Propulsion loads and structures

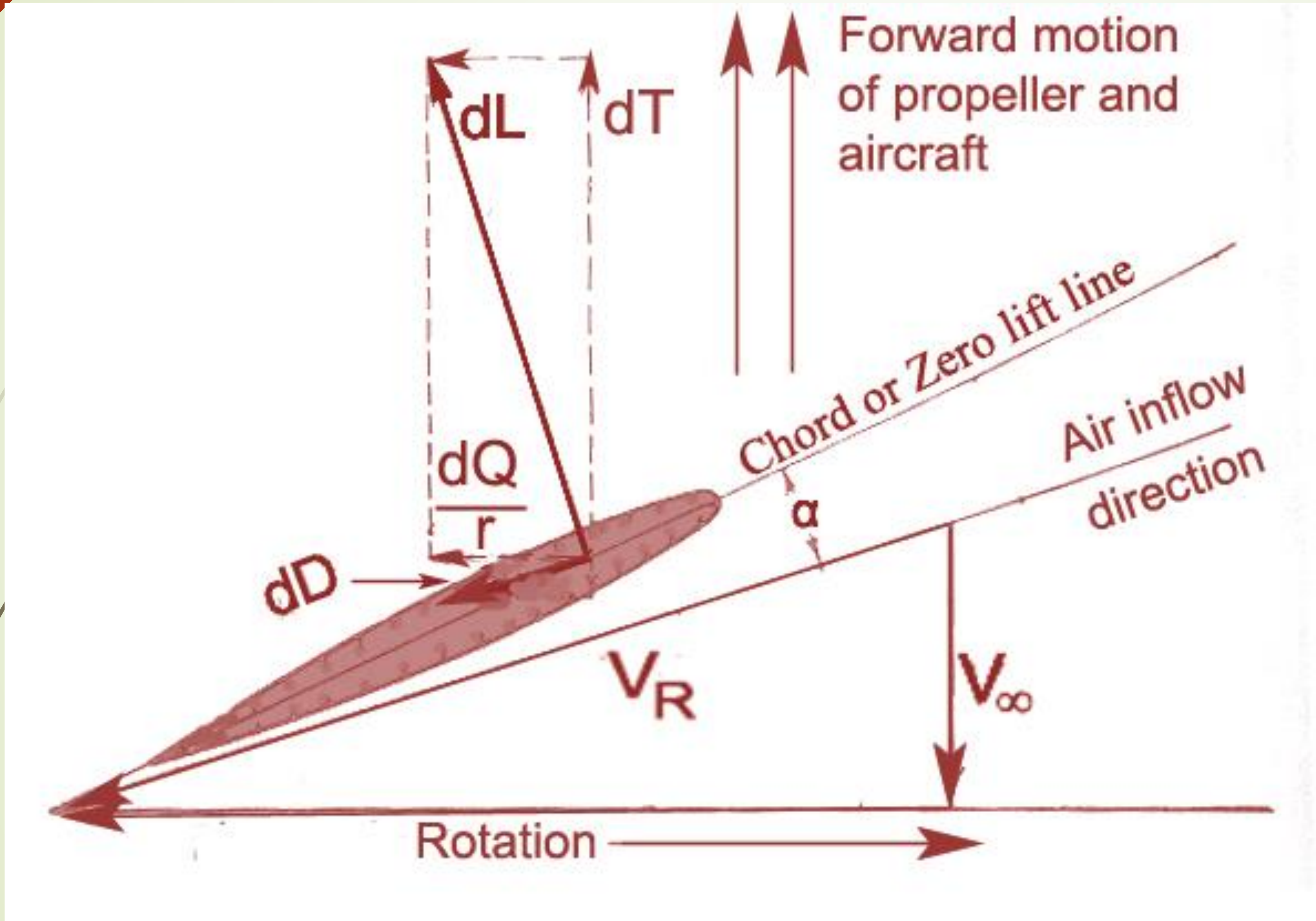
Module - 4

Propulsion - **Overview**

- Two aspects of propulsion are addressed in this chapter.
- The first is the **aerodynamics of generating thrust** or what is called "**powered lift**," which is lift that is directly generated by a rotor or fan and is very similar to **upward thrust**, but uses somewhat different terminology for historical reasons.
- The second aspect of propulsion is the **source of the power** to **produce the thrust or lift**, which is the **engine or motor** that moves a **propeller or rotor or fan or generates a high-speed jet** of **exhaust gasses.**
- In this section, **both the traditional internal combustion and turbine engines are addressed**, as well as the **electric propulsion** that is **almost unique to the UAV world** and is becoming more common there in **both the mini-/micro-UAV and high-altitude, extremely long endurance segments of that world**.

Thrust Generation

- We are familiar with the **generation of lift using regular airfoils and wings.**
- **Most UAVs use propellers that can be thought of as little wings**.
- **Propellers generate a force called thrust** just as **wings generate a force called lift**.
- There are **many ways** of describing **how this force is actually generated**.
- One explanation is that **lower air pressure on the curved surface resulting from an increase in velocity over that part of the surface as predicated by Bernoulli pulls the propeller.**
- While this description is essentially correct, the fact remains that the fundamental principle for **the generation of thrust and lift is the reaction to the change in momentum of the mass of air pulled through the propeller disk or wing planform**.



Forward motion of propeller and aircraft
dL
dT
Chord or Zero lift line
Air inflow direction
dQ/r
α
dD
V_R
V_∞
Rotation

Thrust Generation

- One must have a momentum generator to produce lift whether it is a wing or an actuator disk (rotor, fan), jet or a propeller.
- The force F of a momentum generator is:

$$F = T = \frac{dm}{dt}(v_{in} - v_{out}) \tag{6.1}$$

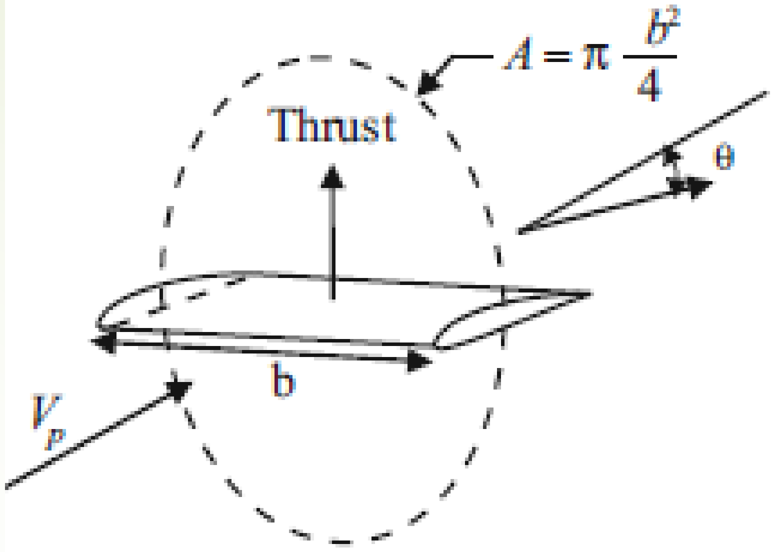


Figure 6.1 Momentum generator

Where $\frac{dm}{dt}$ is the mass flowing through the momentum generator per unit time, given by:

$$\frac{dm}{dt} = \rho v A \tag{6.2}$$

and

in = entry conditions
out = exit conditions
A = disk area
ρ = air density
v = velocity at the same point in the flow at which the area and density are measured.

Thrust Generation

A wing is a vertical momentum generator and produces lift in the manner shown in Figure 6.1. Similarly, a propeller can be thought of as a horizontal lift (thrust) generator. The rate at which an air mass flows past a wing or propeller can be calculated as:

$$\frac{dm}{dt} = \rho v \frac{\pi b^2}{4} \tag{6.3}$$

where $\pi b^2/4$ is the capture area of the air flowing past the wing and v is the velocity.

The change in momentum due to the deflection of the air downward is simply $(dm/dt)V\sin\theta$, where θ is the angle by which the air mass is deflected. The force generated by this momentum change in the vertical direction is lift, as shown below:

$$\text{Lift} = L = \frac{dm}{dt} v \sin\theta \tag{6.4}$$

The power to generate this lift, called induced power, is equal to the rate of change of energy in the downward direction:

$$P = \frac{1}{2}\frac{dm}{dt} v^2 \sin^2\theta \tag{6.5}$$

substituting for dm/dt and $\sin\theta$ from Equation (6.4), the induced power in terms of lift becomes:

$$P = 2\frac{L^2}{\rho \pi v b^2} \tag{6.6}$$

One can see from Equation (6.6) that the power required to produce a given amount of lift is inversely proportional to the square of the wingspan or propeller diameter (b).

Powered Lift

Lift can also be generated by an actuator disk consisting of a helicopter rotor or a ducted fan, as shown in Figure 6.2.

For an un-ducted rotor, ambient air is sucked into the disk defined by the spinning fan, and passes through it with a velocity v_d and continues to accelerate to a final exit velocity v_e. It is well known and easily proved that:

$$v_d = \frac{v_e}{2} \tag{6.7}$$

and the mass flow is:

$$\frac{dm}{dt} = \rho A v_d = \frac{1}{2}\rho A v_e \tag{6.8}$$

where A is the area of the disk, so the lift of the disk is:

$$L = \frac{dm}{dt} v_e = \frac{\rho A v_e^2}{2} \tag{6.9}$$

The induced power is:

$$P = \frac{1}{2}\frac{dm}{dt} v_e^2 \tag{6.10}$$

and by substituting for dm/dt from Equation (6.8) and for v_e^3 from Equation (6.9), we find that:

$$P = \frac{L^{3/2}}{\sqrt{2\rho A}} \tag{6.11}$$

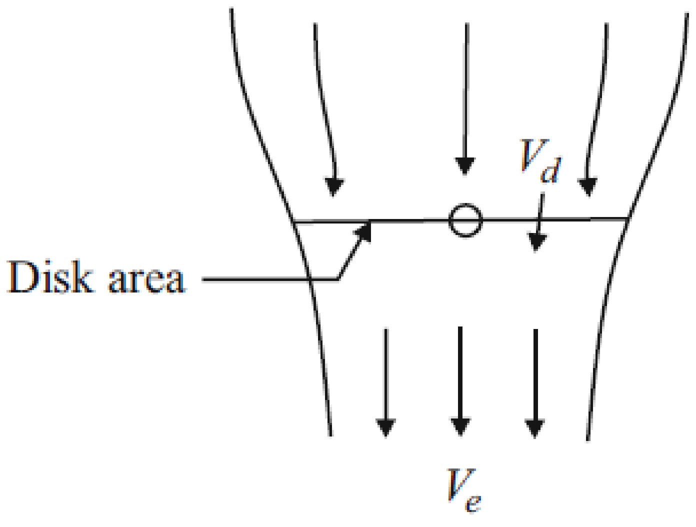


Figure 6.2 Actuator disk

Powered Lift

a slight rearrangement leads to:

$$\frac{L}{P} = \sqrt{\frac{2\rho}{L/A}} \tag{6.12}$$

which tells us that the lift per unit power is inversely proportional to the square root of the disk loading (L/A) and directly proportional to the square root of the density. Plotting power loading against disk loading for helicopters, tilt rotor/wing, and fans (Figure 6.3) shows the relative efficiency of each. While the units of power in Equation (6.12) are N or ft·lb/s, we plot the results of the calculation in the commonly used units of horsepower.

Combining the expressions for lift and power in terms of exit velocity in Equations (6.9) and (6.10), we find that:

$$\frac{L}{P} = \frac{2}{V_e} \tag{6.13}$$

This indicates that lift per unit power is inversely proportional to exit velocity. From this, it is clear that the most efficient powered lift is generated by using a large mass of air at a low velocity.

