8.0 NORMAL AND ABNORMAL COMBUSTION

In a conventional spark-ignition engine the fuel and air are mixed together in the intake system, inducted through the intake valve into the cylinder, where mixing with residual gas takes place, and then compressed. Under normal operating conditions, combustion is initiated towards the end of the compression stroke at the spark plug by an electric discharge. Following inflammation, a turbulent flame develops, propagates through this essentially premixed fuel, air, burned gas mixture until it reaches the combustion chamber walls, and then extinguishes.

Combustion in a spark ignition engine is termed normal if it is initiated by a timed spark plug and the air-fuel mixture (charge) is consumed solely by the propagating flame front which originated from the discharged spark and completely moves across the combustion chamber. Pressure oscillations from combusting charge, which results from abnormal combustion; which could be detrimental to the engine components, does not occur in normal combustion. Abnormal combustion in spark ignition engine majorly occurs as knock and surface ignition. While all abnormal combustion in spark ignition engines do not lead to knock (as seen in non-knocking surface ignition), most do.

Knock being a form of abnormal combustion, can be defined as a phenomenon which leads to high pressure oscillation in the combustion chamber of an engine as a result of the spontaneous auto-ignition of end-gases ahead of the propagating flame in the combustion engine. This auto-ignition of these end-gases occur as a result of increase in temperature experienced by the end gases as a result on the compression from the propagating flame and heat transfer through radiation from the propagating flame.

Surface ignition being the ignition of air-fuel mixture by hot spots in the engine combustion chamber like glowing combustion deposits, over heated valves or spark plugs by other means other than a timed spark plug discharge. Surface ignition can take place before or after the introduction of spark and such ignition before and after the introduction of spark is known as preignition and postignition respectively.

8.1 Knock in Engines

Increasing the intake air density of an engine through supercharging or turbocharging increases the indicated mean effective pressure (IMEP) of an engine with a slight increase in frictional mean effective pressure (FMEP). This translates to the realisation of an increased engine brake mean effective pressure (BMEP) over the non-boosted engine in-take. Realization of a required power output from an engine of a reduced size, by increasing the intake air through turbocharging is known as engine downsizing but this increase in the intake air density has been known to also increase the tendency of severe knock to occur in the engine. Engine knock is a combustion phenomenon that is unacceptable in engine operation because the possibility of damage to engine components if severe and prolonged and the sound which is unpleasant to the ears.

