

## Low Temperature Combustion after Treatment Strategy and Particle Emission Correlation with different Ratio of Dual Fuel

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### Abstract

Low-Temperature combustion (LTC) has demonstrated huge potential to simultaneously control nitrogen oxide ( $\text{NO}_x$ ) and particle matter (PM) significantly in automotive engines. Hydrocarbons (HCs) and carbon monoxide (CO) are key challenges due to low combustion temperatures in dual fuel combustion. The selection of diesel oxidation catalyst (DOC) and precious group metal (PGM) content is critical for low-temperature combustion (dual fuel) to control HC and CO emissions norms. An experimental test bed study was conducted in a 3.8 litre diesel common rail engine with a gasoline port injection to evaluate the after-treatment strategy in low and high-reactive fuel. Three DOCs with different PGM content were tested along with different dual fuel compositions to understand their effectiveness and particle matter composition. The chemical composition of exhaust particles from engine Out and DOC out are compared. An increase in low reactive fuel (D15G85) and an increase in PGM content highlights a significant reduction in PM from 31 mg/kWhr to 2 mg/kWhr. The major reduction in particle size distribution observed with high PGM loading is 40 nm with a dual fuel configuration of D15G85 as the best approach to meet emission standards. Additionally, a detailed study was made to investigate the characteristics of particle mass and particle size distribution in the engine and after-treatment emissions. The particle number (PN) and their correlation for engine out, DOC Out, and DPF out emission are demonstrated with different dual fuel combinations of D50G50, D25G75, and D15G85 compared with diesel fuel. To comprehend its characteristic of particle number and particle mass correlation, dual fuel is tested in different ratios. A linear correlation of PM and PN emissions is observed between engine out and DOC out as particulate diameter of the particle size with the total number concentration of particles in engine and DOC out. The nonlinear trend is observed for DPF out due to small particle size (around 5nm) with different ratios of dual fuel. Particle matter filter paper analyses were performed to understand chemical composition with different DOCs and dual fuel ratios to understand Soluble Organic Fraction (SOF) and Insoluble Organic Fraction (IOF) content.

**Keywords:** Particle Number; Particle mass; Diesel Oxidation Catalyst; Diesel Particle Filter; Precious Group Material; Hydrocarbon; Carbon monoxide

### Abbreviations

HC- Hydrocarbon; CO - Carbon Monoxide; PM - Particle Matter;  $\text{NO}_x$  - Oxides of Nitrogen; LTC - Low temperature combustion; PN - Particle Number; Nm - Newton Meter; nm- Nanometer; mm-millimetre; CI- Compression Ignition; EMS- Engine Management System; EGR- Exhaust Gas Recirculation;  $\text{CO}_2$  - Carbon Dioxide; ECU - Electronic Control Unit; NABL - National Accreditation Board for Testing and Calibration Laboratories; IOCL - Indian Oil Corporation Limited; D100- Diesel Fuel Only; D50G50 - Diesel 50% and Gasoline 65%; D25G75 - Diesel 25% and Gasoline 75%; D15G85 - Diesel 15% and Gasoline 85%; DOC - Diesel Oxidation Catalyst ; DPF - Diesel Particle Filter; SCR - Selective Catalyst Reduction; BSVI - Bharat Stage VI Emission; PGM - Precious Group Material; SOF - Soluble Organic Fraction; IOF - Insoluble Organic Fraction; GVW - Gross Vehicle Weight

### Introduction

LTC is advanced dual fuel combustion having different reactivity of fuel to get optimised emission in different engine operating points [1-3]. This is a proven technology and demonstrated in multiple diesel engines operated with a different blending of fuel of low and high reactive fuel along with the different compositions of dual fuel [4-6]. LTC reduces significantly both  $\text{NO}_x$  and PM during combustion with dual fuel due to low temperature [7-8]. Lower in-cylinder temperature leads to incomplete combustion of premixed low reactive fuel-air combination and prevents stored or trapped fuel-air mixture from participating in combustion, which is the cause of greater CO and

