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Version 1.00

Applied Thermodynamics

Applied thermodynamics is the science of the relationship between heat, work, and systems that analyze energy processes. The energy processes that convert heat energy from available sources such as chemical fuels 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:

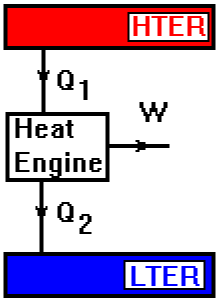
- Laws of thermodynamics
    - The zeroth law of thermodynamics
    - The first law of thermodynamics
    - The second law of thermodynamics
- Heat engines
- Heat transfer
- Adiabatic mixing
- Power

Turbines
Heat exchangers
Energy
Working fluid

Heat Engine

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

Forward Heat Engine



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

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

$\mathbf{Q}_1 - \mathbf{Q}_2 - \mathbf{W} = 0$

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

$$\eta < \eta_c < 1.0$$

It can be shown that:

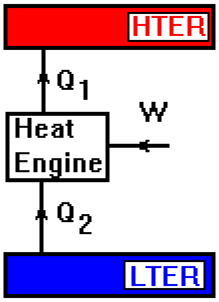
$$\mathbf{Q}_1 > \mathbf{W}$$

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

$$\mathbf{Q}_2 > 0$$

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 work input such as heat pump and refrigerator. Applying the first law of thermodynamics to the cycle gives:

$$-\mathbf{Q}_1+\mathbf{Q}_2+\mathbf{W}=0$$

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

$$\mathbf{W}>0$$

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

Energy

Energy is an inherent property of a system. 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 work to heat.

The SI 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:

- The first law of thermodynamics

Pressure

The pressure of a system is defined as the force exerted by the system on unit area 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 SI 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:

$\mathbf{c}+273.15$

the Fahrenheit scale will show:

$1.8\,\mathbf{c}+32$

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

$\mathbf{f}+459.69$

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:

- length (meter, m)
- mass (kilogram, kg)
- time (second, s)
- electric current (ampere, A)
- thermodynamic temperature (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 energy that is transferred from one body (system) to another body (system or surroundings). Heat transfer can occur when there is a temperature 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).

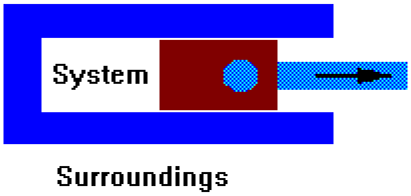
The SI unit of heat is joule (J). Other units are:

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

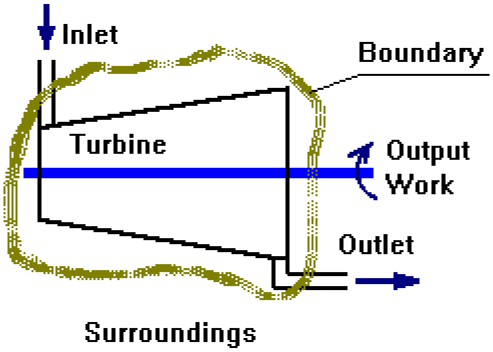
A system is a collection of matter within defined boundaries. The boundaries may be flexible. There are two types of system: closed system and open system.

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 system is the mass of the unit volume of the system. Note that the density is reciprocal of specific volume i.e.

ρ=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 SI unit od density is kg/m^3 (kilogram per cubic meter). Other units are:

1 t/m^3= 1000 kg/m
1 lbm/ft^3= 16.018 kg/m
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
1 g/cm^3= 1000 kg/m
1 U.K.ton/yd^3= 1328.94 kg/m
1 U.S.ton/yd^3= 1186.5 kg/m

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 m^3/kg (cubic meter per kilogram). Other units are:

1 m^3/t= 1 m/ton= 0.001 m/kg

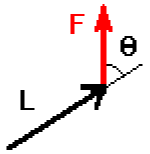
1 L/kg=1 lit/kg= 1 dm^3/kg= 0.001 m3/kg

1 cm^3/g= 0.001 m/kg

1 in^3/lbm= 3.6175E-5 m/kg

1 ft^3/lbm= 0.0625 m/kg

Work



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

W=**F.L**=**F L** cos(θ)

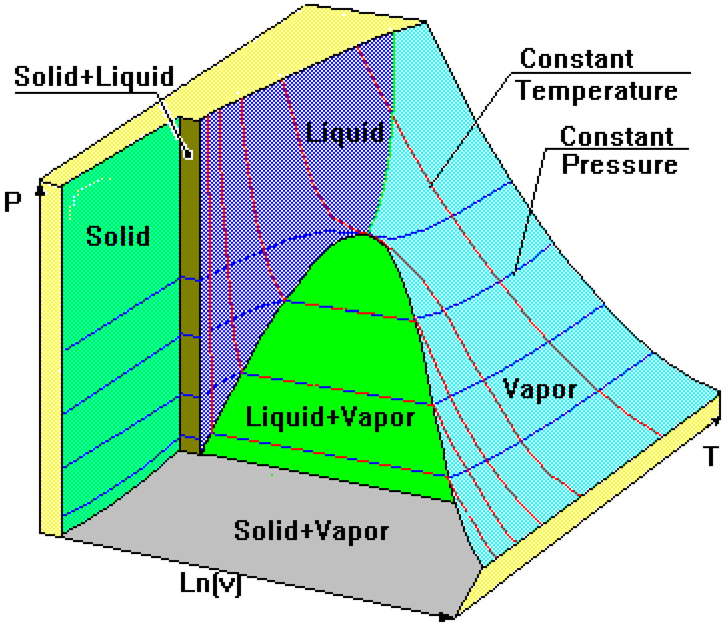
This is equivalent to the product of the force and the distance moved in the direction of the force. For instance, when a boundary of a system moves in the direction of the force acting on it, the surroundings do work on the system. If the direction of the movement is reversed, then the work is done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

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,

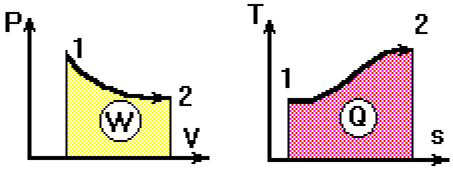
- temperature-entropy (T-s) diagram,
- enthalpy-entropy (h-s) diagram.

