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Engine Thermodynamics

Thermodynamics – study of heat related to matter in motion.

Engineering thermodynamics mainly concerned with work producing or utilising machines such as

engines,

turbines and

compressors

together with the working substances used in the machines.

Working substance – fluids: capable of deformation, energy transfer, common: air and steam

Pressure

$$P = \frac{F}{A}$$

Force per unit area. Unit: Pascal (Pa) N/m^2

 $1 \ bar = 10^5 Pa$

1 standard atmosphere = 1.01325 *bar*

1 bar = 14.504 psi (pound force / square inch, 1N = 0.2248 pound force)

1 *psi*= 6894.76 *Pa*

Psia vs Psig

a- absolute g- gauge

psia = psig + 1 atmosphere pressure
e.g:



Phase

Nature of substance. Matter can exists in three phases: solid, liquid and gas

Cycle

If a substance undergoes a series of processes and return to its original state, then it is said to have been taken through a cycle.



Process

A substance is undergone a process if the state is changed by operation having been carried out on it

Constant temperature process Isothermal process

Constant pressure process Isobaric process

Constant volume process

Isometric process or isochoric process

Adiabatic Process

An adiabatic process is a process in which no heat is transferred. This is the case if the process happens so quickly that there is no time to transfer heat, or the system is very well insulated from its surroundings.

Polytropic process

A process which occurs with an interchange of both heat and work between the system and its surroundings. Nonadiabatic expansion or compression of a fluid is an example of a polytropic process.

Energy Capacity of doing work

Work

A force is moved through a distance

e.g. In a piston,

work done =
$$PA \times L = P \times AL = P(V_2 - V_1)$$

Unit of work: Nm = J (joule)

Power

Rate of doing work J/s = Watt



In general case, work

work done =
$$\int_{V_1}^{V_2} P \, dV$$



Polytropic Process

 $PV^n = C$ - constant – a law for the general case of expansion or compression

n- the index of expansion or compression, or an polytropic exponent.

E.g. air *n* =1.4

This is the general case of process for gas.

Work done in polytropic process

workdone

$$= \int_{V_1}^{V_2} P dV$$

= $C \int_{V_1}^{V_2} V^{-n} dV$
= $\frac{C}{-n+1} \left(V_2^{-n+1} - V_1^{-n+1} \right)$
= $\frac{P_1 V_1 - P_2 V_2}{n-1}$

Heat

Temperature t (Celsius) = T-273.15 (Kelvin)

Q – heat energy joules/kg

Specific heat capacity:

heat transfer per unit temperature:

$$c = \frac{dQ}{dt}$$

Unit: joules/kg K (joules per kg per K)

Calorific value: the heat liberated by burning unit mass or volume of a fuel.

e.g. petrol: 43MJ/kg

Enthalpy

H = U + P V

U–*internal energy*

P-pressurev-volume

Specific Enthalpy

h = U/m = u + P v



Principle of the thermodynamic engine



Thermal efficiency

$$\eta = \frac{Work \ done}{Heat \ received} = \frac{W}{Q}$$

Heat Engines

An engine in which transfers energy results from difference in temperature.

Mechanical Power

 $Power = \frac{Work \ done}{Time \ Taken}$ Unit: J/s = watt

Electrical Power

W = I V

Unit: J/s=Watt

The Conservation of Energy

For a system

Initial Energy + Energy Entering = Final Energy + Energy Leaving

Potential energy = *gZ*

Kinetic energy
$$= \frac{1}{2}mC^2$$



Laws of Thermodynamics

The zeroth Law

If body A and B are in thermal equilibrium, and A and C are in thermal equilibrium, then, B and C must in thermal equilibrium.

The first law

W=Q

Means if some work W is converted to heat Q or some heat Q is converted to work W, W=Q. It does not mean all work can convert to heat in a particular process.

The second law

Nature heat transfer will occur down a temperature gradient.

The third law

At the absolute zero of temperature the entropy of a perfect crystal of a substance is zero.