HC emissions [9-10]. The major challenge is HC and CO emissions from LTC combustion, which can be only addressed with DOC [11-13]. DOC contains different amounts of PGM content like Platinum (Pt) and Palladium (Pd) to reduce both HC and CO emissions [14-15]. The selection of DOC and PGM is the most important factor to meet the emission level of Bharat Stage VI (BSVI) with dual fuel combustion. This can be optimised based on application, cost, and emission durability requirements for any engine. Particle number and particle mass from diesel engine emissions attract attention due to health-related concerns. Particle size with a diameter of 10 microns or less ( $\text{PM}_{10}$ ) can cause lung-related problems in the human body. Fine particle matter ( $\text{PM}_{2.5}$ ) is defined as a particle with a diameter of 2.5 millimetres or less. This results in  $\text{PM}_{2.5}$  making up a fraction of  $\text{PM}_{10}$ . The composition of particulates  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$  are made up of distinct chemicals and come from diverse sources of pollution. This is causing casualties from air pollution-related causes such as heart disease, lung cancer, and other respiratory disorders [16].

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Multiple pieces of literature highlighted the impact of particle matter health effects depending on its composition, particle size, and particle nature [17-18]. Particle emissions concentration is very high in a diesel engine in comparison to gasoline engines because of the high carbon content in the exhaust gas. This is very important to understand the formation of particle matter with gasoline and diesel fuel with respect to particle number and size distribution characteristics. Diesel exhaust particle matter emission composition contains carbon soot with compounds of absorbed organic which increase during gas to particle conversion method [19]. PM consists of the composition of fine particles, and liquid drops including ash, water SOF, nitrates, and oil and fuel content (SOF) from diesel engines [20]. Smoke opacity indicates the amount of soot in the exhaust gas. The majority of particle matter is generated by incomplete combustion of fuel hydrocarbons and oil with lubricating oil playing a minor role.

### Particle Emission formation in High Reactivity Fuel Combustion

Due to high injection pressure and temperature in diesel engines, there was better fuel atomisation and spray penetration which leads to better mixing of air and fuel with better combustion efficiency. Due to the non-uniform dispersion of these droplets, the excess air ratio value changes at every position of the combustion chamber. This is relatively low near the droplet surface and increases as you get further away from it. The local excess air ratio is particularly low near droplets, indicating that incomplete combustion is caused due to a lack of oxygen. PM is formed mostly due to incomplete combustion. Particle matter consists of an Insoluble organic fraction (IOF) and a soluble organic fraction (SOF) as explained in Figure.1 [Figure 1]

### Particle Emission formation in Low Reactivity Fuel Combustion

In an SI engine, achieving optimum combustion and temperature require the presence of liquid fuel and oxygen to ignite the mixture, and determine particle formation in a heterogeneous phase reaction. Particle matter in gasoline engines is strongly influenced by air /fuel ratios of both global and local ratios. To achieve minimum particle mass concentration and PN, the ratio of global air/fuel ratio should be below 10% of the stoichiometric ratio. Multiple experiments and researchers highlighted from PM are lowest when the stoichiometric air/fuel ratio is 10-20% lean and further increases when the ratio is rich or extremely lean in SI engines [21-22].

