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Experimental Investigations of Particulate Emitted by an Alcohol-Fuelled HCCI/CAI Combustion Engine

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Abstract – *Environmental concerns have increased significantly world over in the past decade. To fulfill the simultaneous emission requirements for near zero pollutant and low CO_2 levels, which are the challenges of future powertrains, many research studies are currently carried out world over on new engine combustion process, such as Controlled Auto Ignition (CAI) for gasoline engines and the Homogeneous Charge Compression Ignition (HCCI) for diesel engine. These combustion processes have potential of ultra-low NO_X and particulate matter (PM) emission in comparison with a conventional gasoline or diesel engine. Regulatory agencies are becoming increasingly concerned with particulate emissions as the health and environmental effects are getting understood better due to rapid developments in instrumentation. In this paper, combustion and emission characteristics of a HCCI engine fuelled with methanol were investigated on a modified two-cylinder, four-stroke engine. In this investigation, port injection technique is used for preparing homogeneous charge. The experiment is conducted with varying intake air temperature of 120, 130 and 150^{0}C at different air-fuel ratios, for which stable HCCI combustion is achieved. The experimental results indicated that the engine load or air-fuel ratio have significant effects on the maximum cylinder pressure and its position relative to TDC, the shape of the pressure rise curve and the heat release rate.*

The engine exhaust particle sizer (EEPS) was used for size, surface area and mass distributions of soot particles emitted under different operating conditions under different combustion modes. EEPS measures particle size ranging from 5.6 to 560 nanometers. It was found that number and size distribution of soot particles depends on engine load and the width of the size distribution increased with increasing engine load. The number distributions were found to obey log-normal distribution.

Keywords – Engine exhaust particle sizer, controlled auto-ignition, homogeneous charge compression ignition, nano-particulate, particulate size-number distribution.

1. INTRODUCTION

Internal combustion engines are the key to the development and existence of modern society. Without the transportation by the millions of personalized vehicles on the road and at the sea, we would not have reached the contemporary living standard (in terms of physical facilities). The vast majority of engines used in vehicles today are piston engines propelled by combustion of petroleum based fossil fuels. The most frequently used types are Direct Injection Compression Ignition (DICI) engines and Spark Ignition (SI) engines. Engines and fuel for transportation as well as off-road applications are facing double challenge. First, to bring the local pollution to a level mandated by most stringent city air quality standards, and second to reduce CO_2 emissions in order to minimize the global warming threat [1]. These goals stimulate new developments both of conventional and alternative engines and fuel technology. New combustion processes known as CAI (Controlled Auto Ignition) for gasoline and HCCI (Homogeneous Charge Compression Ignition) for diesel are subject of research worldwide. The HCCI is the third alternative mode for the combustion in the reciprocating engine. HCCI a hybrid of well-known spark ignition (SI) and compression ignition (CI) combustion concepts and has potential of combining the best features of both [2]. HCCI means that the fuel and air should be mixed homogeneously before the combustion starts and the mixture is auto-ignited due to increase in temperature towards the end of the compression stroke. Thus HCCI is similar to SI in the sense that both combustion concepts use a premixed charge and HCCI is similar to CI as both concepts rely on auto-ignition for combustion initiation. However, the combustion process is totally different for the three types [3]. HCCI engines are investigated for their potential for efficient energy conversion with low environmental impact [4]. That is, HCCI engines have the potential for high efficiency like direct injection diesel engines [5] while emitting extremely low NOx and no smoke. However, it is difficult to control ignition timing and combustion duration of such engines, as they do not have the conventional control (direct control) such as spark plug and fuel injector.

Many researchers have studied HCCI combustion during last two decades. The earliest reported works [6], [7] showed the basic characteristics of HCCI, which have been validated by subsequent researchers, namely: very little cyclic variation and no flame propagation. The HCCI combustion process has been studied with certain success in two stroke [6], [7] and four stroke engines [8]-[10], and with liquid [1]-[8] and gaseous [9], [10] fuels. Due to the economics of large scale production of the alcohol fuels only methanol and

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ethanol is suitable as neat alternative fuels. Both methanol and ethanol exhibit good HCCI combustion characteristics. In particular, methanol has demonstrated a significant widening of the HCCI operating regime when compared to gasoline [11].

In addition to NOx emission, soot emission and its size is of concern from environment point of view.

