A Review of Combustion Process

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Abstract: *Combustion based noise plays an important role in emissions in engines. In this work these emissions have been analyzed and various factors affecting it have been discussed.*

Keywords: *Piston secondary motion, liner system*

1. Introduction

Combustion noise generated mainly depends on rapid rise of cylinder pressure due to ignition delay period in combustion engines. Design of combustion chamber as well as variations in various injection parameters like injection pressure, amount of fuel injected and its timings also play a crucial role in noise emissions [1]. Depending upon type of engine and various operational parameters, overall noise emissions from a typical engine are in range 80-110dBA [2]. Anderton has investigated the effects of turbo charging on noise emissions from engines [3] .Split injection using electronic control reduces the premixed combustion and hence is an effective way to reduce overall noise emissions by about 5-8dBA [4]. Head and Wakes have shown that during transient operational conditions, overall noise levels are 4-7dBA higher as compared with steady state operations [5]. Cold starting conditions lead to higher ignition delay period which in turn causes more premixed combustion and hence an increase in noise emissions [6]. Quality of fuel also affects combustion noise emissions from engines. It has been seen that reduction of centane number of diesel from 50 to 40 causes a rise of 3 dBA in combustion based noise [7]. In gasoline engines, the ignition delay period is longer due to lesser compression ratio which leads to lower temperature of charge and hence more noise [7]. For a naturally aspirated engine the combustion noise depends upon amount of fuel that mixes with air charge during injection delay period and hence compression ratio of engine also plays a vital role [7].

2. Background

Due to high efficiency, diesel engines have been a favorite choice for heavy duty applications including trucks [8].However they suffer from drawbacks of high noise, weight and vibrations. These engines are of two types: > Direct Injection (D.I.) Engines; > Indirect Injection Engines
In the D.I. engines, the fuel is directly injected inside combustion chamber and due to lesser time for mixing, a heterogamous mixture consisting of both rich and lean parts is formed in the chamber.

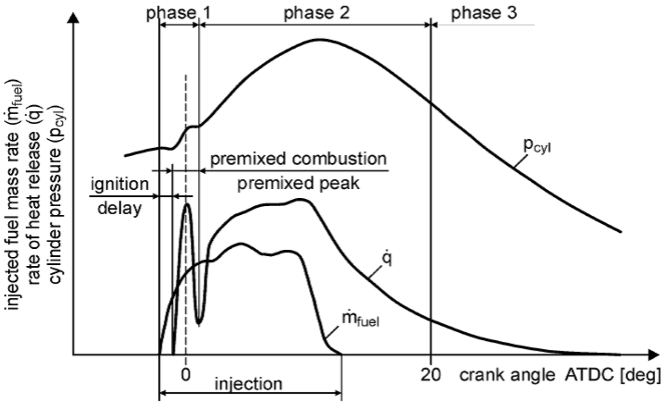

Fig. 1. Phases of Diesel Engine Combustion

Figure no 1 shows the three phases of combustion in a conventional diesel engine. The first phase starts with start of injection process and ends with premixed combustion phase. The direct injection of fuel into combustion chamber begins some crank angle degree before top dead center positions depending upon engine operational conditions. As soon as cold jet of fuel penetrates into chamber, it mixes up with hot compressed air. The droplets begin to vaporize forming a sheath of vaporized fuel-air mixture around jet periphery. When temperatures reach around 750K, the first break down of Cetane fuel occurs. Further reactions produce C_2H_2, C3H3, C2H4, CO2 and water vapors [9].
Resulting rise in temperature causes complete combustion of fuel-air mixture. This sudden combustion causes rise in heat release rate and high pressure gradient $\frac{dP}{d\theta}$ which further leads to high temperatures in pre-mixed zone and NO_x production. The premixed combustion consumes all mixture around inner spray region where temperatures of ranges 1600-1700K are reached and all oxygen available for combustion is consumed [8]. Now various partial burnt particles diffuse to outer layers and are burnt in a thin reaction region at periphery of spray which leads to formation of diffusion flame.
This kind of combustion is known as diffusion controlled combustion and is depicted by region 2 and 3 in the above figure. The high temperatures along with lack of oxygen is ideal for soot formation.