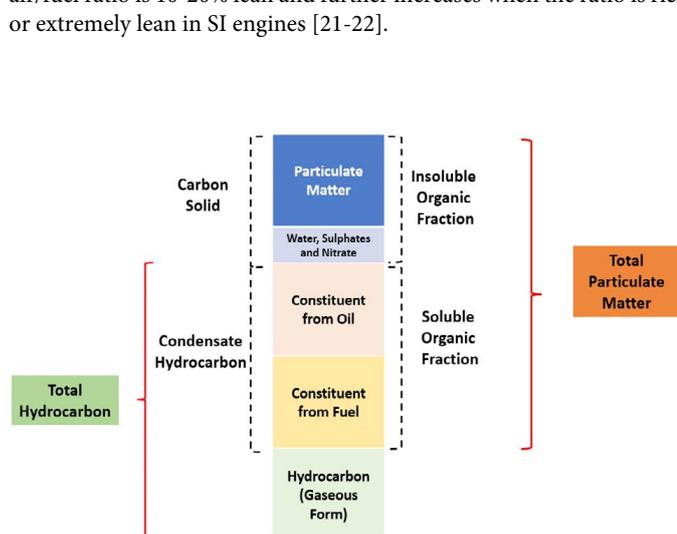


Figure 1: Composition of particle matter in diesel engine exhaust emission.

### Particle Emission formation in Low-Temperature Combustion

Many studies have shown that reduction of combustion temperature can reduce both levels of soot formation and  $\text{NO}_x$  emissions simultaneously with dual fuel [23]. Soot production in LTC mode occurs mainly downstream in the jet's head as opposed to the upstream soot-producing core found in traditional jets in diesel combustion engines [24]. The charge dilution as well as mixing between the end of injection and second-stage ignition account for this change used in LTC. The relationship between soot reduction and  $\text{NO}_x$  reduction is more complicated in LTC combustion. At about 48 percent EGR, PCI combustion conditions achieved by late injection have been documented to produce very low amounts of particle matter in engine out emission [25]. Denbratt and Alriksson [26] experiment data mention that 50% of EGR with 25% load found the lowest peak combustion temperature. They have observed an increase of soot up to 50% EGR and abruptly decreased due to soot oxidation in this condition. Figure 2 shows the reaction pathway of diesel combustion in low and high-temperature combustion and its related emission products. [Figure 2] "Data taken from Ref. [27]"

Dual fuel combustion results in a significant reduction of  $\text{NO}_x$  and PM emissions. However, it also leads to an increase in HC and CO emissions. A Diesel Oxidation Catalyst (DOC) can play an important role in reducing HC and CO emissions. The selection of DOC and its PGM loading content is very important to meet the stringent emission norms. DOCs with different PGM loading are evaluated to understand their impact on SOF and HC reduction. The major motivation for this study is to understand the correlation between particle matter and particle number from the engine out, DOC out, and DPf out with different dual-fuel configurations. This correlation assists in optimising EATS selection to meet emission norms. The novelty of the work is the study of particle matter behaviour and composition with low reactivity and high reactivity dual-fuel in low-temperature combustion. Filter paper analysis was conducted to understand the SOF and IOF content in soot with a dual-fuel engine.

### Experimental Set Up

Engine testing is performed on a four-cylinder diesel engine with a common rail diesel injection system for this experiment test in engine

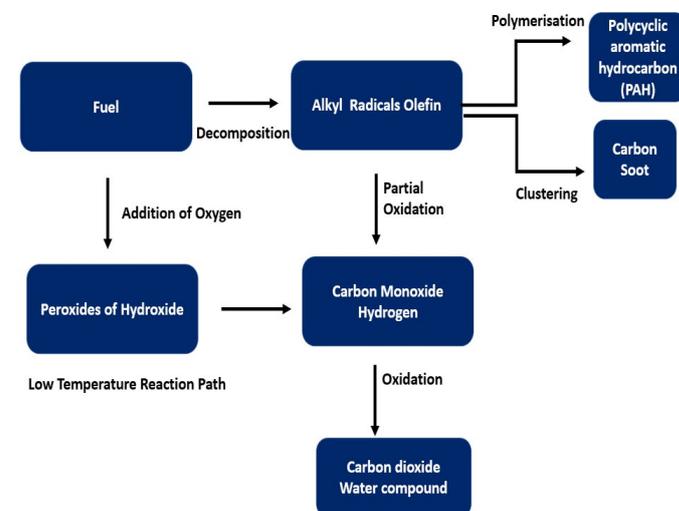


Figure 2: Reactions at low and high temperatures in fuel reaction "Data taken from Ref. [27]"

dyno. A gasoline injection system is installed in the intake manifold, which is controlled by EMS. The specifications of engine base hardware are given in Table 1. [Table 1]

