Applied Thermodynamics

Applied thermodynamics is the science of the relationship between <u>heat</u>, <u>work</u>, and <u>systems</u> that analyze energy processes. The energy processes that convert heat energy from available sources such as chemical <u>fuels</u> into mechanical work are the major concern of this science. Thermodynamics consists of a number of analytical and theoretical methods which may be applied to machines for energy conversion.

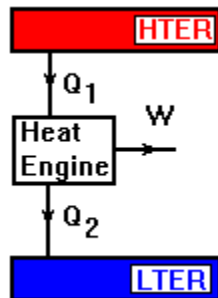**Related topics:**
- Laws of thermodynamics
  - <u>The zeroth law of thermodynamics</u>
  - <u>The first law of thermodynamics</u>
  - <u>The second law of thermodynamics</u>
  - <u>Heat engines</u>
- <u>Turbines</u>
  - <u>Heat transfer</u>
- <u>Heat exchangers</u>
  - <u>Adiabatic mixing</u>
- <u>Energy</u>
  - <u>Power</u>
- <u>Working fluid</u>

Heat Engine

Heat engine is defined as "a device that converts <u>heat</u> energy into mechanical <u>energy</u>" or more exactly   "a <u>system</u> which operates continuously and only heat and <u>work</u> may pass across its boundaries".
The operation of a heat engine can best be represented by a <u>thermodynamic cycle</u>. Some examples are: <u>Otto</u>, <u>Diesel</u>, <u>Brayton</u>, Stirling and <u>Rankine</u> cycles.

Forward Heat Engine

LTER= Low Temperature Energy Reservoir
HTER= High Temperature Energy Reservoir

A forward heat engine has a positive <u>work</u> output such as <u>Rankine</u> or <u>Brayton</u> cycle. Applying the <u>first law of thermodynamics</u> to the cycle gives:

$Q_1 - Q_2 - W = 0$

The <u>second law of thermodynamics</u> states that the <u>thermal efficiency</u> of the cycle, η, has an upper limit, η_c (the thermal efficiency of the <u>Carnot cycle</u>), i.e.

$\eta < \eta_c < 1.0$

It can be shown that:
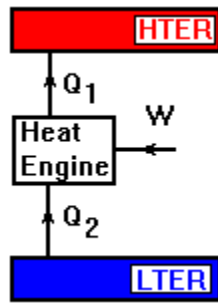
$Q_1 > W$

which means that it is impossible to convert the whole heat input to work and

$Q_2 > 0$

which means that a minimum of heat supply to the cold reservoir is necessary.

Reverse Heat Engine

LTER= Low Temperature Energy Reservoir
HTER= High Temperature Energy Reservoir

A reverse heat engine has a positive <u>work</u> input such as heat pump and refrigerator. Applying the <u>first law of thermodynamics</u> to the cycle gives:

$$-Q_1 + Q_2 + W = 0$$

In case of a reverse heat engine the <u>second law of thermodynamics</u> is as follows:
It is impossible to transfer heat from a cooler body to a hotter body without any work input i.e.

W > 0

which means that the <u>coefficient of performance</u> for a heat pump is greater than unity.

Energy

Energy is an inherent property of a <u>system</u>. Any system at a given set of conditions (e.g. pressure and temperature) has a certain energy content. The concept of energy invented to describe a number of processes such as conversion of <u>work</u> to <u>heat</u>.

The <u>SI</u> unit of energy is joule (J). Other units are:

      1 cal (calorie)= 4.1868 J
      1 kcal= 4186.8 J
      1 Btu (British thermal unit)= 1055.05 J
      1 thermie= 4.184E6 J
      1 ft.lbf= 1.35582 J
      1 kJ= 1000 J
      1 MJ= 1E6 J
      1 hp.h (horsepower.hour)= 2.6845E6 J
      1 kWh= 3.6E6 J
      1 MWh= 3.6E9
      1 eV (electron volt)= 0.16021E-18 J
      1 erg= 1E-7 J

Related topic:
- <u>The first law of thermodynamics</u>

Pressure

The pressure of a <u>system</u> is defined as the <u>force</u> exerted by the system on unit <u>area</u> of its boundaries. This is the definition of the absolute pressure. Often in measurements a   gauge is used to record the   pressure difference between the system and the atmospheric pressure.   This is called gauge pressure and can be stated by the following Eq.:

$P=Pg+Po$

P=absolute pressure,
Pg=gauge pressure,
Po=atmospheric pressure.

If the pressure of a system is below atmospheric, it is called vacuum pressure.The <u>SI</u> unit of pressure is pascal (Pa):

1 Pa=1 N/m2

"bar" is used in many industrial applications:

1 bar=0.1 MPa

This unit is approximately equal to atmospheric pressure:

Standard atmospheric pressure=1.01325 bar= 101325 Pa

In hydraulic "m of water" is common:

1 m of water=9806.65 Pa

Many gauges use Mercury (Hg) as the measurement medium.

1 mmHg=torr=133.4 Pa

Other units are:

dyn/cm2=0.1 Pa
kgf/cm2=kp/cm2=at=98067 Pa
lbf/ft2=47.879 Pa
in (H2O)=249.08 Pa
in (Hg)=3386.4 Pa
psi=lbf/in2=6894.7 Pa
ksi=1000 psi=68.947 MPa

Temperature

Temperature is a measure of hotness and can be related to the kinetic energy of molecules of a substance. A number of physical phenomena can be used for measuring the temperature of an object. An instrument used for measuring temperature is called a thermometer and is constructed by using one of the following principles:

● the change of length, such as length of a mercury column,
● the change of volume, such as volume of a fixed mass of gas at constant pressure,
● the change of pressure, such as pressure of a fixed mass of gas at constant volume,
● the change in electric resistance, as in a thermistor,
● the flow of electricity due to Seebeck effect, as in a thermocouple,
● the radiation, as in radiation pyrometers.

All thermometers require a scale. This scale should be defined by easily repeatable circumstances or fundamental properties. For instance the Centigrade scale has been defined from the melting (0 C) and boiling (100 C) points of pure water at atmospheric pressure. For temperature the following units can be used:

C, K, F.

where symbol C is for Centigrade (or Celsius), K for kelvin and F for Fahrenheit. If the temperature is **c** on the Centigrade (or Celsius) scale, then the absolute temperature on the kelvin scale will be:

c+273.15

the Fahrenheit scale will show:

1.8 **c**+32

There is also another temperature scale, called Rankine (symbol R). If the temperature is **f** on the Fahrenheit scale, the Rankine scale will show:

f+459.69

Absolute temperature or thermodynamic temperature (degree kelvin, K) is a fundamental dimension. It can be related to the energy possessed by matter and is an SI base unit.

SI Units

The international System of Units, SI, was adopted by the General Conference of Weights and Measures in 1960.   In SI units six physical quantities are assigned unit value. The six quantities are:

- <u>length</u> (meter, m)
- <u>mass</u> (kilogram, kg)
- <u>time</u> (second, s)
- electric current (ampere, A)
- thermodynamic <u>temperature</u> (degree kelvin, K)
- luminous intensity (candela, cd)

All other physical quantities are derived from these; for example, velocity=length/time has units of m/s.

Heat

Heat is a form of <u>energy</u> that is transferred from one   body (<u>system</u>) to another body (<u>system or surroundings</u>). <u>Heat transfer</u> can occur when there is a <u>temperature</u> difference. Assume two bodies with different temperatures are brought into contact with each other. The heat transfers from the hotter body to the colder one. This will continue until the temperature of the bodies are the same (thermal equilibrium).

The <u>SI</u> unit of heat is joule (J). Other units are:

> 1 cal (calorie)= 4.1868 J
> 1 Btu (British thermal unit)= 1055.05 J
> thermie= 4.184E6 J
> ft.lbf= 1.35582 J
> kJ= 1000 J
> MJ= 1E6 J
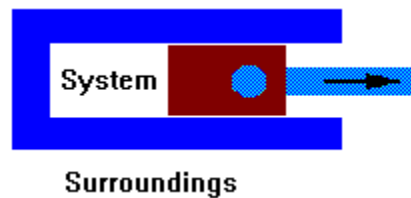> hp.h (horsepower.hour)= 2.6845E6 J
> kWh= 3.6E6 J
> MWh= 3.6E9

System

A system is a collection of matter within defined boundaries.   The boundaries may be flexible. There are two   types of system: closed system and open system.

Closed System

In closed systems, nothing leaves the system boundaries. As an example, consider the fluid in the cylinder of a reciprocating engine during the expansion stroke. The system boundaries are the cylinder walls and the piston crown. Notice that the boundaries move as the piston moves.

Open System
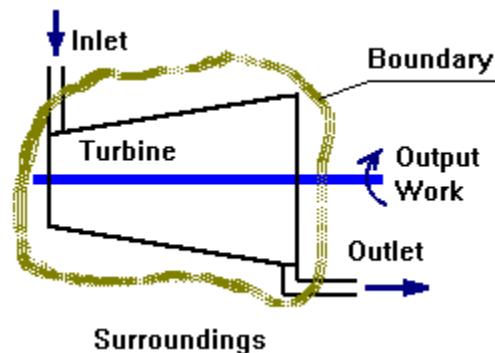
In open systems there is a mass transfer across the system's boundaries; for instance the steam flow through a steam turbine at any instant may be defined as an open system with fixed boundaries.

Density

Density, ρ, of a <u>system</u> is the <u>mass</u> of the unit <u>volume</u> of the system. Note that the density is reciprocal of <u>specific volume</u> i.e.

$\rho=1/v$

The density of gases and vapors is dependent on temperature and pressure while density of most solids and liquids is dependent only on temperature with good precision for many engineering applications.The <u>SI</u> unit od density is kg/m^3 (kilogram per cubic meter). Other units are:

1 t/m^3= 1000 kg/m^3

1 lbm/ft^3= 16.018 kg/m^3

1 lbm/(U.K.gal)= 99.776 kg/m^3

1 lbm/(U.S.gal)= 119.83 kg/m^3

1 slug/ft^3= 515.38 kg/m^3

1 g/cm^3= 1000 kg/m^3

1 U.K.ton/yd$^\bullet$= 1328.94 kg/m$^\bullet$

1 U.S.ton/yd$^\bullet$= 1186.5 kg/m$^\bullet$
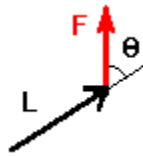
Specific Volume

The specific volume, **v**, of a system is the volume occupied by unit mass of the system. The relationship between the specific volume and density is:

v=1/ρ

The SI unit od specific volume is m³/kg (cubic meter per kilogram). Other units are:

1 m³/t= 1 m³/ton= 0.001 m³/kg

1 L/kg=1 lit/kg= 1 dm³/kg= 0.001 m3/kg
1 cm³/g= 0.001 m³/kg

1 in³/lbm= 3.6175E-5 m³/kg

1 ft³/lbm= 0.0625 m³/kg

Work

Work is defined as the scalar product of a force, **F**, and a distance,**L**.

W=F.L=F L cos(θ)

This is equivalent to the product of the <u>force</u> and the <u>distance</u> moved in the direction of the force. For instance, when a boundary of a <u>system</u> moves in the direction of the force acting on it, the surroundings do work on the system. If the direction of the movement is reversed, then the work is done by the system on its surroundings. The <u>SI</u> unit of work is joule (J) that is the same unit as <u>energy</u>.
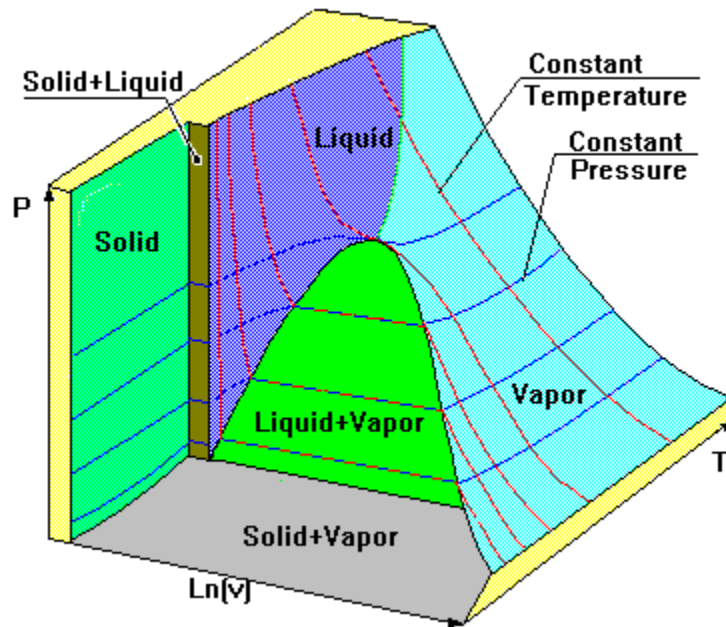
1 J= 1 N.m= 1 W.s

Other units are:

1 kpm= 9.80665 J
1 ft.lbf= 1.35582 J

State of Working Fluid

Working fluid is the matter contained within boundaries of a system. Matter can be in solid, liquid, vapor or gaseous phase. The working fluid in applied thermodynamic problems is either approximated by a perfect gas or a substance which exists as liquid and vapor. The state of the working fluid is defined by certain characteristics known as properties. Some of the properties which are important in thermodynamic problems are:

- Pressure(P)
- Temperature(T)
- Specific enthalpy(h)
- Specific entropy(s)
- Specific volume(v)
- Specific internal energy(u)

The thermodynamic properties for a pure substance can be related by the general relationship, **f(P,v,T)=0**, which represents a surface in the **(P,v,T)** space. The thermodynamic laws do not give any information about the nature of this relationship for the substances in the liquid and vapor phases. These properties may only be related by setting up measurements. The measured data can be described by equations obtained e.g. by curve fitting. In this case the equations should be thermodynamically consistent.
The state of any pure working fluid can be defined completely by just knowing two independent properties of the fluid. This makes it possible to plot state changes on 2D diagrams such as:

- pressure-volume (P-V) diagram,

- temperature-entropy (T-s) diagram,
- enthalpy-entropy (h-s) diagram.