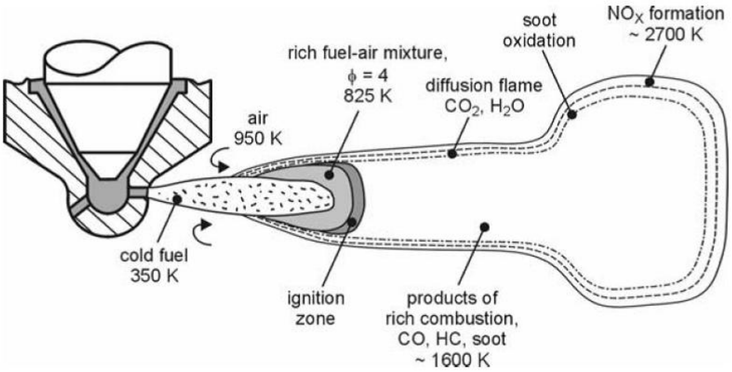

Fig. 2. Conventional diesel engine spray formation

The diffusion flame is fed with oxygen from surrounding environment and high temperatures of range 2700K is reached consuming all the soot formed. At outer region of flame there is enough oxygen content for formation of NO_x.
Figure no 3 shows soot formation concentration as a function of crank angle. Most of soot produced at early crank angles is consumed later and final exhaust emissions have only a fraction of initial one. As seen from figure no 1, the diffusion controlled combustion can be divided into two sub phases. During phase 2 of combustion the burning rate is controlled by mixing of fuel fragments and air and rate of reaction is must faster. During the phase 3 the final oxidation of remaining unburnt particles and soot takes place, however due to decrease of gas temperature during expansion stroke and lack of oxygen the reaction rate is much slower.

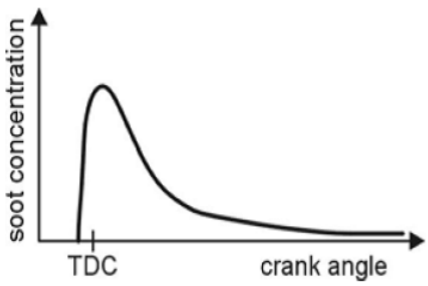

Fig. 3. Rate of soot formation

NO_X and soot formation in combustion engines show an opposite trends as shown in figure no 4. In order to reduce NO_x ,it is necessary that local temperatures must not rise above 2000K.A possible way to do so is to inject fuel late in cycle inside combustion chamber which shifts combustion phase towards expansion phase and hence significant reduction in chamber temperatures. However consumption of fuel and soot formation increases due to late combustion.

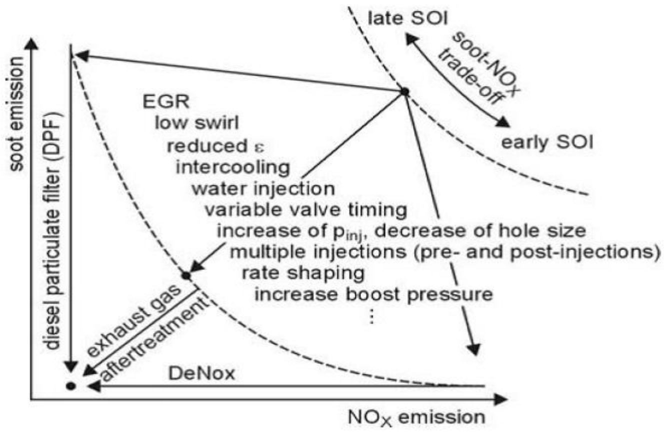

Fig. 4. Soot & NOx trade off

Hence modern injection systems use multiple injection techniques in order to reduce both soot as well as NO_x emissions as seen from figure no 5[8, 10, 11].

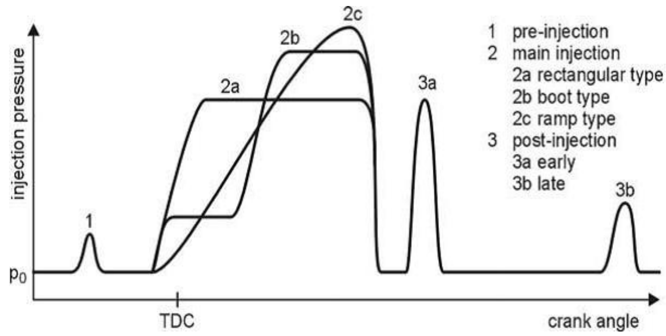

Fig. 5. Multiple injection methods adopted for modern diesel engines

These generally use three phases of injection namely pre-injection Period, Main –Injection Period & Post injection period as seen from figure no 5.There is delay period between the start of ignition process and fuel injected inside diesel engine. More this ignition delay more is the temperature during combustion and hence better condition for NOx formation. To shorten the delay period, small amount of fuel is pre-Injection before main injection during the phase pre-Mixed combustion phase. The torque and power produced in engine depends upon main injection period. It is advantageous to vary injected fuel mass with time to reduce the specific fuel consumption. This method is known as rate shaping. Rate shaping may be rectangular, step or boot in shape. Post-injection of fuel is done to reduce soot emissions and in some cases may be useful for Exhaust gas recirculation treatment of gases [12]. It has been reported that post injection reduces soot by about 70% without increasing the fuel consumption [13].

3. Phase analysis

This part of work presents experimental data in which signals from accelerometers and cylinder pressure transducers are used for analysis of combustion behavior of engines. Previous works have shown that engine vibrations are sensitive towards change in engine injection parameters. Accelerometer signals have been able to locate the important features of combustion process in diesel engines [14, 15]. The aim of present part of work is to explore the relationship between block vibrations and in cylinder pressure development process. Experiments were done at various load and speed conditions to explore the sensitivity of vibration data.