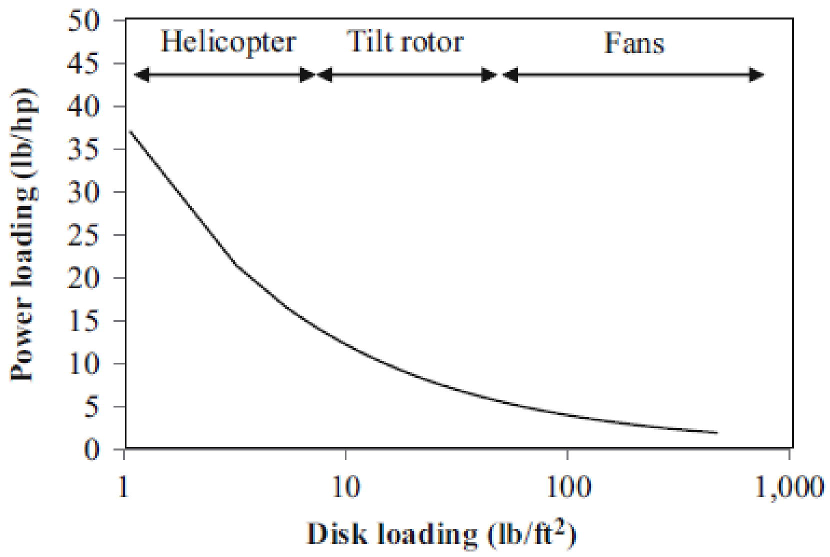


Figure 6.3 Disk loading versus power loading

Powered Lift

- Figure 6.4 shows momentum generators classified as a function of lift-to-power ratio or exit velocity.
- Rotors, **with large disk areas and large amounts of air flowing rather slowly, are the most efficient for hovering.**
- Fans are at a disadvantage compared to rotors, and turbojets at a disadvantage compared to fans, all the way down to rockets, which have the highest exit velocities.

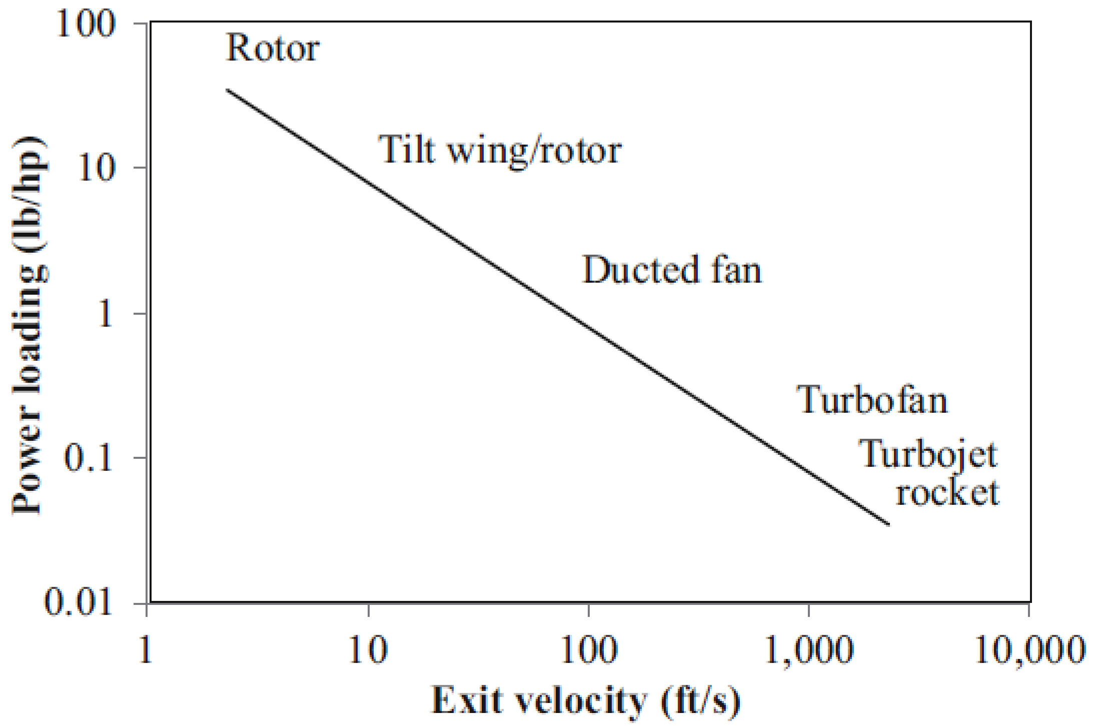


Figure 6.4 Lift-to-power ratio versus exit velocity

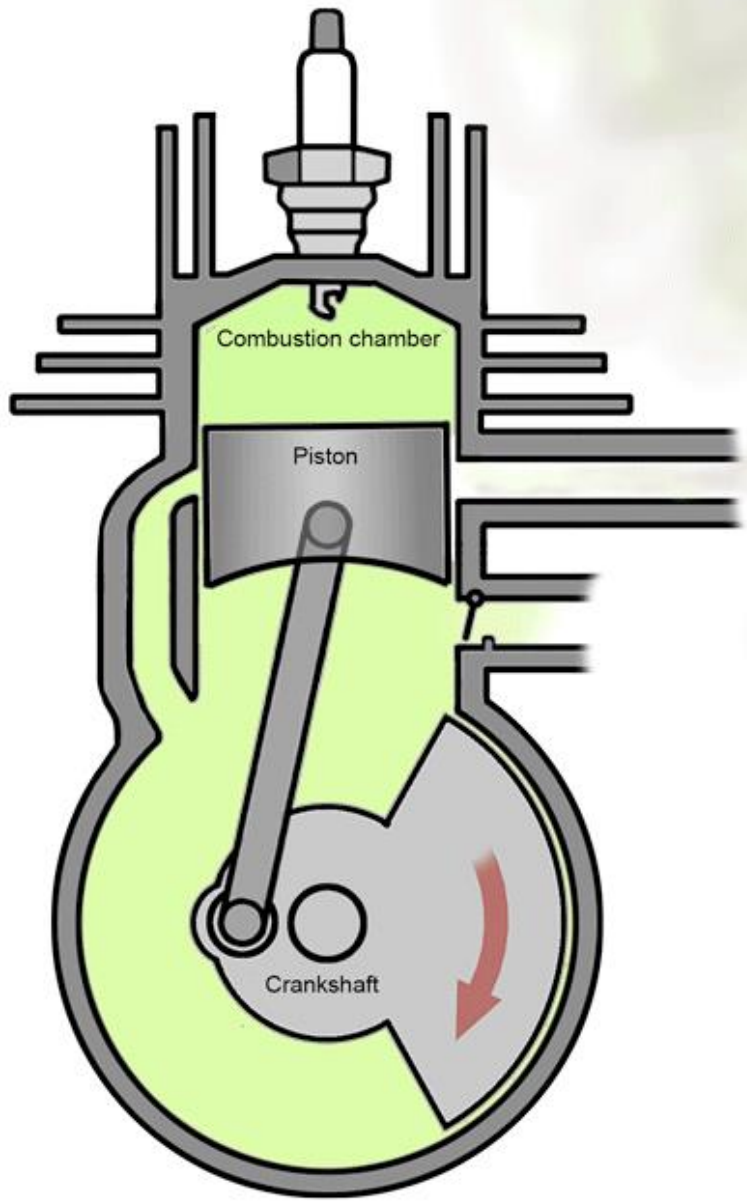
- **Vertical-lift UAVs are difficult to control in a hover** and they are **more mechanically complex,** both of which will add to the cost.
- In addition, **engine failure** is probably a more serious problem with a **VTOL than a fixed-wing air vehicle** that can **glide or parachute to safety.**
- To minimize this possibility, rotary-wing designers opt for the more reliable, and also more costly, **gas turbine power plant**.
- **Having said all of this**, there are many missions where the **VTOL UAV is superior to fixed-wing UAVs.**
- **Without the need for launch and recovery equipment**, they can attain battlefield mobility that is difficult if not impossible to realize with a fixed-wing vehicle, especially the larger-sized vehicles.
- There is also the problem of accomplishing **landings in small areas**.
- Even **with flaps**, which **add weight, cost, and complexity**, the typical **fixed-wing UAV cannot attain a steep enough glide angle to land in very small fields surrounded by trees or other obstacles and be caught by a net.**
- **Small ships cannot afford the luxury of a net system**; there simply is not space available.
- The **larger ships cannot tolerate nets if they interfere with helicopter operations**.
- A **VTOL UAV offers a great deal of flexibility for combined UAV and helicopter operations**.
- All of these advantages and disadvantages must be carefully weighed when deciding whether the mission is **worth the cost of a VTOL vehicle**.

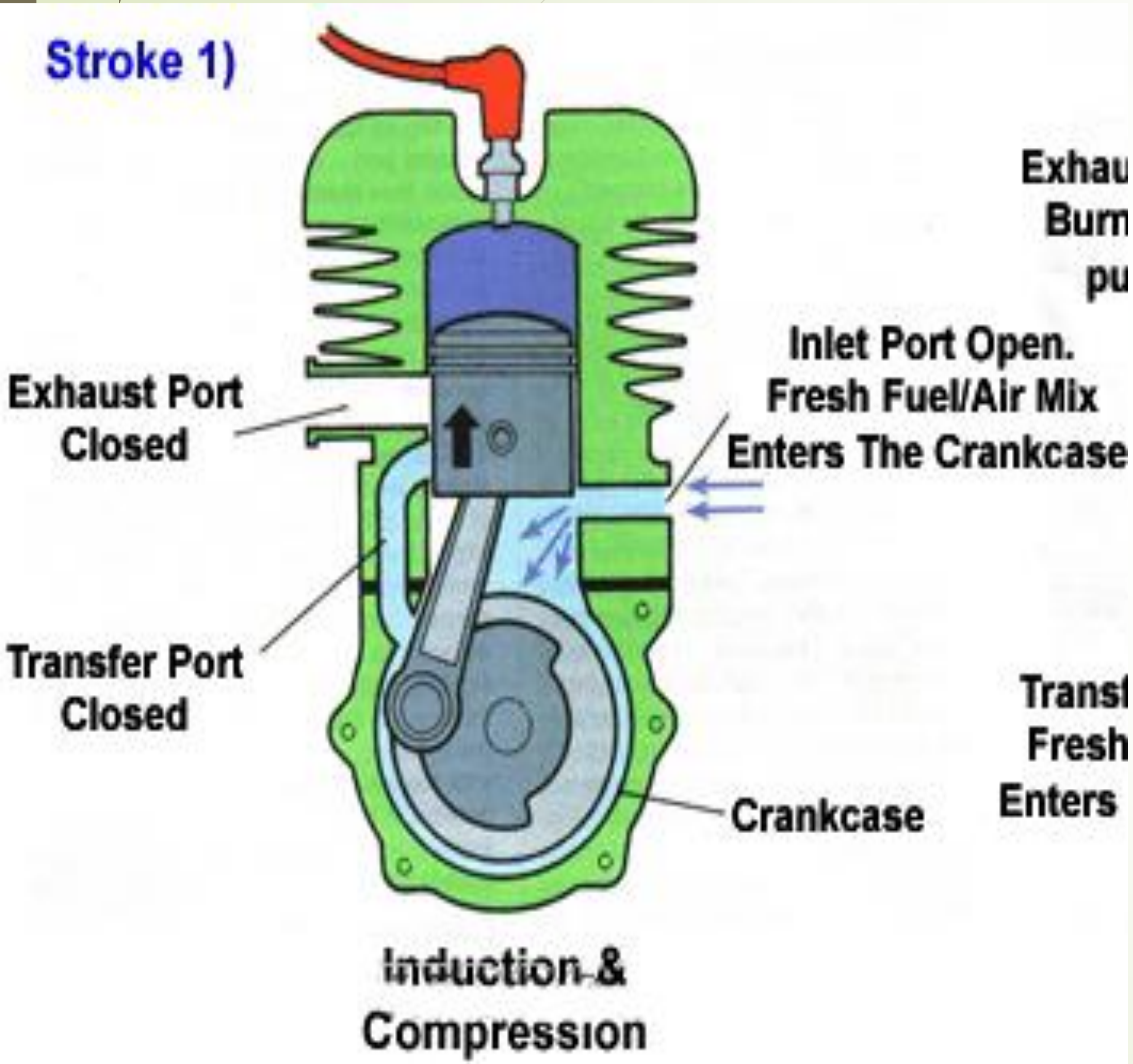
Sources of Power

- There are four primary types of engines used to propel UAVs. They are
  - **four-cycle and two cycle**
  - **reciprocating internal combustion engines,**
  - **rotary engines, and**
  - **gas turbines**.
  - A fifth, the **electric motor,** is beginning to appear and is playing an increasing role on the UAV scene.
- All four internal combustion engines generate power **by burning gasoline, a gasoline/oil mixture, jet fuel (kerosene), or diesel fuel.** The electric motor **uses batteries, solar cells, or fuel cells**.

