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A Study on Homogeneous Charge Compression Ignition (HCCI) Combustion of Diesel Fuel with External Mixture Formation

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Abstract

Conventional diesel engines operate at higher compression ratios than SI engines. In this type of engine, the air-fuel mixture auto-ignites because of piston compression instead of ignition by spark plug. The in-cylinder temperature in a conventional diesel engine is about 2700 K, which leads to a significant production of Oxides of Nitrogen (NOx) emissions. In the present work, homogeneous mixture was prepared outside the combustion chamber by using Ultrasonic fuel injection (USFI) system and Diesel fuel vaporizer system. The investigation was carried out at different fuel injection frequencies to study the combustion, emission and performance characteristics. Similarly, in the second approach, the Diesel fuel vaporizer receives fuel in liquid state and it converts into vapour form by means of an external power source, and effectively mixes with the incoming air to form a uniform fuel-air mixture. The investigation was carried out with diesel vapour induction with and without EGR to study the combustion, emission and performance characteristics. The experimental results show that, NOx and smoke reduces by about 80 % and 92 % respectively with USFI system. Whereas, in Diesel fuel vaporizer (DFV) system, the NOx and smoke reduction is about 95 % and 83 % respectively. The brake thermal efficiency decreases by about 2-8 % in both the systems. The engine operated from no load to 75 % load without any problem in the case of diesel fuel vaporizer system, whereas in USFI system the engine operated between 25% to 75% load only.

Keywords: Ignition, Spark plug and Diesel fuel.

1. Introduction

Emissions and fuel consumption are the two major worldwide environmental and energy challenges in the current century. Given the large number of vehicles manufactured worldwide, transportation is one of the largest sources of both gas emissions and fuel consumption in the world. One major solution to decrease emissions and fuel consumption in transportation is the use of cleaner fuels and more efficient combustion in engines. Homogeneous Charge Compression Ignition (HCCI) is a promising concept for combustion engines to reduce both emissions and fuel consumption. HCCI is a high-efficiency technology for combustion engines. This makes HCCI an alternative technology to conventional Spark/Diesel engines. HCCI engine fundamentals, history, challenges and proposed solutions are introduced in this chapter. An important HCCI problem is then identified for the study and the scope of this study is outlined

2. Review of Literature

HCCI combustion in diesel engines has two combustion stages such as low temperature and high temperature combustion. Phasing this combustion event is a major challenge.

More work was done on internal mixture formation methods (Early Injection, Late injection). Both Experimental and simulation work was done in this area.

Models like Zero dimensional model, Single Zone model and multi-zone models were used to predict the controlling parameters. A viable method for controlling the HCCI combustion phasing is by control-oriented modeling. A most probable indirect variable to control the start of combustion is EGR Rate.

External mixture formation is found to be a suitable method to form homogeneous mixture than internal mixture formation schemes.

Adoption of any one of the physics based control oriented model available depends upon the experimental flexibility.

Zero dimensional single zone modeling does HCCI combustion phasing. Start of combustion is characterized by modified Arrhenius equation and double –Wiebe equation for HCCI engines**.**

A control-oriented model is to be developed for steady state as well as for the transient state conditions, which can be useful to improve knowledge on HCCI combustion process. From the literature survey carried out, it was found that the much work was not reported on HCCI combustion with external mixture formation methods. It has therefore been perceived as a motivation for the current work. In addition, combustion control strategy has been observed with respect to in- cylinder injection process. Most of the research work that has been carried out for combustion control in an HCCI engine used is-octane type of fuel and in- cylinder injection process, and not using n-heptane type of fuel with external mixture formation. The current work reports, the two new methods of fuel-air mixture preparation with the following systems. 1. Diesel Fuel vaporizer system 2.Ultra sonic fuel injection system. Experimental investigation was carried out with the above systems to study the combustion, performance and emission characteristics. Based on the experimental data computational work was performed to predict the in-cylinder pressure, temperature, fuel distribution and droplet diameter. HCCI combustion control studies were also carried out and presented.

3. Objectives

To develop external mixture formation methods for proper fuel-air preparation to achieve the HCCI combustion in a single cylinder diesel engine. To study the HCCI engine performance, emissions and combustion characteristics using external mixture formation methods.