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:

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

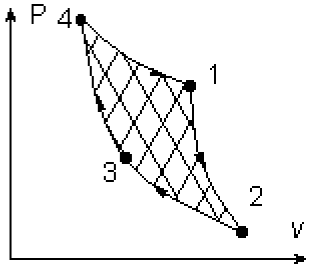
and the heat supplied to a system during a reversible process is:

$\mathbf{Q}=\int_1^2 \mathbf{T}\, d\mathbf{s}$= 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 working fluid 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 reversible 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.

$$\Delta \mathbf{U}=\mathbf{U}_2-\mathbf{U}_1=\mathbf{Q}+\mathbf{W}$$

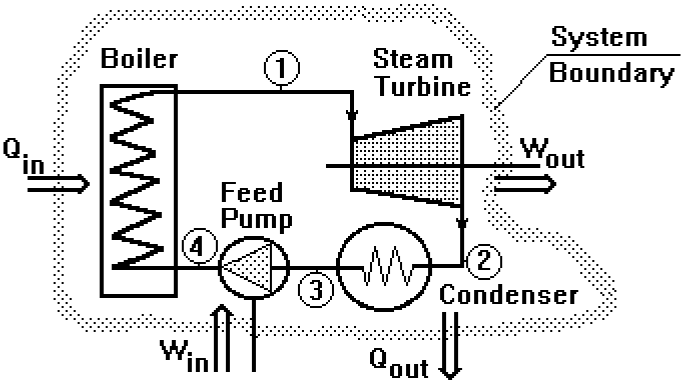
where $\mathbf{U}_1$ and $\mathbf{U}_2$ are intrinsic energy of the system at initial and final states, respectively. The special case of the equation applied to a steady flow system is known as steady-flow energy equation.
Applying this general principle to a thermodynamic cycle, when the system undergoes a complete cycle, i.e. $\mathbf{U}_1=\mathbf{U}_2$, results in:

$$\Sigma\mathbf{Q}+\Sigma\mathbf{W}=0$$

where:

$\Sigma\mathbf{Q}$= The algebraic sum of the heat supplied to (+) or rejected from (-) the system.
$\Sigma\mathbf{W}$= 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:

$$\Sigma\mathbf{Q}=\mathbf{Q}_{in}-\mathbf{Q}_{out}$$
$$\Sigma\mathbf{W}=\mathbf{W}_{in}-\mathbf{W}_{out}$$
$$\mathbf{Q}_{in}+\mathbf{W}_{in}-\mathbf{Q}_{out}-\mathbf{W}_{out}=0$$

where,

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

$$\mathbf{U}_{\text{total}}=\mathbf{u}+\mathbf{C}^2/2+\mathbf{Z}\,\mathbf{g}$$

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.

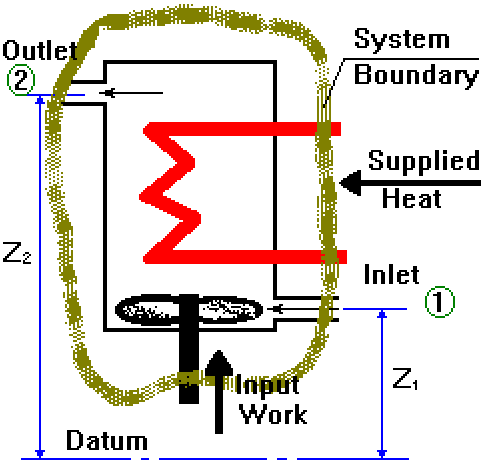
Steady Flow

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 first law of thermodynamics to a steady-flow system, defined by control volume shown above, gives:

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

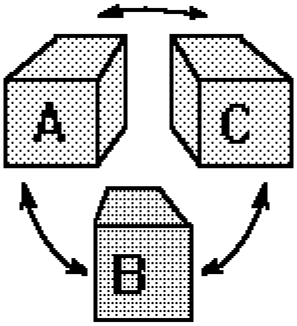
known as steady-flow energy equation. Where,

$d\mathbf{Q}/d\mathbf{t}$= Supplied heat to the system per unit time,
$d\mathbf{W}/d\mathbf{t}$= Input work to the system per unit time,
m= Mass flow rate,
$\Delta\ \mathbf{h}=\mathbf{h}_2-\mathbf{h}_1$,
h= Specific enthalpy,
$\Delta\ \mathbf{C}^2/2$= Difference in kinetic energy between outlet and inlet,
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:

$$\mathbf{P}\ \mathbf{V} = \text{constant}$$

Boyle's law is a special case of the perfect gas equation.

Charles's Law

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

$$\mathbf{V}=\text{constant }(\theta+273.15)$$

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

$$\mathbf{V}=\text{constant }\mathbf{T}$$

where **T** is the absolute temperature. Charles's law is a special case of the perfect gas 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".