Boyle's law

For perfect gas

PV=C -constant *Temperature remains constant.*

or $P_1V_1 = P_2V_2$ - constant *T* (Isothermal process)

Charle's Law

 $\frac{V}{T}$ = constant - constant *P* (Isobaric process)

Gay-Lussac's law

 $\frac{P}{T}$ = constant -- constant V (Isometric process)

Combined gas law

$$\frac{PV}{T} = a \qquad (\text{constant})$$

or

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Let mR = a, where *m* is the mass,

R - specific gas constant (air: R=287 J/kgK)

$$\frac{PV}{T} = mR$$
 - characteristic equation of gas

Joule's law

Internal energy of gas is the function of temperature only and independent of changes in volume and pressure.

The specific heat capacity at constant volume

C_v

$$U_2 - U_1 = mc_v (T_2 - T_1)$$
 (change in internal energy)

The specific heat capacity at constant pressure c_p

$$U_{2} - U_{1} + P(V_{2} - V_{1}) = mc_{p}(T_{2} - T_{1})$$

Polytropic Process

 $PV^n = C$

From

 $P_1V_1^n = P_2V_2^n$

$$\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^n = \left(\frac{V_1}{V_2}\right)^{-n} \quad and \quad \frac{V_1}{V_2} = \left(\frac{P_1}{P_2}\right)^{-1/n}$$



From the characteristice equation

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

$$\frac{T_1}{T_2} = \frac{P_1V_1}{P_2V_2} = \left(\frac{V_2}{V_1}\right)^n \frac{V_1}{V_2} = \left(\frac{V_2}{V_1}\right)^{n-1}$$
and
$$\frac{T_1}{T_2} = \frac{P_1V_1}{P_2V_2} = \frac{P_1}{P_2} \left(\frac{P_1}{P_2}\right)^{-1/n} = \left(\frac{P_1}{P_2}\right)^{\frac{n-1}{n}}$$

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{n-1}$$
$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{n-1}$$



Entropy



Revisable heat transfer: Q_{rev}

$$dQ_{rev} = T \, ds$$
$$Q_{rev} = \int_{s_1}^{s_2} T \, ds$$

An isolated system can only change to states of equal or greater entropy.

Entropy for gas

Polytropic process $PV^n = C$

Heat transferred

$$dQ = \frac{\overline{c} - n}{\overline{c} - 1} P dv \qquad \overline{c} = \frac{c_p}{c_v}$$

$$ds = \frac{dQ}{T} = \frac{\overline{c} - n}{\overline{c} - 1} \frac{P}{T} dv = \frac{\overline{c} - n}{\overline{c} - 1} \frac{R}{v} dv \text{ (combined characteristic eq.)}$$

where s - specific entropy v is a unit of V.

$$\int_{s_1}^{s_2} ds = \frac{\overline{c} - n}{\overline{c} - 1} R \int_{v_1}^{v_2} \frac{dv}{v}$$

$$s_2 - s_1 = \frac{\overline{c} - n}{\overline{c} - 1} R \ln \frac{v_2}{v_1}$$

$$s_2 - s_1 = \frac{\overline{c} - n}{\overline{c} - 1} R \ln \frac{v_2}{v_1}$$

$$s_2 - s_1 = c_v \frac{\overline{c} - n}{n - 1} \ln \frac{T_1}{T_2}$$

$$s_2 - s_1 = c_v \frac{\overline{c} - n}{n} \ln \frac{P_1}{P_2}$$

$$s_{2} - s_{1} = c_{v} \frac{\overline{c} - n}{n - 1} \ln \frac{T_{1}}{T_{2}} = c_{v} \frac{\frac{c_{p}}{c_{v}} - n}{n - 1} \ln \frac{T_{1}}{T_{2}} = \frac{c_{p} - c_{v} n}{n - 1} \ln \frac{T_{1}}{T_{2}}$$
$$= \frac{-c_{p} (n - 1) + c_{p} n - c_{v} n}{n - 1} \ln \frac{T_{1}}{T_{2}}$$
$$= -c_{p} \ln \frac{T_{1}}{T_{2}} + (c_{p} - c_{v}) \frac{n}{n - 1} \ln \frac{T_{1}}{T_{2}}$$
$$= c_{p} \ln \frac{T_{2}}{T_{1}} - R \ln \left(\frac{T_{1}}{T_{2}}\right)^{\frac{n - 1}{n}} \qquad (c_{p} - c_{v} = R)$$

i.e

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

Let $s_1 = 0$,

choose (arbitrarily)

$$T_1 = 273.15K$$
, (0°C)
 $P_1 = 0.101MN / m^2 = 1.01bar$ (1 standard atmosphere

$$s_2 = c_p \ln \frac{T_2}{273.15} - R \ln \frac{P_2}{0.101}$$





Example: The air at T=288K and standard atmosphere is compress to P=5 times of standard atmosphere pressure with a temperature 456.1K. Calculate the entropy values. For air Cp=1005 J/kgK, R=287 J/kgK.