Fig. 1: Effect of abnormal combustion on engine components

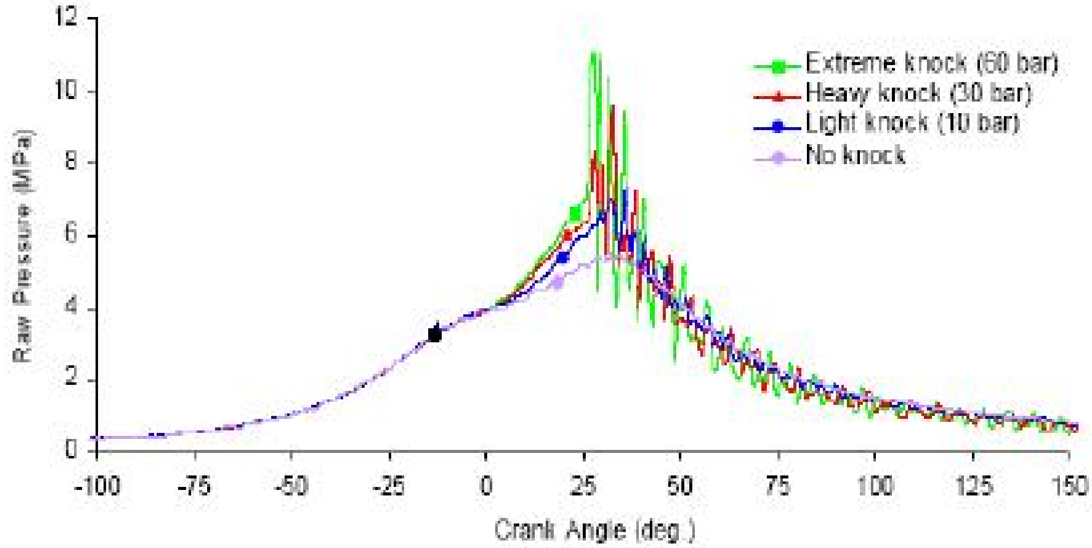

Fig. 2: Pressure data of firing cycles

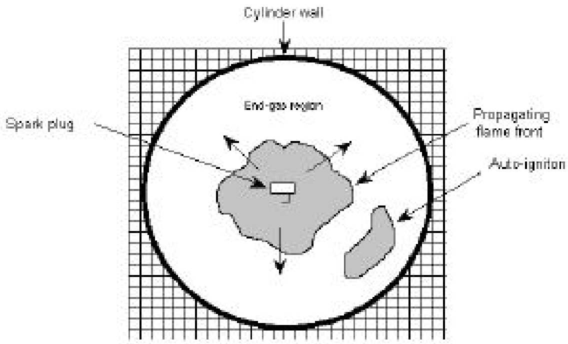

Fig.3: A diagram of a propagating flame with an auto-ignited end-gas

Engine knock is an abnormal combustion in engines which results to high pressure oscillation in the engine combustion chamber. This occurs as a result of the autoignition/detonation of ends gases at the later stages of combustion or preignition. The high pressure oscillation observed during the detonation of end gases, during flame propagation, has a detrimental effect on the engine component and this makes engine designer and manufacturers avoid the knocking regions during spark ignition engine operation. The abnormal combustion as a result of engine knock, limits the compression ratio at which a spark ignition engine can operate at. The knocking effect is eliminated in spark ignition engines by retarding the spark timing.

Autoiginition in spark ignition engines is the spontaneous ignition and combustion of the air/fuel mixture in the engine cylinder without the introduction of spark from the spark plug. Autoignition in spark ignition engines could either be pre-ignition or post-ignition which depends on the time of occurrence. Pre-ignition being the auto-ignition of the air/fuel mixture before the introduction of spark from the spark plug while post-ignition is the auto-ignition of the air/fuel mixture far ahead of the propagating flame. In both cases, the combustion is abnormal. It should be noted that, not all autoignition in spark ignition engines leads to engine knock. In the occurrence of abnormal combustion in spark ignition engines, the major phenomena are KNOCK and SURFACE IGNITION.

Knock is the audible pinging sound heard as a result of auto-ignition of the air/fuel mixture in a spark ignition engine combustion chamber which sound level and oscillation depends on the on the intensity of the knock while surface ignition is the autoignition of the air/fuel mixture from a hot or glowing spot in the combustion chamber. These hot or glowing spots could be at the spark plug, the valve or soot on the piston crown.

While spark-knock can be controlled by retarding the spark timing in the spark ignition engine, knock as a result of surface ignition cannot be controlled by retarding the spark timing. Knocking from surface ignition, most of the time, results from pre-ignition which is caused by a glowing/very hot surface in the combustion as a result of combustion deposit. Non-knocking surface ignition occurs normally during post-ignition period.

Other auto-ignition phenomena which are also seen during abnormal combustion in spark ignition engines are:

For knocking surface ignition:

1) Preignition, if significant deposits are present on critical combustion chamber components. This could lead to runaway preignition.
2) Runaway knock-spark-knock occurring earlier and earlier, and therefore more and more intensely. This soon leads to severe engine damage.
3) Gradual erosion of regions of the combustion chamber, even if runaway knock does not occur.

The other abnormal combustion phenomena in Fig.4, while less common, have the following identifying names.

- Wild ping is a variation of knocking surface ignition which produces sharp cracking sounds in bursts. It is thought to result from early ignition of the fuel-air mixture in the combustion chamber by glowing loose deposit particles. It disappears when the particles are exhausted and reappears when fresh particles break loose from the chamber surfaces.

- Rumble is a relatively stable low-frequency noise (600 to 1200 Hz) phenomenon associated with deposit caused surface ignition in high-compression-ratio engines. This type of surface ignition produces very high rates of pressure rise following ignition. Rumble and knock can occur together.
- Run-on occurs when the fuel-air mixture within the cylinder continues to ignite after the ignition system has been switched off. During run-on, the engine usually emits knock-like noises. Run-on is probably caused by compression ignition of the fuel-air mixture, rather than surface ignition.
- Runaway surface ignition is surface ignition that occurs earlier and earlier in the cycle. It is usually caused by overheated spark plugs or valves or other combustion chamber surfaces. It is the most destructive type of surface ignition and can lead to serious overheating and structural damage to the engine