Particle size influences the environmental impact in several ways e.g. it influences residence time of the particulate in the atmosphere, optical properties of the particulate, particle surface area, its ability to participate in atmospheric chemistry, and its health effects. The residence time of particulate in the atmosphere is longest for 0.1-10 μm diameter particles and it is typically about one week. Larger particulate are removed from the atmosphere rather quickly by gravity settling process and smaller particulate by diffusion and coagulation process. Typical residence time for 10 nm particulate is only about 15 minute [12]. The main mechanism for removal of these tiny particulate is coagulation with particles in the accumulation mode. Thus, although they loose their identity as individual particles, they remain in the atmosphere for essentially the same time as the larger accumulation mode particulate. The optical properties of exhaust particulates influence atmospheric visibility and soiling of buildings. These properties depend on particulate size, shape, and composition [13]-[14]. Particles interact with light by absorption and scattering. For diesel exhaust particulate, absorption is much stronger than scattering and is relatively independent of particulate size for light in the visible range. The absorption is due to the carbon content of the particulate. Light scattering is strongly dependent on particulate size and shape and is typically maximum for particulate a few tenths of a micron in diameter. The scattering is mainly due to particles in the accumulation mode size range (0.1 to 1μm). Ultrafine (D_p<100 nm) and nanoparticles (D_p<40 nm) scatter light very weakly.

Nearly all of the surface area of individual nuclei that comprise the agglomerates is available for adsorption. Thus the surface area of diesel particulate is probably more a function of the size of the individual nuclei in the agglomerates rather than the agglomerate size. This surface area may be available for atmospheric reactions. In the atmosphere, various atmospheric constituents will compete with exhaust constituents for this surface area.

The aspect of particulate size that is attracting the greatest attention is the influence of fine and ultrafine particles on human health. Adverse health effects seem to be linked with smaller particles. The efficiency of deposition of particulate in the human respiratory tract depends upon particulate size. In particular, pulmonary deposition increases with decreasing particulate size. Recently, special concerns have been raised for particulate in ultrafine and nano-particle diameter range. Particulate which are non-toxic in μm size range may be toxic in nm size range. Thus, there are serious concerns about the negative effects of sub-micrometer airborne diesel exhaust particulate on the human health and the climate. Therefore, recent reports regarding the correlation of diesel particulate with health effects and environmental degradation have prompted regulatory agencies to set more stringent emissions regulations for diesel engines.

By considering the advantage of HCCI combustion and use of alternative fuels, current investigation is carried out to assess the particle size and number distribution from the HCCI combustion mode and the results are compared with normal CI combustion mode.

2. PARTICULATE SIZE MEASURING INSTRUMENT

In this study, Engine Exhaust Particle Sizer (EEPS) is used to measure the particulate size and number distribution in the engine exhaust. EEPS is an advanced version of scanning mobility particle size (SMPS) system, which is widely used to measure the size distribution of atmospheric aerosols. Since the SMPS requires a minimum sampling duration of 60 seconds to make a measurement, its use has been limited to stable engine operating conditions.

Engine Exhaust Particle Sizer (EEPS) spectrometer provides both high temporal resolution and reasonable size resolution by using the same basic technique as that of SMPS system but with multiple detectors working in parallel. This makes the EEPS ideal for measuring engine operating under transient conditions. The EEPS is designed specifically to measure particulate emitted from engines and vehicles. It measures particle size from 5.6 to 560 nm with a size resolution of 16 channels per decade (a total of 32 channels). Reading the particle size distribution 10 times per second (10Hz) allows transient measurement possible.

Diesel particulates enter the instrument through a cyclone with a 1 μm particulate cut-off limit. This removes large particles that are above the instrument's measurement capabilities. These particles then pass through an electrical diffusion charger, where ions are generated. These ions mix with the particulate to provide a predictable charge based on their size. The charged particles then enter an annular space between two cylinders that is filled with clean sheath air. The particles pass by a central rod that has a high voltage to produce an electric field which repels the particulate outward to the electrometer rings. The particles are collected on electrometer rings transferring their current to the sensitive electrometers, on each ring depending on their size.

Small particles are detected at the top of the column and larger particles at the bottom. The electrometers are scanned at 10 Hz frequency by a microprocessor, which then inverts the current data to get particle size and number distribution. The schematic diagram of EEPS is shown in Figure 1.