$$\mathbf{V} = \text{constant } \mathbf{n}$$

where **n** is the number of moles 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 perfect gas at STP is:

$$\mathbf{V_m} = \mathbf{V/n} = 22.414 \text{ L/mol}$$

the same value under SATP will be:

$$\mathbf{V_m} = \mathbf{V/n} = 24.789 \text{ L/mol}$$

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:

$$PV = nRT$$

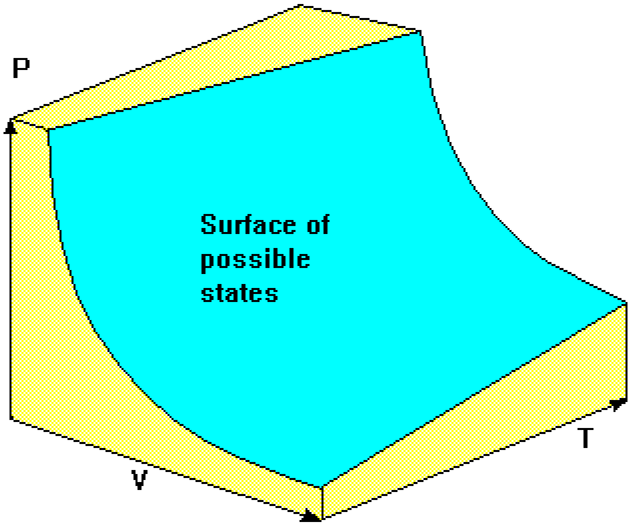
known as perfect gas equation. Where,

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:

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

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 Joule's law and we obtain a set of thermodynamically consistent equations. The above equation can be used directly for calculation of specific heat capacity of the gas:

$$C_p=(\partial h/t)_p=R\ (a_1+a_2\ T+a_3\ T+a_4\ T+a_5\ T)$$

By using the relationship:

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

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

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

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

Related Topics:

- Dalton's law
- Gas turbine
- Compressor

Enthalpy

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

$$\mathbf{H}=\mathbf{m}\ \mathbf{h}$$

Specific Enthalpy

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

$$\mathbf{h}=\mathbf{u}+\mathbf{P}\ \mathbf{v}$$

where,

u= Specific internal energy
P= Pressure
v= Specific volume

Specific enthalpy has the same dimension as [energy/mass]. The SI 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 system, is the energy 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 first law of thermodynamics.

Specific Internal Energy

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

Entropy

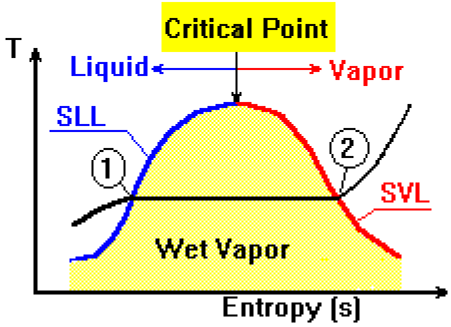
Entropy of system, is a measure of the avaialability of its energy. A system with high entropy can do less useful work. This concept was formally used to define the second law of thermodynamics.

Specific Entropy

Specific entropy of a system is the entropy of the unit mass of the system and has the dimension of energy/mass/temperature. The SI 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.

$$\mathbf{T}_2=\mathbf{T}_1=\mathbf{f}(\mathbf{P})$$

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.

$\mathbf{h}=\mathbf{f}_1(\mathbf{P},\mathbf{T})=$Specific enthalpy
$\mathbf{v}=\mathbf{f}_2(\mathbf{P},\mathbf{T})=$Specific volume
$\mathbf{s}=\mathbf{f}_3(\mathbf{p},\mathbf{T})=$Specific entropy

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 heat required to raise unit mass of substance by one degree of temperature. This can be stated by the following Eq.:

$$\Delta \mathbf{Q} = \mathbf{m}\ \mathbf{c}\ \Delta \mathbf{T}$$

where,
$\Delta \mathbf{Q}$= Heat supplied to substance,
m= Mass of the substance,
c= Specific heat capacity,
$\Delta \mathbf{T}$= Temperature rise.

There are two definitions for vapors and gases:

- $\mathbf{C}_p$= Specific heat capacity at constant pressure, i.e.

$$\mathbf{C}_p = (\partial \mathbf{h}/\mathbf{T})_p$$

- $\mathbf{C}_v$= Specific heat capacity at constant volume, i.e.

$$\mathbf{C}_v = (\partial \mathbf{u}/\mathbf{T})_v$$

It can be shown that for a perfect gas:

$$\mathbf{C}_p - \mathbf{C}_v = R$$

where **R** is the gas constant. The ratio, $\mathbf{C}_p/\mathbf{C}_v$, has been given symbol γ,

$$\gamma = \mathbf{C}_p/\mathbf{C}_v$$

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 $\mathbf{H}_2$, $\mathbf{N}_2$, **CO** and $\mathbf{O}_2$) have a γ ratio about 1.4 and triatomics (such as $\mathbf{SO}_2$ and $\mathbf{CO}_2$) 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 pressure of working fluid remains constant.

Isentropic Process

An isentroic process is one during which the entropy of working fluid remains constant.

Joule's Law

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

$$\mathbf{u}=\mathbf{f}(\mathbf{t})$$

Polytropic Process

Many processes can be approximated by the law:

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

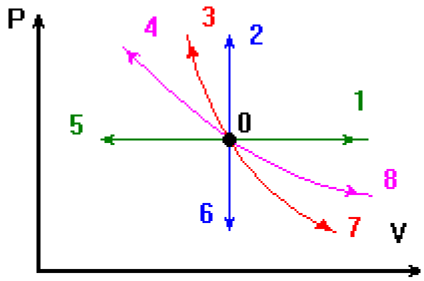
where,

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:



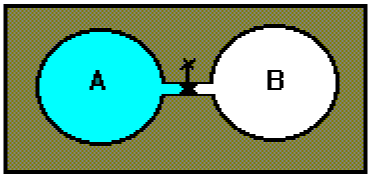
The initial state of working fluid is shown by point **0** on the P-V diagram. The polytropic state changes are:

- 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 heat is supplied to or rejected from the working fluid. A reversible isentropic 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.

$$\mathbf{Q}+\mathbf{W}=\mathbf{U}_2-\mathbf{U}_1$$

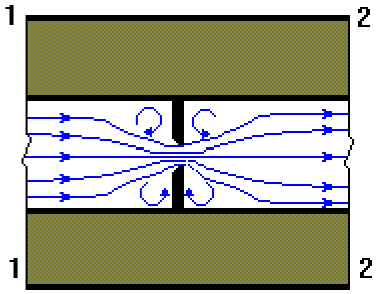
where indices 1 and 2 represent initial and final states.