Reversibility

In a reversible process the state of working fluid and system's surroundings can be restored to the original ones. This requires that the working fluid goes through a continuous series of   equilibrium states. A reversible process should satisfy the following criteria:

● No internal or mechanical friction is allowed.
● The temperature and pressure difference between the working fluid and its surroundings should be infinitely small.

There are no truly reversible processes in practice. The real processes are called irreversible. However, there are some processes that can be assumed internally reversible with good approximation, such as processes in cylinders with reciprocating piston. The working fluid is always in an equilibrium state in internally reversible process. But the surroundings undergo a state change that can never be restored.
Some processes may not be assumed internally reversible, such as processes in turbo machinery. The irreversibility of these processes are due to the high degree of turbulence of the working fluid.
A reversible process between two states may be shown by a continuous curve on any diagram of properties. Different points on the curve represent the intermediate states.
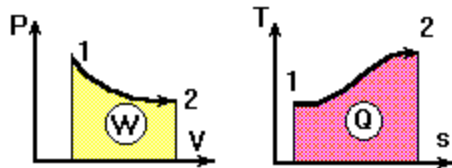
The work input to a system during a reversible process is:

$$\mathbf{W} = -\int_1^2 \mathbf{P}\, d\mathbf{V} = \text{Marked area on the P-V diagram.}$$

and the heat supplied to a system during a reversible process is:

$$\mathbf{Q} = \int_1^2 \mathbf{T}\, d\mathbf{s} = \text{Marked area on the T-s diagram.}$$

Intermediate states for an irreversible process is indeterminate, therefore these processes are often shown by a dotted line joining the initial and final states.

Thermodynamic Cycle

Thermodynamic cycle is defined as a process in which a <u>working fluid</u> undergoes a   series of state changes and finally returns to its initial state. A cycle plotted on any diagram of properties forms a closed curve.
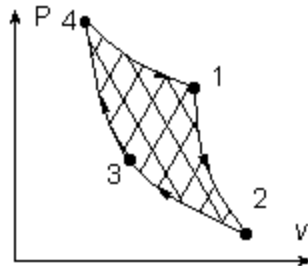
A <u>reversible</u> cycle consists only of reversible processes. The area enclosed by the curve plotted for a reversible cycle on a p-v diagram represents the net work of the cycle.

● The work is done on the system, if the state changes happen in an anticlockwise manner.
● The work is done by the system, if the state changes happen in a clockwise manner.

The First Law of Thermodynamics
Conservation of Energy

The principle of the conservation of energy states that energy can neither be created nor destroyed. If a system undergoes a process by heat and work transfer, then the net heat supplied, **Q**, plus the net work input, **W**, is equal to the change of intrinsic energy of the working fluid, i.e.

$$\Delta U = U_2 - U_1 = Q + W$$

where U_1 and U_2 are intrinsic energy of the system at initial and final states, respectively. The special case of the equation applied to a steady flow system is known as steady-flow energy equation.
Applying this general principle to a thermodynamic cycle, when the system undergoes a complete cycle, i.e. $U_1 = U_2$, results in:
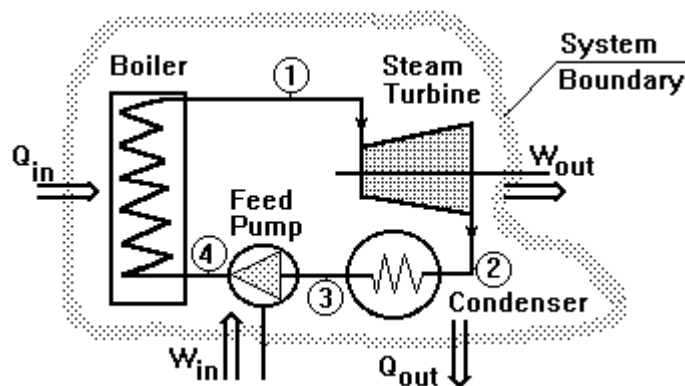
$$\Sigma Q + \Sigma W = 0$$

where:

ΣQ = The algebraic sum of the heat supplied to (+) or rejected from (-) the system.
ΣW = The algebraic sum of the work done by surroundings on the system (+) or by the system on surroundings (-).

Applying the rule to the power plant shown in figure below,

gives:

$$\Sigma Q = Q_{in} - Q_{out}$$
$$\Sigma W = W_{in} - W_{out}$$
$$Q_{in} + W_{in} - Q_{out} - W_{out} = 0$$

where,

Q$_{in}$= Heat supplied to the system through boiler,
W$_{in}$= Feed-pump work,
Q$_{out}$= Heat rejected from the system by condenser,
W$_{out}$= Turbine work.

Intrinsic Energy of Working Fluid

Intrinsic energy of working fluid is the sum of internal, kinetic and potential energy. The intrinsic energy for the unit mass of the working fluid is:

$$U_{total} = u + C^2/2 + Z\,g$$

where **u** is the specific internal energy of the working fluid. **C** is the velocity of the fluid and **Z**, the height above a datum level.
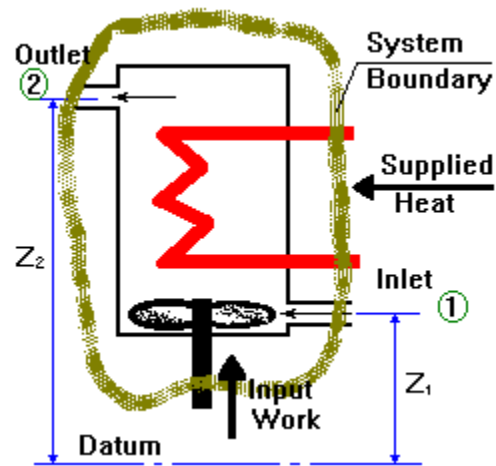
Steady Flow

If the rate of the fluid that flows through a machine or a system is constant, then the flow type is called steady flow.

Related topics:
- Continuity of Mass
- Steady Flow System

Steady-Flow System

Applying the <u>first law of thermodynamics</u> to a <u>steady-flow</u> system, defined by control volume shown above, gives:

$$d\mathbf{Q}/d\mathbf{t}+d\mathbf{W}/d\mathbf{t}=\mathbf{m}\ [\Delta\ \mathbf{h}+\Delta\ \mathbf{C}^2/2+\Delta\ \mathbf{Z}\ \mathbf{g}]$$

known as steady-flow energy equation. Where,

$d\mathbf{Q}/d\mathbf{t}=$ Supplied heat to the system per unit time,
$d\mathbf{W}/d\mathbf{t}=$ Input work to the system per unit time,
$\mathbf{m}=$ Mass flow rate,
$\Delta\ \mathbf{h}=\mathbf{h_2}\text{-}\mathbf{h_1}$,
$\mathbf{h}=$ <u>Specific enthalpy</u>,
$\Delta\ \mathbf{C}^2/2=$ Difference in kinetic energy between outlet and inlet,
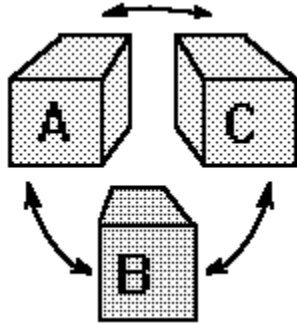$\mathbf{Z}=$ Height measured from some reference datum,
1, 2 = refer to inlet and outlet, respectively.

Isometric Process

An isometric process is one during which the volume of working fluid remains constant.

The Zeroth Law of Thermodynamics

This law states that "if object A is in thermal equilibrium with object B, and object B is in thermal equilibrium with object C, then object C is also in thermal equilibrium with object A.

This law allows us to build thermometers.   For example the length of a mercury column (object B) may be used as a measure to compare the temperatures of the two other objects.

Boyle's Law

The pressure and volume of a fixed amount of any gas at constant temperature are related by:

P V=constant

Boyle's law is a special case of the <u>perfect gas</u> equation.

Charles's Law

The volume of a fixed amount of any gas at constant pressure varies linearly with temperature i.e.

V=constant (θ+273.15)

where θ is the gas temperature on Celsius scale. Charles's law concludes that the volume of any gas should extrapolate to zero at θ=-273.15 C.   This law may be stated as following equation:

V=constant **T**

where **T** is the <u>absolute temperature</u>. Charles's law is a special case of the <u>perfect gas</u> equation.

Avogadro's Principle

All gases at same pressure and temperature contain almost the same numbers of molecules.In other words "the molar volumes of all gases are approximately the same at constant pressure and temperature".

V=constant **n**

where **n** is the number of <u>moles</u> of the gas. The proportionality constant in the above equation is not dependent on the identity of the gas. Avogadro's principle becomes increasingly exact at low pressures. The molar volume of a <u>perfect gas</u> at <u>STP</u> is:

Vm=**V/n**=22.414 L/mol

the same value under <u>SATP</u> will be:

Vm=**V/n**=24.789 L/mol

Standard Temperature and Pressure

Standard Temperature and Pressure is a condition which corresponds to (0 C) and (1 atm).

Related Topic:
      Standard Ambient Temperature and Pressure (SATP)

Standard Ambient Temperature and Pressure

Standard Ambient Temperature and Pressure is a condition which corresponds to (25 C) and (0.1 MPa).

Related Topic:
Standard Temperature and Pressure (STP)

Perfect Gas or Ideal Gas

Experimental information about gases at low pressures i.e. Charles's law, Boyle's law and Avogadro's principle may be combined to one equation:

P V=n R T

known as perfect gas equation. Where,

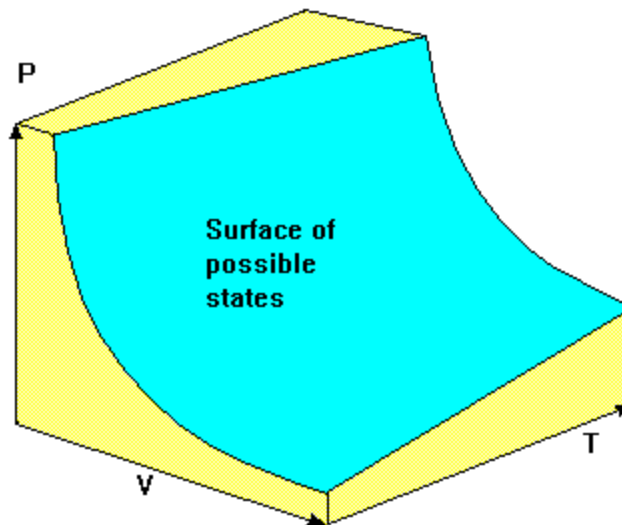**P**= pressure,
T= absolute temperature,
V= volume of the gas,
n= number of moles,

and **R** is a constant, known as gas constant.

R=8314.51 J/(kmol.K)

The surface of possible states, **(P,V,T)**, of a fixed amount of a perfect gas is shown in figure below.

Any gas that obeys the above mentioned equation under all conditions is called a perfect gas (or ideal gas). A real gas (or an actual gas), behaves like a perfect gas only at low pressures.
Some properties of actual gases such as specific heat at constant pressure and specific enthalpy are dependent on temperature but the variation due to pressure is negligible. There are empirical relations that calculate gas properties.   The following polynom is a good approximation for the specific enthalpy of gases:

$$h=R\left(a_1 T+a_2 T^2/2+a_3 T^3/3+a_4 T^4/4+a_5 T^5/5+a_6\right)$$

where a_1 to a_6 are constants depending only on the type of the gas. It should be noted that this formulation will agree with <u>Joule's law</u> and we obtain a set of <u>thermodynamically consistent equations</u>. The above equation can be used directly for calculation of <u>specific heat capacity</u> of the gas:

$$C_p=(\partial h/\partial t)_p=R\left(a_1+a_2 T+a_3 T^2+a_4 T^3+a_5 T^4\right)$$

By using the relationship:

$$\partial s/\partial T=C_p/T$$

The specific entropy of the gas, **s**, will be:

$$s=R\left(a_1 \ln(T)+a_2 T+a_3 T^2/2+a_4 T^3/3+a_5 T^4/4+a_7-\ln(P/P_0)\right)$$

where a_7 is a constant and P_0 is a reference pressure.

Related Topics:
- <u>Dalton's law</u>
- <u>Gas turbine</u>
- <u>Compressor</u>

Enthalpy

Enthalpy of a <u>system</u> is defined as the <u>mass</u> of the system, **m**, multiplied by the specific enthalpy of the system, **h** i.e.

H=**m h**

Specific Enthalpy

Specific enthalpy of a <u>working fluid</u>, **h**, is a property of the fluid which is defined as:

h=**u**+**P v**

where,

u= <u>Specific internal energy</u>
P= <u>Pressure</u>
v= <u>Specific volume</u>

Specific enthalpy has the same dimension as [<u>energy</u>/<u>mass</u>]. The <u>SI</u> unit of specific enthalpy is J/kg. Other units are:

1 kJ/kg= 1000 J/kg
1 erg/g= 1E-4 J/kg
1 Btu/lbm= 2326 J/kg
1 cal/g= 4184 J/kg

Internal Energy

Internal energy of a <u>system</u>, is the <u>energy</u> content of the system due to its thermodynamic properties such as pressure and temperature. The change of internal energy of a system depends only on the initial and final states of the system and not in any way by the path or manner of the change. This concept is used to define the <u>first law of thermodynamics</u>.

Specific Internal Energy

Specific internal energy is defined as the internal energy of the system per unit <u>mass</u> of the system and naturally has the same dimension as [energy/mass] or <u>enthalpy</u>.

