Turbulent Combustion

The motion of the charge in the engine cylinder is always 
**turbulent**, when it is reached by the flame front. The charge motion is usually composed by 
**large vortexes**, whose length scales are limited in size by system boundaries, that distort the flame front, and by 
**small eddies**, whose scale length is smaller than the thickness of the flame front, that intensify the processes of energy and mass transfer in the reaction zone, enlarging the front thickness. When the flame front approaches the relatively cold walls, **quenching** occurs, that leaves a thin (<0.1 mm) layer of unburned mixture. Sometimes the flame could even be extinguished due to a very low combustion rate, leaving a finite volume of charge only partially burned. During the expansion stroke the cylinder pressure decreases and the elements of unburned mixture come out of the small volumes and are desorbed from deposits and oil film. Then, during the exhaust stroke, the piston scrapes the quenching layer from the cylinder walls and mixes it up with the cylinder charge. Part of the hydrocarbons which escaped the primary combustion process are then oxidised, but only if the gas temperature is sufficiently high and in presence of enough oxygen.

Normal vs Abnormal Combustion in SI engine

**SI Combustion**

In SI engines, combustion is started, close to the end of the compression stroke, by the electrical discharge produced by the spark-plug electrodes of the ignition system.

In a conventional SI engine, the fuel is completely vaporized and homogeneously premixed with air and residual gas when combustion occurs. Under normal operating conditions, the mixture is ignited by the spark-plug at an optimized instant of the cycle, around the end of the compression stroke (usually 20-40° BTDC).

The combustion is **normal** when 2 conditions are respected:
1) the ignition of combustible mixture is controlled by the spark plug, with a present timing
2) after the ignition, the flame propagates regularly to the whole mixture, without any sudden increase of velocity.
Usually 3 combustion phases are distinguished:

1) Initial flame development, during which the small volume of mixture, ignited by the spark plug, is gradually transformed into a developed front of turbulent flame. This phase start with the spark ignition and ends when the pressure inside the cylinder clearly increase because of combustion.

2) Turbulent flame propagation
The turbulent flame rapidly spreads over the main part of the combustion chamber, whose volume remains almost constant, since in this phase the piston moves slowly around TDC. This is the main phase characterized by a rapid burning. It begins when 4-8% of the mixture volume has been ignited and it ends when the flame front comes near the walls and the max pressure in the cylinder is reached.

3) Burnout, during which the mixture completes its oxidation processes behind the flame front, when the expansion stroke is occurring.

Engine speed
The engine speed varies but the engine is regulated such a way the peak of pressure is almost independent from \( n \) and happen between TDC and 20° ATDC. This is the optimal synchronization of pressure evolution inside the cylinder in order to obtain a max torque. The In-cylinder turbulence intensity is proportional to the mean piston speed, which scales with \( n \). When the time available for combustion is reduced, because of higher \( n \), the combustion velocity is almost proportionally increased by the higher turbulence. As a consequence, combustion duration, expressed in crank angle degrees does not depend on the rotational speed in a SI engine.

Engine load
Velocity of flame propagation clearly decreases with reducing the load, the combustion process becomes slower and longer at partial load because:
- There is a higher dilution of the fresh charge with the inert residual gases of the previous cycle;
- Thermal losses produce a more important reduction of the burning charge temp;
- Charge density is lower at the beginning of compression stroke and so, being equal the compression ratio, also at the beginning of the combustion process.
As a consequence, when the engine load decreases, it becomes necessary to increase the spark-advance, in order to equally distribute the combustion duration around TDC.
**Equivalence ratio**

The minimum combustion duration is obtained for **slightly rich mixtures** ($\phi = 1.05 \sim 1.15$), where the laminar flame speed is maximum. For **leaner** or **richer mixtures**, combustion duration increases. In both cases, the reacting mixture is diluted with either an air or a fuel excess, thus reducing the stoichiometric concentration of oxygen or fuel, respectively.

The curve is not symmetric, but is **steeper** on the **leaner side**. In this condition, influence of charge dilution (mainly by N2 in air) becomes more significant. As a consequence, SI engines can work with relatively rich mixtures, while operation with lean mixtures is much narrower.

In spite of a great interest for **lean mixtures**, because of lower fuel consumptions and emissions, the operation becomes unstable for equivalence ratio $\phi < 0.80$. Indeed with such a lean mixture the combustion duration becomes too long and the **cyclic variations** too high.
**Abnormal combustion**

When the 2 conditions of normal combustion do not occur, the combustion process is abnormal, causing engine damages or simply performance worsening and noise. There are two forms of abnormal combustion in SI engines:

1) **Surface ignition**: combustion originates from some hot spots in the combustion chamber. The flame front generated by surface ignition is really similar to the turbulent burning generated by a spark plug, BUT in this case the moment of ignition is not controlled. Pre-ignition in most dangerous because it advance the ignition moment, therefore the useful work output decrease, temperature and pressure of the working fluid increase. This process is self-increasing, until some engine components collapse. This problem can be solve by a proper design of the engine and the use of good quality lubricant.

2) **Knock**: the fresh charge auto-ignites before being reached by the flame front. It is caused by the high temperatures and pressures reached within the cylinder. The high release of energy due to the sudden combustion of a large mass of end gas produces a significant local increase of the gas pressure, causing a shock wave to propagate from the auto-ignition point through the combustion chamber. Then the pressure waves are repeatedly reflected by the walls and they create an oscillatory pressure trend versus time. Knock is the name given to the metallic noise (a sort of hammering) produced by the vibrations of the engine components, excited by these pressure oscillations. Knock intensity depends on the amount of end-gas mass that auto-ignites.

**Engine parameters which influences knock tendency:**

1) **Compressiion ratio**: at high compression ratios, even before spark ignition, the fuel-air mixture is compressed to a high pressure and temperature which promotes auto-ignition.

2) **Engine speed**:
   - at low engine speeds the flame velocity is slow and thus the burn time is long, this results in more time for auto-ignition
   - at high engine speeds there is less heat loss so the unburned gas temperature is higher which promotes auto-ignition

3) **Spark timing**: maximum compression from the piston occurs at TDC, increasing the spark advance makes the end of combustion at TC (crank angle) and this leads to high pressure and
temperature and presence of end gas that increase the risk of knock. Spark timing is set 1% below the point of max brake torque (MBT) to avoid this situation.

**Engine layouts decreasing knock tendency:**
- Compact combustion chamber shape
- Central spark plug (symmetric flame propagation)
- Hot spots close to spark plug
- Controlled gas motion