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:

$$\mathbf{U}_2=\mathbf{U}_1$$

The free expansion process is adiabatic but irreversible. If the working fluid is a perfect gas, then $\mathbf{U}_2=\mathbf{U}_1$ is equivalent to $\mathbf{T}_2=\mathbf{T}_1$.

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:

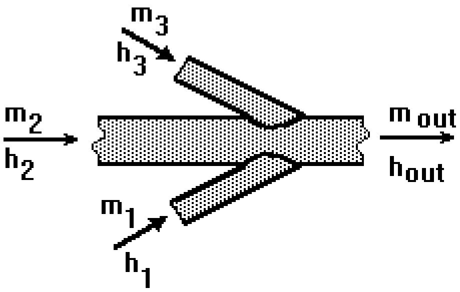
$$dQ/dt + dW/dt = m\,[\Delta h + \Delta C^2/2 + \Delta Z g]$$

$dQ/dt = 0$ because the system is thermally insulated. dW/dt 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, ΔZ, is negligible, then we can write:

$$\Delta h = h_2 - h_1 = 0$$

where h_1 and 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 adiabatically. Mixing process is highly irreversible because of eddying of fluid streams.
Consider the steady flow system shown in figure above. If the changes of kinetic energy are negligible, then the law of conservation of energy gives:

$$\mathbf{m}_1\ \mathbf{h}_1+\mathbf{m}_2\ \mathbf{h}_2+\mathbf{m}_3\ \mathbf{h}_3=\mathbf{m}_{out}\ \mathbf{h}_{out}$$

or in general,

$$\Sigma(\mathbf{m}_{in}\ \mathbf{h}_{in})=\mathbf{m}_{out}\ \mathbf{h}_{out}$$

and the law of conservation of mass gives:

$$\mathbf{m}_1+\mathbf{m}_2+\mathbf{m}_3=\mathbf{m}_{out}$$

or in general,

$$\Sigma\mathbf{m}_{in}=\mathbf{m}_{out}$$

where **m** and **h** represent mass flow and specific enthalpy of the fluids.

The Second Law of Thermodynamics

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

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

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

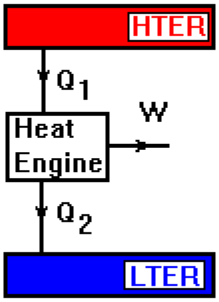
$$\mathbf{W} < \mathbf{W}_{max} = \mathbf{Q}\ \eta_c$$

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

Related topic:

- Exergy

Thermal Efficiency



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

The thermal efficiency, η, of a cycle (or more precisely a forward heat engine) is defined as the ratio of net work output, **W**, to the heat supplied at high temperature, $\mathbf{Q}_1$, i.e.

$$\eta = \mathbf{W}/\mathbf{Q}_1$$

Related Topics:

- Coefficient of Performance
- Carnot Cycle

Exergy or Availability

Exergy of a system is defined as the theoretical maximum amount of work 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 pressure and temperature P_0 and T_0. The specific exergy of a non-flow system is:

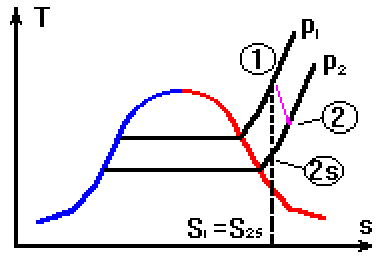
$$u+P_0\,v-T_0\,s$$

and for a steady flow system:

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

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

Isentropic Efficiency



Expansion from pressure $\mathbf{P}_1$ to $\mathbf{P}_2$.

The isentropic efficiency for an expansion process is defined as:

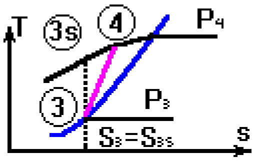
$\eta_{i,e}$=(actual work)/(isentropic work)

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

actual work=$\mathbf{m}$ ($\mathbf{h}_1$-$\mathbf{h}_2$)

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

$\eta_{i,e}=(\mathbf{h}_1-\mathbf{h}_2)/(\mathbf{h}_1-\mathbf{h}_{2s})$



Compression from pressure $\mathbf{P}_3$ to $\mathbf{P}_4$.

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=$\mathbf{m}$ ($\mathbf{h}_4$-$\mathbf{h}_3$)

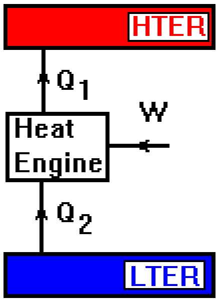
isentropic work=$\mathbf{m}$ ($\mathbf{h}_{3s}$-$\mathbf{h}_3$)

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

Related Topics:

- Pump
- Steam Turbine

Coefficient of Performance



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

The effectiveness of a reversed heat engine is defined in terms of a coefficient of performance (COP). The COP for a refrigerator is defined as:

$$\mathbf{COP} = \mathbf{Q}_2 / \mathbf{W}$$

and for a heat pump as:

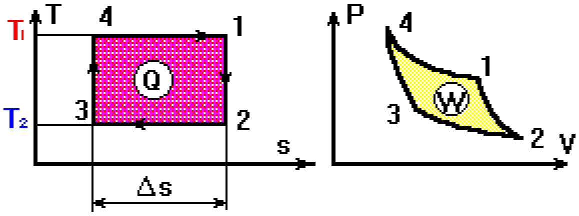
$$\mathbf{COP} = \mathbf{Q}_1 / \mathbf{W}$$

Related Topic:

- Thermal Efficiency

Carnot Cycle

By using the second law of thermodynamics it is possible to show that no heat engine can be more efficient than a reversible 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: Isentropic expansion
- 2 to 3: Isothermal heat rejection
- 3 to 4: Isentropic compression
- 4 to 1: Isothermal heat supply