Combustion process monitoring and analysis is an important feature in NVH feature improvement of diesel engines since a major portion of noise is attributed towards the combustion process occurring inside cylinders. Use of in cylinder pressure transducers and other non-intrusive methods of monitoring form an important methodology of combustion analysis. Microphones located at a distance from engine also provide information about engine performance; however there is risk of contamination of signals during engine operational conditions [16-19].The combustion process in diesel engines have various phases as discussed in previous section. The frequency spectrum of combustion noise form diesel engines is divided into three regions as discussed later in this work. The aim of this work is to establish a relationship between engine vibrations and in cylinder pressure development.

4. Results and discussions

The aim of this part is to provide an overview of combustion noise generation process. This was done by analyzing the methodology provided in previous works done. Engine combustion noise originates from combustion process taking place in cylinder. When fuel is injected inside the combustion chamber where high pressure air is present, then part of ignitable gas starts to burn causing a rapid rise in pressure as well as temperatures inside combustion chamber. The pressure wave thus generated also strikes the walls of combustion chamber causing resonance of structure. The vibrations are radiated in air through engine structure and are perceived as combustion noise.
In actual practice it is difficult to distinguish between combustion noise and piston slap as both coincide near top dead center positions. For sake of convenience it is assumed that combustion noise originates due to pressure vibrations inside engine cylinder and is transmitted to cylinder cover, piston, connecting rod, crank shaft and engine surroundings. Mechanical noise includes noise from piston-liner impact, valve operations, pump operations, injector operations as well as operation of various accessories and valve trains. Generally for indirect injection diesel engines and gasoline engines, the combustion process is less severe as compared with diesel engines; hence the combustion noise is lesser as compared with mechanical noise.
The cause of combustion noise is rapid change in cylinder pressure during combustion process. The effects of combustion process consist of high frequency gas vibrations and dynamic load due to rapid pressure change. The intensity of combustion noise (I) is dependent upon the values of maximum pressure value (P_{max}) and maximum rate of pressure rise as [20]:

$$I\alpha[(\frac{dP}{dt})_{max}P_{max}]^2 \quad (1)$$

In a direct injection diesel engine, combustion process occurs in following four phases: retarded, rapid, early and late phase. Combustion noise is mainly generated during rapid phase of combustion however retarded phase has an indirect effect on combustion noise. During this phase of combustion, the firing and fuel propagation results in impulsive pressure wave that gets reflected multiple times after striking walls of chamber. This process causes high frequency oscillations. The frequency (f_g) can be estimated from engine bore diameter (D) &Wave propagation speed (C_c) by:

$$f_g = \frac{C_c}{2D} \quad (2)$$

Further the spectrum plot of cylinder pressure can be obtained from acquired about in cylinder as seen in figure no 6.

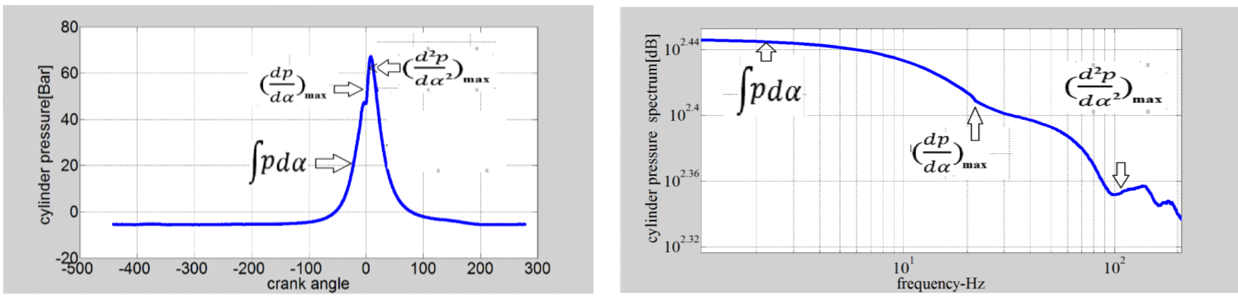

Fig. 6. Regions of combustion noise

The graph is marked by following three distinct regions [20]:
a) Region of low frequency-in this region the curve depends upon peak cylinder pressure. Higher the maximum value of cylinder pressure, higher is the peak in low frequency range.
b) Medium frequency range-in this part the pressure levels decrease in logarithmic range with slope depending upon rate of cylinder pressure Larger the value of pressure gradient, steeper is the slope of curve.
c) High frequency range –in this range rapid evolution of in cylinder pressure occurs due to onset of combustion process which results in high frequency vibrations of cylinder structure having amplitude dependent on second cylinder pressure derivative.
Combustion noise is not only dependent upon cylinder pressure but also upon the structural response and damping effects of engine. The difference between in cylinder pressure and outside noise radiated in engines is characterized by a decay which reflects the structural attenuation of engine structure. Figure no 7 shows a typical plot of structural attenuation of an engine which is independent of exciting forces and cylinder pressure spectrum. Various operational parameters of engine e.g. load, speed & fuel injection parameters have no significant effects on structural attenuation property.

5. Conclusions

This work considers the effects of combustion process on various parameters of noise generated in engines. The various phases and regions of combustion noise in frequency domain were considered.

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