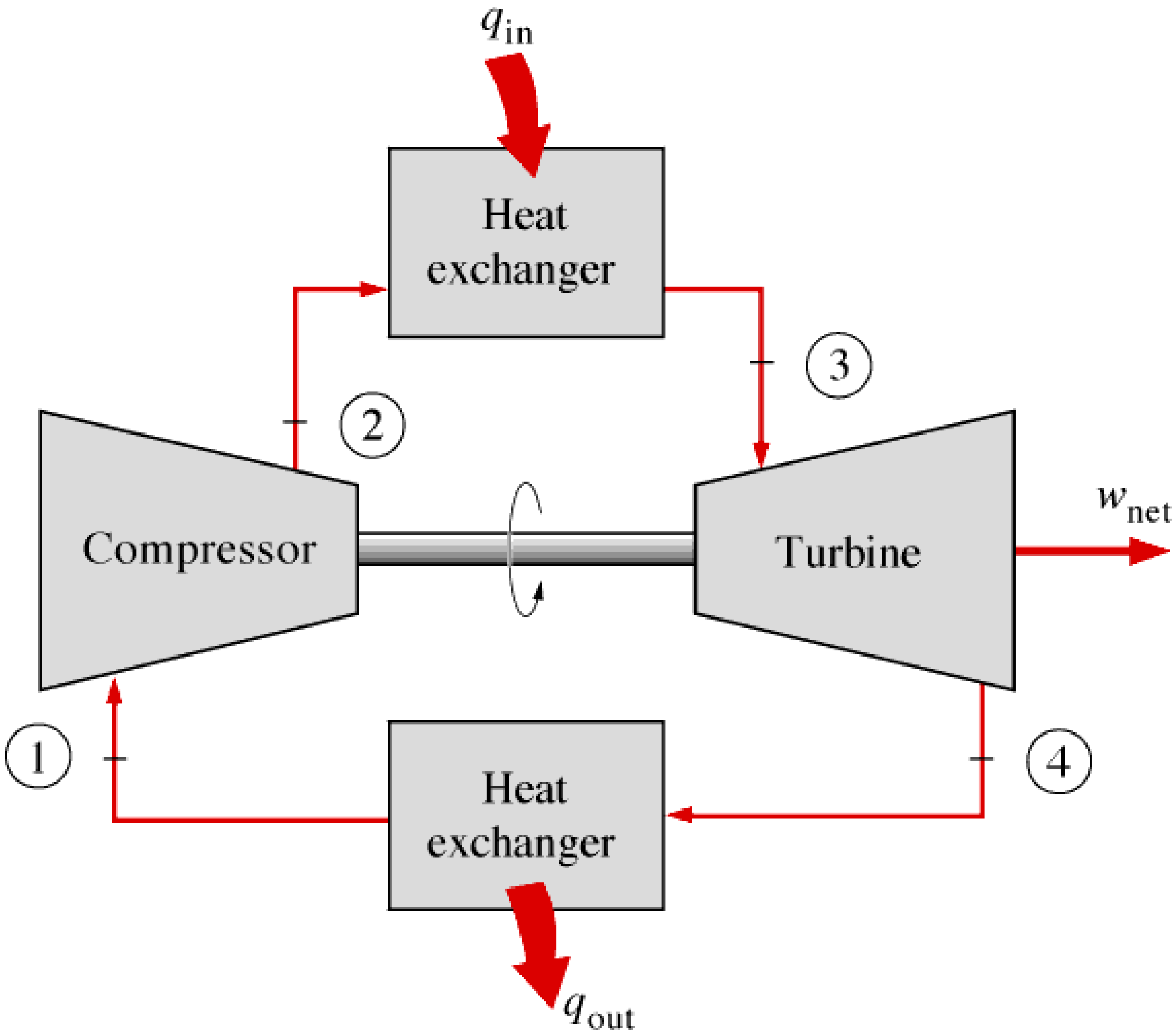
Other applications of Brayton cycle

- Power generation - use gas turbines to generate electricity…very efficient
- Marine applications in large ships
- Automobile racing - late 1960s Indy 500 STP sponsored cars

Schematic of simple cycle

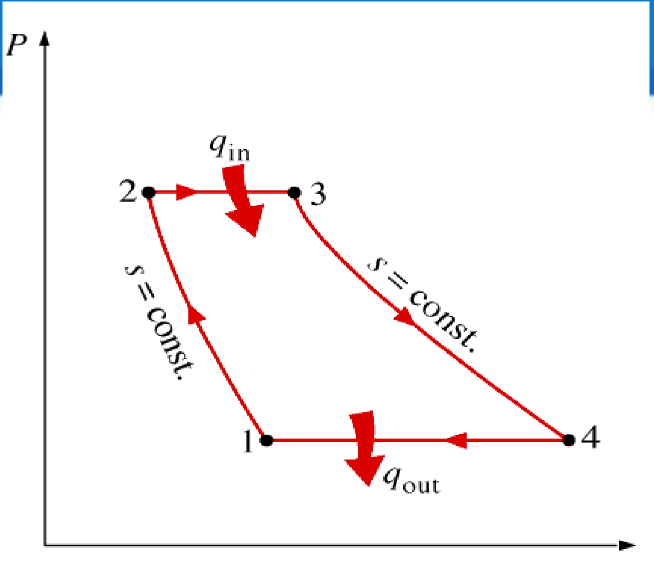


Idealized Brayton Cycle

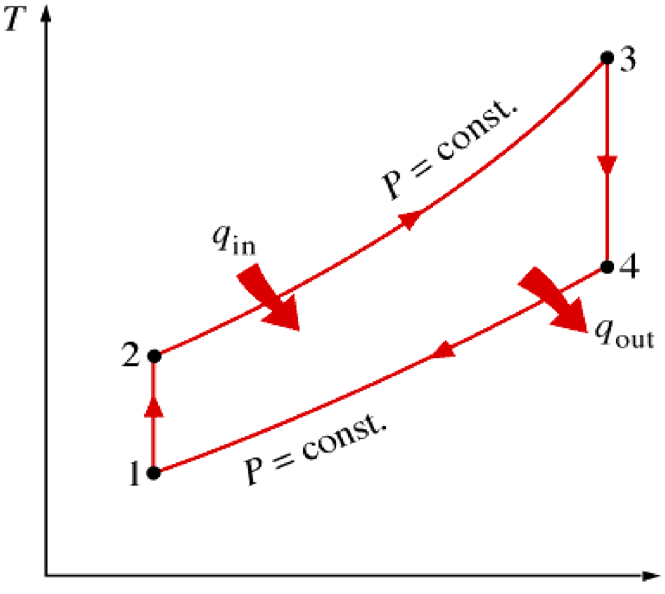


Brayton Cycle

- 1 to 2--isentropic compression
- 2 to 3--constant pressure heat addition (replaces combustion process)
- 3 to 4--isentropic expansion in the <u>turbine</u>
- 4 to 1--constant pressure heat rejection to return air to original state



(b) *P*- υdiagram



(a) *T*-*s* diagram

Brayton cycle analysis

net work:

$$w_{net} = \left| w_{turb} \right| - \left| w_{comp} \right|$$

Substituting:

$$w_{net} = (h_3 - h_4) - (h_2 - h_1)$$

Thank You