TWO STROKE CYCLE ENGINE (PETROL ENGINE)

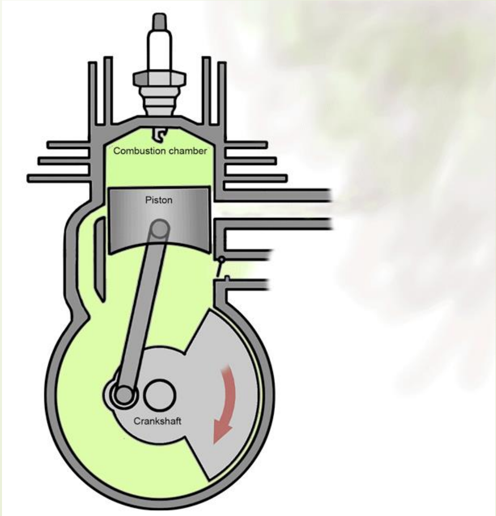
- In two stroke cycle engines, the whole sequence of **events i.e., suction, compression, power and exhaust** are completed **in two strokes of the piston** i.e. **one revolution of the crankshaft**.
- **There is no valve in this type of engine.** Gas movement takes place **through holes called ports in the cylinder.**
- **The crankcase of the engine is air tight** in which the crankshaft rotates.





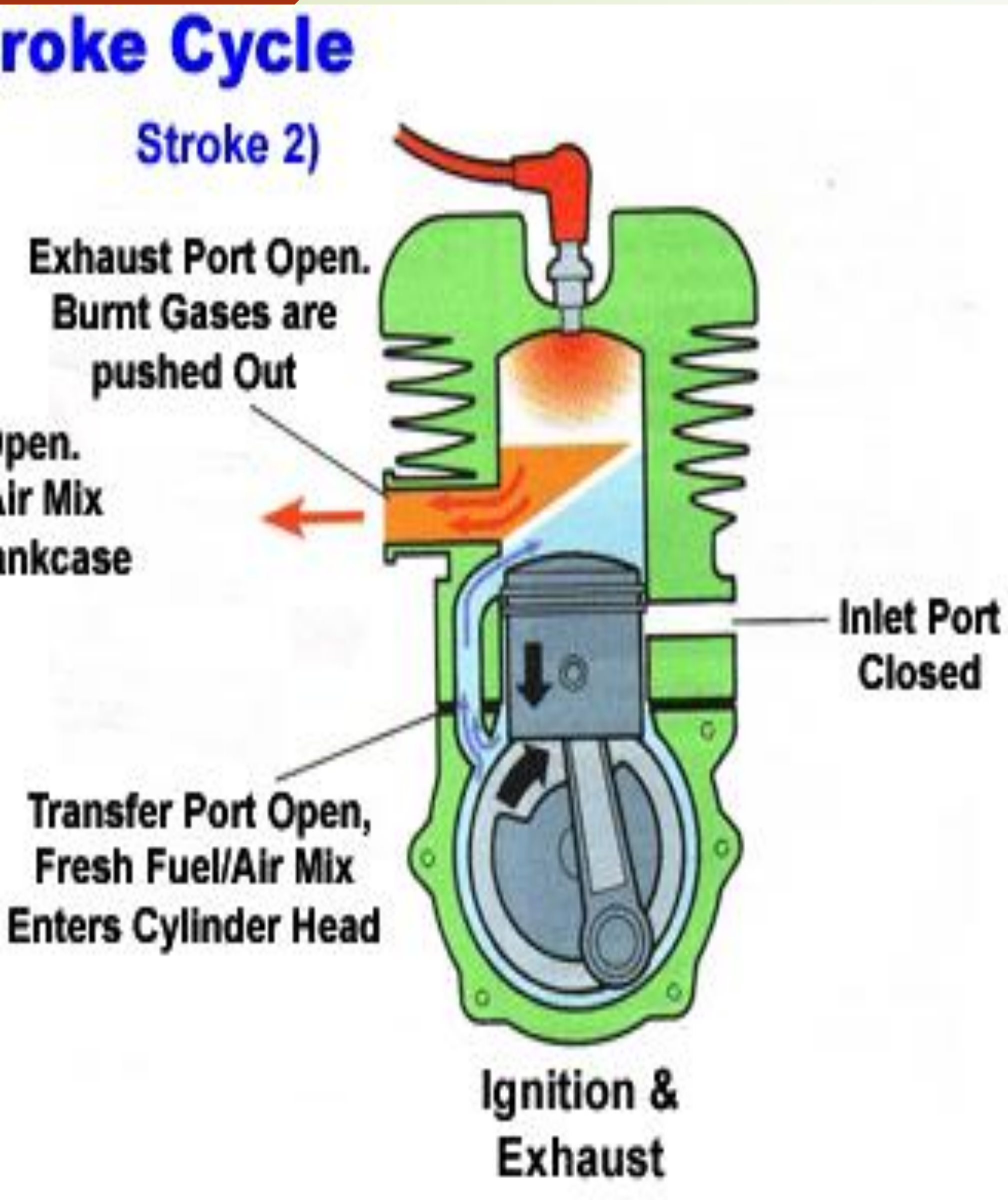
Upward stroke of the piston (Suction + Compression):

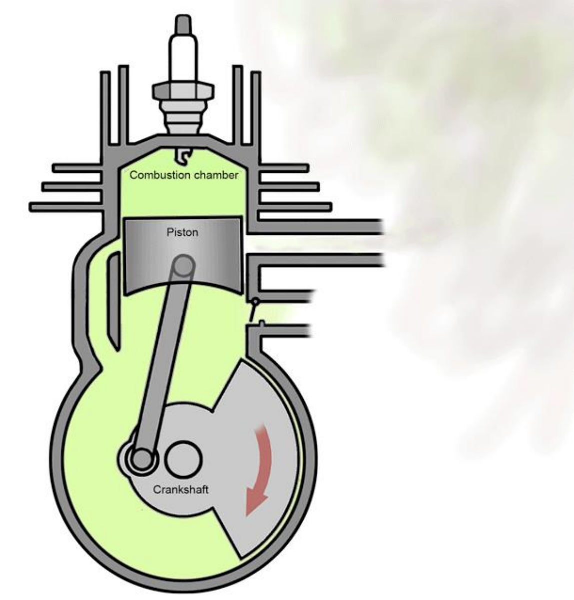
- When the piston **moves upward** it **covers two of the ports, the exhaust port and transfer port**, which are normally almost opposite to each other.
- This **traps the charge of air- fuel mixture drawn already in to the cylinder.**
- Further upward movement of the piston **compresses the charge and also uncovers the suction port**.
- **Now fresh mixture is drawn through this port into the crankcase**.
- **Just before the end of this stroke, the mixture in the cylinder is ignited by a spark plug**.
- Thus, during this stroke both **suction and compression** events are completed.

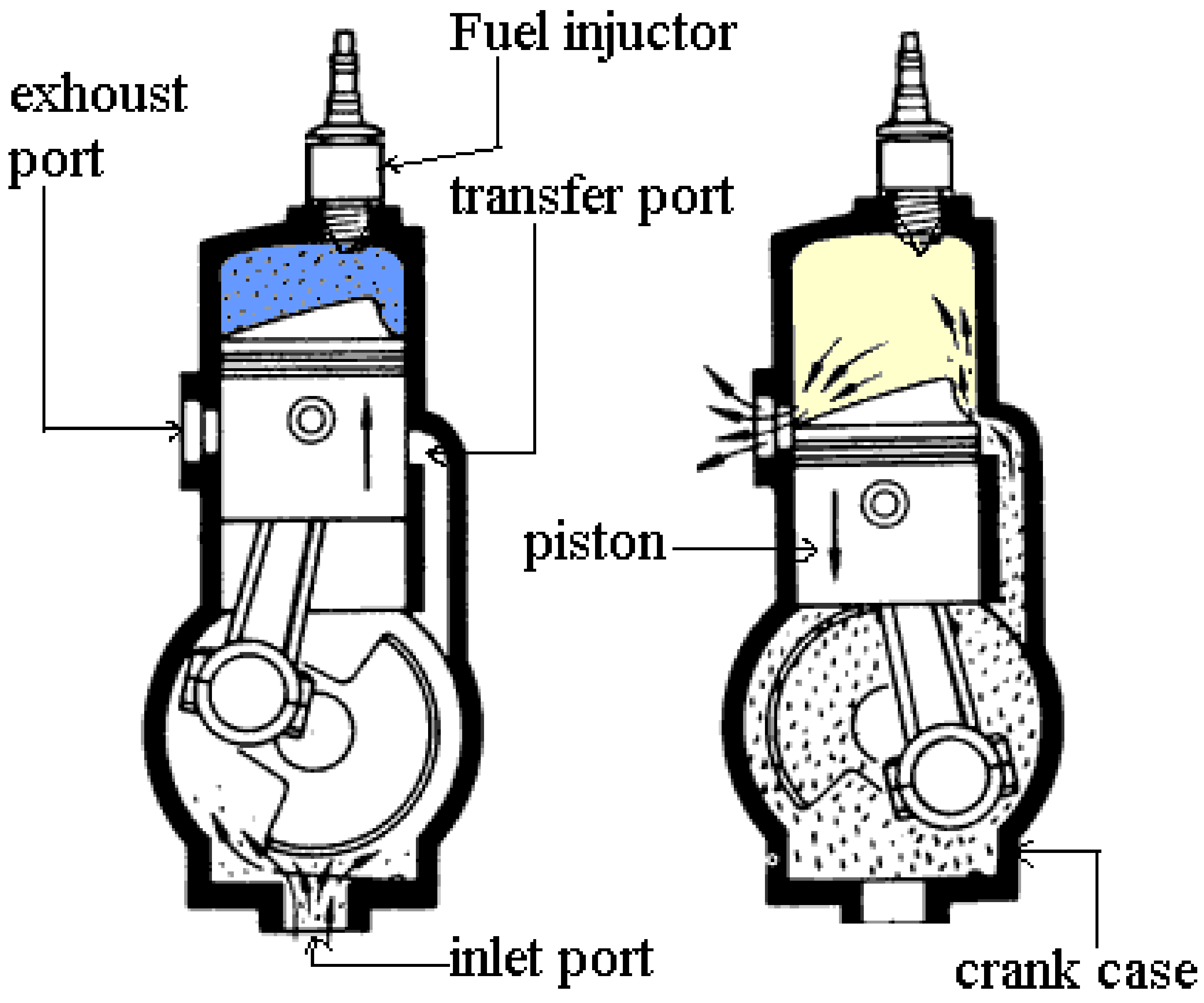


Downward stroke (Power + Exhaust):

- **Burning of the fuel rises the temperature and pressure of the gases which forces** the piston to move **down the cylinder**.
- When the piston moves down, **it closes the suction port**, trapping the fresh charge drawn into the crankcase during the previous upward stroke.
- Further downward movement of the piston **uncovers first the exhaust port and then the transfer port.**
- Now **fresh charge** in the crankcase moves in to the cylinder through **the transfer port** driving out the burnt gases through the exhaust port.
- During the downward stroke of the piston **power and exhaust** events are completed.