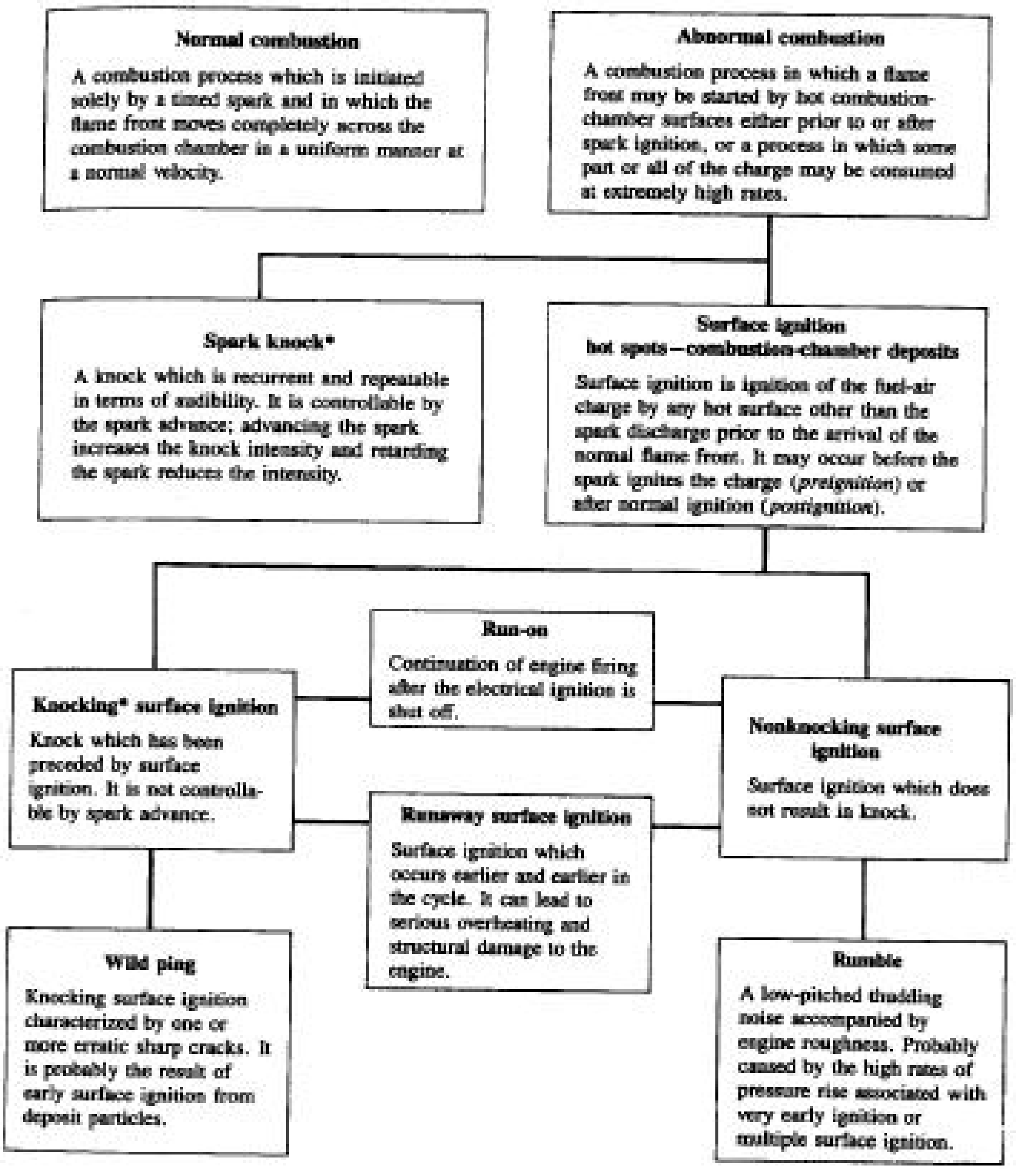

Fig. 4: Combustion phenomena (normal and abnormal)

8.2 Trends in Engine Knock Analysis

Burnt et al and Rothe et al investigated the effect of sample size, the location of the mounted pressure transducer and the effect of sampling frequency on the knock analysis result using pressure data. Various knock detection methods for engine pressure data were compared by Burgdorf and Denbratt. The effect of octane sensitivity (RON-MON) on the anti-knock quality of fuel was investigated by Bell, and it was found that fuels with high octane sensitivities were more resistant to knock than the fuels with lower sensitivity.

Mittal et al, Revier B. M. investigated knock onset in spark-ignition engines, using the in-cylinder and microphone knock analysis technique. Merola et al conducted an investigation of abnormal combustion in a boosted SI engine running on PRF90. Optical investigation of the combustion process of a blend of butanol and gasoline in a boosted engine was investigated by Merola et al. and optical analysis in spark-ignition engines. Fitton and Nates investigated the role of knock on the seizure of piston in spark-ignition engines.