3. EXPERIMENTAL SETUP

A two cylinder, four-stroke, air-cooled, naturally aspirated, bowl shaped combustion chamber; direct injection diesel engine was modified for the experiment. The engine specification was given in Table 1. One of the two cylinders of the engine is modified to operate in HCCI mode, while the other cylinder is operated like an ordinary diesel engine, thus motoring the first cylinder until HCCI conditions are achieved. A schematic diagram of the experimental setup is shown in Figure 2.

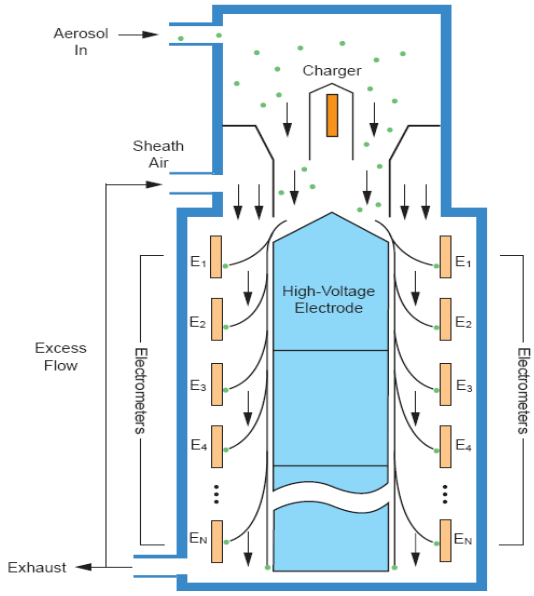
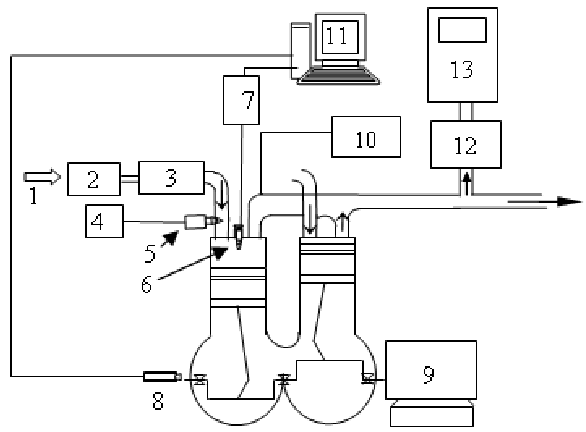


Fig. 1. Schematic layout of EEPS.



1: Intake Air, 2: Air Box, 3: Heater, 4: Injection Timing Circuit,

5: Electronic Fuel Injector, 6: Piezo-electric Pressure Transducer,

7: Charge Amplifier, 8: Shaft Encoder, 9: Dynamometer, 10: Emission Analyzer,

11: Combustion Analyzer 12: Exhaust Gas Diluter 13: EEPS

Fig. 2. Schematic diagram of experimental setup.

Table 1. Detailed engine specifications.

Make, Model	Indec, PH2, Diesel Engine
Injection Type	Direct Injection
Number of Cylinders	Two
Bore/ Stroke	87.3/ 110 mm
Power per Cylinder	4.85 kW @ 1500 rpm
Compression Ratio	16.5
Displacement	1318 cc
Fuel Injection Timing	24°b TDC
Fuel Injection Pressure	210 kg/cm^2 @1500 rpm

Test fuel used for this investigation is methanol. A fuel premixing system was installed in the intake manifold. This system consists of an electronic fuel injector and an injection timing and injection duration controller electronic circuit. Fresh air entering the engine is heated by an air pre-heater positioned upstream of the intake manifold. The in-cylinder pressure was measured using a water-cooled piezo-electric pressure transducer (Make: Kistler, Switzerland; Model: 6061B) which is mounted flush in the cylinder head. The pressure transducer minimizes thermal shock error by using a double walled diaphragm and integral water cooling system. To measure the crank angle position, a precision shaft encoder (Make: Encoders India, Model: ENC58/6-720ABZ/5-24V) is coupled with the crank shaft using a helical coupling. The cylinder pressure history data acquisition and combustion analysis is done using a program based on LabVIEW, developed at Engine Research Laboratory IIT Kanpur. The raw exhaust gas analysis for NO_x, CO and THC were carried out using exhaust gas emission analyzer (Make: AVL, Austria; Model: Di-GAS 444).