Entropy

Entropy of <u>system</u>, is a measure of the avaialability of its <u>energy</u>. A system with high entropy can do less useful <u>work</u>. This concept was formally used to define <u>the second law of thermodynamics</u>.

Specific Entropy

Specific entropy of a system is the entropy of the unit <u>mass</u> of the system and has the dimension of <u>energy</u>/<u>mass</u>/<u>temperature</u>. The <u>SI</u> unit of specific entropy is J/kg,K. Other units are:

1 kJ/kg,K= 1000 J/kg,K
1 erg/g,K= 1E-4 J/kg,K
1 Btu/lbm,F= 4186.8 J/kg,K
1 cal/g,C= 4186.8 J/kg,K

Liquids and Vapors
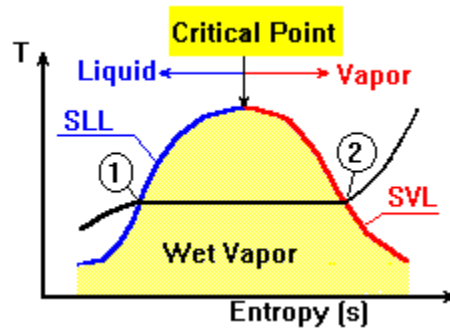
If a pure liquid is heated at a constant pressure there is a fixed temperature at which bubbles of vapor form in the liquid; this phenomenon is known as boiling. The states of substance at this condition represents a point on the properties diagram, known as boiling point; e.g. point 1. A slight addition of heat to the liquid at this state changes some of it into vapor.
Saturated liquid line, SLL, is formed by connecting a series of boiling points. Boiling temperature known also as saturation temperature, T, for a pure liquid is only a function of pressure, P, i.e.

$$T_2 = T_1 = f(P)$$

Vaporization continues by further heat supply to the system until no liquid is left. This state is known as dry saturated vapor, e.g. point 2. If the system is slightly cooled at this state, then droplets of liquid will begin to form. Connecting a series of points at dry saturated vapor builds a line, known as saturated vapor line, SVL. The state of substance between saturated liquid and dry vapor is called wet vapor.
Further heating of a dry saturated vapor at constant pressure causes a rise of vapor temperature and it becomes superheated. The state of substance is completely defined by its pressure and temperature if it is in liquid or superheated vapor phase i.e.

$h = f_1(P,T) =$ <u>Specific enthalpy</u>
$v = f_2(P,T) =$ <u>Specific volume</u>
$s = f_3(p,T) =$ <u>Specific entropy</u>

These properties for different substances are either tabulated or can be calculated by certain equations, e.g. IFC formulation for water and steam properties. The state of wet vapor can not be defined by just pressure and temperature until one other property is given. The condition or quality of wet vapor is often defined by its dryness or wetness fraction.

dryness fraction, x = the mass of dry vapor in 1 kg of the mixture,

and,
wetness fraction, 1-**x**=the mass of liquid in 1 kg of the mixture.

For wet vapor with the dryness fraction, **x**,

$h=(1-x)\ h_f+x\ h_g$
$v=(1-x)\ v_f+x\ v_g$
$s=(1-x)\ s_f+x\ s_g$

where $_f$ and $_g$ indicate the property of the substance at saturated liquid and dry saturated vapor states respectively. The heat supplied to the liquid for the complete phase change is called the specific enthalpy of vaporization.

$h_g-h_f=h_{fg}$

Related Topic:
- State of Working Fluid

Mole

Mole is defined by 1971 General Conference of Weights and Measures. The amount of mass of a system, also known as mole, is the quantity which contains as many elementary entities (atoms, ions or molecules) as there are atoms in 0.012 kg of carbon-12. The unit for mole in SI system is mol. Another unit is:

1 kmol=1000 mol

Molar Mass

Molar mass is defined as the mass per number of moles, e.g. molar mass of oxygen (O_2) is 32 kg/kmol. The SI unit used for molar mass is kg/kmol. Other units are:

      1 g/mol= 1 kg/kmol
      1 lbm/kmol= 0.453 kg/kmol

Specific Heat Capacity

The specific heat capacity of a solid or liquid is defined as the <u>heat</u> required to raise unit mass of substance by one degree of <u>temperature</u>. This can be stated by the following Eq.:

$$\Delta Q = m\, c\, \Delta T$$

where,
ΔQ= Heat supplied to substance,
m= Mass of the substance,
c= Specific heat capacity,
ΔT= Temperature rise.

There are two definitions for vapors and gases:

- C_p= Specific heat capacity at constant pressure, i.e.

$$C_p = \left(\frac{\partial h}{\partial T} \right)_p$$

- C_v= Specific heat capacity at constant volume, i.e.

$$C_v = \left(\frac{\partial u}{\partial T} \right)_v$$

It can be shown that for a <u>perfect gas</u>:

$$C_p - C_v = R$$

where R is the gas constant. The ratio, C_p/C_v, has been given symbol γ,

$$\gamma = C_p/C_v$$

and is always greater than unity. The approximate value of this ratio is 1.6 for monatomic gases such as **Ar** and **He**. Diatomic gases (such as H_2, N_2, **CO** and O_2) have a γ ratio about 1.4 and triatomics (such as SO_2 and CO_2) 1.3.

Isothermal Process

An isothermal process is one during which the temperature of working fluid remains constant.

Isobaric Process

An isobaric process is one during which the <u>pressure</u> of <u>working fluid</u> remains constant.

Isentropic Process

An isentroic process is one during which the <u>entropy</u> of <u>working fluid</u> remains constant.

Joule's Law

Joule's law state that the <u>internal energy</u> of a <u>perfect gas</u> is a function of the <u>temperature</u> only, i.e.

u=f(t)

Polytropic Process

Many processes can be approximated by the law:

$$P v^n = \text{constant}$$

where,
   P= Pressure,
   v= Volume,
   n= an index depending only on the amount of heat and work during
the process.

Polytropic processes are internally reversible.   Some examples are vapors
and perfect gases in many non-flow processes, such as:

● **n**=0, results in **P**=constant i.e. isobaric process.
● **n**=
∞, results in **v**=constant i.e. isometric process.
● **n**=1, results in **P v**=constant, which is an isothermal process for a perfect
gas.
● **n**=γ, which is a reversible adiabatic process for a perfect gas.

Some polytropic processes are shown in figure below:
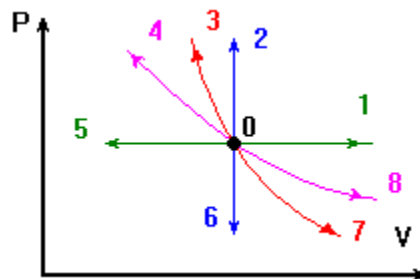
The initial state of working fluid is shown by point **0** on the P-V diagram. The
polytropic state changes are:

● 0 to 1= constant pressure heating,
● 0 to 2= constant volume heating,
● 0 to 3= reversible adiabatic compression,
● 0 to 4= isothermal compression,
● 0 to 5= constant pressure cooling,
● 0 to 6= constant volume cooling,
● 0 to 7= reversible adiabatic expansion,
● 0 to 8= isothermal expansion.

Adiabatic Process

Adiabatic process is defined as a process in which no <u>heat</u> is supplied to or rejected from the <u>working fluid</u>. A <u>reversible</u> <u>isentropic</u> process is also an adiabatic process.

Free Expansion
Unresisted Expansion

Initial State
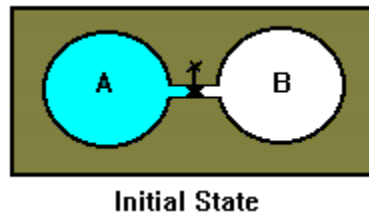
Consider two vessels A and B which are connected to each other by a pipe and a valve. Vessel A is initially filled with a fluid at a certain pressure and B is completely evacuated.
By opening the valve, the fluid in the vessel A will expand until it fills both vessels. This process is known as free or unresisted expansion. It is an irreversible process because it needs external work to be done to restore the fluid to its initial condition. Consider a system, consisting of both vessels which is perfectly thermally insulated. Apply the first law of thermodynamics to the system, i.e.

$$Q+W=U_2-U_1$$

where indices 1 and 2 represent initial and final states.
$Q=0$, because the thermal insulation will not allow any heat transfer between the system and the surroundings. $W=0$ because the boundaries of the system are not moved. The result will then be:

$$U_2=U_1$$

The free expansion process is adiabatic but irreversible. If the working fluid is a perfect gas, then $U_2=U_1$ is equivalent to $T_2=T_1$.

Throttling
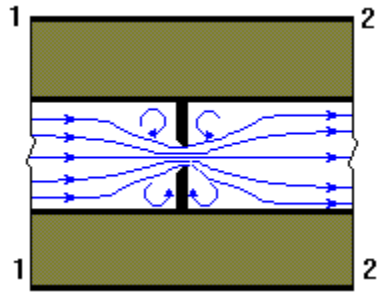
A fluid can be throttled by several means. Examples are: a partly open valve, an orifice or any other sudden reduction in the cross-section of the flow. The enthalpy remains almost constant and pressure reduces in this process. Throttling is an irreversible process due to eddying of the fluid.

Consider a perfectly thermally insulated pipe which fluid flows steadily through an orifice. Applying the first law of thermodynamics to the steady flow system defined by the control volume between sections 1-1 and 2-2, gives:

$$d\textbf{Q}/d\textbf{t}+d\textbf{W}/d\textbf{t}=\textbf{m} [\Delta \textbf{h}+\Delta \textbf{C}^2/2+\Delta \textbf{Z} \textbf{g}]$$

$d\textbf{Q}/d\textbf{t}=0$ because the system is thermally insulated. $d\textbf{W}/d\textbf{t}$ is also zero. If velocities at sections 1-1 and 2-2 are small or approximately equal and the height difference between these two sections, $\Delta \textbf{Z}$, is negligible, then we can write:

$$\Delta\textbf{h}=\textbf{h}_2-\textbf{h}_1=0$$

where $\textbf{h}_1$ and $\textbf{h}_2$ represent the enthalpy of the working fluid at sections 1-1 and 2-2 respectively.

Adiabatic Mixing
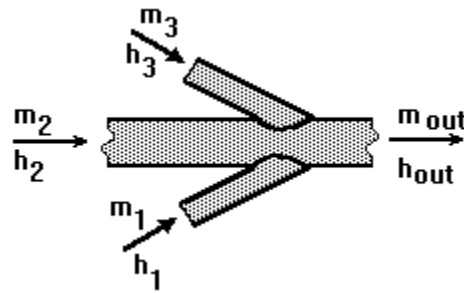
The mixing of several streams of fluid is quite common in engineering practice. The process can usually be assumed to occur <u>adiabatically</u>. Mixing process is highly <u>irreversible</u> because of eddying of fluid streams. Consider the <u>steady flow</u> system shown in figure above. If the changes of kinetic energy are negligible, then the law of <u>conservation of energy</u> gives:

$$m_1\ h_1 + m_2\ h_2 + m_3\ h_3 = m_{out}\ h_{out}$$

or in general,

$$\Sigma(m_{in}\ h_{in}) = m_{out}\ h_{out}$$

and the law of <u>conservation of mass</u> gives:

$$m_1 + m_2 + m_3 = m_{out}$$

or in general,

$$\Sigma m_{in} = m_{out}$$

where **m** and **h** represent <u>mass flow</u> and <u>specific enthalpy</u> of the fluids.

The Second Law of Thermodynamics

The second law of thermodynamics states that no <u>heat engine</u> can be more efficient than a <u>reversible</u> heat engine working between two fixed temperature limits (<u>Carnot cycle</u>) i.e. the maximum <u>thermal efficiency</u>, η_{max}, is equal to the thermal efficiency of the <u>Carnot cycle</u>, η_c:

$$\eta < \eta_{max} = \eta_c$$

or in other words "If the heat input to a <u>heat engine</u> is **Q**, then the work output of the engine, **W** will be restricted to an upper limit **W**$_{max}$" i.e.

$$W < W_{max} = Q\ \eta_c$$

It should be noted that real <u>cycles</u> are far less efficient than the <u>Carnot cycle</u> due to mechanical friction and other <u>irreversibility</u>.

Related topic:
- <u>Exergy</u>

Thermal Efficiency

●

LTER= Low Temperature Energy Reservoir
HTER= High Temperature Energy Reservoir

The thermal efficiency, η, of a cycle (or more precisely a <u>forward heat engine</u>) is defined as the ratio of net work output, **W**, to the <u>heat</u> supplied at high temperature, **Q**1, i.e.

η=**W**/**Q**1

Related Topics:
●<u>Coefficient of Performance</u>
●<u>Carnot Cycle</u>

Exergy or Availability

Exergy of a <u>system</u> is defined as the theoretical maximum amount of <u>work</u> that can be obtained from the system at a prescribed state (**P**, **T**, **h**, **s**, **u**, **v**) when operating with a reservoir at the constant <u>pressure</u> and <u>temperature</u> P_0 and T_0. The specific exergy of a non-flow system is:

$$u + P_0\, v - T_0\, s$$

and for a <u>steady flow</u> system:

$$h + C^2/2 + Z\, g - T_0\, s$$

where,
u = <u>Specific internal energy</u>,
h = <u>Specific enthalpy</u>,
v = <u>Specific volume</u>,
s = <u>Specific entropy</u>,
C = <u>Velocity</u>,
Z = Height of the system measured from a fixed datum,
g = Gravity constant.

Isentropic Efficiency
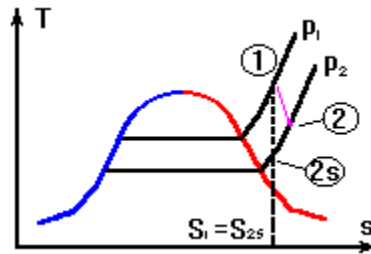
Expansion from pressure P_1 to P_2.