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

$$\mathbf{Q}_1=\mathbf{T}_1\ \Delta\mathbf{s}$$

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

$$\mathbf{Q}_2=\mathbf{T}_2\ \Delta\mathbf{s}$$

By applying the first law of thermodynamics to the cycle, we obtain:

$$\mathbf{Q}_1-\mathbf{Q}_2-\mathbf{W}=0$$

And the thermal efficiency of the cycle will be:

$$\eta=\mathbf{W}/\mathbf{Q}_1=1-\mathbf{T}_2/\mathbf{T}_1$$

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:

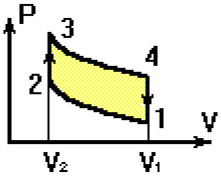
$$\mathbf{W}_g=\mathbf{W}_{4-1}+\mathbf{W}_{1-2}$$

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

$\mathbf{W/W}_g$

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 air standard cycle which consists of four processes:

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

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

$$\eta = 1-(\mathbf{T}_4-\mathbf{T}_1)/(\mathbf{T}_3-\mathbf{T}_2)$$

It can be shown that:

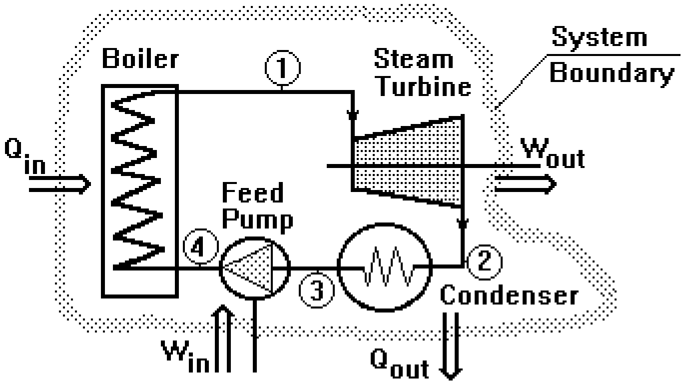
$$\eta = 1-\mathbf{r}^{\mathbf{n}}$$

where,

$\mathbf{r} = \mathbf{V}_1/\mathbf{V}_2$ = Compression ratio

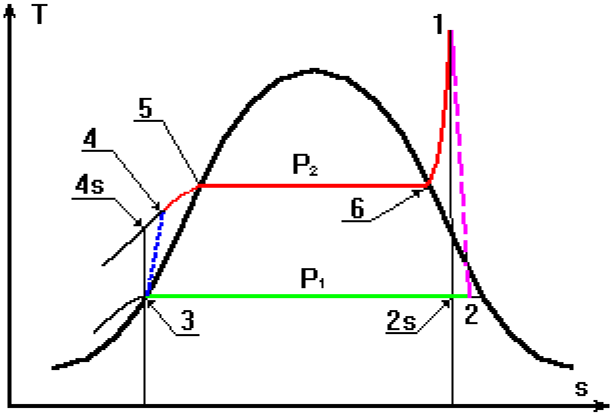
$\mathbf{n} = 1-\gamma$ = a constant depending on specific heat capacity

Rankine Cycle



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

- 1 to 2: Isentropic expansion (Steam turbine)
- 2 to 3: Isobaric heat rejection (Condenser)
- 3 to 4: Isentropic compression (Pump)
- 4 to 1: Isobaric heat supply (Boiler)



T-s diagram for a Rankine cycle.

Work output of the cycle (Steam turbine), $\mathbf{W}_1$ and work input to the cycle (Pump), $\mathbf{W}_2$ are:

$$\mathbf{W}_1=\mathbf{m}\ (\mathbf{h}_1-\mathbf{h}_2)$$
$$\mathbf{W}_2=\mathbf{m}\ (\mathbf{h}_4-\mathbf{h}_3)$$

where **m** is the mass flow of the cycle. Heat supplied to the cycle (boiler), $\mathbf{Q}_1$ and heat rejected from the cycle (condenser), $\mathbf{Q}_2$ are:

$$\mathbf{Q}_1=\mathbf{m}\ (\mathbf{h}_1-\mathbf{h}_4)$$

$$Q_2 = m\,(h_2 - h_3)$$

The net work output of the cycle is:

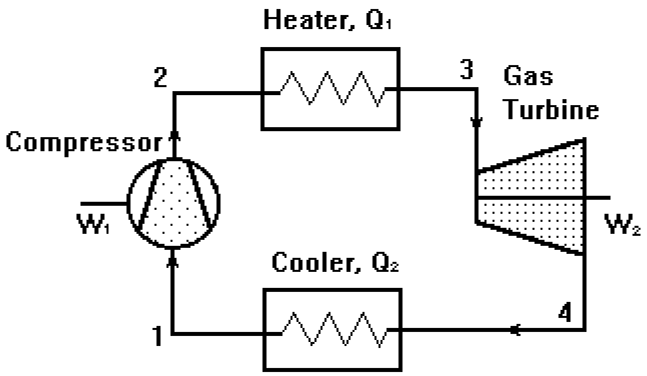
$$W = W_1 - W_2$$

The thermal efficiency of a Rankine cycle is:

$$\eta = W/Q_1$$

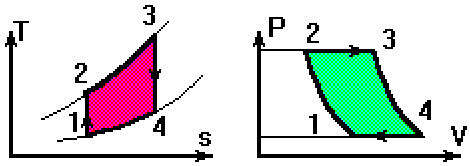
The efficiency of the Rankine cycle is not as high as Carnot cycle but the cycle has less practical difficulties and more economic.

Brayton or Joule Cycle



Brayton cycle is an ideal air standard cycle 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: Isentropic compression
- 2 to 3: Isobaric heat supply
- 3 to 4: Isentropic expansion
- 4 to 1: Isobaric heat rejection



T-s and P-V diagrams for Brayton cycle.