4. Methodology

Development of experimental setup using a single-cylinder, air-cooled, naturally aspirated, four-stroke diesel engine with all necessary instrumentation to measure performance, emission and pressure – crank angle data. Experiments at constant speed and variable load to obtain baseline results on the above CI engine for comparison. Develop a Diesel fuel vaporizer with ECU (Electronic Control Unit) and temperature controller to meter the fuel quantity and temperature at various loads. Develop an Ultrasonic Fuel Injection (USFI) system (also referred as ultrasonic atomizer in the thesis) with a controller for operating at different Ultrasonic frequency to vary the fuel droplet size. Experiments with the above-developed systems in HCCI mode to study the engine performance, emissions and combustion characteristics. Compare results with the base diesel operation and suggest suitable method of operation in the HCCI mode with the two techniques developed**.**

5. Ultrasonic Fuel Injection System

5.1 Introduction

In conventional diesel diffusion combustion, as the speed of the chemical reaction is incomparably faster than the speed of the mixing of the fuel and air, the combustion starts near stoichiometric air-fuel ratio and proceeds across a wide-ranging region from lean to rich. NOx and soot are accordingly generated and it is difficult to reduce these simultaneously. To solve this problem, it is desirable to complete the mixing process before combustion begins, and to burn the fuel in a lean homogeneous state. Proper fuel-air mixture preparation plays a vital role in combustion and emission formation. In the present work, a new system called Ultrasonic Fuel Injection system (USFI) was developed, in which fuel was atomized by ultrasonic energy.

5.2 Development Of An Ultrasonic Fuel Injection System

Ultrasonic atomization of fuels results from the unstable surface waves generated at the level of the thin fuel film that forms as the fuel spreads over the atomizing surface. A fine atomization, a low spray velocity and a simple fuel supply system mainly characterize this integration technique. An ultrasonic atomization technique is well suited for combustion application. Some experimental investigations dealing with ultrasonic atomization. The results clearly show that when the amplitude and the frequency of the surface is tuned, unstable surface wave occur on the fuel free surface and give rise to droplets formation. The droplet diameter decreases by increasing the ultrasonic frequency. In the present work, USFI system was developed in two stages, tested and demonstrated before it was fitted on to the engine. The first stage ultrasonic fuel injection system. It consists of Lead Zirconia Titanite (LZT) crystal Piezo amplifier, Function Generator and Low-pressure Fuel supply system.

The Fuel supply system consists of a low-pressure electric pump (0- 6 bar) and Low-pressure port fuel injector (0-10 bar). The Piezo amplifier multiplies the given input voltage by six times and impress on the bonded crystal plate. The bonded crystal plate was made to vibrate at the required frequency by applying voltage through the amplifier. The applied frequency was measured and tuned through the scope corder and function generator respectively. The applied frequency induces the unstable surface waves. When the plate vibrates at an ultrasonic frequency, the fuel was injected at a very low pressure of 2 bar on an atomizing surface. Ultrasonic disintegration of fuel into droplets results from the unstable surface waves generated at the free surface of a film that forms as the fuel spreads over atomizing surface. Very fine droplets were observed (decrease in droplet diameter) when the frequency was increased. To predict the droplet diameter a CFD analysis was done using STAR-CD software. The photographic view of second stage USFI system. The second stage atomizer system consists of a Vibrating probe, Probe holder, and Vibrocell and fuel supply system. The probe holder was designed and fabricated according to the probe configuration. The function of the Vibrocell is to control the amplitude and frequency. The frequency was varied from 20 kHz to 40 kHz. Studies were conducted within this range to investigate the effect of frequency on engine combustion, emission and performance.

6. Experimental Setup, Instrumentation And Experiments

This chapter describes the experimental setup that was developed for studies on HCCI combustion with external mixture formation techniques. The experimental setup was equipped with instruments for observing performance, emission and combustion characteristics of the engine at different operating conditions. An experimental setup consisting of a single-cylinder, diesel engine coupled to an eddy current dynamometer was developed and used.

6.1 Diesel Fuel Vapouriser

The intake manifold was modified to house the fuel vaporizer. The fuel vaporizer of length 150 mm consists of a heating element, ceramic pipe and stainless steel pipe of diameter 20 mm, which was inserted into a ceramic pipe of 22 mm diameter. The heating element (chrome) was wound over the ceramic pipe. The ceramic pipe was provided to conduct the heat alone. The fuel vaporizer was insulated with glass wool, which also adds cushioning effect to the brittle ceramic pipe to protect against engine vibration during engine operation.