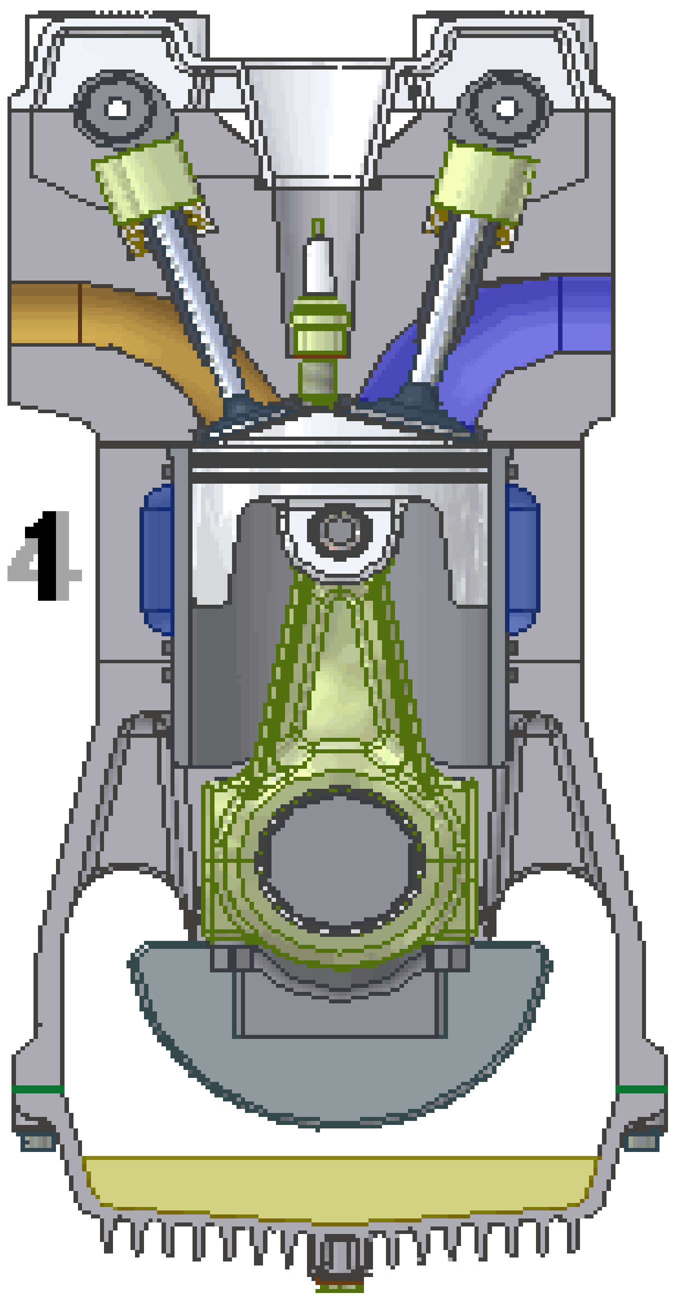


I st Stroke II nd Stroke

FOUR STROKE CYCLE ENGINE (DIESEL/ PETROL ENGINE)

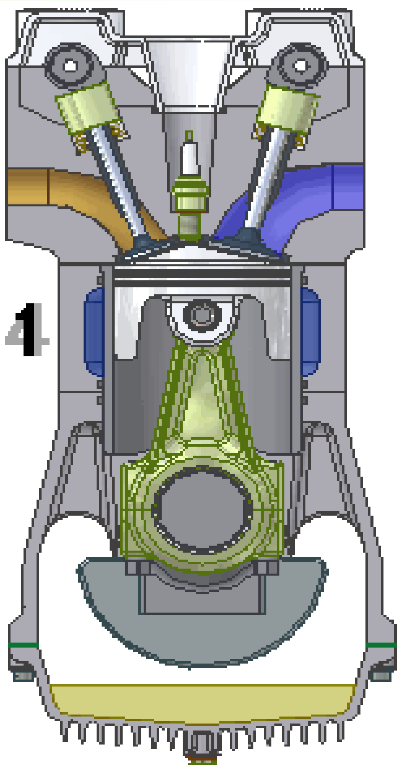
The events taking place in I.C. engine are as follows:

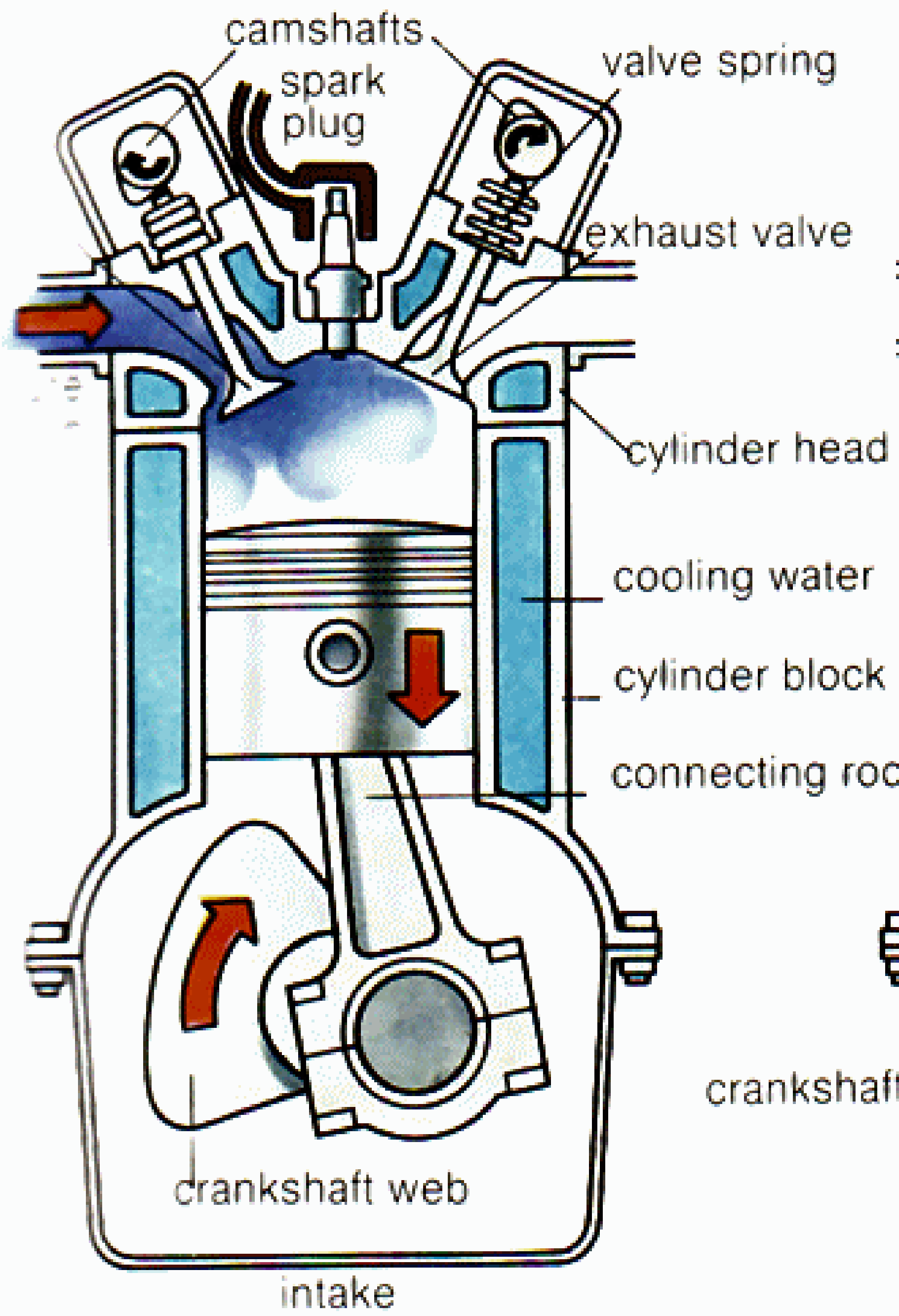
- **Suction stroke**
- **Compression stroke**
- **Power stroke**
- **Exhaust stroke**



Suction stroke:

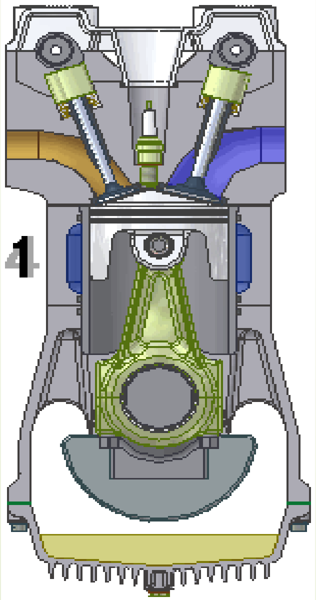
- During suction stroke **inlet valve opens** and the **piston moves downward**.
- Only **air or a mixture of air and fuel** are drawn inside the cylinder.
- The **exhaust valve remains in closed** position during this stroke.
- The **pressure in the engine cylinder is less than atmospheric pressure during this stroke.**