Existing knock indicators for SI engines were investigated by Brecq et al, with a development on an ungraded indicator which easier to calibrate. A model with the ability to predict knock onset in SI engine with cooled EGR was developed by Chen et al. Probability Density Function (PDF) approach was employed with detailed chemical kinetics for the prediction of knock in a boosted direct injection spark ignition engine by Linse et al.. Knock occurrence in a turbo-charged SI engine was characterised both numerically and experimental by Galloni et al with an insight in the positioning of pressure transducers for knock tests.

8.3 Factor Influencing Knock Onset in Engines

Knock in SI engine is an abnormal combustion phenomenon which is undesirable to engines manufacturers and users. It results as from auto-ignition of the air-fuel mixture at an undesirable period during engine operation. Some factors are known to influence knock onset in engines and they include:- Spark timing, inlet pressure, inlet temperature, compression ratio, equivalence ratio, engine speed, in-cylinder flow condition and combustion chamber geometry.

8.3.1 Spark Timing

During the operation of a spark ignition engine, advancing it spark timing increase the peak in-cylinder pressure realised from combustion. A continued advancement in the spark timing, lead to high pressure oscillation in the combustion chamber as a result of the detonation of the end gas which effect is detrimental to the engine components if the engine is ran in this condition for a period of time. This type of knock is called **spark-knock** and it is eliminated by retarding the engine spark timing.

8.3.2 Inlet Pressure

Increasing the inlet pressure of an engine, translates to increasing the amount of air-fuel mixture inducted into the engine cylinder which in-turn releases higher combustion energy and also increases the tendency of auto-ignition and knock.

8.3.3 Inlet Temperature

An increase in the air-fuel mixture inlet temperature increases it reactivity and increases the chances of the auto-ignition of the air-fuel mixture during compression stroke.

8.3.4 Compression Ratio

Knock in spark ignition engines is the limiting factor in the increase of the efficiency of an engine. Increase in engine compression ratio increases the temperature of the air-fuel mixture during compression which could lead to auto-ignition of the mixture to occur if the auto-ignition temperature is attained before the introduction of spark.

8.3.5 Equivalence Ratio

Experiments have shown that spark ignition engines running on lean mixtures are more prone to knock than the richer mixtures. This can be attributed to a reduction in flame speed with reduction in mixture equivalence ratio which gives time for the auto-ignition of the end gas.

8.3.6 Engine Speed

For engine operation, the engine spark timing is advanced with an increase in engine speed. A slower engine speed gives more time and increases the tendency of the end gas auto-igniting as a result of increase in temperature and pressure. Experiments performed by Atashkari came up with a correlation that relates engine turbulence intensity U' for a ported engine with radial opposed intake with the piston speed $\bar{S}_p$ at the Top Dead Centre (TDC) to be:

$$U' \approx 0.47 + 0.49\bar{S}_p$$

Increased turbulence intensity increases the in-cylinder turbulent burning velocity which does not give the end gas time to auto-ignition before being consumed by the propagating flame.

8.3.7 In-cylinder Flow Condition

Increase in turbulence and swirl in the combustion chamber enhances the mass burning rate of the mixture which enhances combustion.

8.3.8 Combustion Chamber Geometry

The shape of the combustion chamber and the location of the spark plug influences combustion rate. The faster the combustion of the mixture, the lesser the tendency of knock onset in the engine. The combustion chamber shape also determines the in-cylinder flow condition.

NB: In spark ignition engine combustion cycles being operated at the knock regime, faster burning cycles have been observed to be prone to knock than the slower burning cycles. This could be explained thus: during engine operation, increase in temperature of the unburnt charge (end gas) does not only come from the piston compression; the propagating flame also compresses the end gas leading to a increase in temperature. The faster the propagating flame the higher the compression which translates to rapid increase in end gas temperature. If the auto-ignition temperature is attained before the propagating flame arrives, auto-ignition of the end gas takes place.

8.4 Knock Onset Detection

To detect the onset of knock in engines, various techniques have been employed. They include:-

- In-cylinder pressure data analysis
- Heat transfer data analysis
- The use of accelerometer to detect engine vibration.
- Spark plug Ionization probe
- Optical detector
- The use of microphones/headphones
- By listening

8.4.1 In-cylinder Pressure Data

In-cylinder pressure data processing is one of the most widely used technique in knock onset detection and knock analysis. The method of data processing, using pressure data for engine knock analysis, has been carried-out in different ways by different researchers which have made the adoption of a data processing technique difficult. The pressure oscillations are filtered at a cut-off frequency (about 5 kHz and 8 kHz) and the high frequency pressure oscillation signals are used to calculate the knock indices. Mittal et al found knocking pressure oscillation frequencies to occur above 6 kHz.