The port fuel injector (0-10 bar pressure) was mounted on top of the fuel vaporizer to supply the correct quantity of fuel to the vaporizer. An Electronic Control Unit (ECU) that controls both the timing and quantity of the fuel controlled the port fuel injector. The key features of ECU design and ECU timing range. The bench test was conducted with ECU by varying the injection pressure and injection duration to determine the fuel consumption. The data obtained from the bench test and it was compared with the fuel consumption of an engine with conventional operation. From the results obtained by calculating the fuel consumption of the vaporizer at each load. The ECU controls the low-pressure fuel injector that injects the pre-determined quantity of fuel into the diesel fuel vaporizer. The fuel vaporizer was heated by an electrical power supply. A temperature controller was used to maintain the temperature of 360°C to provide diesel vapour at all the loads. A low-pressure electrical pump (0-6 bar) was used to supply diesel fuel to the low-pressure injector. Both the pump and the injector were controlled by ECU.

In the present investigation, a homogeneous mixture of fuel and air was prepared by using a diesel fuel vaporizer. The diesel vapour provided by this device forms a very light and dispersed aerosol, where due to their sizes, the droplets lose their momentum a short distance downstream of the nozzle (no wall targeting), follow the air motion very well, have very fast evaporation due to very high surface to volume ratio, and disperse very uniformly in the surrounding air stream. All the properties of this ‘‘gas-like’’ aerosol make it ideally suitable for external diesel mixture preparation, with the creation of a highly disperse and homogeneous mixture, minimal wall- wetting and very fast evaporation during the compression stroke.

6.2 Ultrasonic Fuel Atomiser

Suitable modification was done on the test engine to mount the ultrasonic atomizer. The fuel was supplied to the ultrasonic atomizer using the same fuel injection system described above. The ultrasonic atomizer receives the fuel in the liquid state and by means of ultrasonic vibration energy, performs work on the fuel, transforming it to a highly atomized state. The ultrasonic fuel atomizer consists of a power supply, converter and atomizing probe.

6.3 Data acquisition system, Crank Angle Encoder and Pressure Transducer.

The in-cylinder pressure was measured using a Kistler (601A) water cooled pressure transducer. A Kistler crank angle encoder on the crankshaft was used to clock pressure data acquisition. For each measured point, the pressure data of 137 cycles were recorded. The pressure data saved was fed to the Engine Combustion Pressure (ECP) analysis software to determine the heat release rate, cumulative heat release rate, combustion mass rate, in-cylinder temperature, and indicated mean effective pressure

6.4 Heat Release Rates

The variation of cylinder pressure is mainly due to the movement of the piston, combustion, blow by and heat transfer. Therefore, with raw pressure-crank angle data, the combustion process cannot be well explained. The estimation of the heat release rate from the cylinder pressure-crank angle data separates the effects of volume change, heat transfer, blow by, and gives an insight into the nature of the combustion process. Parameters like ignition delay, combustion rate, extent of combustion and combustion duration can be evaluated from the heat release analysis. The heat release rate was calculated from cylinder-pressure data using the first law of thermodynamics. The assumptions involved in the calculation are: (i) the cylinder charge is homogeneous and behaves like ideal gases; (ii) the spatial variation of pressure and temperature are negligible; and (iii) crevice effects are negligible.

6.5 Measurement Of HC, CO, CO2 AND Nox Emission

Carbon monoxide (CO), Carbon dioxide (CO_2) and Unburned Hydrocarbon (HC) were measured using a Qrotech Non-Dispersive Infra-Red (NDIR) exhaust gas analyzer. The analyzer works on the principle of selective absorption of the infrared energy at particular wavelength peculiar to a certain gas, which will be absorbed by that gas. The photographic view of the exhaust gas analyzer. Nitric oxide (NO) emission in the exhaust gas was measured with an electrochemical cell. NO constitutes 90% of the total oxides of nitrogen. The instrument was periodically calibrated using a standard gas which contained a known mixture of NO and NO_2 in a background of nitrogen.

6.6 Experiments Conducted

All the experiments were conducted at a constant speed of 1500 rpm at different load conditions. At each load, airflow rate, fuel flow rate, exhaust gas temperature, TDC position signals, cylinder pressure signals, HC, NO and smoke emission readings were measured and recorded. Optimize the injection timing of the base diesel engine and obtain performance and emission characteristics in the standard diesel mode for comparison. Study the effect of external mixture formation techniques on performance, emissions and combustion characteristics. Study the effect of injection timing in diesel HCCI mode with fuel vaporizer on engine performance, emissions and combustion characteristics. Optimize the injection pressure of diesel fuel supplied into the fuel vaporizer for better performance, emissions and combustion characteristics in HCCI mode. Study the effect of EGR as diluent to control the combustion rate in the external mixture formation HCCI mode and study its influence on performance, emissions and combustion characteristics. Study the effect of ultrasonic frequency in diesel HCCI mode with ultrasonic atomizer on engine performance, emissions and combustion characteristics.