The isentropic efficiency for an expansion process is defined as:

$\eta_{i,e}$=(actual work)/(isentropic work)

For a unit time and a mass flow, **m**, we can write:

actual work=**m** (**h**$_1$-**h**$_2$)

isentropic work=**m** (**h**$_1$-**h**$_{2s}$)

$\eta_{i,e}$=(**h**$_1$-**h**$_2$)/(**h**$_1$-**h**$_{2s}$)
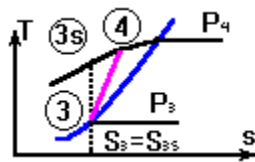
Compression from pressure P_3 to P_4.

and for a compression process:

$\eta_{i,c}$=(isentropic work)/(actual work)

For a unit time and a mass flow, **m**, we can write:

actual work=**m** (**h**$_4$-**h**$_3$)

isentropic work=**m** (**h**$_{3s}$-**h**$_3$)

$\eta_{i,c}$=(**h**$_{3s}$-**h**$_3$)/(**h**$_4$-**h**$_3$)

Related Topics:
- Pump
- Steam Turbine

Coefficient of Performance

LTER= Low Temperature Energy Reservoir
HTER= High Temperature Energy Reservoir

The effectiveness of a <u>reversed heat engine</u> is defined in terms of a coefficient of performance (COP).   The COP for a refrigerator is defined as:
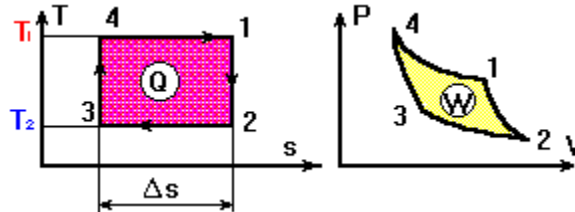
COP=**Q**$_2$/**W**

and for a heat pump as:

COP=**Q**$_1$/**W**

Related Topic:
<u>Thermal Efficiency</u>

Carnot Cycle

By using <u>the second law of thermodynamics</u> it is possible to show that no <u>heat engine</u> can be more efficient than a <u>reversible</u> heat engine working between two fixed temperature limits. This heat engine is known as Carnot cycle and consists of the following processes:

T-s and P-V diagrams for Carnot Cycle.

- 1 to 2: <u>Isentropic</u> expansion
- 2 to 3: <u>Isothermal</u> heat rejection
- 3 to 4: <u>Isentropic</u> compression
- 4 to 1: <u>Isothermal</u> heat supply

The supplied heat to the cycle per unit mass flow is:

$$Q_1 = T_1 \, \Delta s$$

The rejected heat from the cycle per unit mass flow is:

$$Q_2 = T_2 \, \Delta s$$

By applying <u>the first law of thermodynamics</u> to the cycle, we obtain:

$$Q_1 - Q_2 - W = 0$$

And the <u>thermal efficiency</u> of the cycle will be:

$$\eta = W/Q_1 = 1 - T_2/T_1$$

Due to mechanical friction and other irreversiblities no cycle can achieve this efficiency.
The gross work output of cycle, i.e. the work done by the system is:

$$W_g = W_{4\text{-}1} + W_{1\text{-}2}$$

and work ratio is defined as the ratio of the net work, **W**, to the gross work output, **W**$_g$, i.e.

W/W$_g$

The Carnot cycle has a low work ratio. Although this cycle is the most efficient system for power generation theoretically, it can not be used in practice. There are several reasons such as low work ratio, economical aspects and practical difficulties.

Otto Cycle
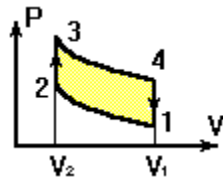
P-V diagram for an Otto cycle.

Several engines may be approximated by an Otto cycle, such as petrol engine and gas engine. The otto cycle is an ideal <u>air standard cycle</u> which consists of four processes:

- 1 to 2: <u>Isentropic</u> compression
- 2 to 3: <u>Reversible</u> constant volume heating
- 3 to 4: <u>Isentropic</u> expansion
- 4 to 1: <u>Reversible</u> constant volume cooling

The <u>thermal efficiency</u> of an Otto cycle with a <u>perfect gas</u> as <u>working fluid</u> is:

$$\eta = 1 - (T_4 - T_1)/(T_3 - T_2)$$

It can be shown that:

$$\eta = 1 - r^{\bullet}$$

where,
$r = V_1/V_2 =$ Compression ratio
$n = 1 - \gamma =$ a constant depending on <u>specific heat capacity</u>

Rankine Cycle

●

Rankine cycle is a <u>heat engine</u> with vapor power cycle. The common <u>working fluid</u> is water. The cycle consists of four processes:

● 1 to 2: <u>Isentropic</u> expansion (<u>Steam turbine</u>)
● 2 to 3: <u>Isobaric</u> heat rejection (Condenser)
● 3 to 4: <u>Isentropic</u> compression (Pump)
● 4 to 1: <u>Isobaric</u> heat supply (Boiler)
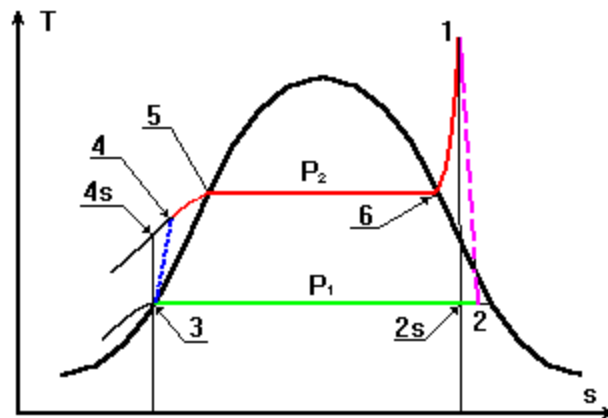
T-s diagram for a Rankine cycle.

Work output of the cycle (Steam turbine), W_1 and work input to the cycle (Pump), W_2 are:

$$W_1 = m (h_1 - h_2)$$
$$W_2 = m (h_4 - h_3)$$

where **m** is the <u>mass flow</u> of the cycle. Heat supplied to the cycle (boiler), Q_1 and heat rejected from the cycle (condenser), Q_2 are:

$$Q_1 = m (h_1 - h_4)$$
$$Q_2 = m (h_2 - h_3)$$

The net work output of the cycle is:

$$W = W_1 - W_2$$

The <u>thermal efficiency</u> of a Rankine cycle is:

$$\eta = W/Q_1$$

The efficiency of the Rankine cycle is not as high as <u>Carnot cycle</u> but the cycle has less practical difficulties and more economic.

Brayton or Joule Cycle
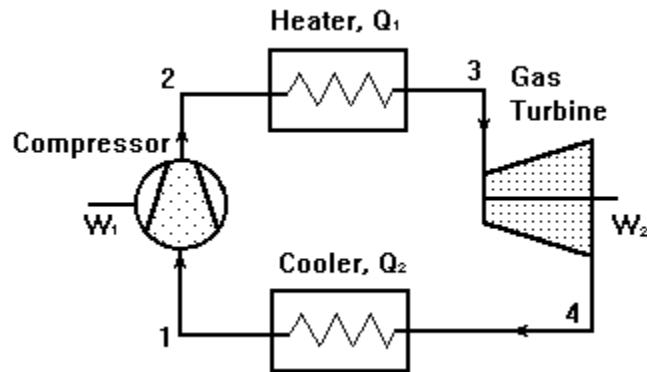
Brayton cycle is an ideal <u>air standard cycle</u> for the closed cycle gas turbine unit. Both the heat supplied and rejected from the cycle occur at constant pressure, therefore this cycle is also known as constant pressure cycle. The cycle consists of four processes:

- 1 to 2: <u>Isentropic</u> compression
- 2 to 3: <u>Isobaric</u> heat supply
- 3 to 4: <u>Isentropic</u> expansion
- 4 to 1: <u>Isobaric</u> heat rejection
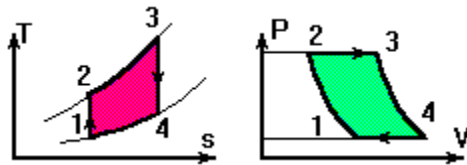
T-s and P-V diagrams for Brayton cycle.

Work input to the cycle (<u>compressor</u>), **W**1 and work output of the cycle (gas turbine), **W**2 are:

$$W_1 = m\ (h_2 - h_1)$$
$$W_2 = m\ (h_3 - h_4)$$

wher **m** is the <u>mass flow</u> of the cycle. Heat supplied to the cycle (heater), **Q**1 and heat rejected from the cycle (cooler), **Q**2 are:

$$Q_1 = m\ (h_3 - h_2)$$
$$Q_2 = m\ (h_4 - h_1)$$

The <u>thermal efficiency</u> of a Brayton cycle with a <u>perfect gas</u> as <u>working fluid</u> is:

$$\eta = 1-(T_4-T_1)/(T_3-T_2)$$
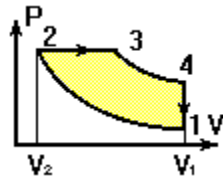
It can be shown that:

$$\eta = 1-r^{\bullet}$$

where,
$r = P_2/P_1 =$ pressure ratio
$n = -1+1/\gamma =$ a constant depending on γ

Air Standard Cycle

Air standard cycle is defined as a <u>reversible</u> <u>heat engine</u> in which the source of heat supply and the sink for heat rejection are external to the air.
This cycle is a good approximation for many so-called <u>internal combustion cycles</u>.

Diesel Cycle

P-V diagram for an Diesel cycle.

The Diesel cycle is an ideal air standard cycle which consists of four processes:

- 1 to 2: Isentropic compression
- 2 to 3: Reversible constant pressure heating
- 3 to 4: Isentropic expansion
- 4 to 1: Reversible constant volume cooling

By defining the compression ratio, **r**, as:

r=V_1/V_2

and cut-off ratio, β, as:

b=V_3/V_2

The thermal efficiency of an Diesel cycle with a perfect gas as working fluid is:

η= 1-[**r** (β● -1)]/[(β-1) γ **r**
●]

where,
n=γ= a constant depending on specific heat capacity

Power

Power is defined as <u>work</u> (or <u>energy</u> transfer) per unit <u>time</u>:

$P = dW/dt$

The <u>SI</u> unit of power is watt (w).

1 w = 1 J/s

Other units are:

1 kw = 1E3 w
1 Mw = 1E6 w
1 kpm/s = 9.80665 w
1 cal/s = 4.1868 w
1 kcal/h = 1.163 w
1 erg/s = 1E-7 w
1 hp (horse power) = 745.7 w
1 ft.lbf/s =   1.35582 w
1 Btu/h = 0.293071 w

Velocity

The dimension of velocity is <u>distance</u>/<u>time</u>. The <u>SI</u> unit of velocity is m/s (meter per second). Other units are:

1 mm/s= 0.001 m/s
1 cm/s= 0.01 m/s
1 km/s= 1000 m/s
1 in/s= 0.0254 m/s
1 ft/s= 0.3048 m/s
1 mph (mile per hour)= 0.4471 m/s

Force

The <u>SI</u> unit of force is N (newton). Other units are:

1 kN= 1000 N
1 kp= 9.80665 N
1 dyn= 1E-5 N
1 lbf= 4.44822 N

Torque

Torque (moment) has the dimension of <u>force</u> multiplied by <u>length</u>. The <u>SI</u> unit of torque is Nm (netwon.meter). Other units are:

1 kNm= 1000 Nm
1 kpm= 9.8066 Nm
1 dyn.cm= 1E-7 Nm
1 lbf.ft= 1.35582 Nm

Length

The SI unit of length or distance is meter (m). Other units are:

1 mm= 0.001 m
1 cm= 0.01 m
1 dm= 0.1 m
1 km= 1000 m
1 in (inch)= 0.0254 m
1 ft (foot)= 0.3048 m
1 yd (yard)= 0.9144 m
1 mile= 1609.344 m

Area

The <u>SI</u> unit of area is square meter (m^2). Other units are:

- 1 mm^2 = 1E-6 m
- 1 cm^2 = 1E-4 m
- 1 dm^2 = 0.01 m
- 1 in^2 (square inch)= 6.4516E-4 m
- 1 ft^2 (square foot)= 0.09299 m
- 1 yd^2 (square yard)= 0.83613 m

Volume

The <u>SI</u> unit of volume is cubic meter (m^3). Other units are:

- 1 mm^3 = 1E-9 m^3
- 1 cm^3 = 1E-6 m^3
- 1 dm^3 = 1 L (liter)= 0.001 m^3
- 1 in^3 (cubic inch)= 1.6387E-5 m^3
- 1 ft^3 (cubic foot)= 2.8317E-2 m^3
- 1 yd^3 (cubic yard)= 0.76455 m^3

Mass Flow

Mass flow rate is the amount of <u>mass</u> which enters or leaves a <u>system</u> per unit <u>time</u>. The <u>SI</u> unit for mass flow rate is kg/s. Other units are:

1 kg/h= 1/3600 kg/s
1 t/h= 1/3.6 kg/s
1 lbm/s= 0.453 kg/s

Thermodynamically Consistent Set of Equations

There are differential relations between properties of <u>working fluid</u>. By using the so-called thermodynamic potentials i.e. specific free energy (Helmholtz function **f**) and specific free enthalpy (Gibbs function **g**), which are related by the following Eq.:

g=**f**+**P v**

we can write:

h=**g**+**T s**=**f**+**P v**+**T s**

$$P = -\left(\frac{\partial f}{\partial v}\right)_T$$

$$s = -\left(\frac{\partial g}{\partial T}\right)_P = -\left(\frac{\partial f}{\partial T}\right)_v$$

$$v = +\left(\frac{\partial g}{\partial P}\right)_T$$

where,

P= <u>Pressure</u>
T= <u>Temperature</u>
v= <u>Specific volume</u>
h= <u>Specific enthalpy</u>
s= <u>Specific entropy</u>

Any set of equations which satisfy the above mentioned relations is called a thermodynamically consistent set of equations. These equations can be based by on experimentally obtained data.