Experiments were conducted on the modified engine at constant engine speed of 1500 rpm and intake air temperature of 120, 130 and 150 ^{0}C.

4. RESULTS AND DISCUSSION

In this section the experimental results at different engine load at constant engine speed are presented with ethanol as fuel at intake air temperature of the 120, 130 and 150^{0}C respectively.

Operating Region

To study the HCCI combustion criteria as to what constitutes HCCI combustion must be defined. The HCCI operation region is limited by the misfire and knocking. The operation boundaries are associated with these factors (misfire and knock). The first boundary defines the lower limit for the HCCI combustion. At low loads, fuel flow rates are low hence the net heat release also decreases. It is believed that the resulting gradual reduction of average combustion temperature results in more unburned charge that is characterized by high CO and THC emissions and by increase in cycle-to-cycle variation. Cycle-to-cycle variation of the combustion process in an engine can be monitored by the cylinder pressure transducer. Fluctuations of indicated mean effective pressure (IMEP) were used as a measure of cycle-to-cycle variations. The Coefficient of Variation (COV) of IMEP is calculated for 100 consecutive engine cycles and was calculated as standard deviation (σ) divided by mean value (IMEP) as a percentage [15].

$$COV_{IMEP} = \frac{\sigma_{IMEP}}{IMEP} \times 100\% \qquad (1)$$

Since the drivability problems in automobiles normally arise when COV_{IMEP} exceeds 10 percent [15], this study used this value for the misfire boundary.

When the fuelling rate is increased (lower λ), the HCCI combustion rate also increases and intensify, and gradually causes unacceptable noise and may potentially cause engine damage, and eventually lead to unacceptably high level of NO_x emissions. Therefore knocking combustion can be defined as being at the upper limit of the HCCI combustion. In this investigation, the upper limit of the HCCI combustion is limited by the rate of pressure rise in a cylinder. When the rate of pressure rise exceeds 1.0 MPa per crank angle degree (^{0}CAD) ($dP/d\theta_{max}$= 1.0 MPa / ^{0}CAD) for each individual cycle, it is considered to be the upper limit of HCCI.

The recorded pressure traces in the cylinder determine the value of COV_{IMEP}, and $dP/d\theta_{max}$. Therefore, the HCCI operating region is the area, in which the values of COV_{IMEP} are less than 10 percent and values of $dP/d\theta_{max}$ are less than 1.0 MPa/^{0}CAD. This definition is applied for present investigations and a value of relative air fuel ratio (λ) for which this condition is fulfilled, is considered to be the stable HCCI operating range as shown in Figure 3. It was observed that for stable HCCI operating conditions, engine runs at richest mixture for lower intake air temperature. Combustion and particle size analysis is done for the λ in the HCCI operating range.

Engine Load, Imep

One major limitation of HCCI combustion is the requirement of a highly diluted mixture in order to slow down the speed of the chemical reactions sufficiently so that engine is not damaged and this leads to slower combustion. With lean operation, this significantly reduces the output for a given air-flow through the engine. The rich side limit for IMEP is limited by the rate of combustion and hence that of rate of pressure rise. The maximum IMEP encountered in this investigation is 3.5 bar. Maximum IMEP at different relative air fuel ratios (λ) in HCCI stable operating mode at different temperature is shown in Figure 4. It can be observed that maximum IMEP is higher at lower intake air temperatures. This is justified because for lower intake air temperature, engine can be operated at richer fuel-air mixture (Figure 3).

Cylinder Pressure and Rate of Heat Release

The in-cylinder pressure was measured for all engine operating conditions. The cylinder pressure-time was recorded for 100 cycles, with a resolution of 0.5 crank angle degrees. Figures 5 to 7 show the pressure history and heat release rate for different relative air fuel ratios (λ) at different intake air temperatures. For all plots, the trace with the highest maximum pressure correspond to the operating condition with the richest mixture and the lowest maximum pressure corresponds to the leanest mixture at any given temperature. With the increase in engine load (IMEP), the maximum pressure becomes higher; the crank angle at which maximum pressure occurs decreases. It means the combustion starts earlier. It can also be observed from rate of heat release curve.

The main observation from pressure traces and heat release curves, from point of view of this study of particulates, is that the HCCI combustion is achieved for all air-fuel ratios in HCCI operating range shown in Figure 3.