ECU is used to control gasoline and diesel injectors. Table number 2 provides technical specifications of diesel and gasoline injectors, respectively. Both injectors are precisely controlled in fuel flow demand and actual as physically verified before the engine tests. [Table 2]

Engine tests are conducted in AVL transient test bed dynamometer. The temperature of the coolant is maintained at 80±2°C and the lubricating oil temperature is kept constant during the testing. Intake air is conditioned at 1000 millibar pressure, 25°C temperature, and 40% humidity during the tests. EGR is precisely controlled with electronic control EGR valve based on ECU input. EGR rate is expressed as the ratio of the concentration of CO<sub>2</sub> in intake and exhaust gases. AVL AMAi60 emission analyser to measure NO, NO<sub>x</sub>, HC, CO, CO<sub>2</sub> and O<sub>2</sub> concentrations independently. Filter Smoke Number (FSN) and Soot Concentration are measured at engine out using AVL 415S (SM) and AVL Micro Soot Sensor (MSS). The Particle Number (PN) concentration in exhaust gas was measured using an AVL Particle Counter (APC). AVL Micro Soot Sensor uses a photoacoustic technique to measure solely solid components of particle matter (mainly soot). Smokemeter measures the blackening of filter paper through which

Table 1: Engine specification.

Engine	3.8 L, 4-cylinder
Diesel fuel injection system	Electronic–Direct Injection System
Compression ratio	17:05
Maximum torque	450 Nm @ 1200-1600 rpm
Maximum power	100 kW @ 2600 rpm
Maximum peak combustion pressure	160 bar
Bore x Stroke (mm)	100x 120
Swirl Ratio	2.0

Table 2: Diesel and Gasoline Injector Specification.

Injector Specification	Diesel Fuel Injector	Gasoline Fuel Injector
Type of Actuation	Solenoid Actuated	Saturated operated
Injector make	CRIN Bosch Injector	Bosch Injector
Hydraulic Through Flow	600 mm <sup>3</sup> /30 sec	7.2 kg/hr
Number of holes	9	6
Diameter of Hole	0.18 mm	65 µm
Injector Spray Angle	148°	30°
Maximum injection pressure	1800 bar	9 bar
Injection Strategy	Multiple Injection	Single Injection

exhaust gases flow in the measurement line. A detailed description of test bed instrumentation and its accuracy is mentioned in Table 3. [Table 3]

Diesel (High Reactive) and gasoline (Low Reactive) fuels are considered for this experimental study as this widely used across the world. Both these fuels are hydrocarbon derivative fossil fuels used for the internal combustion engine. The fuel ignition delay period and self-ignition temperature properties of both fuels differentiate them and impact combustion behaviour. The physical and chemical properties of fuels verified in IOCL Lab (NABL Certified) are compared in Table 4. [Table 4]

A schematic of the engine and instrument layout is given in Figure 3. Single-point gasoline injection is used in the intake manifold of the engine for this experimental test. Two sample line emission analysers are used pre and post-after-treatment systems to understand their emission characteristic and behaviour. Different configuration of DOCs samples was used to understand particle matter and particle number behaviour. Filter paper analysis is done to understand the characteristic of IOF and SOF content with different content of the dual-fuel composition. [Figure 3]

Filter paper analysis is performed on particle mass emissions on filter paper. The primary, secondary and blank filter papers holding particle matter are separately weighted and both filters are taken together with Soxhlet solvent extraction in the laboratory. For SOF analysis, chromatographic is analysed to determine fuel composition and oil-derived hydrocarbon fractions in SOF using the method of standard IP 442 testing conditions. IOF Contents were analysed by Thermo Gravimetric Analysis (TGA) method. Particle matter collected on primary, secondary and black filter paper is subjected to a TGA test after solvent extraction. The Thermo grams are evaluated for weight loss over the defined temperature range of 40- 540°C and 540-700°C to determine (sulphates +nitrates+ water) and (carbon soot and metal oxide + others). AVL Smoke meter is used for measurement of FSN (Filter Smoke Number). FSN is an index that measures the number of carbon particles (soot) available in exhaust gas.