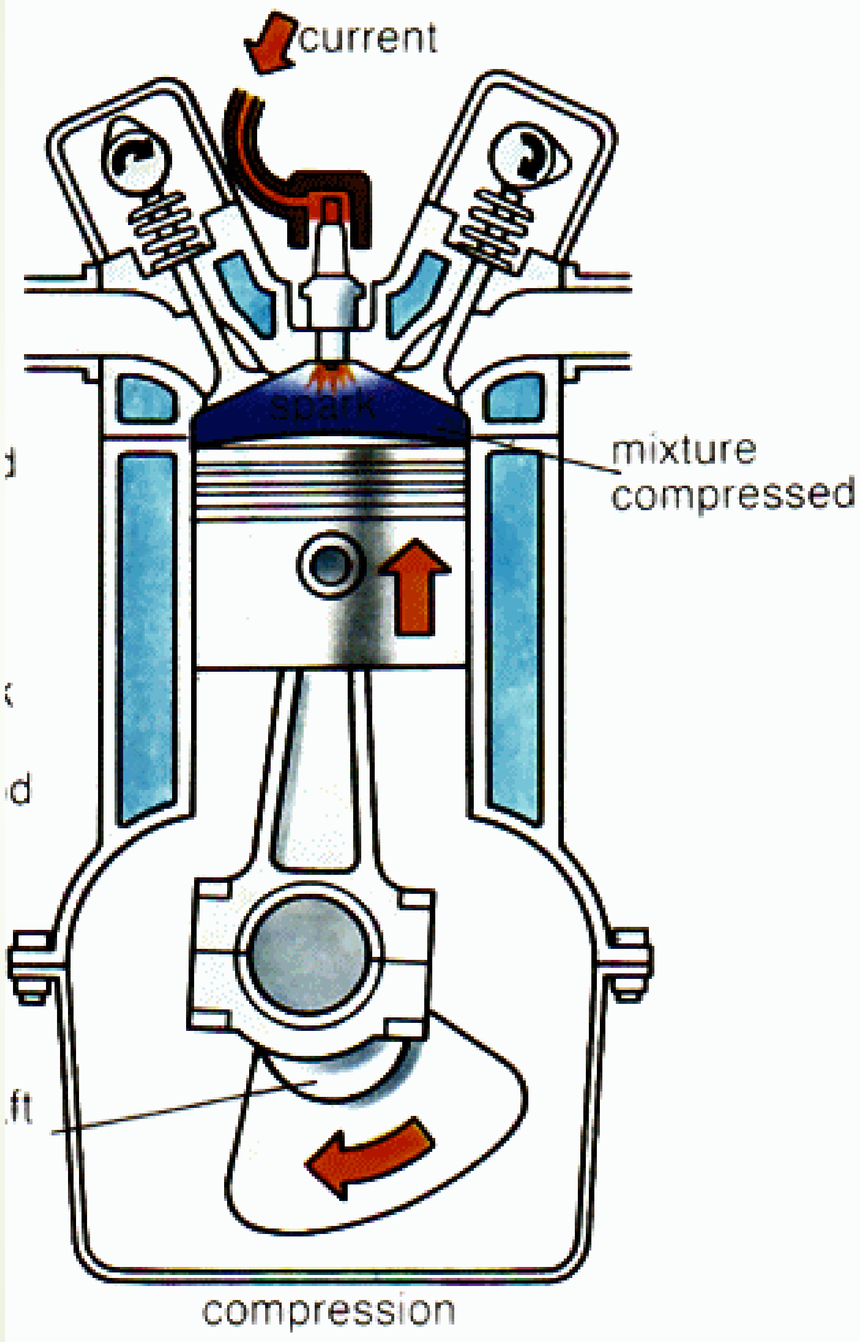




Compression stroke:

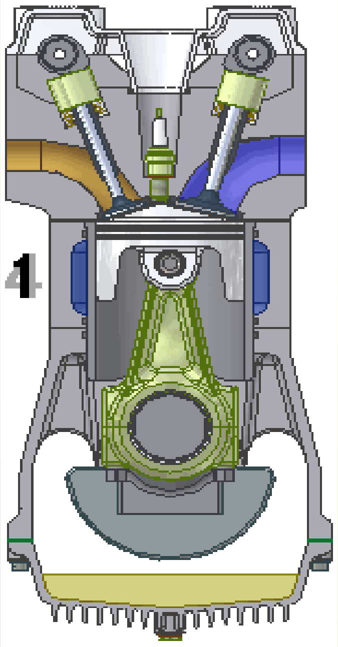
- During this stroke the piston moves upward. **Both valves are in closed position.**
- The **charge taken in the cylinder is compressed** by the upward movement of piston.
- If **only air is compressed, as in case of diesel engine**, **diesel is injected at the end of the compression stroke** and **ignition of fuel takes place due to high pressure and temperature of the compressed air**.
- If **a mixture of air and fuel** is compressed in the cylinder, as **in case of petrol engine,** the mixture is ignited by a spark plug.

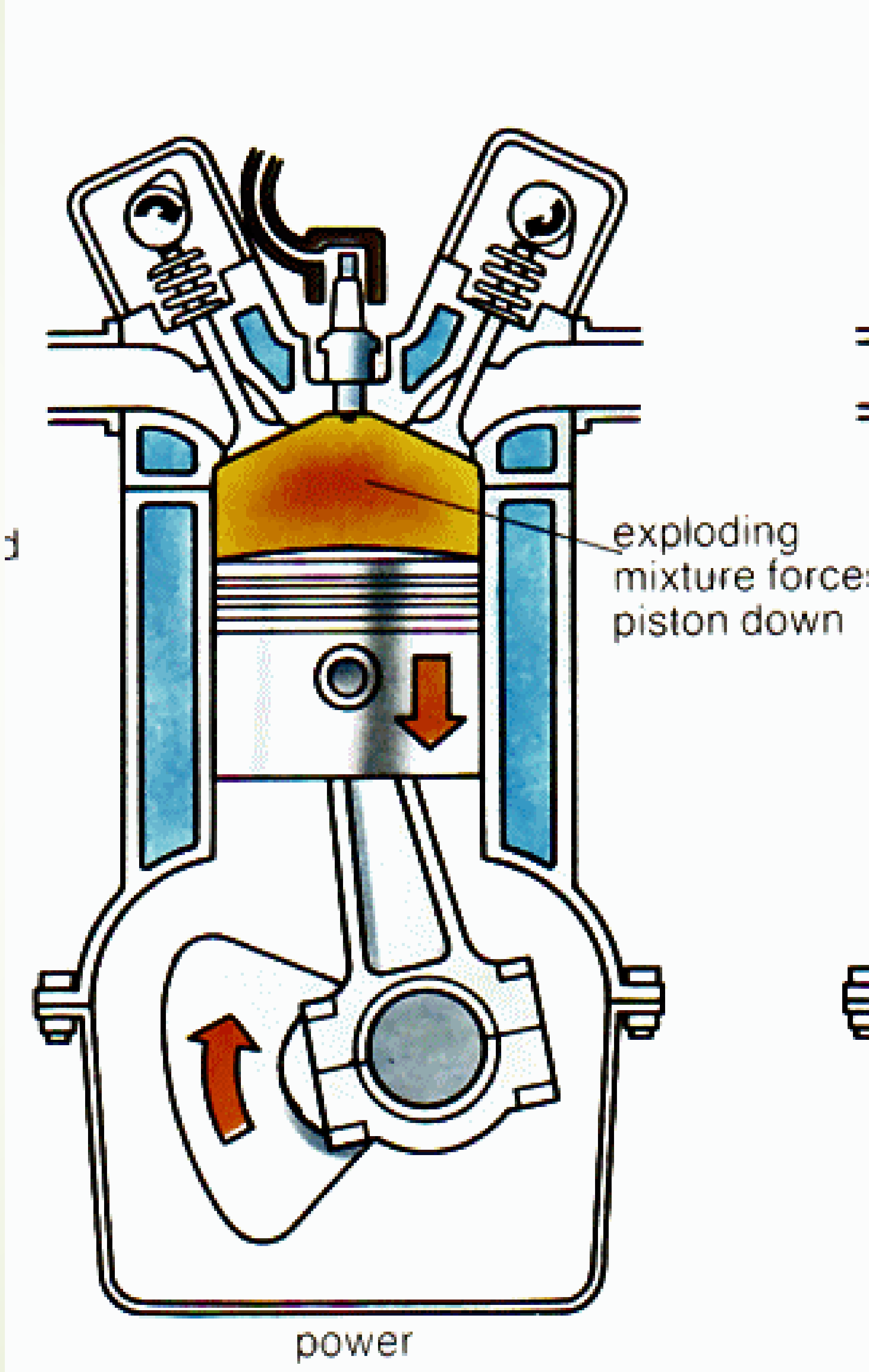




Power stroke:

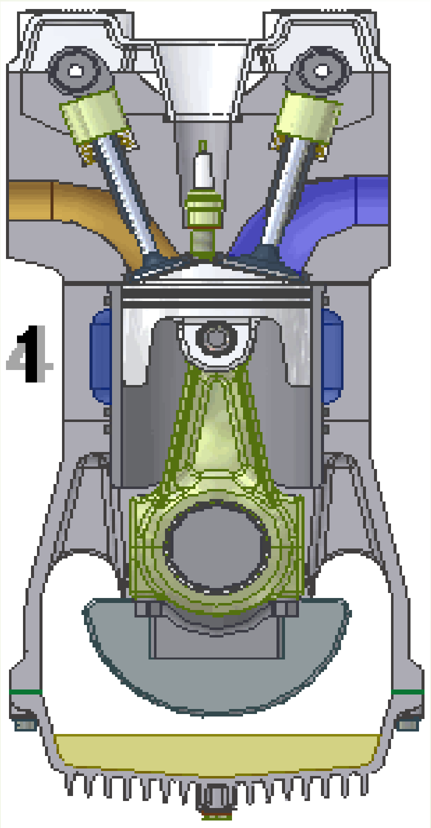
- **After ignition of fuel**, tremendous amount of **heat is generated**, causing very **high pressure in the cylinder which pushes the piston downward.**
- The downward movement of the piston at this instant is called power stroke.
- The **connecting rod transmits the power from piston to the crank shaft** and **crank shaft rotates.**
- **Mechanical work can be taped at the rotating crank shaft.**
- Both **valves remain** closed during power stroke.