Before compression

$$s_2 = 1005 \ln \frac{288}{273.15} - 287 \ln \frac{0.101}{0.101} = 53$$

After compression

$$s_2 = 1005 \ln \frac{456.1}{273.15} - 287 \ln \frac{5*0.101}{0.101} = 53$$

No change in entropy.

Isentropic Process

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



Petrol Engine

The cycle in a four-stroke cycle modern petrol engine is called the Otto cycle after German engineer Nikolaus Otto, who introduced it in 1876. It improved on earlier engine cycles by compressing the fuel mixture before it was ignited.



Side and end section views of the OHC engine



(Courtesy of Tiscali ENCYCLOPAEDIA)



Diesel Engine

Fuel is injected on the power stroke into hot compressed air at the top of the cylinder, where it ignites spontaneously. The four stages are exactly the same as those of the four-stroke or Otto cycle.





Rudolf Christian Karl Diesel, inventor of the Diesel engine. Born in Paris, France, March 18, 1858; died in the English Channel, September 29, 1913.



Mr Diesel's first engine





Nicolaus August Otto Four Stroke Engine 1876



Isentropic Compression or expansion

T - temperature (K)

p - pressure

v - volume

s - Entropy

- C_p = specific heat at constant pressure
- C_v = specific heat at constant volume

 $R = c_p - c_v$ gas constant

 $\gamma = c_p / c_v$

or $\frac{R}{c_p} = 1 - \frac{1}{\gamma}$

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1}$$

For reversible Compression and expansion,

$$s_2 = s_1$$

Therefore

$$c_p \ln \frac{T_2}{T_1} = \frac{R}{c_p} \ln \frac{p_2}{p_1}$$

Effect of pressure on temperature

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}}$$

Equation of state:

pv = RT

Effect of volume of pressure

$$\frac{p_2}{p_1} = \left(\frac{v_2}{v_1}\right)^{\gamma}$$





Otto cycle

Otto Thermodynamic Cycle is used in all internal combustion engines.

Stage 1 being the beginning of the intake stroke of the engine. The pressure is near atmospheric pressure and the gas volume is at a minimum. Between Stage 1 and Stage 2 the piston is pulled out of the cylinder with the intake valve open. The pressure remains constant, and the gas volume increases as fuel/air mixture is drawn into the cylinder through the intake valve.

Stage 2 begins the compression stroke of the engine with the closing of the intake valve. Between Stage 2 and Stage 3, the piston moves back into the cylinder, the gas volume decreases, and the pressure increases because work is done on the gas by the piston.

Stage 3 is the beginning of the combustion of the fuel/air mixture. The combustion occurs very quickly and the volume remains constant. Heat is released during combustion which increases both the temperature and the pressure, according to the equation of state.

Stage 4 begins the power stroke of the engine. Between Stage 4 and Stage 5, the piston is driven towards the crankshaft, the volume in increased, and the pressure falls as work is done by the gas on the piston.

Stage 5: the exhaust valve is opened and the residual heat in the gas is exchanged with the surroundings. The volume remains constant and the pressure adjusts back to atmospheric conditions.

Stage 6 begins the exhaust stroke of the engine during which the piston moves back into the cylinder, the volume decreases and the pressure remains constant. At the end of the exhaust stroke, conditions have returned to Stage 1 and the process repeats itself.

Work Done

During the cycle, work is done on the gas by the piston between stages 2 and 3.

Work is done by the gas on the piston between stages 4 and 5.

The difference between the work done by the gas and the work done on the gas is the area enclosed by the cycle curve and is the work produced by the cycle.

The work times the rate of the cycle (cycles per second) is equal to the power produced by the engine.

Ideal Otto cycle: no heat entering (or leaving) the gas during the compression and power strokes, no friction losses, and instantaneous burning occurring at constant volume.