Mass

The <u>SI</u> unit of mass is kg (kilogram). Other units are:

1 g= 0.001 kg
1 t (metric ton)= 1 ton= 1000 kg
1 lbm (pound mass)= 0.453 kg
1 slug= 14.594 kg
1 U.K.ton (long ton)= 1016.05 kg
1 U.S.ton (short ton)= 907.185kg

Time

The <u>SI</u> unit of time is s (second). Other units are:

1 min (minute)= 60 s
1 h (hour)= 3600 s

Internal Combustion Cycle

Internal combustion cycle is a cycle in which <u>fuel</u> is burned directly in the <u>working fluid</u>.   Working fluid may attain high temperatures in these cycles, since <u>heat</u> is not transferred through some <u>heat exchanger</u> walls. The high temperature of the working fluid will benefit the <u>thermal efficiency</u> of the cycle. Some examples of these cycles are:

- <u>Open cycle gas turbine unit</u>
- <u>Otto cycle</u>
- <u>Diesel cycle</u>

Open Gas Turbine Cycle
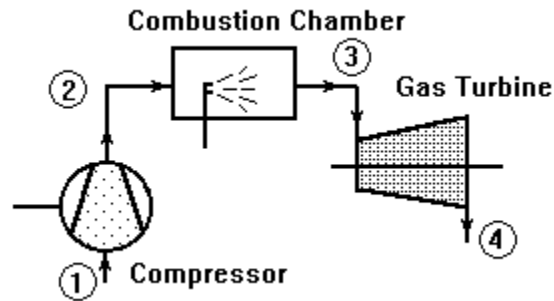
 Open gas turbine cycle is the most basic gas turbine unit.   The working fluid does not circulate   through the system, therefore it is not a true cycle.   It consists of a compressor, a combustion   chamber and a gas turbine. The compressor and the   gas turbine are mounted on the same shaft.   The compressor unit is either centrifugal or axial flow type. The working fluid goes through the   following processes:

● 1-2   irreversible but approximately adiabatic compression
● 2-3   constant pressure heat supply in the combustion chamber
● 3-4   irreversible but approximately adiabatic expansion of combustion gases
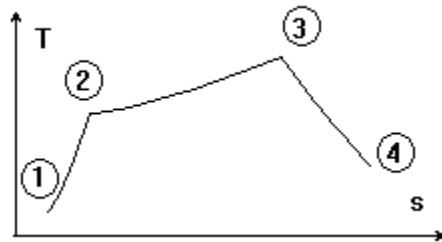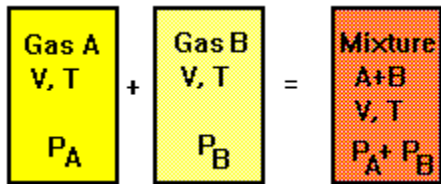

 In the simplified T-s diagram, shown above, pressure loss at compressor inlet, in combustion   chamber and at turbine outlet are neglected. Thermal efficiency of the cycle is:

$$\eta = \frac{\text{Net Work Output}}{\text{Heat supplied}} = 1 - \frac{h_1 - h_4}{h_3 - h_2}$$

Important topics:

Modified Gas Turbine Cycle

Dalton's law of additive pressures

The pressure of a gas mixture is equal to the sum of the partial pressure of the constituents. The partial pressure is that pressure which a constituent would exert if it existed alone at the mixture temperature and volume.

Heat Exchanger

Heat exchangers are devices built for efficient <u>heat transfer</u> from one fluid to another and are widely used in engineering processes.   Some examples are intercoolers, preheaters, boilers and condensers in power plants.
By applying the <u>first law of thermodynamics</u> to a heat exchanger working at steady-state condition, we obtain:

$$\Sigma m_i\,\Delta h_i = 0$$

where,
m_i = <u>mass flow</u> of the i-th fluid
Δh_i = change of <u>specific enthalpy</u> of the i-th fluid

There are several types of heat exchanger:
- recuperative type, in which fluids exchange heat on either side of a dividing wall
- regenerative type, in which hot and cold fluids occupy the same space containing a matrix of material that works alternatively as a sink or source for heat flow
- evaporative type, such as cooling tower in which a liquid is cooled evaporatively in the same space as coolant.

The recuperative type of heat exchanger which is the most common in practice may be designed according to one of the following types:

- <u>Parallel-flow</u>
- <u>Counter-flow</u>
- <u>Cross-flow</u>

Polytropic Efficiency

    The polytropic efficiency of a process is defined as the <u>isentropic efficiency</u> of the process for an infinitely small stage. It is independent of the pressure ratio (unlike the isentropic efficiency).
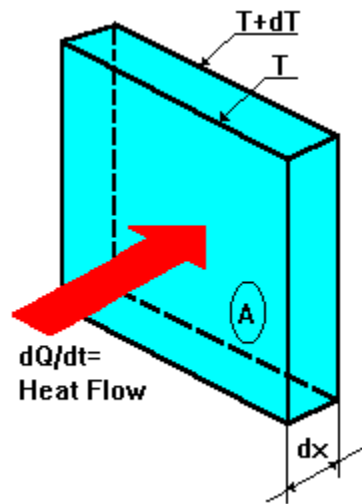
Heat Transfer

Heat may transfer across the boundaries of a system, either to or from the system. It occurs only when there is a temperature difference between the system and surroundings. Heat transfer changes the internal energy of the system. Heat is transferred by conduction, convection and radiation, which may occur separately or in combination.

Related topics:
- Fouriers's law of conduction
- Newton's law of cooling
- First law of thermodynamics

Fourier's Law of Conduction

Heat transfer through a solid

Fourier's law is an empirical law based on observation. It states that the rate of heat flow, dQ/dt, through a homogenous solid is directly proportional to the area, **A**, of the section at right angles to the direction of heat flow, and to the temperature difference along the path of heat flow, dT/dx i.e.

$$dQ/dt = -\lambda \, A \, dT/dx$$

The proportionality ratio, λ, is called thermal conductivity of the material.

Newton's Law of Cooling
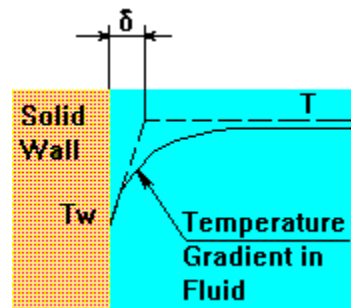
At contact surfaces between a fluid and a solid wall, there is always a thin layer of fluid through which the <u>heat</u> is transferred by <u>conduction</u>. Whenever there is an appreciable movement of the fluid, <u>conduction</u> heat transfer in fluid may be neglected compared with <u>convection</u> heat transfer.
The <u>heat transfer</u> from the solid surface to the fluid can be described by Newton's law of cooling. It states that the <u>heat transfer</u>, d**Q**/d**t**, from a solid surface of area **A**, at a temperature **T**$_w$, to a fluid of temperature **T**, is:

d**Q**/d**t**=α **A** (**T**$_w$-**T**)

where α is the <u>heat transfer coefficient</u>.

Related topics:
- <u>Forced convection</u>
- <u>Free convection</u>

Conduction

Conduction <u>heat transfer</u> occurs only when there is physical contact between bodies (<u>systems</u>) at different temperatures. <u>Heat transfer</u> through solid bodies is by conduction alone, whereas the heat may transfer from a solid surface to a fluid partly by conduction and partly by <u>convection</u>.

Related topics:
- <u>Fourier's law of conduction</u>
- <u>Newton's law of cooling</u>

Convection

Convection is the <u>heat transfer</u> within a fluid, involving gross motion of the fluid itself. Fluid motion may be caused by differences in <u>density</u> as in <u>free convection</u>. Density differences are a direct result of <u>temperature</u> differences between the fluid and the solid wall surface. In <u>forced convection</u>, the fluid motion is produced by mechanical means, such as a domestic fan-heater in which a fan blows air across an electric element.

Thermal Radiation

Thermal radiation is the energy radiated from hot surfaces as electromagnetic waves. It does not require medium for its propagation. Heat transfer by radiation occur between solid surfaces, although radiation from gases is also possible. Solids radiate over a wide range of wavelengths, while some gases emit and absorb radiation on certain wavelengths only.
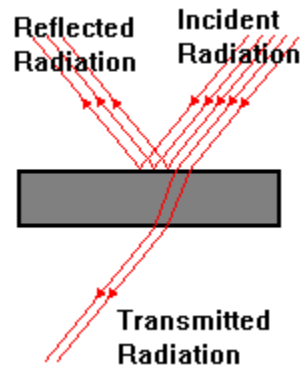
Thermal radiation striking a surface.

When thermal radiation strikes a body, it can be absorbed by the body, reflected from the body, or transmitted through the body. The fraction of the incident radiation which is absorbed by the body is called absorptivity (symbol α). Other fractions of incident radiation which are reflected and transmitted are called reflectivity (symbol ρ) and transmissivity (symbol τ), respectively.
The sum of these fractions should be unity i.e.

$$\alpha + \rho + \tau = 1$$

For many solids and liquids used in engineering, transmissivity, τ, is negligible. Therfore we can write:

$$\alpha + \rho = 1$$

Thermal Conductivity

The thermal conductivity of a substance is defined as the <u>heat</u> flow per unit <u>area</u> per unit <u>time</u> when the <u>temperature</u> decreases by one degree in unit <u>distance</u>. The <u>SI</u> unit of thermal conductivity is W/m,K. Other units are:

    1 kW/m,K= 1000 W/m,k

Related topic:
- <u>Fourier's law of conduction</u>

Heat Transfer Coefficient

The heat transfer coefficient, α, defined in <u>Newton's law of cooling</u>, depends on the properties of the fluid and also on fluid velocity.   It is usually necessary to evalute it experimentally.
The <u>SI</u> unit of heat transfer coefficient is W/m^2,K. Other units are:
        1 kW/m^2,K= 1000 W/m^2,K

Forced Convection

Forced convection studies the <u>heat transfer</u> between a moving fluid and a solid surface. There are various types of forced convection, such as flow in a tube or across a flat plate and so on. In general there are no mathematical solution available to all types of forced convection problems. These problems are usually analyzed by equations based on empirical values and generalized by dimensional analysis. The analysis can be formulated by the following Eq.:

$$\mathbf{Nu}=\mathbf{f(Pr,Re,Ma)}$$

where,
Nu= Nusselt number
Pr= Prandtl number
Re= Reynolds number
Ma= Mach number

In cases when the flow speed is low, the influence of the Mach number can be neglected and we obtain:

$$\mathbf{Nu}=\mathbf{f(Pr,Re)}$$

Free Convection

Natural convection or free convection is caused by fluid motion due to density differences. In most practical cases, the free convection may be neglected when there is a fluid flow i.e. <u>forced convection</u>.
A dimensional analysis of the <u>heat transfer</u> by free convection results in:
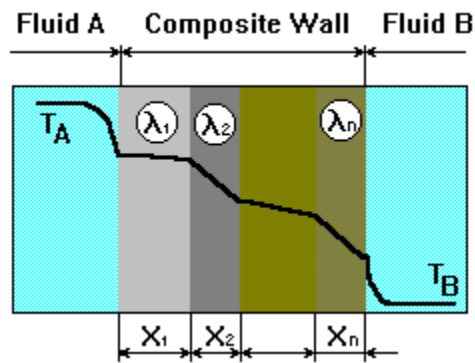
$$\mathbf{Nu} = \mathbf{f(Pr, Gr)}$$

where,
Nu= Nusselt number
Pr= Prandtl number
Gr= Grashof number

Heat Flow through a Wall

[Heat transfer](#) through a composite wall

The composite wall is constructed from different materials in layers. The thickness of layers are, x_1, x_2,..., x_n. The [thermal conductivity](#) of layers are, λ_1, λ_2,..., λ_n. The fluid on one side of the wall is at temperature T_A, and the [heat transfer coefficient](#) from fluid to wall is α_A. The temperature and heat transfer coefficient for the fluid on the other side of the wall are T_B and α_B. By using [Fourier's law of conduction](#) and [Newton's law of cooling](#), it can be shown that for a steady state [heat transfer](#):

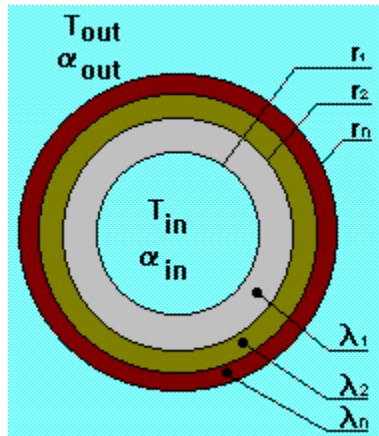$$dQ/dt = U\ A\ (T_A - T_B)$$

where,

$$1/U = 1/\alpha_A + 1/\alpha_B + \Sigma(x/\lambda)$$

dQ/dt = The transferred heat per unit time
A = Area of the wall

U which has the same unit as [heat transfer coefficient](#) is known as the overall heat transfer coefficient.