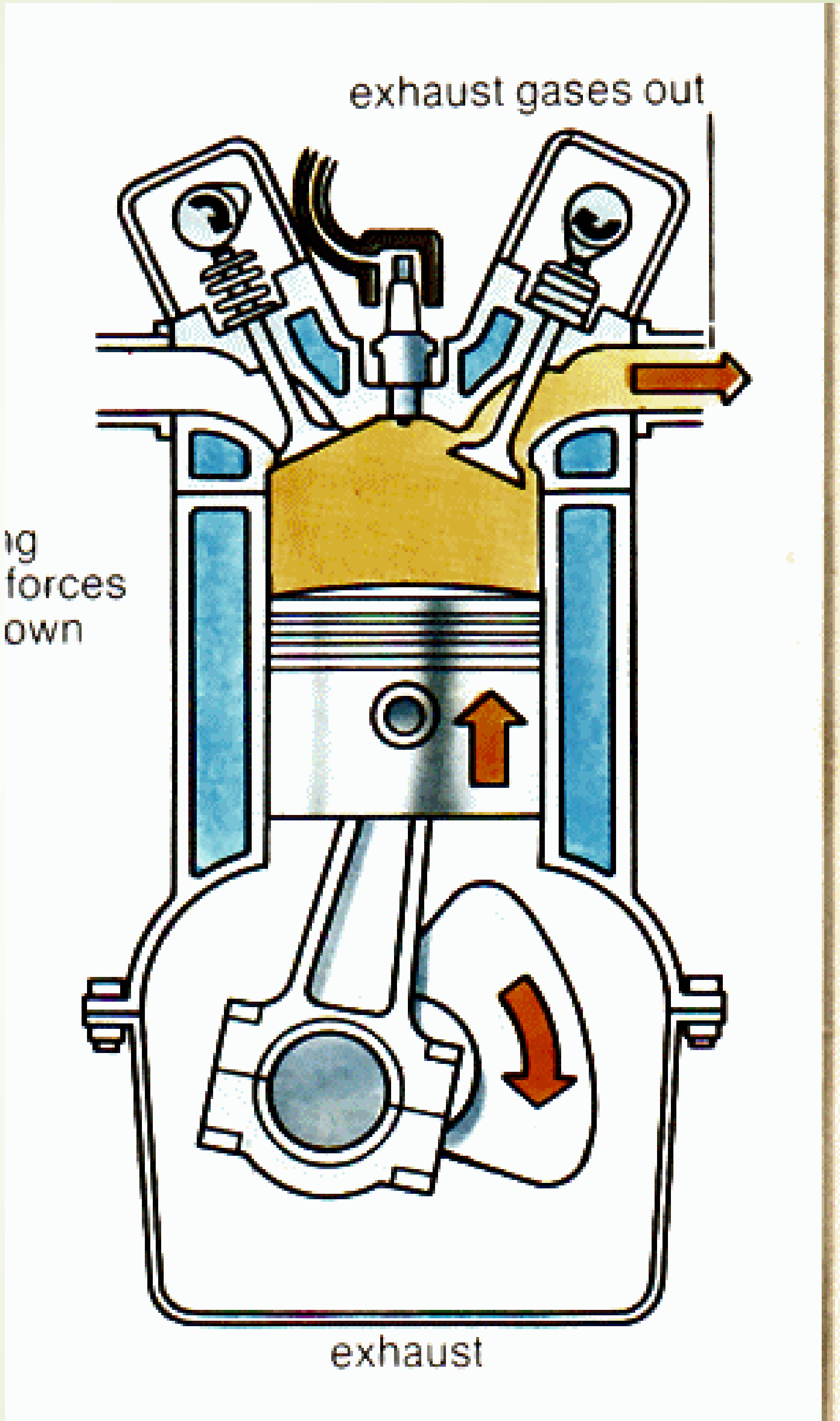


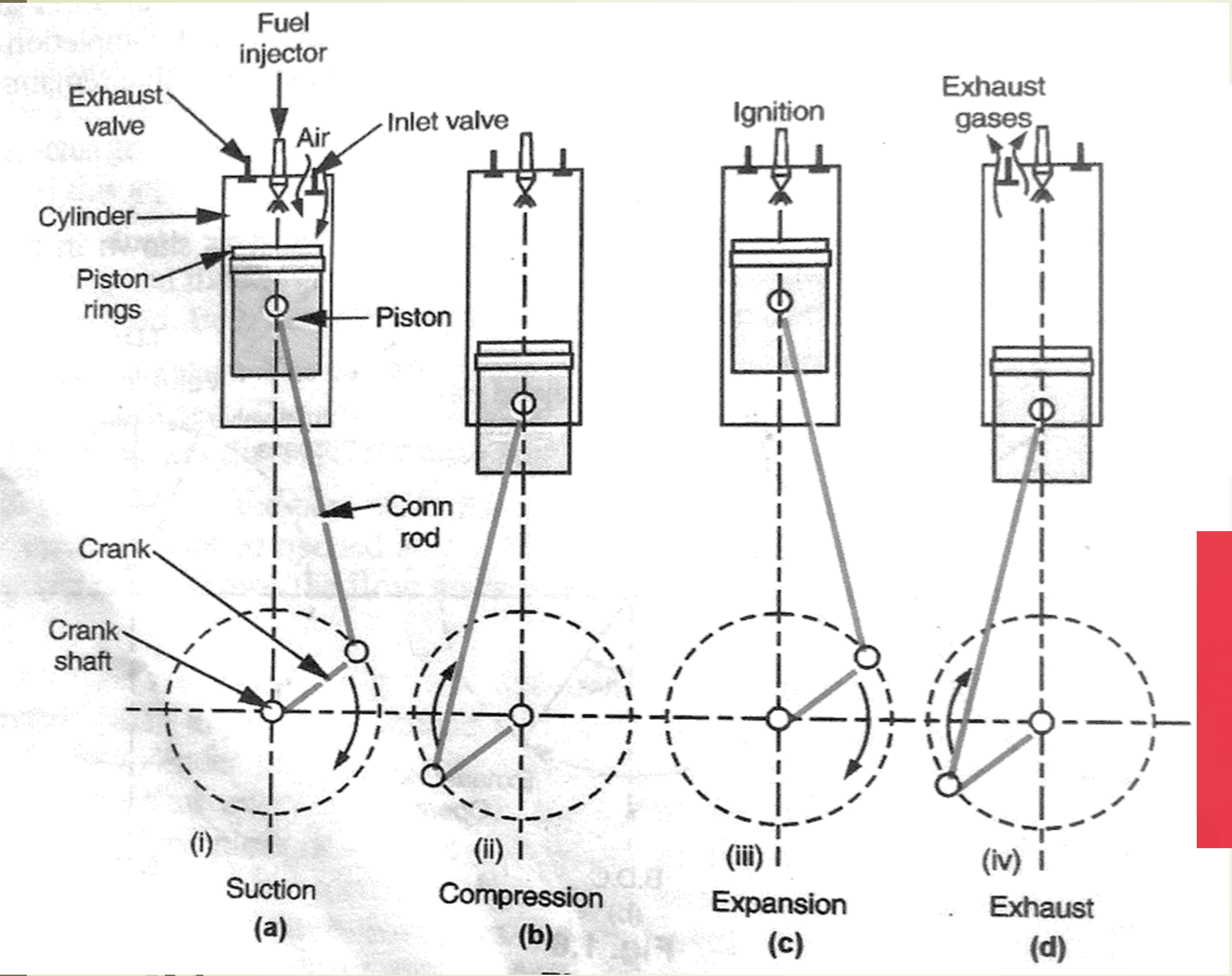


Exhaust stroke

- During this stroke piston moves upward.
- **Exhaust valve opens** and exhaust gases go out through exhaust valves opening.
- All the **burnt gases go out of the engine** and the cylinder becomes ready to receive the fresh charge.
- During this stroke **inlet valve remains closed**.






Fuel injector
Exhaust valve
Air
Inlet valve
Cylinder
Piston rings
Piston
Conn rod
Crank
Crank shaft
Ignition
Exhaust gases
(i)
Suction
(a)
(ii)
Compression
(b)
(iii)
Expansion
(c)
(iv)
Exhaust
(d)

Four stroke engine	Two stroke engine
1. One power stroke for every two revolutions of the crankshaft.	One power stroke for each revolution of the crankshaft.
2. There are inlet and exhaust valves in the engine.	There are inlet and exhaust ports instead of valves.
3. Crankcase is not fully closed and air tight.	Crankcase is fully closed and air tight.
4. Top of the piston compresses the charge.	Both sides of the piston compress the charge.
5. Size of the flywheel is comparatively larger.	Size of the flywheel is comparatively smaller.
6. Fuel is fully consumed.	Fuel is not fully consumed.
7. Weight of engine per hp is high.	Weight of engine per hp is comparatively low.
8. Thermal efficiency is high.	Thermal efficiency is comparatively low.
9. Removal or exhaust gases easy.	Removal of exhaust gases comparatively difficult.
10. Torque produced is even.	Torque produced is less even.

The Rotary Engine

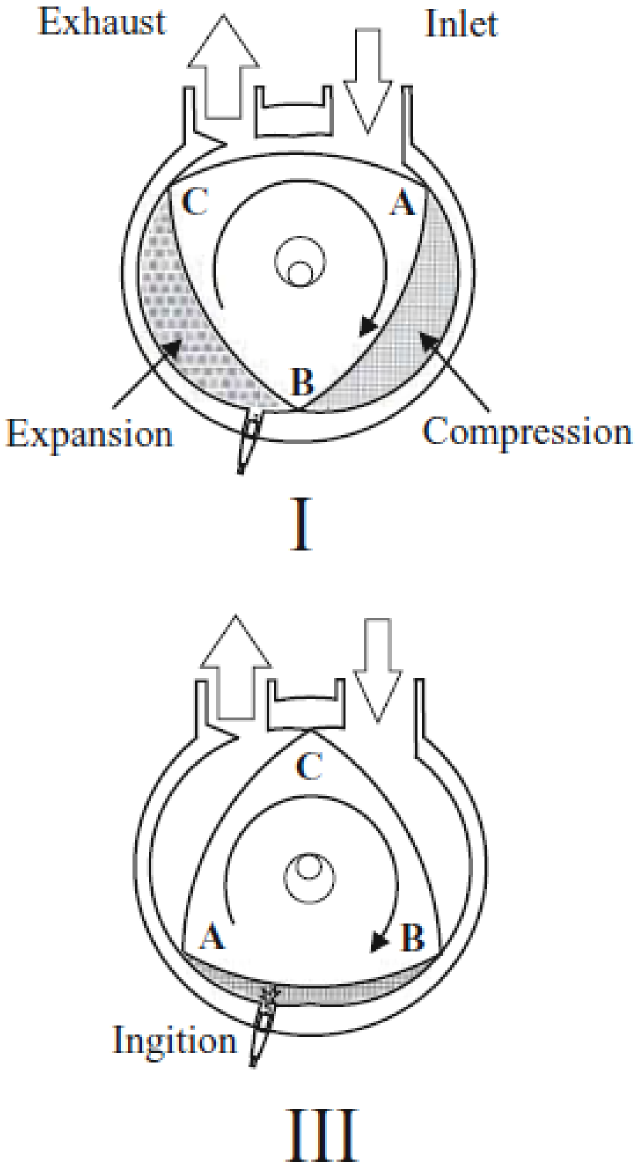
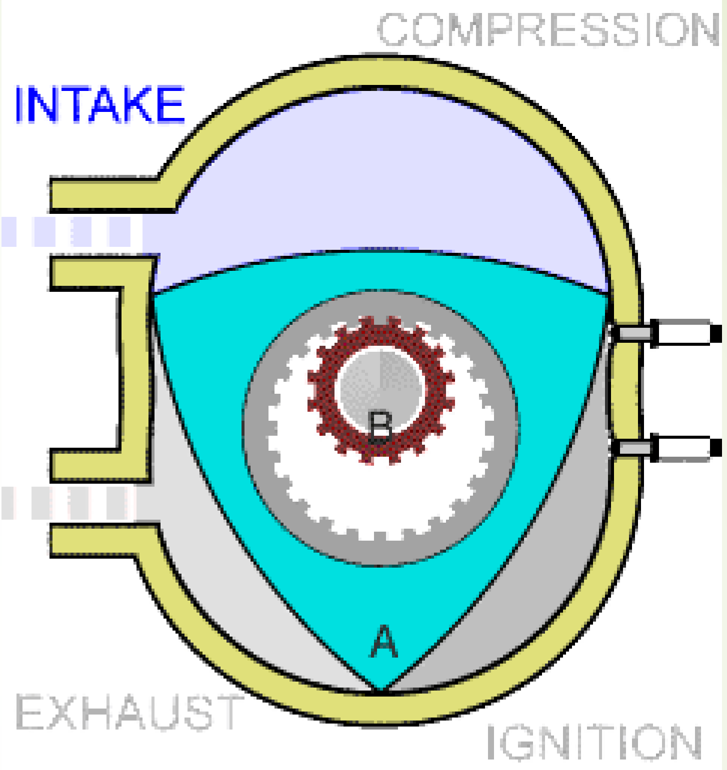
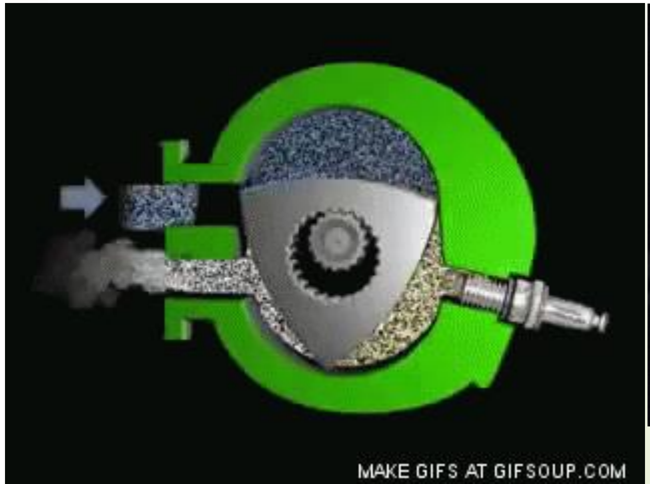
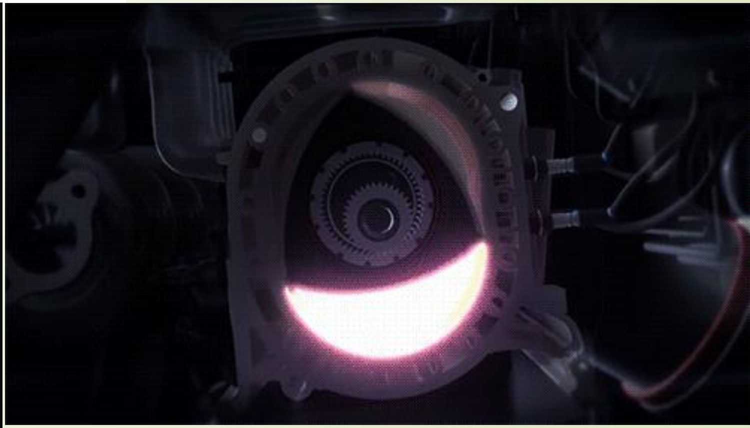