The in-cylinder pressure was analyzed using a single zone heat release model [16], which gives the rate of heat release. Figures 5 to 7 show the rate of heat release curves for all engine operating conditions under investigation.

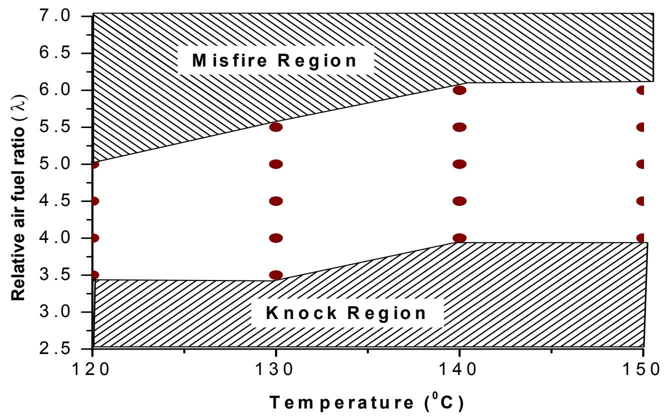


Fig. 3. HCCI stable operating range.

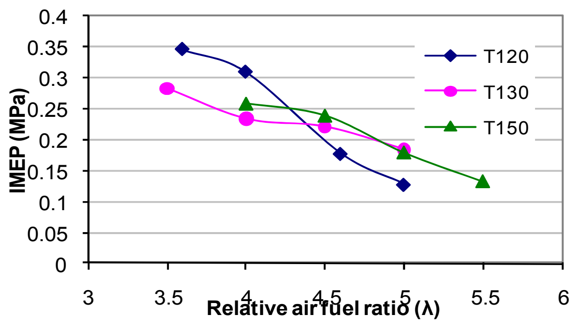


Fig. 4. IMEP for stable HCCI range at different relative air fuel ratios (λ).

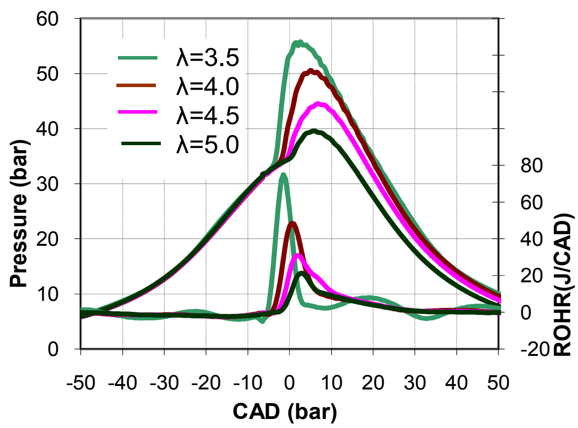


Fig. 5. P-θ and rate of heat release for different relative air fuel ratios (λ) at intake air temperature of 120°C.

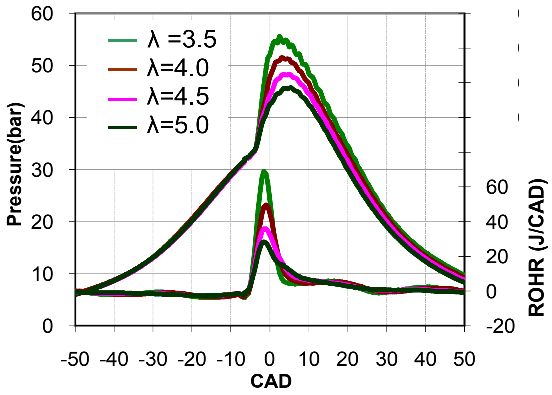


Fig. 6. P-θ and rate of heat release for different relative air fuel ratios (λ) at intake air temperature of 130^{0}C.