Heat Flow through a Pipe

Heat transfer through a pipe

The heat transfer through a pipe is dependent on the thickness of the pipe and isolation layers. The thickness of the pipe and layers can be defined by the radius of layers i.e. r_1, r_2,..., r_n. The thermal conductivity of layers are, λ_1, λ_2,..., λ_n. The fluid within the pipe is at temperature T_{in}, and the heat transfer coefficient from fluid to the wall is α_{in}. The temperature and heat transfer coefficient for the fluid outside the pipe are T_{out} and α_{out}. By using Fourier's law of conduction and Newton's law of cooling, it can be shown that for a steady state heat transfer:

$$d\mathbf{Q}/d\mathbf{t} = \mathbf{U} \; \mathbf{A} \; (\mathbf{T}_{in} - \mathbf{T}_{out})$$

where,

$$\frac{1}{U} = r_1 * \left[\frac{1}{\alpha_{in} * r_1} + \frac{1}{\alpha_{out} * r_n} + \sum \frac{\ln(r_{i+1}/r_i)}{\lambda_i} \right]$$

$d\mathbf{Q}/d\mathbf{t}$ = The transferred heat per unit time
$\mathbf{L}$ = Length of the pipe
$\mathbf{A}$ = $2 \, \pi \, \mathbf{L} \, r_1$

$\mathbf{U}$ which has the same unit as heat transfer coefficient is known as the overall heat transfer coefficient.

Reflectivity

Reflectivity is a property of the body surface and is dependent on the temperature of the body and the wavelength of the incident radiation. It is a dimensionless value and measured as the fraction of incident radiation that is reflected from the body.
Surface finish plays an important role in the reflectivity of a material. Smooth surfaces reflect radiation specularly, therefore they are not good absorbers or emitters. Rough surfaces which reflect diffusely are better absorbers and also better emitters than smooth surfaces.

Related topic:
- Thermal radiation

Absorptivity

Absorptivity is a property of the body surface and is dependent on the temperature of the body and the wavelength of the incident radiation. It is a dimensionless value and measured as the fraction of incident radiation that is absorbed by the body.

Related topics:
- Thermal radiation
- Monochromatic absorptivity

Transmissivity

Transmissivity is a property of the body material and is dependent on the temperature of the body and the wavelength of the incident radiation. It is a dimensionless value and measured as the fraction of incident radiation that is transmitted   through the body.

Related topic:
- Thermal radiation
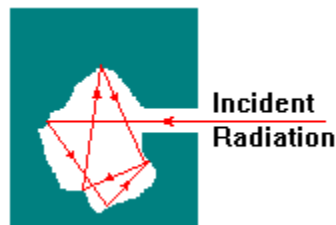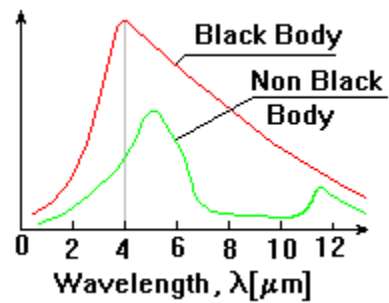- Gas radiation

Black Body

Black body by definition is an object that absorbs all radiation falling on it or in other words it has an <u>absorptivity</u> equal to unity.

$$\alpha = 1$$

therefore there is no reflection from a black body. Applying the <u>Kirchoff's law</u> to a black body results in that it should have an <u>emissivity</u> of unity i.e.

$$\varepsilon = 1$$

This means that a good absorber of radiation is also a good emitter of radiation. There are no totally black bodies in practice, but many surfaces approximate to the definition.

A hole leading to a chamber.

A close approximation to a black body is a hole leading to a chamber. <u>Thermal radiation</u> entering the hole is absorbed almost completely by the walls of the chamber, therefore only a small fraction is emitted from the hole.

Emissive Power

Emissive power is defined as the <u>energy</u> radiated from a body per unit <u>area</u> per unit <u>time</u>.

Related topic:
- <u>Stefan-Boltzmann law</u>

Kirchoff's Law

Kirchoff's law states that the <u>absorptivity</u> and <u>emissivity</u> of a <u>grey body</u> are equal at any given temperature. i.e.

$$\alpha = \varepsilon$$

where α is the total <u>absorptivity</u> and ε, total <u>emissivity</u> over all wavelengths.

Emissivity

Emissivity is a property of the body surface and is dependent on the temperature of the body and the wavelength of the emitted radiation. It is a dimenssionless value.

Related topics:
- Monochromatic emissivity
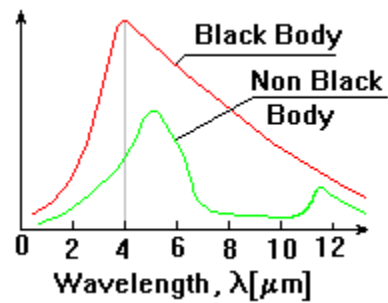- Stefan-Boltzmann law

Monochromatic Emissivity

Distribution of <u>emissive power</u>.

Monochromatic <u>emissivity</u>, ε_λ, is defined as the ratio of the emitted radiation at a specific wavelength and temperature to the emitted radiation from a <u>black body</u> at the same wavelength and temperature. By applying the <u>Kirchoff's law</u> to a <u>grey body</u>, we obtain:

$$\varepsilon_\lambda = \alpha_\lambda$$

where α_λ is the <u>monochromatic absorptivity</u> of the body.

Monochromatic Absorptivity

Distribution of abosorbed radiation.

Monochromatic absorptivity, α_λ, is defined as the ratio of the absorbed radiation at a specific wavelength and temperature to the absorbed radiation by a black body at the same wavelength and temperature. By applying the Kirchoff's law to a grey body, we obtain:

$$\alpha_\lambda = \varepsilon_\lambda$$

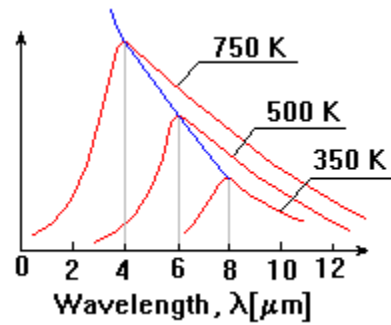where α_λ is the monochromatic emissivity of the body.

Grey Body

A grey body is defined as a body with constant <u>emissivity</u> over all wavelengths and temperatures. Such an ideal body does not exist in practice but the assumption is a good approximation for many objects used in engineering.

Related topics:
- <u>Thermal radiation</u>
- <u>Black body</u>
- <u>Kirchof's law</u>

Wien's Law

Distribution of <u>emissive power</u> from a <u>black body</u>.

The Wien's law states that the wavelength, λ_{max}, for maximum <u>emissive power</u> from a <u>black body</u> is a function of temperature i.e.

$\lambda_{max} = 2900/\mathbf{T}$

where λ_{max} is in μm and $\mathbf{T}$ is body temperature in K.

Stefan-Boltzmann Law

The Stefan-Boltzmann law states that the <u>emissive power</u>, **P**, from a <u>black body</u> is directly proportional to the forth power of its <u>absolute temperature</u> i.e.

$$P = \sigma\, T^4$$

where σ is the Stefan-Boltzmann constant

$$\sigma = 5.67\text{E-}8 \ W/m^2\, K^4$$

The emitted power, **P**, for a non-black body with <u>emissivity</u>, ε, is:

$$P = \varepsilon\, \sigma\, T^4$$
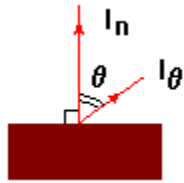
Intensity of Radiation
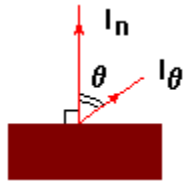
Emitted radiation from a surface.

The intensity of radiation is defined as the rate of emitted energy from unit surface <u>area</u> through unit solid angle.   The radiation from a surface has different intensities in different directions. The intensity of radiation along a normal to the surface is known as intensity of normal radiation, I_n. By using <u>Lambert's cosine law</u> and <u>Stefan-Boltzmann law</u> for a surface at <u>absolute temperature</u>, **T** and <u>emissivity</u>, ε, we obtain:

$$I_n = \varepsilon \, \sigma \, T^{\bullet} / \pi$$
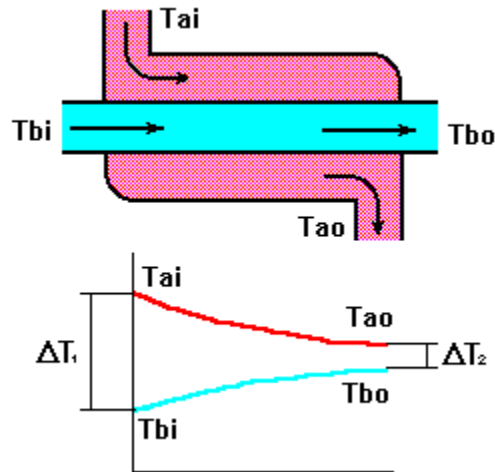
Lambert's Cosine Law

Emitted radiation from a surface.

Lambert's cosine law states that the intensity of radiation along a direction which has angle θ with the normal to the surface is:

$$I_\theta = I_n \cos\theta$$

where I_n is the <u>intensity of radiation</u> in normal direction.

Parallel-flow Heat Exchanger

Temperature distribution along tube axis.

Figure above shows a fluid flowing through a pipe and exchanges heat with another fluid through an annulus surrounding the pipe. In a parallel-flow heat exchanger fluids flow in the same direction. If the specific heat capacity of fluids are constant, it can be shown that:

$$d\mathbf{Q}/d\mathbf{t} = \mathbf{U}\ \mathbf{A}\ \Delta\mathbf{T}$$

where,
$d\mathbf{Q}/d\mathbf{t}$ = Rate of heat transfer between two fluids
$\mathbf{U}$ = Overall <u>heat transfer coefficient</u>
$\mathbf{A}$ = Area of the tube
$\Delta\mathbf{T}$ = Logarithmic mean temperature difference defined by:

$$\Delta\mathbf{T} = (\Delta\mathbf{T}_1 - \Delta\mathbf{T}_2)/\ln(\Delta\mathbf{T}_1/\Delta\mathbf{T}_2)$$

Related topics:
- <u>Counter-flow heat exchanger</u>
- <u>Cross-flow heat exchanger</u>

Counter-flow Heat Exchanger
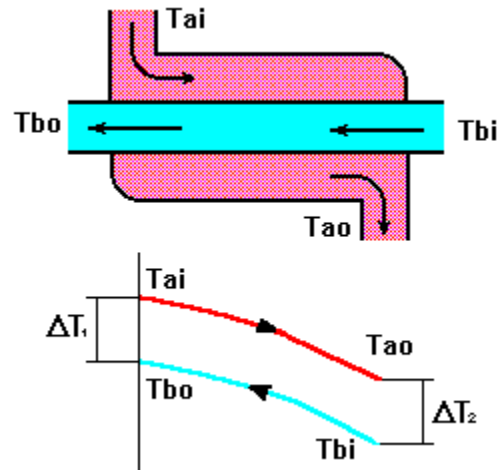
Temperature distribution along tube axis.

Figure above shows a fluid flowing through a pipe and exchanges heat with another fluid through an annulus surrounding the pipe. In a counter-flow heat exchanger fluids flow in the opposite direction. If the specific heat capacity of fluids are constant, it can be shown that:

$$d\mathbf{Q}/d\mathbf{t} = \mathbf{U}\ \mathbf{A}\ \Delta\mathbf{T}$$

where,
$d\mathbf{Q}/d\mathbf{t}$ = Rate of heat transfer between two fluids
$\mathbf{U}$ = Overall heat transfer coefficient
$\mathbf{A}$ = Area of the tube
$\Delta\mathbf{T}$ = Logarithmic mean temperature difference defined by:

$$\Delta\mathbf{T} = (\Delta\mathbf{T}_1 - \Delta\mathbf{T}_2)/\ln(\Delta\mathbf{T}_1/\Delta\mathbf{T}_2)$$

Related topics:
- Parallel-flow heat exchanger
- Cross-flow heat exchanger

Cross-flow Heat Exchanger
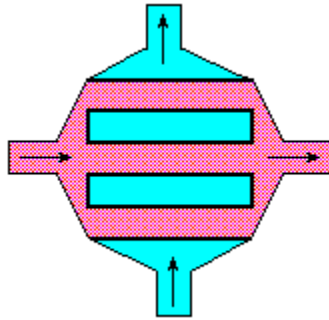
A cross-flow heat exchanger.

In a cross-flow heat exchanger the direction of fluids are prependicular to each other. The required surface area, A_{cross} for this heat exchanger is usually calculated by using tables. It is between the required surface area for counter-flow, $A_{counter}$ and parallel-flow, $A_{parallel}$ i.e.

$$A_{counter} < A_{cross} < A_{parallel}$$

Related topics:
- Counter-flow heat exchanger
- Parallel-flow heat exchanger

Conservation of Mass

The conservation of mass is a fundamental law of nature which states that matter can neither be created nor destroyed. The law allows us to write the so-called mass balance equations. For example for a <u>system</u> working under <u>steady state</u> conditions, we can write:

$$\Sigma\mathbf{m}=0$$

which means that the algebraic sum of mass flow of the fluids to (+) and from (-) a system is zero.

Psychrometry or Hygrometry

Psychrometry or hygrometry is the study of how the properties of moist air can change as a result of <u>air conditioning</u>   processes.

Related topics:
- <u>Specific Humidity</u>
- <u>Relative Humidity</u>
- <u>Percentage Saturation</u>

Air Conditioning

Air conditioning is the means to control atmospheric environment in private and public buildings for the comfort of human beings or animals or for the proper performance of some scientific or industrial processes.
Full air conditioning systems control purity, movement, temperature and relative humidity of the air.
Typical air conditioning systems for buildings are:

- Perimeter induction
- Fan coil
- Chilled ceiling
- Single duct
- Dual duct
- Variable air volume
- Terminal heat recovery

Specific Humidity or Moisture Content of Air

Specific humidity or moisture content of air is the ratio of the mass of water to the mass of dry air in a given volume of moist air.

Related topics:
- Air Conditioning
- Psychrometry

Humidity Ratio or Relative Humidity

 Humidity ratio or relative humidity is the ratio of the actual mass of water vapor in the air to the mass of water vapor that would saturate the air at the same temperature.