(Courtesy of NASA)









 $p_3 = p_2 \left(\frac{V_2}{V_3}\right)^{\gamma}$ $T_3 = T_2 \left(\frac{V_2}{V_3}\right)^{\gamma-1}$









 $p_5 = p_4 \left(\frac{V_4}{V_5}\right)^{\gamma}$

 $T_5 = T_4 \left(\frac{V_4}{V_5}\right)^{\gamma-1}$





5-6 Heat Rejection Process

 $T_6 = T_5 - \frac{Q}{c_v}$ $p_6 = p_5 \frac{T_6}{T_5}$







Work Done

$$= \int_{V_1}^{V_2} P_{2-3} dV - \int_{V_2}^{V_1} P_{5-6} dV$$

A Comparison between a working cycle of a piston engine and a turbo-jet engine



Working cycle and airflow

A comparison between the working cycle of a turbo-jet engine and a piston engine.

Four Stroke Diesel Cycle

Fig. 1: 4-stroke diesel engine

1 Induction stroke, 2 Compression stroke, 3 Working stroke, 4 Exhaust stroke.









Intake stroke



The piston moves down the cylinder and the pressure will drop (negative pressure). The intake valve is opened. Because of the low pressure the air /fuel mixtures are sucked into the cylinder

Compression



At bottom dead centre (BDC) the cylinder is at its maximum volume and the intake is closed. Now the piston moves round to Top dead centre (TDC) and compresses the air/fuel mixtures. The pressure is increased and the volume decreased. The necessary work for the compression increases the internal energy of the mixtures – the temperature is increased. Because of the fast compression only a small part of the energy is transferred to the environment



Ignition



Near the end of the compression stroke, the ignition starts the combustion and the mixture burns very rapidly. The expanding gas creates a high pressure against the top of the piston. The resulting force drives the piston downward.

The rapid increase in pressure gives rise to the noise levels associated with combustion.



Power stroke



The force drives the piston downward to the crankshaft (the valves are closed). The volume is increased and the pressure is decreased. No more energy is added and because of this the internal energy of the gas is decreased, as is the temperature.

Exhaust



At BDC the exhaust valve is opened and the piston moves up the cylinder. The pressure drops to a level near to atmospheric because of the opened exhaust valve. Exhaust gas leaves the cylinder and the volume is decreased. When exhaust gases leave the cylinder the surrounding air-cools them. The carbon dioxide gas produced will remain as a gas but the steam produced will condense to form water droplets.



Intake stroke



The piston moves down the cylinder and the pressure will drop (negative pressure). The intake valve is opened. Because of the low pressure the air /fuel mixtures are sucked into the cylinder



Introduction to diesel fuels

- Diesel fuels consist of a number of hydrocarbons, which have boiling points between 180° and 360° C
- As there is no external ignition system (yet!), diesel fuel must ignite when introduced into heated compressed air with the minimum possible delay.Ignition property of the fuel is defined as the property of the fuel, which serves to initiate auto ignition.
- This ignition quality is expressed by the cetane number (CN). The higher the CN the easier it is for the fuel to ignite.
- The numbers allocated are 100 for very good, down to methylnapthalene that has poor ignition qualities and a cetane of 0
- The minimum CN for diesel fuel is 45, a CN of 50 is the optimum for current engines



Cold behaviour of diesel fuel

- At low temperatures, paraffin crystals can cause filters to clog and block off the fuel delivery.
- For untreated fuel, this crystallisation starts at 0 $^{\circ}$ C
- With this in view, cold weather additives are added at the refinery and standard UK pump fuels are good to -22 $^\circ\,$ C



Density of diesel fuel

- The diesel fuel's calorific value is approximately related to its density.
- It increases with increasing density
- If fuels with a differing density are used with the same fuel injection equipment at the same settings, there will be fluctuations in the calorific values which in turn will lead to increased smoke and sot emissions from higher density fuels.
- Reference fuel barrel storage methods are critical to ensure minimal loss of light ends.



Diesel fuel Calorific value

- The calorific value of diesel fuel is lower than that of gasoline.
- Diesel fuel ranges from 40Mj/kg to 43 Mj/kg and it is a function of the fuel density (Density 0.815 to 0.855)
- Gasoline fuel ranges from 42.7 Mj/kg to 43.5 Mj/kg (Density 0.715 to 0.780)
- In the case of diesel fuels, the higher the sulphur content, the lower the calorific value, this has a big impact upon new emission regulations.

Four Stroke Diesel Cycle



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Engine Movie (Ford)...