Work input to the cycle (compressor), $\mathbf{W}_1$ and work output of the cycle (gas turbine), $\mathbf{W}_2$ are:

$$\mathbf{W}_1=\mathbf{m}\ (\mathbf{h}_2-\mathbf{h}_1)$$
$$\mathbf{W}_2=\mathbf{m}\ (\mathbf{h}_3-\mathbf{h}_4)$$

wher **m** is the mass flow of the cycle. Heat supplied to the cycle (heater), $\mathbf{Q}_1$ and heat rejected from the cycle (cooler), $\mathbf{Q}_2$ are:

$$\mathbf{Q}_1=\mathbf{m}\ (\mathbf{h}_3-\mathbf{h}_2)$$
$$\mathbf{Q}_2=\mathbf{m}\ (\mathbf{h}_4-\mathbf{h}_1)$$

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

$$\eta = 1-(\mathbf{T}_4-\mathbf{T}_1)/(\mathbf{T}_3-\mathbf{T}_2)$$

It can be shown that:

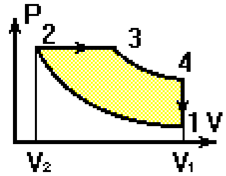
$$\eta = 1-\mathbf{r}^{\mathbf{n}}$$

where,
$\mathbf{r} = \mathbf{P}_2/\mathbf{P}_1$ = pressure ratio
$\mathbf{n} = -1+1/\gamma$ = a constant depending on γ

Air Standard Cycle

Air standard cycle is defined as a reversible heat engine 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 internal combustion cycles.

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:

$$\mathbf{r}=\mathbf{V}_1/\mathbf{V}_2$$

and cut-off ratio, β, as:

$$\mathbf{b}=\mathbf{V}_3/\mathbf{V}_2$$

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

$$\eta= 1-[\mathbf{r}\ (\beta^{\mathbf{n}}-1)]/[(\beta-1)\ \gamma\ \mathbf{r}]$$

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

Power

Power is defined as work (or energy transfer) per unit time:

P=d**W**/d**t**

The SI 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 distance/time. The SI 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 SI 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 force multiplied by length. The SI 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 SI 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 SI unit of volume is cubic meter (m^3). Other units are:

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

Mass Flow

Mass flow rate is the amount of mass which enters or leaves a system per unit time. The SI 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 working fluid. 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= Pressure
T= Temperature
v= Specific volume
h= Specific enthalpy
s= Specific entropy

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

- Open cycle gas turbine unit
- Otto cycle
- Diesel cycle

Heat Exchanger

Heat exchangers are devices built for efficient heat transfer 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 first law of thermodynamics to a heat exchanger working at steady-state condition, we obtain:

$$\Sigma \mathbf{m}_i \, \Delta \mathbf{h}_i = 0$$

where,
$\mathbf{m}_i$= mass flow of the i-th fluid
$\Delta \mathbf{h}_i$= change of specific enthalpy 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:

- Parallel-flow
- Counter-flow
- Cross-flow

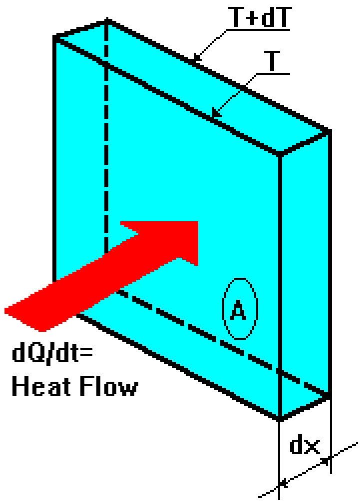
Heat Transfer

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



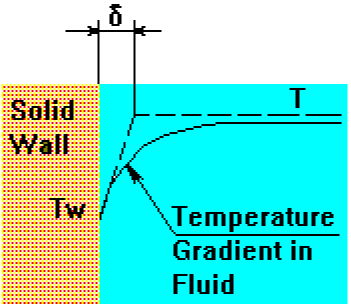
Heat transfer through a solid

Fourier's law is an empirical law based on observation. It states that the rate of heat flow, $d\mathbf{Q}/d\mathbf{t}$, 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, $d\mathbf{T}/d\mathbf{x}$ i.e.

$$d\mathbf{Q}/d\mathbf{t} = -\lambda\ \mathbf{A}\ d\mathbf{T}/d\mathbf{x}$$

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 heat is transferred by conduction. Whenever there is an appreciable movement of the fluid, conduction heat transfer in fluid may be neglected compared with convection heat transfer.
The heat transfer from the solid surface to the fluid can be described by Newton's law of cooling. It states that the heat transfer, $d\mathbf{Q}/d\mathbf{t}$, from a solid surface of area $\mathbf{A}$, at a temperature $\mathbf{T}_w$, to a fluid of temperature $\mathbf{T}$, is:

$$d\mathbf{Q}/d\mathbf{t}=\alpha\ \mathbf{A}\ (\mathbf{T}_w-\mathbf{T})$$

where α is the heat transfer coefficient.

Related topics:

- Forced convection
- Free convection

Conduction

Conduction heat transfer occurs only when there is physical contact between bodies (systems) at different temperatures. Heat transfer 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 convection.

Related topics:

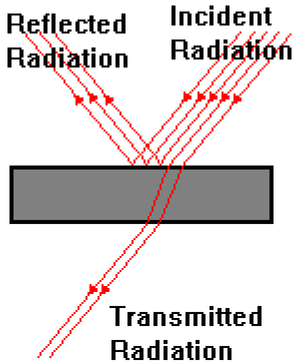
- Fourier's law of conduction
- Newton's law of cooling

Convection

Convection is the heat transfer within a fluid, involving gross motion of the fluid itself. Fluid motion may be caused by differences in density as in free convection. Density differences are a direct result of temperature differences between the fluid and the solid wall surface. In forced convection, 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 (symbolτ), 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 heat flow per unit area per unit time when the temperature decreases by one degree in unit distance. The SI unit of thermal conductivity is W/m,K. Other units are:

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

Related topic:

- Fourier's law of conduction

Heat Transfer Coefficient

The heat transfer coefficient, α, defined in Newton's law of cooling, depends on the properties of the fluid and also on fluid velocity.   It is usually necessary to evalute it experimentally.