Related topics:
- Air conditioning
- Psychrometry

Percentage Saturation

Percentage saturation is defined as the ratio of the <u>specific humidity</u> of air to the specific humidity of saturated air at the same temperature.

Related topics:
- <u>Psychrometry</u>

Perimeter Induction System

 Perimeter induction system is an air conditioning system used in buildings. It uses dehumidified air and either hot or cold water as working mediums. A perimeter induction unit is placed at each space which is to be air conditioned.
The unit delivers dehumidified air at high pressure which passes over a <u>heat exchanger</u> through which hot or cold water flows.

Related topics:
- <u>Air conditioning</u>

Fan Coil System

 Fan coil system is an air conditioning system used in buildings. A fan unit is placed at each place which needs to be heated or cooled. A central plant delivers hot or cold water to fan units. The fan draws air from the room, blows it over the water coil and returns it to the room.
Dehumidified air from a central plant or fresh air from outside may also be used by a fan coil system.

Related topics:
- Air conditioning

Chilled Ceiling System

 Chilled ceiling system is an air conditioning system in which the ceiling of a room is cooled by a supply of chilled water or air from a central plant room.

Related topics:
- Air conditioning

Single Duct System

 Single duct system is an air conditioning system in which dehumidified air at an appropriate temperature is circulated throughout a building in a single branching duct.
The air is supplied from a central plant room. The delivered air volume to each space within the building may be controlled by thermostatically operated dampers on the duct outlet.
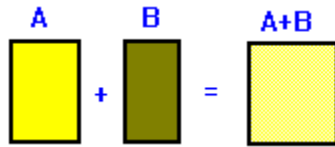
Related topics:
- Air conditioning

Dual Duct System or Double Duct System

 Dual or double duct system is an air conditioning system in which dehumidified air is circulated throughout a building via two parallel ducts. Hot air flows within one duct, cold air within the other.
A central plant supplies both cold and hot air. The proportion of hot and cold air delivered to each room within the building may be controlled by thermostatically operated dampers on the ducts outlet.

Related topics:
- Air conditioning

Composition of Dry Air

Dry air consits mainly of oxygen and nitrogen. The volumetric composition of the standrad dry air is:

Gas	Proportion by Volume
nitrogen, N	78.03
oxygen, O	20.99
carbon dioxide, CO	0.03
hydrogen, H	0.01
argon, Ar	0.94

The average molecular mass of standard dry air is 28.97

Amagat's law of additive volumes

 The volume of a gas mixture is equal to the sum of the volumes of all constituents at the same temperature and   pressure as the mixture.
 Related topics:

- [Ideal Gas](#)

Psychrometric Chart

The psychrometric chart is a useful design tool for air conditioning engineers. The chart presents a number of properties of moist air:

- dry-bulb temperature
- sling wet-bulb temperature
- moisture content
- specific enthalpy
- specific volume
- percentage saturation
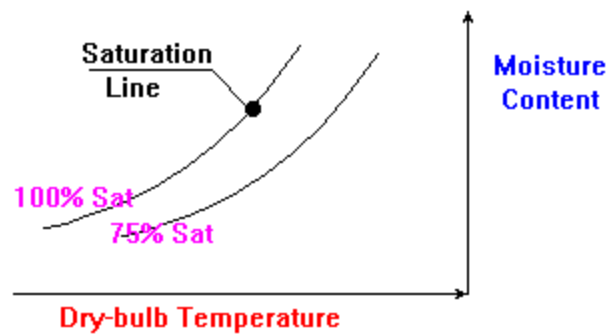
Related topics:
- Ideal Gas
- Psychrometry

Modified Gas Turbine Cycle

It is possible to improve the efficiency of an open gas turbine cycle. This can be achieved by a combination of:

- intercooling of the air after the low-pressure compressor (LPC)
- reheating the exhaust gases after high-pressure turbine (HPT)
- recovering part of the energy of exhaust gases

Compressor

•

Compressors are machines used to increase the pressure of the working fluid.   There are several types of compressors.   The most important types of rotating compressors are   radial-flow, axial-flow and positive displacement.

•

The compression process (1-2) is irreversible but   approximately adiabatic. The work input to the compressor is:

$$W_{in} = m(h_2 - h_1)$$

Where
m= mass flow of air
h2=Enthalpy at outlet
h1=Enthalpy at inlet

The pressure ratio of a compressor is defined as:

$$r = \frac{P_o}{P_i}$$

where
Po=Absolute pressure at outlet
Pi=Absolute pressure at inlet

The isentropic efficiency of the compressor is:

$$\eta = \frac{h_{2s} - h_1}{h_2 - h_1}$$

Important Topic:

Open Gas Turbine Cycle

Fuel

Fuels are chemical substances which may be burned in oxygen   to generate heat. They mainly consist of carbon and hydrogen and sometimes a small amount of sulfur or minerals.   There are solid, liquid and gaseous fuels. Coal and Coke   are examples of solid fuels. Petroleum oils are usually a   mixture of several liquid fuels. Gaseous fuels may be a   mixture of gases such as methane (CH_4), ethane (C_2H_6) and   so on.

The components before the combustion process are called reactants. The combustion process produces new components   which are called products. E.g. combustion of 1 kmol of   carbon with 1 kmol of pure oxygen will produce 1 kmol   carbon dioxide:

C+O2-->CO2
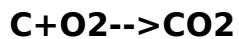
Here, C and O2 are reactants and CO2 is the product.

Related Topics:

Ignition Temperature
Air-Fuel Ratio
Stoichiometric Combustion
Excess Air
Heating Value

Ignition Temperature

   Each fuel should be brought above its Ignition Temperature for starting the combustion process. An appropriate   air-fuel ratio is also necessary. The minimum ignition   temperature at atmospheric pressure for some substances are:

        carbon   400 C
        gasoline 260 C
        hydrogen 580 C
        carbon monoxide 610 C
        methane 630 C

Stoichiometric Combustion

   Stoichiometric or Theoretical Combustion is the ideal combustion process during which a fuel is burned completely. A complete combustion is a process which burns all the carbon (C) to (CO_2), all hydrogen (H) to (H_2O) and all sulfur (S) to (SO_2). If there are unburned components in   the exhaust gas such as C, H2, CO the combustion process   is uncompleted.

Related Topics:

      Air-Fuel Ratio
      Excess Air
      Heating Value

Air-Fuel Ratio

   Air-Fuel Ratio is frequently used in the analysis of the combustion process. It is usually expressed on a mass   basis, i.e.

   AF=(mass of Air)/(mass of Fuel)

Excess Air

Excess Air is defined as the amount of air in excess of the <u>stoichiometric</u> amount. It is common to use more air than the stoichiometric amount in the combustion chamber. It increases the chances of complete combustion. Excess air can also be used to control the temperature of   combustion chamber.

Heating Value

   Heating Value   is defined as the amount of energy released when a fuel is burned completely in a steady-flow process and the products are returned to the state of the reactants. The heating value is dependent on the phase of water/steam in the combustion products.
 If H2O is in liquid form, heating value is called HHV (higher Heating Value). When H2O is in vapor form, heating value is called LHV (Lower Heating Value).

Dew-Point Temperature
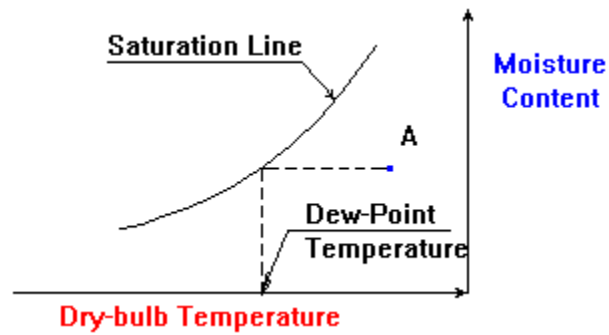
Dew-Point Temperature is the temperature at which air or other gases are so saturated with vapor that condensation takes place. If a vessel filled with humid air at original condition A, is cooled at constant vapor pressure i.e. at constant moisture content, the temperature will eventually reach saturation line and at this point water vapor will begin to condense.

Adiabatic Humidification Process

 In this process, air enters a duct (which is assumed to be perfectly insulated in order to satisfy the condition for an adiabatic process) at dry-bulb temperature T1 and moisture content g1 and leaves the duct at dry-bulb temperature T2 and moisture content g2. The latent heat gained by the air is equal to the sensible heat loss by the air. i.e.

$$h_2 - h_1 = (g_2 - g_1)h_{fg} = C_p(T_1 - T_2)$$

   hfg=latent heat of water
 If the water tank is infinitely long, the air at the outlet will be 100% saturated. The temperature at this condition is known as adiabatic saturation temperature.

Latent Heat

Latent Heat is defined as the heat which flows to or from a material without a change to temperature. The heat will only change the structure or phase of the material. e.g. melting or boiling of pure materials.

Related Topic:
- Sensible Heat

Sensible Heat

Sensible Heat is defined as the heat energy stored in a substance as a result of an increase in its temperature.

Related Topic:
- Latent Heat

Dry-bulb Temperature

The Dry-bulb Temperature of air is measured by a thermometer which is freely exposed to the air but is shielded from radiation and moisture.

Related Topics:
- Wet-bulb Temperature
- Hygrometer

Wet-bulb Temperature

   The Wet-bulb Temperature of air is measured by a thermometer whose bulb is covered by a muslin sleeve which is kept moist with distilled and clean water, freely exposed to the air and free from radiation.

Related Topics:
- Dry-bulb Temperature
- Hygrometer

Hygrometer or Psychrometer
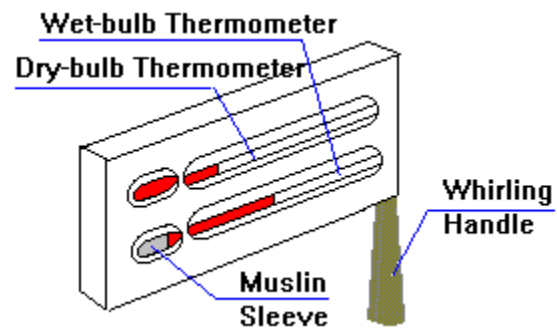
 Hygrometers are devices for measuring the wet-bulb temperature of the air. The temperature reading is affected by air movement over the instrument. There are two types of measuring instrument, sling and screen hygrometer. The sling hygrometer is the more accurate one, therefore it is preferred by air conditioning engineers.

● Sling hygrometer measures the wet-bulb temperature in a moving air stream, preferably above 2 m/s. The instrument has two thermometers. One of these thermometers is covered with muslin sleeve which is kept moist with distilled and clean water. This thermometer will measure the wet-bulb temperature and the other one dry-bulb temperature. A sling wet-bulb temperature may also be obtained by an Assman hygrometer. In the Assman hygrometer, the wet-bulb thermometer is installed in a duct where the air is flowing at reasonable velocity.
● Screen hygrometer measures the wet-bulb temperature in still air. Thermometers are installed in a Stevenson screen as used by meteorologists.

Mixing of Two Air Streams
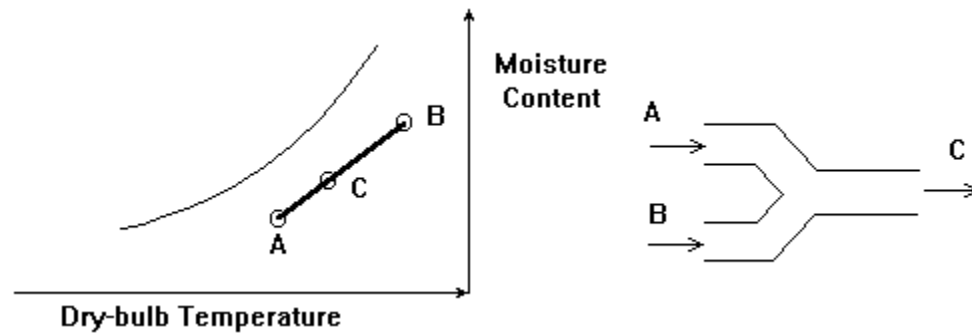
Mixing of two air streams is often used in air conditioning systems, e.g. mixing air from outdoors with air returned from the air conditioned system. The adiabatic mixing of two air streams, A and B will produce a new condition C. The mixing   process can be drawn as a straight line ACB on the psychrometric chart. Using the laws of conservation of mass and energy gives:

$$m_C = m_A + m_B$$

$$h_C \cdot m_C = h_A \cdot m_A + h_B \cdot m_B$$

$$g_C \cdot m_C = g_A \cdot m_A + g_B \cdot m_B$$

Sensible Heating Process
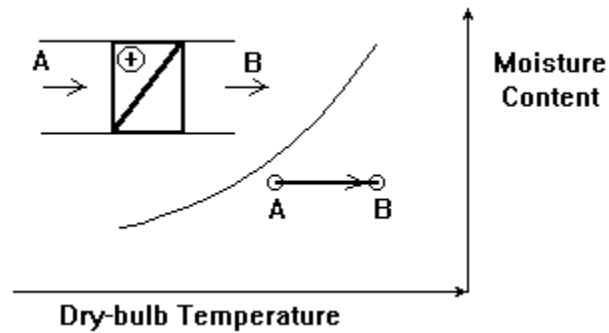
Sensible Heating Process is a process during which the dry-bulb temperature of air is increased. The process occurs at constant moisture content. The air passes over a hot and dry surface which might be pipe coil using steam or hot water, electrical resistance or an air-to-air heat recovery unit. The load on the heater is:

$$Q = m \cdot (h_B - h_A)$$

Sensible Cooling Process at Constant Moisture Content
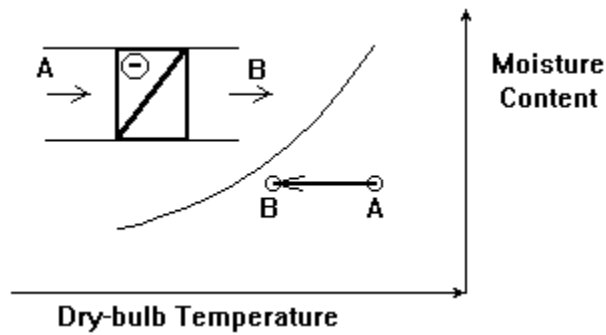
Sensible cooling process at constant moisture content is a process during which the dry-bulb temperature of air is decreased. The air passes over a cooling coil which uses chilled water or direct expansion of some refrigerant into the pipe coil. The load on the cooling coil is:

$$Q = m \cdot (h_A - h_B)$$

Sensible Cooling with Dehumidification
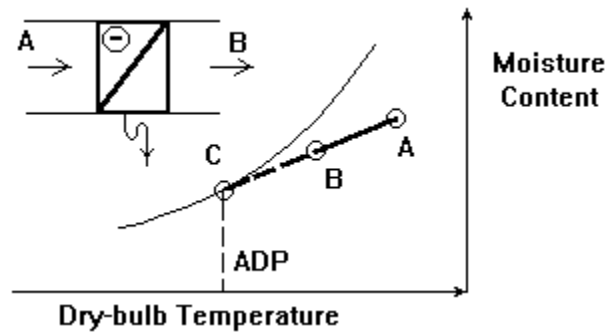
In this process the dry-bulb temperature and the moisture content of air are decreased. The heat in the condensed water is normally very small relative to the total cooling load therefore the load on the cooling coil can be approximated as:

$$Q = m \cdot (h_A - h_B)$$

Dehumidification can only occur, if the coil surface temperature is blew the dew-point temperature of the entering air stream.