6.7 Structure Of The Experiment

The whole experiment was conducted on a single cylinder, naturally aspirated, DI diesel engine integrated with fuel vaporizer and ultrasonic fuel injection system to operate the engine in HCCI mode. To ensure the repeatability and comparability of the measurements for operating conditions, the intake temperature of air, lubricating oil and EGR cooling water were held accurately stable during the experiments. The engine speed was maintained at 1500 rpm. Experiment involves observation of engine performance, emission and combustion characteristics through appropriate instruments. The engine was coupled to an Eddy current Dynamometer that was used to load the engine. The engine torque was recorded by a calibrated load cell. Initially the engine was started under no load condition in direct injection mode through a warm up procedure, and then it was switched into HCCI operation. Once ECU gives the signal to inject the fuel into the vaporizer, which was maintained at a temperature of 360°C, provides the diesel vapour into the intake manifold. In the manifold the diesel vapour mixed with air to form a homogeneous mixture. This homogeneous mixture was inducted inside the cylinder during the intake stroke. When the engine attained the rated speed through diesel vapour-air mixture induction, the engine governor cuts the fuel supply to the conventional fuel injector (200 bar nozzle opening pressure) thereon the engine operated completely in homogeneous mixture of diesel vapour –air mixture. This ensures that engine switched to diesel HCCI operation. Similarly, in ultra sonic fuel injection system, the engine was started under no load and speed was maintained between 500 – 600 rpm. Then the Ultrasonic atomizer into the intake port of the engine supplied the highly atomized fuel during the suction stroke. The highly atomized fuel mixes with the air and forms a homogeneous mixture. This fuel-air mixture was ignited through heat of compression. When the engine speed attained the rated speed the governor cuts the fuel supply to the DI injector and there on engine operated with ultrasonic, fuel injection system (USFI). Engine was loaded up to a brake mean effective pressure (BMEP) of 3.96 bars in both the techniques. Unstable combustion was observed at full load operation (BMEP 5.28 bar). The performance, emission and combustion parameters were recorded for BMEP of 0, 1.32, 2.64 and 3.96 bars.

7 Results And Discussion

The Results Obtained And Findings Of Various Techniques Adopted In The Present Investigation Are Detailed In Five Subsections Such As (I) Ultrasonic Fuel Injection System (Ii) Diesel Fuel Vaporizer System (Iii) Hcci Combustion Phase Control Studies.

7.1 Hcci Mode Using Ultrasonic Fuel Injection System

This section presents the results of HCCI mode using ultrasonic fuel injection system (USFI). The combustion parameters are explained first, and then the emission and performance parameters are discussed in detail for various operating conditions. The engine was always run at its rated speed of 1500 rpm. The frequency mentioned in the legend of the graphs indicates the fuel injection frequency (Frequency at which fuel is atomized and dispersed in the intake) of the USFI system. Results are plotted for various brake mean effective pressures (BMEP) with constant injection frequency and various injection frequencies at constant brake mean effective pressure.

7.2 Combustion Parameters

The in-cylinder pressure and heat release rate pattern in the HCCI mode using USFI system. The fuel was injected at 30 kHz ultrasonic frequency in the inlet port of the test engine during the suction stroke. When the engine was operated at 2.64 bar BMEP the cylinder peak pressure reaches the value of 54 bar at 10 deg CA aTDC and at 3.96 bar, BMEP the peak pressure reaches the value of 58.4 bar at 12 deg CA aTDC. This clearly shows that the engine peak pressure increases with increase in BMEP as well as the peak pressure retards when the engine BMEP is increased. The heat release curve has two distinguishable stages viz., cool flame and main combustion. It can be seen that, the Low Temperature Reactions (LTR) or cool flame begins at about -20 deg CA bTDC and a small energy release occurs for about 7 deg CA when the engine was operated at 3.96 bar BMEP. But for 2.64 bar BMEP the LTR reactions occur for only a few crank angle degrees i.e. it begins at -16 deg CA bTDC and sustained for about 5 deg CA.