Figure 6.8 Rotary engine







The Gas Turbine

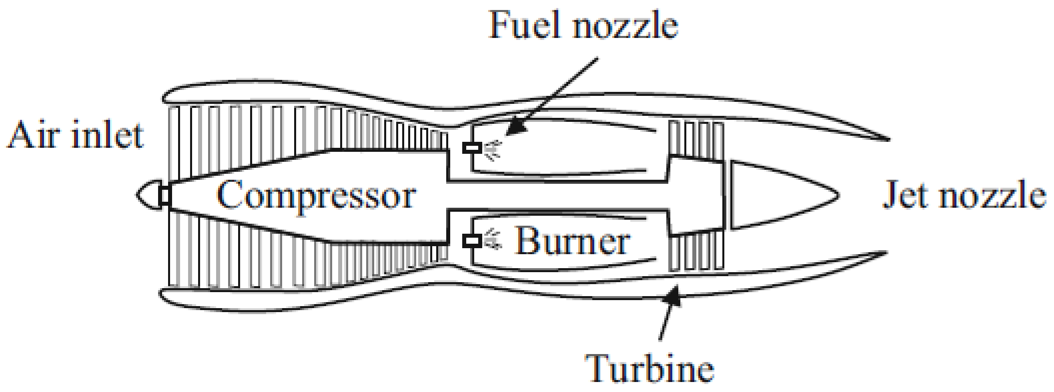


Figure 6.9 Gas turbine schematic

- The gas turbine has **even less vibration than** a rotary engine, is **very efficient at high altitudes,** and burns fuel available on the battlefield or on ships without modification.
- **High-speed** deep penetrators use gas turbines because of their compactness and thrust-producing capabilities.
- **VTOL** vehicles use them for these reasons, and for inherent reliability.
- Their major disadvantages are **high cost** and limitations on their ability to be miniaturized because of aerodynamic scale effects.

Electric Motors

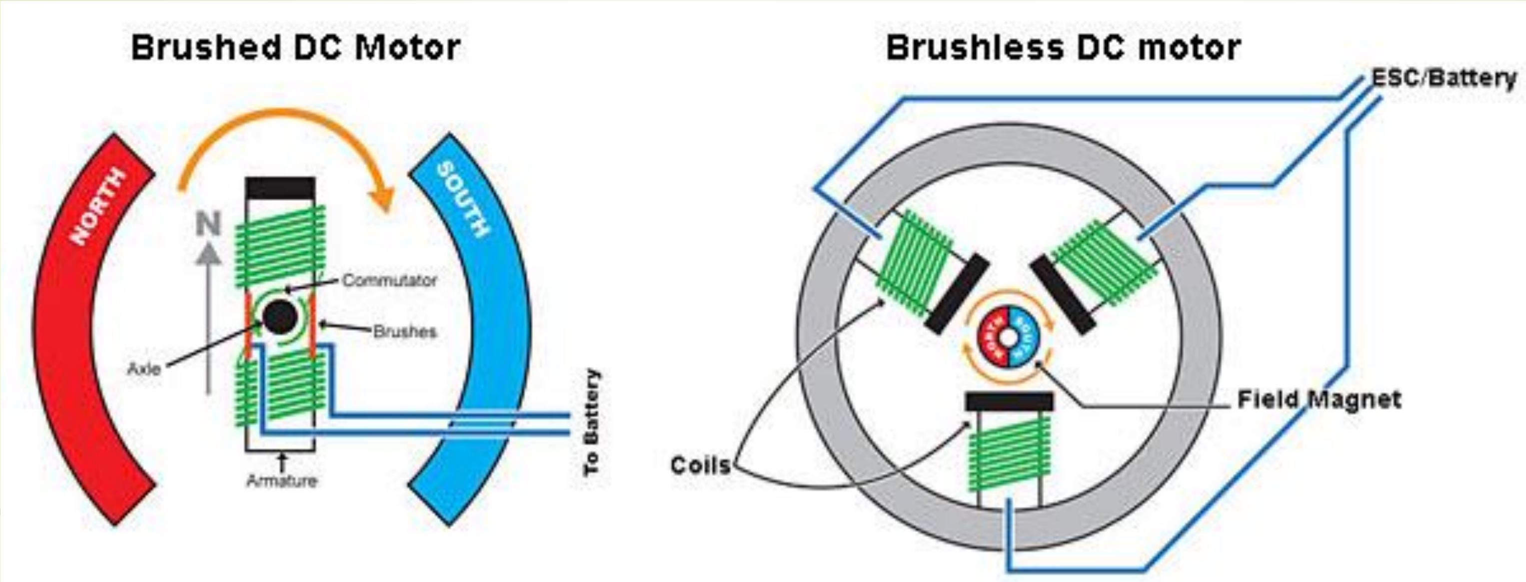
- With the advent of long endurance, high-altitude loitering UAVs and micro-UAV's, electric motors have become a source of propulsion that can be attractive for a number of reasons.
- They may have an electric motor that turns a propeller or rotor or may use electric motors to mimic the flight of birds or insects using flapping wings.
- The energy supplied to the motor can come from a number of sources. It often comes from batteries but also can come from solar cells and/or fuel cells.
- Electrically-powered airplanes or model airplanes are not new. Some were said to have flown as early as 1909, although that has been disputed and it has been claimed that the first one flown was in 1957.
- The range and endurance characteristics of an electrically-powered aircraft are subject to the aerodynamics of the vehicle in a similar way to airplanes powered by other sources of energy.

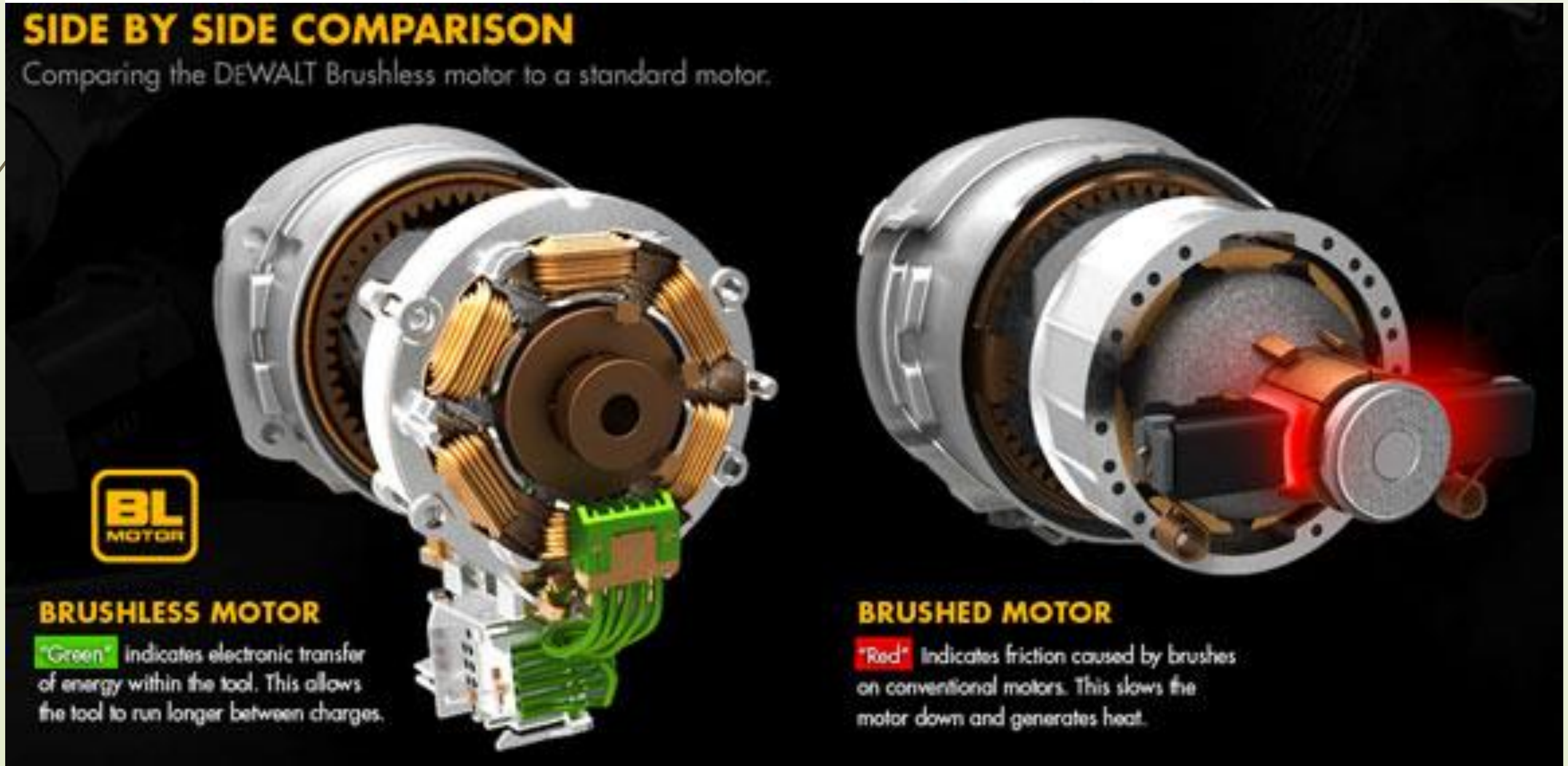
Electric Motors

- There are two types of electric motors commonly used for UAVs.
- The first type is **a “canned” motor**. This is a **standard DC motor with brushes.**
- The second type is a **brushless motor**. Brushless motors are much **more efficient and lighter than canned motors.** Since they have no brushes, there is less friction and are virtually no parts to wear out, apart from the bearings.
- The torque (*J*) produced by an electric motor is proportional to the current (*I*) passing through its coils:

$$J = K_t(I - I_n)$$

- where *In* is the no load current, *I* is the current that produces the torque *J*, and *Kt* is the torque
- constant of the motor, which is a measure of its efficiency. The torque constant usually is
- provided by the motor manufacturer.


Brushed DC Motor
NORTH
SOUTH
N
Commutator
Brushes
Axle
To Battery
Armature
Brushless DC motor
ESC/Battery
Field Magnet
Coils


SIDE BY SIDE COMPARISON
Comparing the DEWALT Brushless motor to a standard motor.
BL MOTOR
BRUSHLESS MOTOR
"Green" indicates electronic transfer of energy within the tool. This allows the tool to run longer between charges.
BRUSHED MOTOR
"Red" Indicates friction caused by brushes on conventional motors. This slows the motor down and generates heat.

- As described earlier in this chapter, **the efficiency of a propeller, rotor, or fan is proportional to the area of its disk, which is proportional to the square of its diameter** and the most **efficient way to produce thrust or lift** with any of them is to have **a large diameter and relatively slow rotation**.
- With **reciprocating internal combustion engines**, it generally is **possible to match the revolutions per minute (RPM) of the engine to the desired RPM of a propeller**, particularly when using **a variable-pitch propeller**.
- **For gas turbine engines**, the factors that affect the efficiency of the engine itself lead to a need to run the engine at **a high RPM and gear down to the desired RPM for the propeller of rotor.**
- With **electric motors**, it is possible to produce **the same torque at all RPM**, but the size and weight of the motor can be reduced by running the motor at high RPM and **gearing it down as needed to produce the desires propeller or rotor torque and RPM**.