8.4.2 Heat data analysis

Knock occurrence in internal combustion can be detected from heat transfer analysis. High increase in heat transfer in engines is observed from with abnormal combustion. This process of knock onset determination technique are not effective for the determination of light knock conditions due to the negligible increase in heat transfer which are associated with light knock and are difficult to detect.

8.4.3 The use of accelerometer to detect engine vibration

Accelerometers have been employed or integrated with spark ignition engines to monitor vibrations in engines at knock in knocking conditions. The sensor sends a feedback to the control unit when the engine speed increases; the sensor could pickup false vibrations from other engine component like vibrations from the valve movement. The voltage output from the accelerometer Electronic Control Unit (ECU) for the knock intensity comes in three different levels: 0 V means non-knocking condition, > 0V & < 2V means light knocking condition and > 2V means heavy knock condition.

8.4.4 Spark plug Ionization probe

Spark plug ionization probe technique is employed in the detection of knock (abnormal combustion) in engine operation. After the ignition, a DC voltage is supplied and the corresponding current measured to test for abnormal combustion in the engine which leads to increase in gas ionization.

8.4.5 Optical detector

The onset of knock could be observed from images obtained form an optical accesses research engine. The auto-ignition of end gases ahead of the propagating flame can be observed from the flame images obtained but these images do not give information on the intensity of the knock phenomena.

8.4.6 The use of Microphone/Headphone

The engine sound output are at various frequencies, are recorded with the aid of recording system setup. Lower frequencies recordings are filtered out (at a cut-off frequency 5-6 Hz) while the higher frequency recordings are processed for the knock indices.

8.4.7 Listening

This is based on the judgement of the listener. The listener determines the onset of knock and it is subject to the listeners hearing and judgement.

8.4.8 Knock Intensity

Knock in spark ignition engine is a phenomenon of abnormal combustion that occurs as a result of auto-ignition of the air/fuel mixture in the combustion chamber. This auto-ignition in most cases (knocking) transmits pressure wave to the engine components that may be damaging to the engine components over time and also metallic or pinging noise which are unpleasant to the human ear. The pressure oscillation which occurs varies in degrees of intensities (from weak to severe oscillation). To quantify the severity of knock in a spark ignition engine, some approaches/ tool are in use.

8.5 Knock Intensity Calculation

Knock intensity could be referred as the magnitude of pressure oscillation or pressure shock wave generated as a result of the in-cylinder detonation which is as a result of the auto-ignition of end gas. Oscillation generated by knock in engines has been found to fall in a frequency range of between 2.5 and 12 kHz which the highest knock frequency amplitude fall in the range of 6 – 8 kHz. This was obtained by using the Matlab fast fourier transform to process audio signal or pressure signals obtained from knock test.

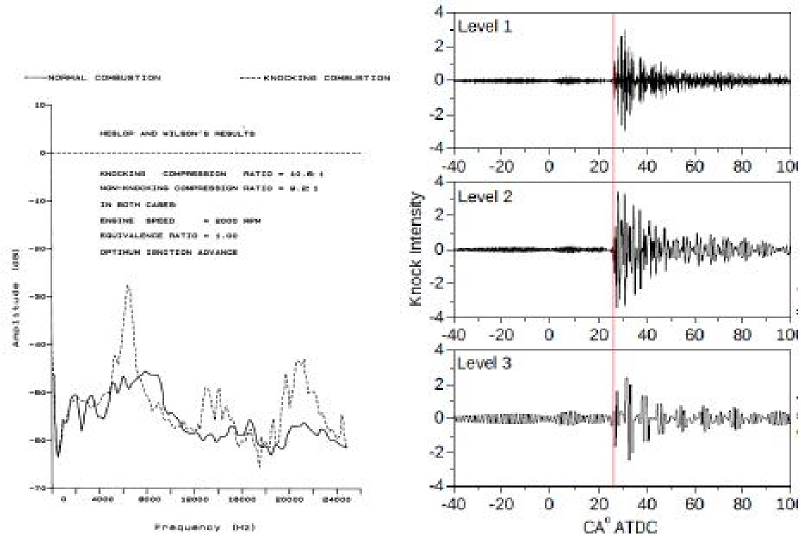

Fig. 5: Knock Intensity