The occurrence, duration and heat release during the cool flame have a large bearing on the Start of Combustion (SOC). It was observed that the High Temperature Reactions (HTR) for 3.96 bar BMEP occurs very early compared to 2.64 bar BMEP. This results in very early peak heat release for 3.96 bar BMEP compared to 2.64 bar BMEP. The main combustion starts at - 11 deg CA and a maximum rate of 43 J/deg CA is seen at about 2 deg CA aTDC at 3.96 bar BMEP. Whereas for 2.64 bars BMEP the energy released is 65 J/deg CA and it is seen at about 6 deg CA aTDC. The maximum energy release rate decreases as the load increases due to the advance of LTR reactions. If LTR occurs early, HTR also starts very early and releases the energy, which can be clearly observed. As the engine load increases, the cylinder temperature may be higher compared to previous load, which may help LTR to take place early and advance the HTR reactions. Similarly, experiments were conducted at 32 kHz, 36 kHz and 38 kHz injection frequency by varying the load and the results obtained are plotted to study the load range extension possibilities in HCCI mode. It was observed that, engine was able to operate from 1.98 to 3.96 bar BMEP. However, in the conventional mode engine was capable of operating from 0 to 5.28 bar BMEP. In HCCI mode at full load, the engine operation was unstable. Hence in HCCI mode, the engine was operated from 1.98 to 3.96 bar BMEP i.e. from 25% to 75% load.

The in-cylinder pressure and heat release variation at 32 kHz injection frequency. It can be observed that when the injection frequency is increased from 30 kHz to 32 kHz in-cylinder pressure was decreased. The peak pressure attained at 30 kHz and 2.64 bar BMEP is 54 bar whereas the peak pressure attained at 32 kHz and 2.64 bar BMEP is 52 bars. It clearly shows that the increase in frequency resulted in better mixing of charge, so the entire mass is active but the reaction rate is low both locally and globally. This means that the combustion process will take some time even if all the charge is active. Unlike conventional diesel combustion, HCCI does not rely on maintaining a flame front. Rather the combustion occurs because of spontaneous auto-ignition at multiple points throughout the volume of the charge gas. This results in the combustion of very lean mixtures leading to lower combustion pressure. At 32 kHz operation, the peak pressure attained for 1.98 bar, 2.64 bar and 3.30 bar BMEP's are 50 bar, 52 bar and 53 bar respectively. The heat release rate for this operating condition. The heat release rate pattern at 32 kHz operation is similar to 30 kHz operation. Combustion is well phased and occurs near to TDC. It can be observed that as the BMEP increases the peak heat release rate advances due to very early start of cool flame reactions. The maximum heat release rate attained at 32 kHz injection frequency is 44 J/deg CA, 53 J/deg CA and 62 J/deg CA for 3.30 bar, 2.64 bar and 1.98 bar BMEP respectively.

The in-cylinder pressure and heat release rate pattern for 36 kHz injection frequency. The cylinder peak pressure values at 2.64 bar BMEP and 3.96 bar BMEP are 51 bar and 55 bar. It clearly shows that the in-cylinder pressure decreases with increase in injection frequency due to better mixing of fuel and air and the droplet size is a function of ultrasonic frequency. The fuel droplet size decreases with increase in ultrasonic frequency. The same trend is observed when the injection frequency increased from 30 kHz to 32 kHz. The Peak pressure attained at 2.64 bar BMEP at 30 kHz, 32 kHz and 36 kHz is 54 bar, 52 bar and 51 bar respectively. It is evident that the cylinder pressure decreases when the injection frequency increases. The heat release pattern also shows a similar trend. The high temperature reactions occurred before TDC at 3.96 bar BMEP operation whereas for 2.64 bar BMEP operation HTR takes place very near to TDC. It is also observed that cool flame reactions advances as the BMEP is increased at 36 kHz injection frequency. From the above combustion parameter study it is inferred that, the engine can be operated from 1.98 to 3.96 bar BMEP. For comparison purpose and for investigation it was decided that operating the engine at 2.64 bar BMEP and 3.96 bar BMEP (50% and 75% Load) by varying the injection frequency from 28 kHz to 38 kHz in order to study the combustion, emission and performance characteristics of the system. The above study provided the information about load extension or load range capabilities of the HCCI mode using USFI system. Load range of operation is a very important factor in HCCI mode of operation.