The SI unit of heat transfer coefficient is W/m ^{2},K. Other units are:

1 kW/m ^{2},K= 1000 W/m,K

Forced Convection

Forced convection studies the heat transfer 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.:

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

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:

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

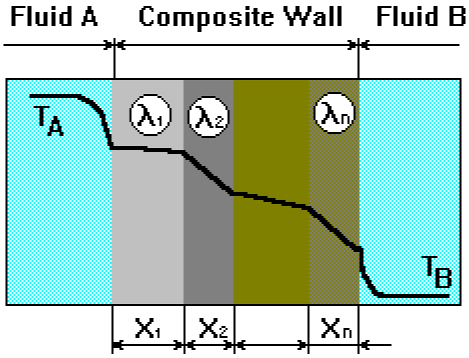
Free Convection

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. forced convection.
A dimensional analysis of the heat transfer by free convection results in:

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

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, $\mathbf{x}_1$, $\mathbf{x}_2$,..., $\mathbf{x}_n$. The thermal conductivity of layers are, λ_1, λ_2,..., λ_n. The fluid on one side of the wall is at temperature $\mathbf{T}_A$, 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 $\mathbf{T}_B$ 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:

$$d\mathbf{Q}/d\mathbf{t}=\mathbf{U}\ \mathbf{A}\ (\mathbf{T}_A-\mathbf{T}_B)$$

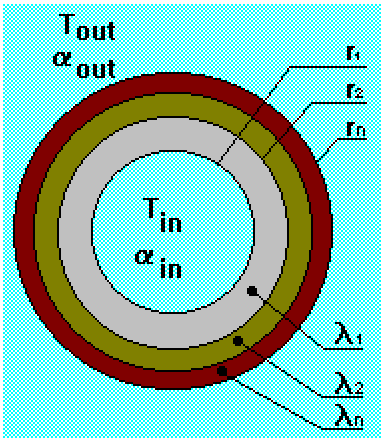
where,

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

$d\mathbf{Q}/d\mathbf{t}$= 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. $\mathbf{r}_1$, $\mathbf{r}_2$,..., $\mathbf{r}_n$. The thermal conductivity of layers are, λ_1, λ_2,..., λ_n. The fluid within the pipe is at temperature $\mathbf{T}_{in}$, 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 $\mathbf{T}_{out}$ 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,

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

d**Q**/d**t**= The transferred heat per unit time
L= Length of the pipe
A= 2 π **L** $\mathbf{r}_1$

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

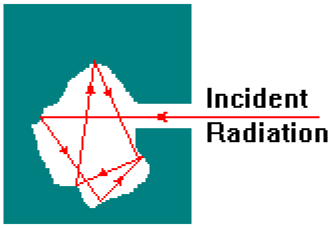
Black body by definition is an object that absorbs all radiation falling on it or in other words it has an absorptivity equal to unity.

$$\alpha=1$$

therefore there is no reflection from a black body. Applying the Kirchoff's law to a black body results in that it should have an emissivity 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. Thermal radiation 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 energy radiated from a body per unit area per unit time.

Related topic:

- Stefan-Boltzmann law

Kirchoff's Law

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

$$\alpha=\varepsilon$$

where α is the total absorptivity and ε, total emissivity over all wavelengths.

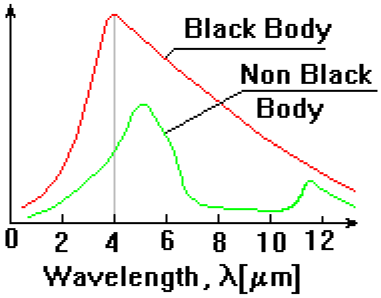
Emissivity

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



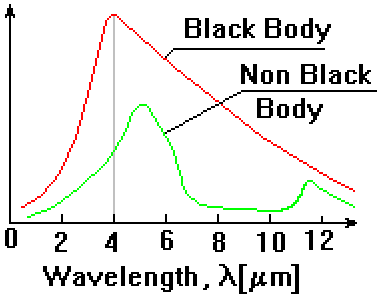
Distribution of emissive power.

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

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

where α_λ is the monochromatic absorptivity 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.

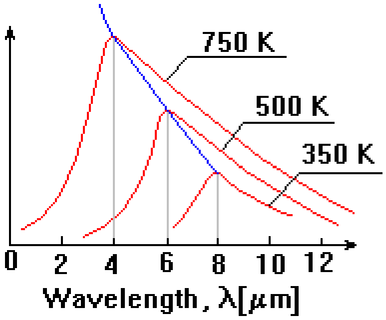
Grey Body

A grey body is defined as a body with constant emissivity 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:

- Thermal radiation
- Black body
- Kirchof's law

Wien's Law



Distribution of emissive power from a black body.

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

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

where λ_{max} is in μm and **T** is body temperature in K.

Stefan-Boltzmann Law

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

$$\mathbf{P} = \sigma \mathbf{T}^4$$

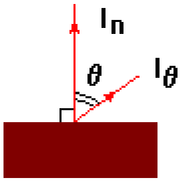
where σ is the Stefan-Boltzmann constant

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

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

$$\mathbf{P} = \varepsilon \, \sigma \, \mathbf{T}^4$$

Intensity of Radiation

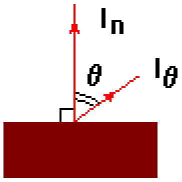


Emitted radiation from a surface.