Sources of Electrical Power

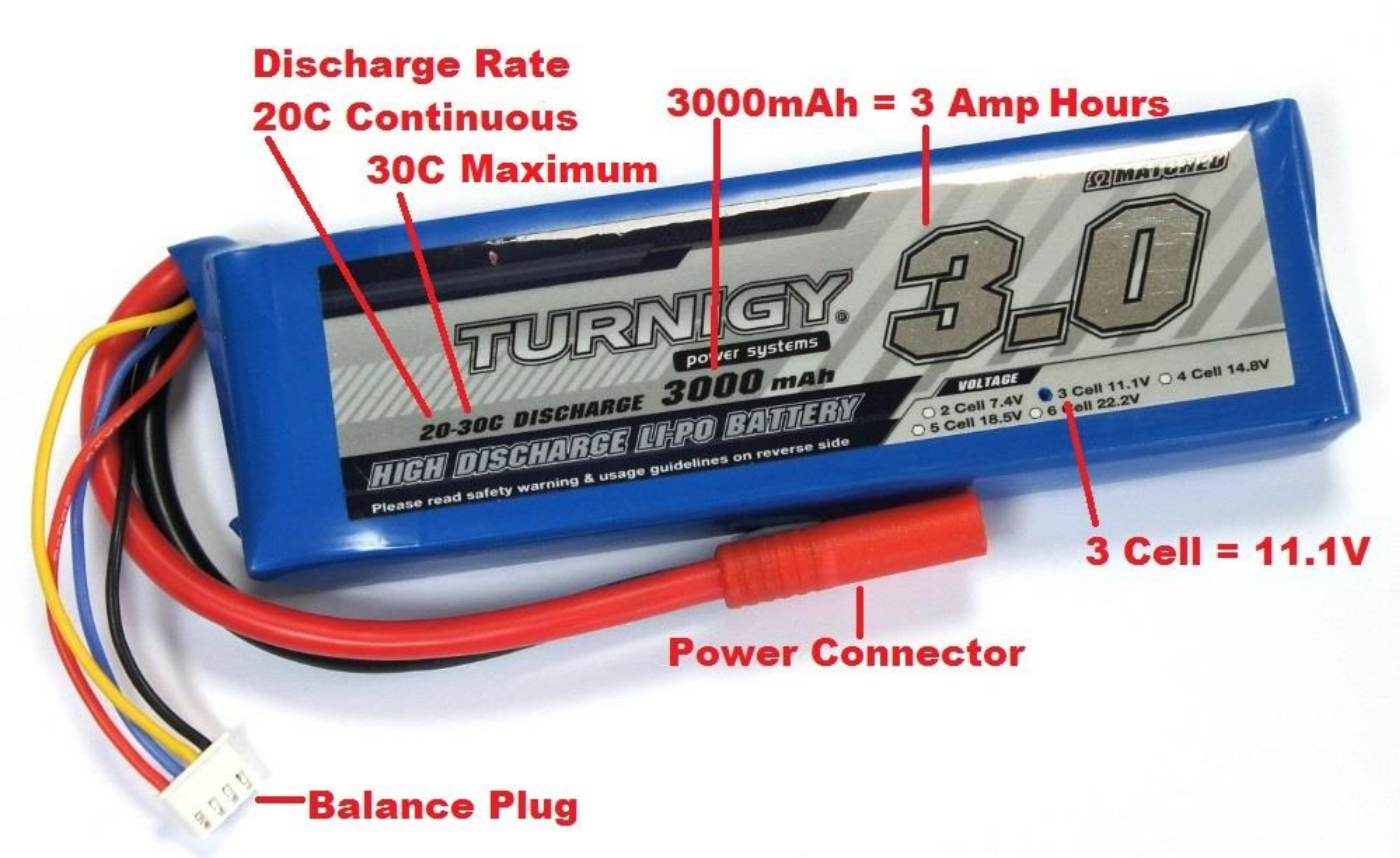
- **the fuels used for internal combustion engines**, which are generally **well understood from everyday experience with ground vehicles**,
- but **electric motors** create a situation in which there are a **number of options** for **how to provide the electrical current that it is the "fuel" that makes the motor run**.
- **Batteries**
  - ***Nickel–Cadmium Battery***
  - ***Nickel–Metal Hydride Battery***
  - ***Lithium-Ion Battery***
  - ***Lithium-Polymer Battery***
- **Solar Cells**
- **Fuel Cells**

Batteries

- **Batteries** can generate **a respectable amount of power (energy per unit time).**
- **The limit** of their **total energy-storage capacity has the same effect on the endurance** of an **air vehicle as the size** of the fuel load has on that of an aircraft using an internal combustion engine.
- Batteries having **a higher energy-storage density per unit weight** are the subject **of intense research**.
- Battery packs for UAVs are usually **rechargeable.**

The key characteristics of a battery are as follows:

- **Capacity**—The **electrical charge effectively stored** in a battery and available for transfer during discharge. Expressed in **ampere-hours (Ah) or milliampere-hours (mAh).**
- **Energy Density**—Capacity/Weight or Ah/weight.
- **Power Density**—Maximum Power/Weight in Watts/weight.
- **Charging/Discharging rate (C rate)—**The maximum rate at which the battery can be charged or discharged, expressed in terms of its total storage capacity in Ah or mAh.
  - A rate of 1 C means transfer of all of the stored energy in 1 h; 0.1C means 10% transfer in 1 h, or full transfer in 10 h.



Discharge Rate
20C Continuous
30C Maximum
3000mAh = 3 Amp Hours
TURNIGY
power systems
3.0
20-30C DISCHARGE
3000 mAh
HIGH DISCHARGE LI-PO BATTERY
Please read safety warning & usage guidelines on reverse side
VOLTAGE
2 Cell 7.4V
3 Cell 11.1V
4 Cell 14.8V
5 Cell 18.5V
6 Cell 22.2V
3 Cell = 11.1V
Power Connector
Balance Plug

Batteries

Nickel–Cadmium Battery

- **The nickel–cadmium (NiCd)** battery **uses nickel hydroxide as the positive electrode (anode)** and **cadmium/cadmium hydroxide as the negative electrode (cathode).**
- **Potassium hydroxide is used as the electrolyte.**
- Among rechargeable batteries, **NiCd is a popular choice** but contains toxic metals.
- NiCd batteries have generally been used **where long life and a high discharge rate is important.**

Battery
Nickel–Metal Hydride Battery

- The **nickel–metal hydride (NiMH**) battery uses a **nickel hydroxide as the positive electrode (anode) and hydrogen-absorbing alloy for the negative electrode (cathode) instead of cadmium.**
- The NiMH has a **high-energy density** and uses **environmentally friendly metals.**
- The NiMH battery offers up to **40% higher energy density compared to NiCd**.
- The NiMH has been **replacing the NiCd in recent years.** This is due both to **environmental concerns** about **the disposal of used batteries** and the **desirability of the higher energy density**.

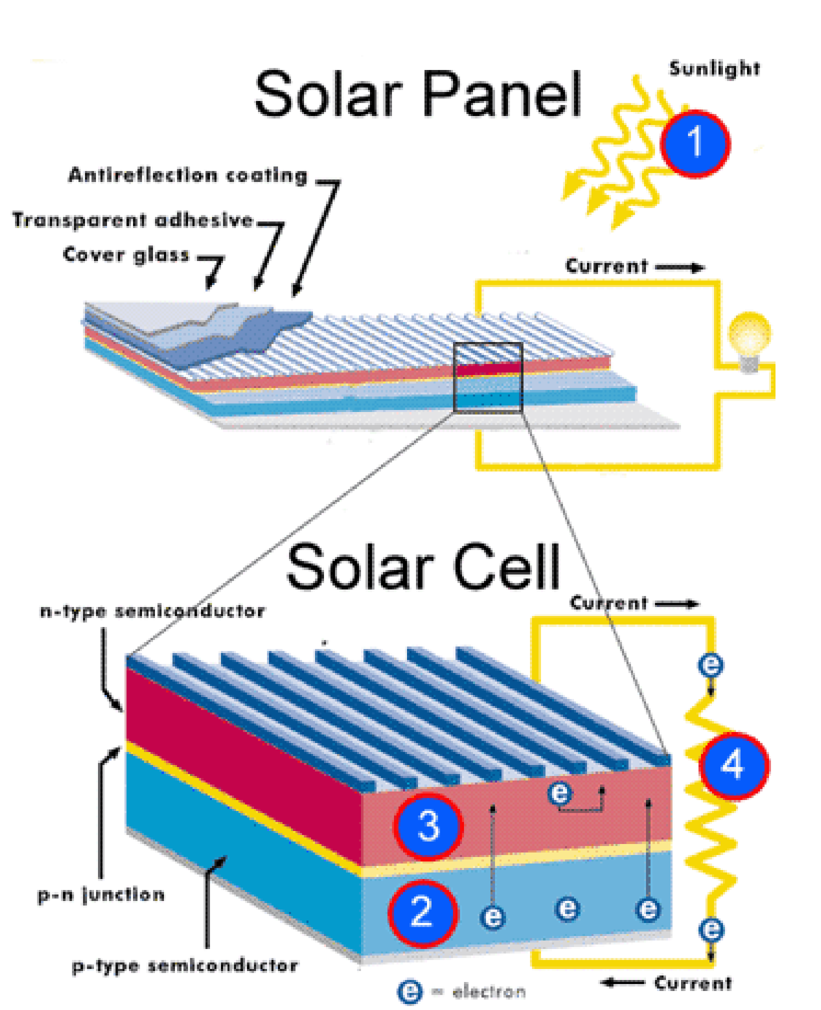
Battery
Lithium-Ion Battery

- The **lithium-ion (Li-ion)** battery is **a fast growing battery technology** because it offers **high energy density and low weight**.
- Although **slightly lower in energy density than lithium metal,** the energy density of the Li-ion is **typically higher than that of the standard NiCd.**
- Li-ion batteries **are environmentally friendly for disposal**.
- Li-ion batteries typically use **a graphite (carbon) anode and an anode made of $LiCoO_2$ or $LiMn_2O_4$. $LiFePO_4$** also is used.
- **The electrolyte is a lithium salt in an organic solvent**. These materials are **all relatively environmentally friendly.**
- Li-ion is the presently used technology for **most electric and hybrid ground vehicles** and its maturity and cost are likely to be driven by the large commercial demand.

Battery
Lithium-Polymer Battery

- **The lithium-polymer (Li-poly)** battery uses **$LiCoO_2$ or $LiMn_2O_4$ for the cathode and carbon or lithium for the anode**.
- The **polymer electrolyte replaces** the traditional porous separator, which is soaked with a liquid electrolyte.
- The **dry polymer design** offers **simplifications with respect to fabrication, ruggedness, safety and thin-profile geometry**.
- It allows **great freedom to choose the shape of the battery, including wafer-thin geometries.**

Solar Cells



- The basic principle of a **solar cell** is that **a photon from the sun** (or any other light source) is **absorbed by an atom in the valence band of semiconductor material** and an **electron is excited into the conduction band of the material**.
- In order for this to happen, **the photon must have enough energy** to allow the **electron to jump through an "energy gap"** that separates the conduction band from the valence band and is due to quantum mechanical effects that create"forbidden" energy states in a crystalline material.