7.3 Combustion Parameter Studies With Constant Bmep And Various Injection Frequencies

From the inference of the above study, experiment was conducted at BMEP's 2.64 bar and 3.96 bar at 28 kHz, 30 kHz, 32 kHz, 36 kHz and 38 kHz to investigate the combustion, emission and performance characteristics. The pressure crank angle diagram and heat release rate diagram for BMEP 2.64 bar at various injection frequencies. The peak cylinder pressure decreases with increase in fuel injection frequency as evident. The influence of the working frequency on the mean droplet diameter has been studied using CFD technique. The results confirm that the droplet diameter decreases with increase in ultrasonic frequency (Fuel injection frequency). Since the fuel is injected at the port, to reduce wall wetting problem the droplet size should be as minimum as possible. The increased fuel injection frequencies atomize the fuel very well and help in proper mixing of fuel and air. The fuel and air are mixed before combustion starts and the mixture auto-ignites as a result of temperature increase in the compression stroke. Thus, the combustion initiates simultaneously at several locations in the absence of heterogeneity as in the case of direct injection CI engine. The resultant low temperature combustion reduces the in cylinder pressure. The peak pressures at BMEP 2.64 bar are 53 bars, 54 bar, 52 bar, 51 bar and 50 bar for 28 kHz, 30 kHz, 32 kHz, 36 kHz and 38 kHz respectively. These peak pressure values occur at about 11 deg CA, 10 deg CA, 10 deg CA, 5 deg CA and 9 deg CA respectively. It is observed that as the fuel injection frequency increases the location of the cylinder peak pressure advances.

The heat release rate diagram for BMEP 2.64 bar at various injection frequencies. The heat release pattern clearly shows that the maximum heat release rate point advances as the injection frequency increases. But at 36 kHz injection frequency the maximum energy released point advances by about 3 deg CA compared with 38 kHz fuel injection frequency. This trend also observed in the pressure crank angle diagram where the peak pressure occurs at 5 deg CA at 36 kHz whereas at 38 kHz the peak pressure occurs at 9 deg CA. The maximum heat release depends upon crank angle, rate of volume rise and rate of pressure rise; hence the heat release is more when the peak pressure is advanced for 36 kHz injection frequency compared with 38 kHz fuel injection frequency. The HCCI combustion of diesel-like fuels displays a peculiar two-stage heat release as shown in Figure 5.8. The first stage of the heat release curve is associated with low temperature kinetic reactions, and the time delay between the first and main heat release is attributed to the "Negative Temperature Coefficient (NTC) regime" which locates between the two-heat release stages. In this NTC regime, the overall reaction rate decreases though the in-cylinder temperature increases, which leads to a lower reactivity of the system. It can be noticed that the energy released during the cool flame reactions decreases with decrease in injection frequency; hence, the maximum energy release rate also increases. The peak energy release rate also retards with decrease in injection frequency. The peak heat release rate values at 2.64 bar BMEP are 68 J/deg CA, 65 J/deg CA, 53 J/deg CA, 48 J/deg CA and 46 J/deg CA and occurs at about 7 deg CA, 6 deg CA, 4 deg CA, 0 deg CA and 3 deg CA aTDC for 28 kHz, 30 kHz, 32 kHz, 36 kHz and 38 kHz injection frequency. It clearly shows that the heat release rate decreases with increase in injection frequency due to decrease in cylinder pressure and temperature.

The cool flame reaction and energy released during the cool flame reactions are entirely responsible for the start of main combustion or high temperature reactions. It is observed that if the energy released during the low temperature reaction is less, then energy released during HTR is also less, similarly if more energy is released during the LTR, then energy released during the HTR is also high. The cool flame reactions or low temperature reactions are characterized by fuel radical's reaction directly with oxygen molecule in the air and high temperature reaction characterized by thermal decomposition of fuel radical and these are post induction kinetics of fuel combustion. The low temperature reactions and high temperature reactions altered with the mixture composition, which was improved through better mixing of fuel and air by enhancing or increasing the fuel injection frequency at the inlet port. After completing the experiments at BMEP 2.64 bar with various injection frequencies, the experiment was conducted at higher load (load 62.5%, BMEP: 3.30 bar) with various injection frequencies to study the combustion, emission and performance characteristics of the engine. Various fuel injection frequencies (30 kHz, 32 kHz and 38 kHz) were selected purely based on observation of combustion, emission and performance of the engine during the previous experimentation.