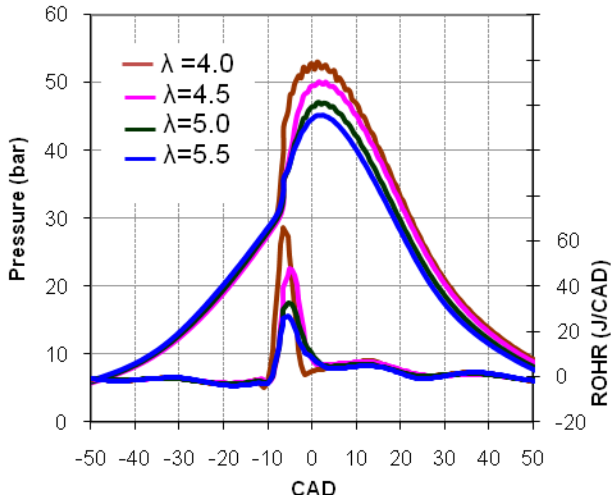


Fig. 7. P-θ and rate of heat release for different relative air fuel ratios (λ) at intake air temperature of 150^{0}C.

It can be noticed that the start of combustion is sensitive to the temperature history during the compression stroke. Start of combustion takes place earlier with richer fuel-air mixtures. Rate of heat release (ROHR) follows similar trend for all intake air temperatures. ROHR curve is very steep for richer fuel-air mixtures. From the heat release curve, it is evident that most of the heat is released in very short crank angle duration (<15 CAD) under all engine operating conditions. This confirms that HCCI combustion mode is very fast and combustion duration is very small compared to conventional compression ignition combustion mode.

Combustion is faster for richer fuel-air mixture compared to leaner mixtures. Similar trend as 120^{0}C is observed at other intake air temperatures but combustion start earlier due to higher temperature reactivity.

Engine Exhaust Particulates

The measurement of particulate size distribution was conducted after the engine attained thermal stabilization at every engine load. The exhaust sampling was carried out for one minute and the sampling frequency was kept at 1 Hz therefore all the results presented in this paper are average of sixty data points. The results are presented in the form of number and size distribution in the exhaust stream (after accounting for the dilution factor). The surface area distribution is very important from toxicology point of view and particulate mass distribution is important from meeting the emission regulation and pollution control equipment design points of view.

Figure 8 shows the number density, surface area and volume distribution of particulate vs. size for different relative air/fuel ratios at 120^{0}C. It can be observed (Figure 8a) that peak concentration of particulates increase with lowering of relative air/fuel ratio. Maximum concentration of particulates for higher λ (λ = 5.0) is 4.57 x 10^8 particles/cm^{3}where as for lower λ (λ = 3.5) it is 1.29 x 10^9. Maximum concentration of particulates falls in the size range of 45.3 nm to 52.3 nm for relative air/fuel ratio 5.0, whereas it is 93.1 nm to 107.5 nm for relative air/fuel ratio 3.5. Thus size range of peak concentration shifts towards higher particulate size as relative air/fuel ratio becomes rich. It can also be observed from Figure 8 that the distribution width of particulate size increases with decreasing relative air/fuel ratio. The distribution broadening seems to have the strongest effect on the right side of the distribution. Another important observation from size distribution graphs can be made that number distribution obeys the log-normal distribution pattern.

Surface area distribution is quite important from particulate toxicology point of view. Smaller particulates tend to have significantly higher surface area (orders of magnitude) for the same particulate mass as that of larger particulates, thus offering very high surface area for condensation of toxic volatile organic compounds (VOC's) and polycyclic aromatic hydrocarbons (PAH's). Also, smaller particles have higher residence time in the atmosphere compared to larger particles thus possibility of their entering into human respiratory system is significantly higher. Therefore, ultra-fine particulates are considered to be more hazardous to human health compared to larger particulates.

Figure 8b shows the surface area distribution of particulate at different relative air/ fuel ratio. Surface area of particulates depends on diameter and number distribution. It can be seen that the surface area of particles in the dominating size range 69.8-80.6 nm is highest for λ = 5 whereas it is 107.5-124.1 nm for λ = 3.5.

The majority of particulate mass is formed during surface growth and agglomeration process thus the residence time during surface growth process has a large influence on the total particulate mass emission. The mass of particulates emitted by engines is very important from emission legislation point of view. As of today, global emission regulation rely on compliance of mass emission of particulate and do not give any weightage to the size and number distribution therefore the mass distribution of the particulates becomes important. However with the increasing awareness about the fact that the particulates of different size range have different degrees of harmful effects on human health, law makers will be forced to take cognizance of particulate size, surface area, and mass distribution.

Figure 8c shows the volume distributions of particulates of different size ranges at different relative air fuel ratios. Particulate volume distribution is directly proportional to mass distribution assuming density of particulates to be constant. Particulate volume depends on mean diameter of particulates and their number. It can be clearly seen from Figure 8c that particulate volume emission increases substantially at lower relative air fuel ratios.