Apparatus dew-point temperature (ADP) is defined as the average coil temperature at air condition C. Where C is the intersection of the saturation line and the straight line through conditions A and B on psychrometric chart.

Contact Factor of a Coil
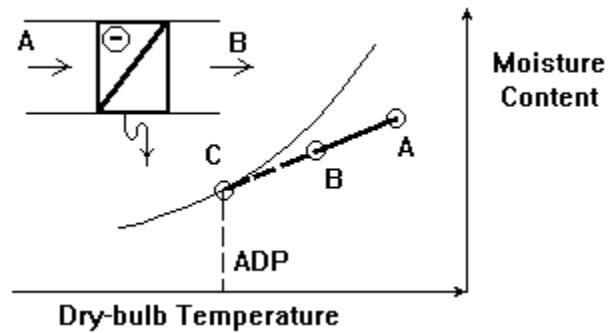
The contact factor of a coil is defined as the efficiency for dehumidification. A 100% efficient coil will bring the moisture content of air to the saturation moisture content at the apparatus dew-point, gC. The contact factor of the coil can be defined by moisture content differences:

$$\beta = \frac{g_A - g_B}{g_A - g_C}$$

or by specific enthalpy differences:

$$\beta = \frac{h_A - h_B}{h_A - h_C}$$

The contact factor of a coil depends on the design of heat transfer surfaces, air velocity and drainage of condensate.

Humidifiers

   Humidifiers are used in air conditioning systems to increase the humidity of the air. There are several types of humidifiers:

- Adiabatic with recirculation of spray water
- Adiabatic without recirculation of spray water
- spray water with recirculation and with heating or cooling

 Steam humidifiers are also used in air conditioning system. The two basic types are:

- Direct steam injection
- Pan steam humidifier

# Adiabatic Humidifier with Recirculation of Spray Water
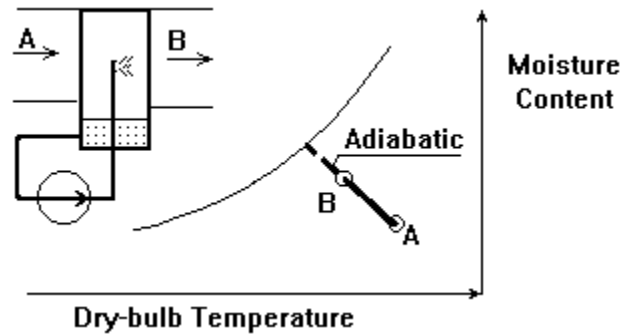
In this system, the water is recirculated through the pipes to nozzles. That part of water which is not evaporated into the air stream, returns to the tank for recirculation. This process can be assumed as an adiabatic process with good approximation. The required make-up water supplied to the tank is:

$$m_W = m_a \cdot (g_B - g_A)$$

The humidifying efficiency is usually expressed by the contact factor.

Contact Factor of nozzles
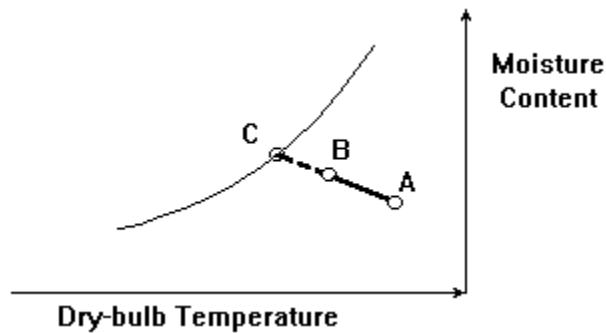
The contact factor of nozzles is defined as the efficiency for humidification. A 100% efficient nozzle system will bring the moisture content of air to the saturation moisture content at the apparatus dew-point, gC. The contact factor of the nozzle system can be defined by moisture content differences:
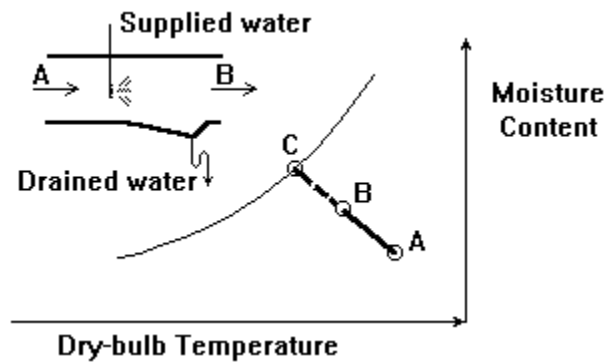
$$\beta = \frac{g_A - g_B}{g_A - g_C}$$

or by specific enthalpy differences:

$$\beta = \frac{h_A - h_B}{h_A - h_C}$$

The contact factor of a nozzle system depends on the design of nozzles, nozzle arrangement and water pressure.

# Adiabatic Humidifiers without Recirculation of Spray Water

 In this system water is injected through nozzles into the air stream. The supplied water is for humidification purposes and water which is not evaporated will be drained from the bottom of the unit. The efficiency of the humidification process can be expressed by the   contact factor of the nozzles.

Spray Water with Recirculation and Heating or Cooling

Spray-type humidifiers may use heating or cooling equipment to achieve the desired air condition. The heat supplied to or gained from the system is:

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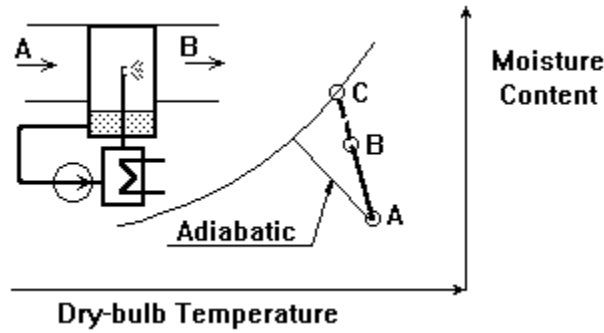
When the heat is supplied to the system, the ADP (Apparatus Dew-Point Temperature) will be higher than the adiabatic process. The process line depends on the contact factor of humidification. In some cases the increase in moisture content is accompanied by sensible cooling and in some others by sensible heating.
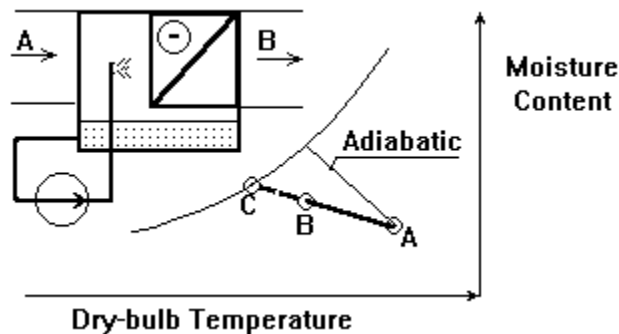
When the heat is gained from the system, the ADP (Apparatus Dew-Point Temperature) will be lower than the adiabatic process. The process line depends on the contact factor of humidification. In some cases the sensible cooling   is accompanied by humidification and in some others by dehumidification.

Direct Steam Injection
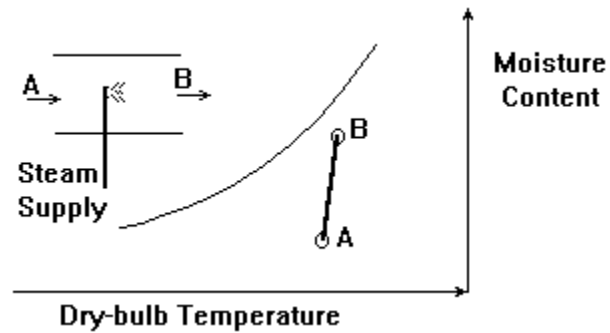
Steam can be directly injected to air stream for air conditioning purposes. In this process, all the latent heat necessary for evaporation of water is added outside the air stream. The supply of water vapor increases the enthalpy of the air. The temperature increase in this process is negligible and it can be assumed as an isothermal process with good approximation.

Pan Steam Humidifier
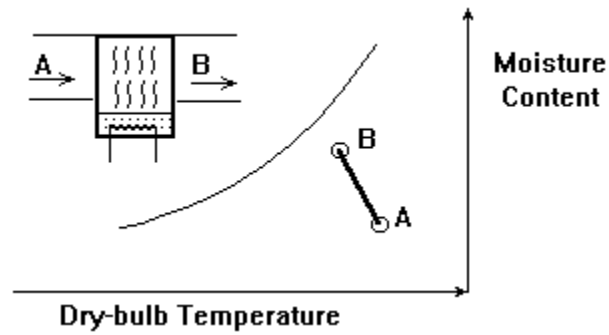
 A Pan Steam Humidifier uses a heating element inside a water tank. The tank is mounted at the bottom of the air duct. The air flowing over the water surface will cause some evaporative cooling which results in drop of air dry-bulb temperature.

Process Line for Air Conditioned Space

   The room process line, known also as room ratio line (RRL) is defined by the condition of supplied air and the desired air condition in the space. The RRL is dependent on both sensible and latent heat load.
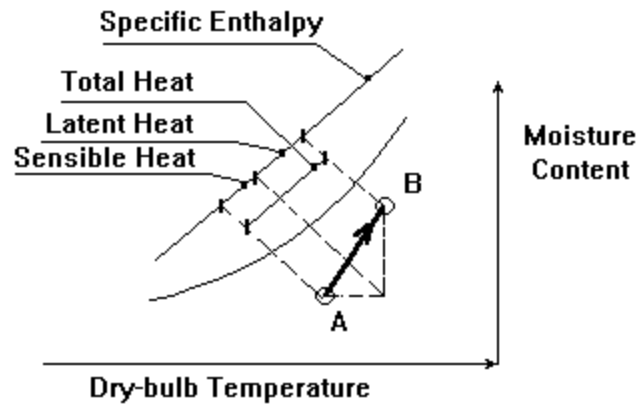
The   sensible heat load is defined as:

$$Q_s = m_a \cdot C_p \cdot (T_B - T_A)$$

ma= mass flow rate of dry air
Cp= Humid Specific Heat
The   latent heat load is defined as:

$$Q_l = m_a \cdot h_{fg} \cdot (g_B - g_A)$$

Turbine

Turbines are devices that convert mechanical energy stored in a fluid into rotational mechanical energy.   These machines are widely used for the generation of electricity. The most important types of turbines are: steam turbines, gas turbines,   water turbines and wind turbines.

Steam Turbine

Steam turbines are devices that convert mechanical energy stored in steam into rotational mechanical energy.   These machines are widely used for the generation of electricity in a number of different cycles, such as:

- Rankine cycle
- Reheat cycle
- Regenerative cycle
- Combined cycle

The steam turbine may consists of several stages. Each stage can be described by analyzing the expansion of steam from a higher pressure to a lower pressure. The steam may be <u>wet</u>, <u>dry saturated</u> or <u>superheated</u>.

Consider the steam turbine shown in the cycle above. The output <u>power</u> of the turbine at <u>steady flow</u> condition is:

P=m (h_1-h_2)

where **m** is the <u>mass flow</u> of the steam through the turbine and h_1 and h_2 are <u>specific enthalpy</u> of the steam at inlet respective outlet of the turbine.

T-s diagram for a Rankine cycle.

The efficiency of the steam turbines are often described by the <u>isentropic efficiency</u> for expansion process. The presence of water droplets in the steam will reduce the efficiency of the turbine and cause physical erosion of the blades. Therefore the <u>dryness fraction</u> of the steam at the outlet of the turbine should not be less than 0.9.

Gas Turbine

●

Gas turbines use hot gases generated directly from the combustion of fossil fuels. The hot gas expands through the blades on the turbine rotor causing them to move. The gas turbine process is:

● 3-4 irreversible but approximately adiabatic expansion of combustion gases

●

The work output of the turbine is:

$$W_{out} = m(h_3 - h_4)$$

where
m=mass flow of hot gases
h3=enthalpy of hot gases at inlet
h4=enthalpy of exhaust gases

The isentropic efficiency of the turbine is:

$$\eta = \frac{h_3 - h_4}{h_3 - h_{4s}}$$