Three configurations of DOCs were evaluated with different PGM content to understand particle mass and particle number trend. Filter paper analysis was carried out to understand SOF and IOF with a different configuration of the dual fuel composition. Technical specification of three numbers of different configurations of the diesel oxidation catalyst is compared in Table no. 5. [Table 5]

The technical specification of DPF is given in Table 6. [Table 6]

Table 3: Instrumentation and Accuracy of Test Bed Measurement Units.

Instrumentation Unit	Model Type	Operating principle	Accuracy
Dynamometer	AVL	Transient Dyno	±2%
Speed Measurement	Magnetic Pick-Up	Inductive Principle	±5rpm
Torque	Load Cell	Strain gauge type load cell	±1%
Fuel mass flow meter	AVL – 735	Coriolis mass flow meter	±0.5%
Air mass flow meter	KVG G100	Hot film anemometer	±0.5%
Pressure Sensor	Piezo-resistive Transducers	Resistance-based Whitestone Type	±25 mbar
Temperature Sensor	Thermocouple – Type K	See-back effect	±2.5 deg C
FSN	Smoke Meter – AVL415S	Exhaust measurement in Filter Paper	+0.001 FSN
Particle Size and number	SMPS – AVL Make	Bio Polar Aerosol Charger	+3.5%
NO <sub>x</sub>	AVL AMAi60	Chemiluminescence detector	2%
HC		Flame ionization detector	
CO		Infrared detector	

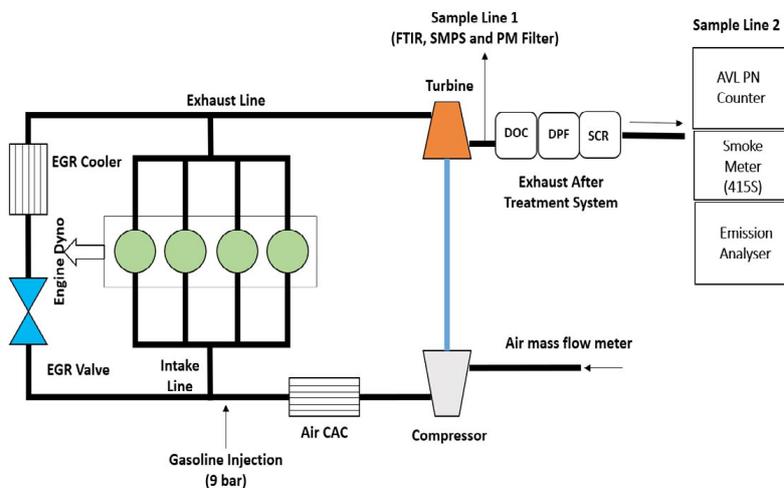


Figure 3: Engine layout configuration with gasoline injection at the intake manifold.

Table 4: Major important Fuel Chemical Properties (Gasoline and Diesel) used in trials.