Figure 9 shows the particulate number density distribution from a single cylinder diesel engine (similar type and similar technology) at different engine load condition (no load, 50%, 80% of rated load). Particulate density distribution mechanism from diesel engine is different from HCCI engine. Number distribution of the particulates decreases as engine load increases in diesel engine. This is due to increase in combustion chamber temperature with increasing engine load, which increases the possibility of burning/ re-burning of the particulates in the combustion chamber before they exit through the exhaust valve, thus effectively reducing their number density. Number distribution of particulates shows opposite trend in HCCI combustion mode. Size distribution of particulates is smaller for diesel operated engine compared to HCCI engine.

Number density, surface area and volume distribution of particulates was also conducted at inlet air temperature 130^0C and 150^0C (Figures 10 and 11, respectively) and they follow the same trend as discussed in Figure 8.

It can be noticed from the Figures 8, 10 and 11 that most of particles are between 30 to 250 nm sizes for the investigated HCCI combustion conditions. Figure 12 shows the variation of total concentration of particulates with varying intake air temperature for different air fuel ratios.

It is observed from the Figure 12 that the total concentration of particles increases with increasing intake air temperature at any given λ. It can also be noticed from the figure that at any constant intake air temperature, the total concentration of particles increases as charge mixture becomes leaner. When richer mixture gets ignited in the combustion chamber, more fuel is burnt and temperature of the combustion chamber becomes higher, which explains the higher total concentration of particles for richer mixtures.

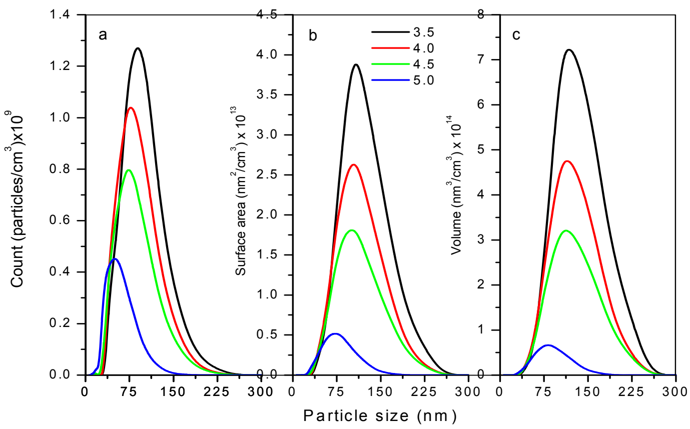


Fig. 8. Particulate number, surface area and volume distribution form HCCI engine at different relative air fuel ratios (λ) at 120^0C.

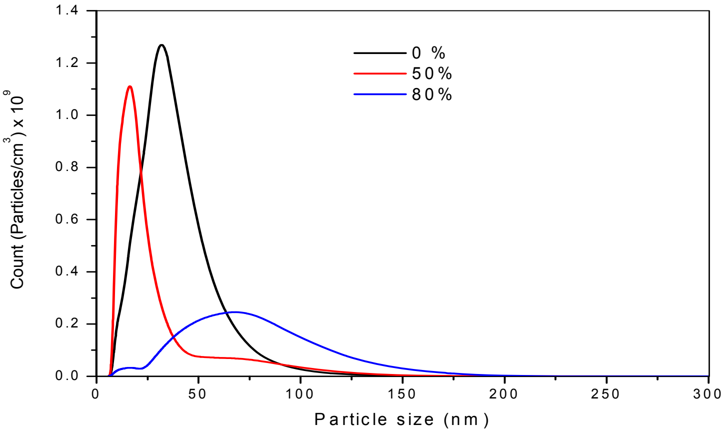


Fig. 9. Number and size distribution of particulate from diesel engine at different loads.