The pattern of the observed pressure crank angle variation. The in-cylinder pressure variation pattern shows the same trend as earlier i.e. the in-cylinder peak pressure decreases with increase in fuel injection frequency. The peak pressure values are 55 bar, 53 bar and 51 bar and it occurs at about 12 deg CA aTDC, 10 deg CA aTDC and 8 deg CA aTDC for 30 kHz, 32 kHz and 36 kHz respectively. The heat release rate pattern.The trend observed is similar to other frequencies. The peak heat release rate values are 57 J/deg CA, 45 J/deg CA and 48 J/deg CA and it is observed at 4 deg CA, 1 deg CA and 2 deg CA for 30 kHz, 32 kHz and 36 kHz respectively. Finally the combustion parameters of 2.64 bar BMEP and 3.30 bar BMEP at 30, 32,and 38 kHz fuel injection frequencies are compared to understand the behavior of the combustion at part load operation. It is noticed that the USFI system performs well at part load operation with respect to combustion parameters. Better combustion also results in better performance and reduction in emissions. A similar trend is observed when the engine was operated at BMEP 3.96 bar. The variation of rate of pressure rise (ROPR) with various injection frequencies at BMEP 2.64 bar. The rate of pressure rise values at BMEP 2.64 bar are 3.8 bar, 4.3 bar, 3.3 bar, 3.6 bar and 2.9 bar and it is observed at 6 deg CA, 6 deg CA, 4 deg CA aTDC, 0 deg CA (TDC) and 3 deg CA aTDC respectively for 28 kHz, 30 kHz, 32 KHz, 36 kHz and 38 kHz injection frequencies. It is noticed that the crank angle at which the maximum ROPR occurs for various injection frequencies, the same crank angle at which the heat release rate also occurs for BMEP 2.64 bar operating condition. A similar trend is observed with the engine operated at BMEP 3.30 bar.

The primary challenge of HCCI combustion is control of combustion phasing close to Top Dead Centre (TDC) to avoid misfire and knocking. The most accurate and reliable signal for combustion is the in-cylinder pressure. With the standard heat release rate equation, it is very easy to extract the combustion onset etc. The most usable parameter for combustion phasing is the crank angle at which 50% of the heat is released. The best representation of combustion phasing was found by extracting the crank angle at which 50% of the maximum amplitude was detected. In HCCI engines combustion phasing is defined by the term CA50 (Crank angle at 50% heat released). CA50 was obtained from the cumulative heat release data. From the total energy released, the crank angle at which 50% heat released was determined for the various fuel injection frequencies such as 28 kHz, 30 kHz, 32 kHz, 36 kHz and 38 kHz for 50% engine load operation (BMEP of 2.64 bar). CA50 data is very important for HCCI combustion studies. The combustion control in HCCI operation was monitored by this data. By phasing the CA50 towards TDC or near to TDC, it is possible to have a good control over the combustion. That CA50 is advanced with increase in fuel injection frequency but it is closer to TDC. The CA50 points obtained for 28, 30 and 32 kHz are well phased and closer to the curve fitting but away from TDC. Even though the other two data marked for 36 and 38 kHz falls away from the curve fitting still it is near to TDC. With the combustion bTDC, TDC, the temperature will be increased by both the chemical reactions and compression due to piston motion. Thus for a given auto-ignition temperature, combustion onset before TDC will not be increased by piston motion, the only temperature driver would be the chemical reactions. This gives more a sensitive system and this is the underlying problem with HCCI combustion control. It is desired to have a late combustion phasing to reduce burn rate and hence pressure rise rate and the peak pressure.

7.4 Emission Characteristics Of Hcci Mode Using Usfi System

Diesel engines are widely used in heavy-duty vehicles and other commercial applications due to its higher efficiency and durability. In diesel engines, Particulate Matter (PM) is formed in fuel rich regions and NOx is formed in the hot stoichiometric regions. This is mainly due to the heterogeneous mixture formation in cylinder. Thus, it is difficult to reduce both NOx and PM simultaneously through combustion improvement. The shortcomings of traditional combustion technique are being continually evaluated and alternative combustion technique is being sought. One interesting combustion technique to reduce NOx and PM simultaneously from diesel engines is HCCI combustion. The emission characteristics of HCCI combustion with USFI system are presented in this section.