Fuel Property	Gasoline	Diesel
Motor Octane Number	82	-
Cetane Number	6	52
Molecular Weight	110	190
Low Caloric Value (MJ/kg)	44.5	42.5
Boiling Point(°C)	190	320
Auto-Ignition Temperature(°C)	450	250
In Flammability limit	6.9	7.7
Latent heat(kJ/kg)	310	270
Viscosity(20°C) (cP)	0.29	3.9

To measure EGR, inlet CO<sub>2</sub> is mounted in intake manifold and exhaust CO<sub>2</sub> is measured after turbo out during test bed trials and EGR is calculated as per equation 1. EGR is measured as per below equation for all experimental trials:

$$EGR(\%) = 100 * \frac{\text{Inlet CO}_2 - \text{Ambient CO}_2}{\text{Exhaust CO}_2} \quad (1)$$

## Results and Discussion

### Effect of PGM Loading in DOC with Dual Fuel

The particle number and size distribution are important aspects to meet the standards set by Bharat Stage VI (BSVI) legislative emissions. Limits on particle number are added in BSVI emission regulation to protect the environment and human health. Emission limits of BSVI emission norms for PN are  $6 \times 10^{11}$  and PM is 0.02 g/kWhr in WHTC cycle above 3.5 Ton vehicle GVW condition [GSR No. 510(E)]. Selection of DOC and PGM content is critical for low-temperature combustion (dual fuel) to control HC and CO indirectly reducing particle mass through SOF content. SOF content in particle exhaust is critical to increasing both particle size and number. Particle mass emission is reduced compared to base engine out emission with the use of DOC system due to reduction of SOF in exhaust particle emission. Technical evaluation of DOC was done with the configuration of PGM loading. Diesel oxidation catalyst reduces hydrocarbon and carbon monoxide from exhaust along with reduction of the soluble organic fraction. Conversion efficiency majorly depends upon exhaust mass and temperature along with the PGM loading of the catalyst. An increase of noble metal content (Platinum) in DOC wash coat leads to

improving the light-off property at the lower temperature required for conversion of HC and CO along with better efficiency to reduce SOF content from particle matter. No selective catalyst reduction (SCR) is required to control NO<sub>x</sub> and a diesel particulate filter (DPF) for PM norms is required with dual fuel due to the very low value (Below 0.001 g/kWhr) observed during testing with dual fuel in this engine mode. Hence, the technical approach for after treatment with dual fuel will be the only requirement of DOC to control HC and CO. Engine out PM and NO<sub>x</sub> is negligible. Tested all 3 samples of DOCs (different PGM loading) can control both HC and CO. This has an impact on the particle number and particle size behaviour due to different content of PGM loading in DOCs.

An experiment was conducted with different compositions of dual fuel (Diesel and Gasoline) from D50G50, D25G75 and D15G85. The results were compared with emissions for pure diesel fuel. The engine was tested at an engine speed of 1500 rpm and a torque of 250 Nm with a constant EGR of 20% across all tests. Dual fuel composition was varied maintaining the same torque to understand its particle matter behaviour. Engine out particle mass reduced from 31 mg/kWhr to 19 mg/kWhr with different DOC configurations. DOC3 showed a high reduction in particle mass due to the high content of noble material (Platinum) that helps in better oxidation of HC, CO and SOF. The increase of low reactive fuel (D15G85) along with an increase of PGM (Platinum) in DOC3 is giving the best result which leads reduce significantly from 31 mg/kWhr to 2 mg/kWhr as per Figure 4.

### Effect of composition with Dual Fuel on Particle Mass Emission

Particle mass decreased with an increase in low reactive fuel (gasoline) as highlighted in Figure 4. Increase of low reactive fuel in dual fuel reduced particle mass from 31 mg/kWhr for (D100) to 7 mg/kWhr for (D15G85). The presence of a homogeneously mixed gasoline elongates ignition delay due to lower temperatures of intake charge which also leads to lower combustion temperature. The strategy to increase low reactivity fuel (gasoline) in diesel engine combustion is a methodology to reduce particle mass from exhaust emission. [Figure 4]