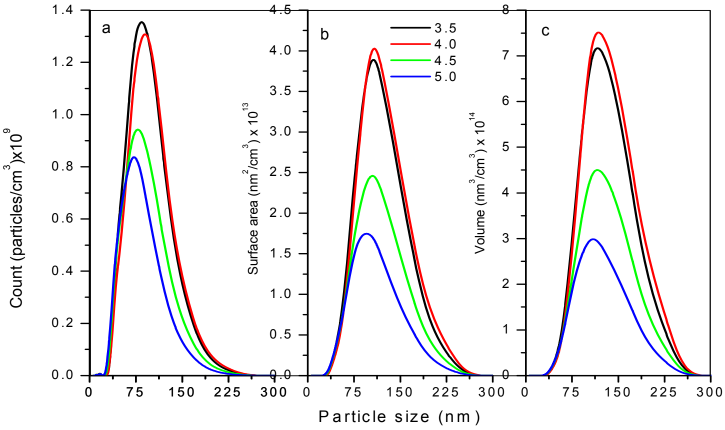


Fig. 10. Particulate number, surface area and volume distribution form HCCI engine at different relative air fuel ratios (λ) at 130^{0}C.

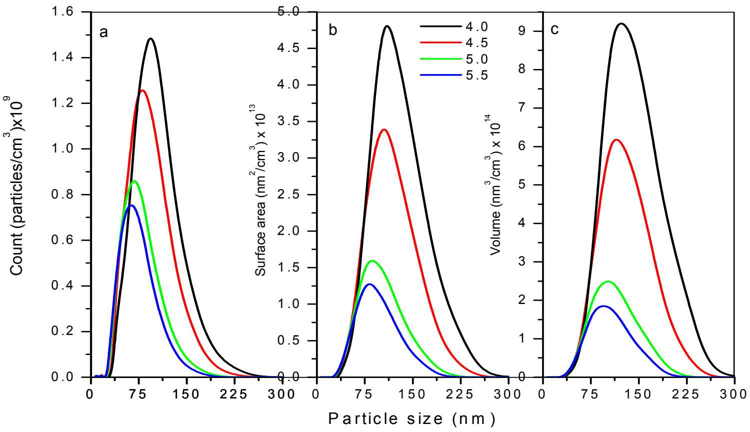


Fig. 11. Particulate number, surface area and volume distribution form HCCI engine at different relative air fuel ratios (λ) at 150^{0}C.

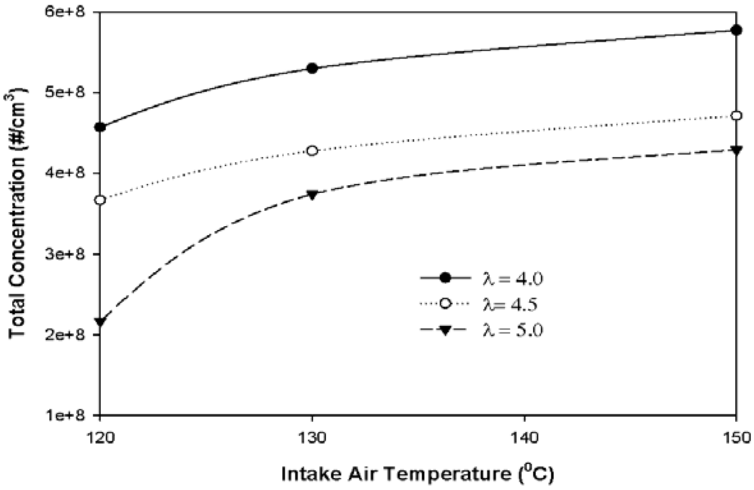


Fig. 12. Variation of total concentration of particles with intake air temperature at different relative air fuel ratios.

5. CONCLUSIONS

The combustion and particulate emission characteristics of HCCI engine were investigated on a modified two cylinder engine. The inlet air was supplied at 120, 130 and 150^{0}C temperature and the engine was operated at a constant engine speed of 1500 rpm, fuelled with methanol in HCCI mode. Successful HCCI combustion is obtained for λ (3.5-6) range. HCCI mode operation of the engine was within a narrow load range of the engine. The maximum IMEP obtained during the experiment was 3.5 bars. The rate of heat release was very high and combustion duration was shorter (less than 15^0 CAD) for all the conditions of engine operation in HCCI mode. Engine exhaust particle sizer (EEPS) was used to measure size and number distribution of particulates. It was found that number distribution of particulate increases with decreasing relative air/ fuel ratio. Total concentration of nano-particles emitted from engine also increases as combustible charge becomes richer. Size of particulates emitted from HCCI engine is higher than diesel particulate and the particulates matter formation mechanism seems to be different for the two combustion modes.

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