The intensity of radiation is defined as the rate of emitted energy from unit surface area 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, $\mathbf{I}_n$. By using Lambert's cosine law and Stefan-Boltzmann law for a surface at absolute temperature, **T** and emissivity, ε, we obtain:

$$\mathbf{I}_n = \varepsilon\, \sigma\, \mathbf{T}^4/\pi$$

Lambert's Cosine Law



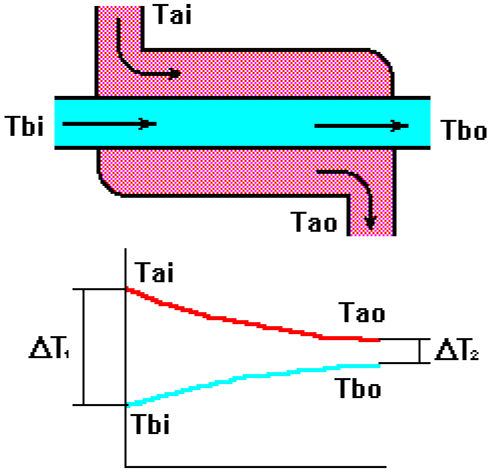
Emitted radiation from a surface.

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

$$\mathbf{I}_\theta = \mathbf{I}_n \cos\theta$$

where $\mathbf{I}_n$ is the intensity of radiation 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:

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

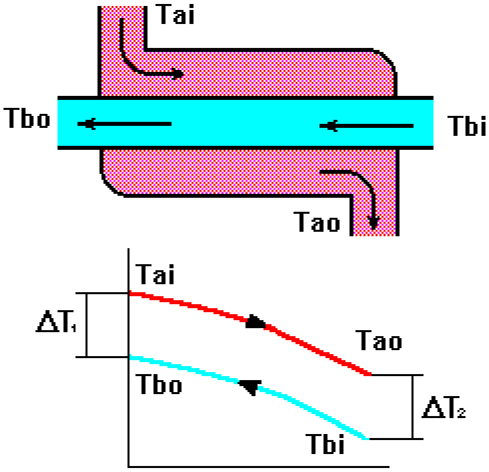
where,
$d\mathbf{Q}/d\mathbf{t}$= Rate of heat transfer between two fluids
U= Overall heat transfer coefficient
A= Area of the tube
$\Delta\mathbf{T}$= Logarithmic mean temperature difference defined by:

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

Related topics:

- Counter-flow heat exchanger
- Cross-flow heat exchanger

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:

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

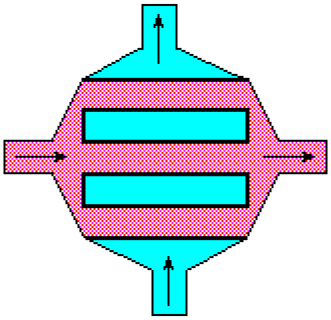
where,
$d\mathbf{Q}/d\mathbf{t}$= Rate of heat transfer between two fluids
U= Overall heat transfer coefficient
A= Area of the tube
$\Delta\mathbf{T}$= Logarithmic mean temperature difference defined by:

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

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, $\mathbf{A}_{\text{cross}}$ for this heat exchanger is usually calculated by using tables. It is between the required surface area for counter-flow, $\mathbf{A}_{\text{counter}}$ and parallel-flow, $\mathbf{A}_{\text{parallel}}$ i.e.

$$\mathbf{A}_{\text{counter}} < \mathbf{A}_{\text{cross}} < \mathbf{A}_{\text{parallel}}$$

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 system working under steady state 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.

Turbine

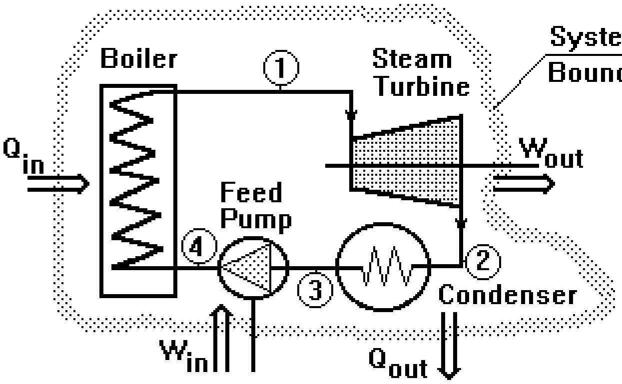
Turbines are devices that convert mechanical energy stored in a fluid into rotational mechanical energy. These machines are widely used for the generation of electricity. The most important types of turbines are: steam turbines, gas turbines, water turbines and wind turbines.

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

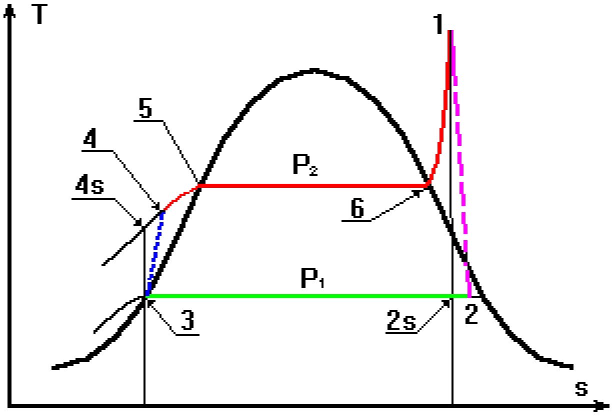
The steam turbine may consists of several stages. Each stage can be described by analyzing the expansion of steam from a higher pressure to a lower pressure. The steam may be wet, dry saturated or superheated.



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

$$\mathbf{P}=\mathbf{m}\ (\mathbf{h}_1\text{-}\mathbf{h}_2)$$

where **m** is the mass flow of the steam through the turbine and $\mathbf{h}_1$ and $\mathbf{h}_2$ are specific enthalpy 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 isentropic efficiency 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 dryness fraction 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.