### Effect of composition with Dual Fuel on Particle Size distribution

Particle size distribution in different dual fuels from D50G50,

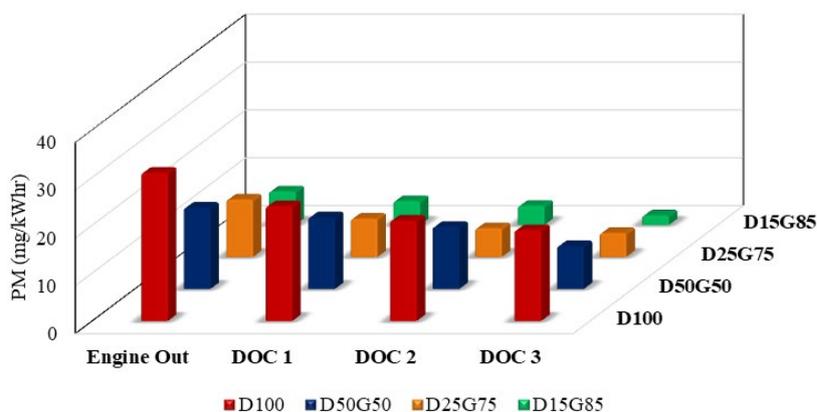
**Table 5:** Technical Specification of Diesel Oxidation Catalyst Configuration.

Specification	DOC 1 (Configuration 1)	DOC 2 (Configuration 2)	DOC 3 (Configuration 3)
Diameter	9.5"	9.5"	9.5"
Length	3"	3"	3"
Volume (Its)	3.48	3.48	3.48
Substrate Material	Cordierite	Cordierite	Cordierite
Nobel Material	Platinum and Palladium	Platinum and Palladium	Platinum and Palladium
PGM loading	10 g/cft <sup>3</sup>	15 g/cft <sup>3</sup>	20 g/cft <sup>3</sup>
Pt: Pd Ratio	4:1	4:1	4:1
CPSI	300	300	300

**Table 6:** Technical Specification of Diesel Particle Filter.

Specification	DPF Specification
Diameter	9.5"
Length	6"
Volume (Its)	7.55
Substrate Material	Recrystallized Silicon Carbide (RSiC)
Nobel Material	Platinum and Palladium
PGM loading	4 g/cft <sup>3</sup>
Pt: Pd Ratio	4:1
CPSI	300

**Particle Matter (mg/kWhr)**



**Figure 4:** Particle Mass behaviour with different dual fuel ratio and DOC configuration.

D25G75 and D15G85 is compared with diesel fuel (D100). The test condition was kept at 1500 rpm engine speed and a torque of 250 Nm with fixed EGR content of 20% was applied. In test data, particle size distribution reduced from 71 nm to 46 nm with an increase of gasoline content from 0% to 85% in dual fuel. No major particle size distribution impact was observed with DOC out with all three DOCs tested during the experiment. The increase of PGM content in DOC plays is having a minor impact on particle size distribution between engine out and DOC out. The behaviour of particle size distribution with different ratios of dual fuel and DOCs is highlighted in Figure 5. The major reduction in particle size distribution observed with DOC3 is 40 nm with a dual fuel configuration of D15G85. The possible cause of this minor reduction in particle size distribution is due to very less soot oxidation taking place inside DOC with dual fuel combustion. [Figure 5]

### SOF and IOF distribution percentage from Engine and DOC Out with Dual Fuel

Filter paper analysis conducted on particle mass emissions emitted

from the engine. IOF and SOF analysis are performed from the engine out emission and all three DOC's out to investigate SOF and IOF content from exhaust emission with dual fuel composition of D50G50 and compared with D100 engine. SOF is formed with hydrocarbon derived from lube oil and diesel fuel. Figure 6 highlights that DOC is useful to reduce SOF content in particle matter from D50G50 and D100 fuels. An increase of Platinum content in DOC from DOC1 (10 g/cft<sup>3</sup>) to DOC3 (20 g/cft<sup>3</sup>) helps in the reduction of SOF content from 17% to 5% in D100 fuel. A similar pattern was observed with D50G50 composition where SOF content is reduced from 31% to 23% with an increase in PGM content. The amount of SOF content is high with D50G50 fuel due to the increase of unburnt hydrocarbon observed in this combustion. However, the total particle mass and particle number are less with D50G50 fuel. [Figure 6]

The selection of DOC configuration and its precious material content is crucial for low-temperature combustion as this reduces both the high content of hydrocarbon and passive soot oxidation in SOF. It can be observed that BSVI emission can be achieved only from DOC with this low-temperature combustion technology.