HCCI has been widely studied as a combustion technology to avoid simultaneously NOx and smoke formation regions. This combustion technique lowers the combustion temperature by forming a lean mixture at an equivalence ratio of 0.5 or less, burning it simultaneously and substantially reduces NOx and smoke. The variation of equivalence ratio at various fuel injection frequencies at BMEP 2.64 bar. A very long mixing period is required to form a lean and uniform mixture and it is necessary to inject at an early time. If the temperature and in-cylinder pressure are low, a large amount of the sprayed fuel adheres to the wall, causing problems of oil dilution and a decline in combustion efficiency. To avoid this, some method of suppression of the penetrating force of the spray using a special nozzle must be devised; this requires substantial modification to engines. In the present study, an ultrasonic atomizer was used, in which fuel was supplied at a very low pressure (2 bar) to the inlet tube of the atomizer, the atomizer vibrates at a high ultrasonic frequency, perform work on the fuel and disintegrate the liquid into very fine particles. This highly atomized fuel was injected at the inlet port of the engine during the intake stroke. It provides enough time for mixing to form a lean and uniform mixture and avoid wall-wetting problem. The oxides of nitrogen emission (NOx) at BMEP 2.64 bar and BMEP 3.96 bar at various injection frequencies. It is observed that the NOx emission is less compared to conventional operation at all injection frequencies at BMEP 2.64 bar and 3.96 bar. NOx ^{levels} are low which is typical of HCCI engines due to very lean mixtures used in actual combustion. In HCCI mode, the charge temperature has a significant influence on NOx emissions. For comparison, the NOx is about 14.5 g/kWh with baseline diesel engine where as for HCCI using USFI system the NOx - levels are 5.3 g/kWh, 5.8 g/kWh, 3.9 g/kWh, 3.8 g/kWh and 3.4 g/kWh at 28 kHz, 30 kHz, 32 kHz, 36 kHz and 38 kHz fuel injection frequencies respectively at BMEP 2.64 bar. The NOx emission decreases with increase in fuel injection frequency; this is due to reduce in-cylinder pressure and temperature, which in turn resulted in reduced heat release rate. Similar trend is observed when the engine BMEP is increased from 2.64 bar to 3.96 bar. The variation in NOx emission for BMEP 3.96 bar. The NOx emission is less compared to conventional (base diesel engine) operation.

The variation of smoke emission at 50% and 75% load. The smoke emission is less compared to base diesel engine due to longer mixing period to form a lean uniform mixture. This longer mixing period reduced smoke, due to elimination of the over-rich mixture equivalent to the smoke formation region. When fuel injection frequency is increased, the homogeneity of fuel air mixture is improved and smoke level falls. It is observed that the smoke level decreases with increase in fuel injection frequency and increases with increase in BMEP. When BMEP is increased with same injection, frequency the energy release decreases as observed in the heat release diagram, which shows that the combustion is better at lower BMEP operating condition than at higher BMEP with same injection frequency. This was very clearly seen when combustion parameters were analyzed. When the injection frequency is increased with constant BMEP a decrease in heat release rate was observed, and when BMEP is further increased at the same injection frequency the heat release rate is further reduced and an increase in smoke level is observed. The variation of HC and CO emission BMEP 2.64 bar and BMEP 3.96 bar. It is observed that the hydrocarbon emission increases with increase in fuel injection frequency. The second main challenge in HCCI operation is the potential increase in HC and CO emissions. As with all homogeneous combustion system, the burned gas temperature is low and this results in significant increase in both HC and CO emissions relative to the conventional combustion. The peak burned gas temperatures are also low to complete the CO to CO2 oxidation at low loads. The increase in CO and HC emission may also be attributed to fuel impingement problem even though the fuel is injected at the inlet port section considering the physical dimensions of the engine at the port section. The mixture becomes leaner with increase in injection frequency so the HC and CO emission increases with increase in injection frequency at all BMEP's.

7.5 Hcci Mode Using Diesel Fuel Vapouriser

In the present investigation a fuel vaporizer was used to achieve excellent HCCI combustion in a single cylinder air-cooled direct injection diesel engine. No modifications were made to the combustion system. In this study, vaporized diesel fuel was mixed with air to form a homogeneous mixture and inducted into the cylinder during the intake stroke. To control the early ignition of diesel vapour–air mixture, cooled (30°C) Exhaust Gas Recirculation (EGR) technique was adopted. Experiments were conducted with diesel vapour induction without EGR and diesel vapour induction with 10%, 20% and 30% EGR and results are compared with conventional diesel fuel operation (DI @ 23 deg before Top Dead Center (bTDC) and 200 bar nozzle opening pressure). The engine performance, emission, and combustion characteristics were investigated and presented in this section.

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