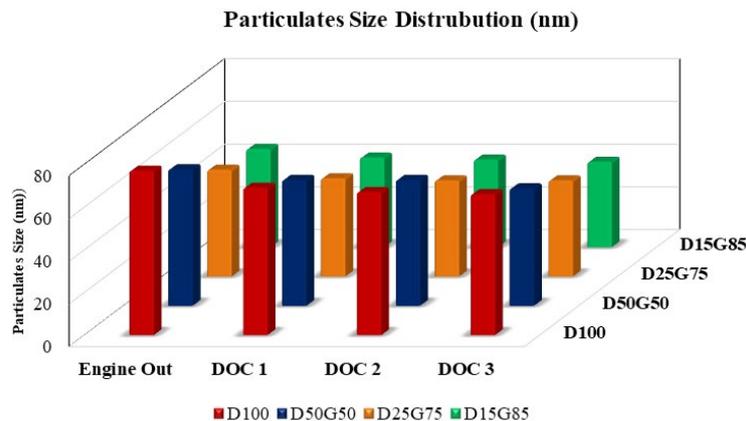


Figure 5: Particle size distribution with different dual fuel ratio and DOC configuration.

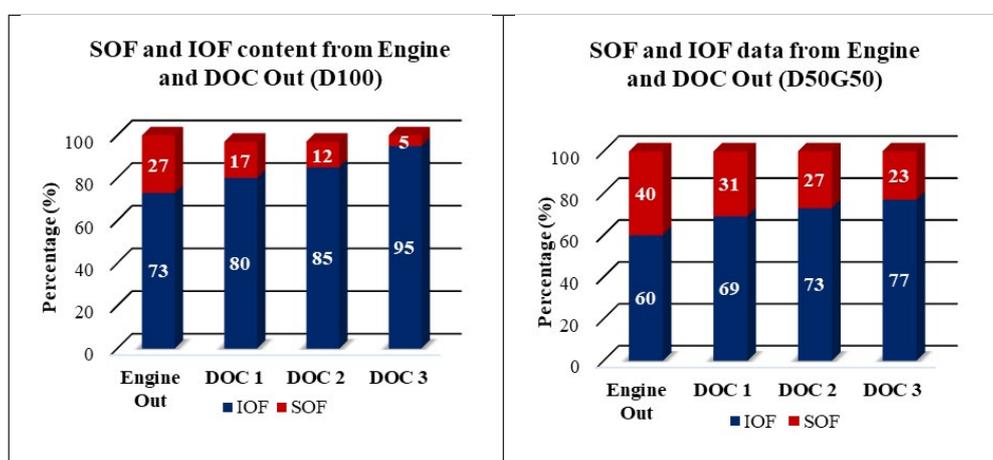


Figure 6: SOF and IOF ratio from Engine and DOC out with D5050 and D100.

### Correlation of Particle Mass and Particle Number with Dual Fuel Ratio

Kittelson [27] highlighted the relationship between particle mass and particle number with respect to particle size distribution. Test results described in this work highlight that the contribution of smaller particle size is very low for particle mass formation and larger particle size is having fewer particle numbers with an increase of particle mass. An experimental study was performed to understand the behaviour and correlation of particle number size distribution, particle mass, and particle number emissions trend after engine out, DOC out and DPF out with D50G50, D25G75 and D15G85 dual fuel in comparison to conventional diesel fuel. In the experiment test, it was observed that particle number and particle mass follow an almost linear correlation in engine out found with diesel and different dual fuel ratios. This leads to PM to PN correlation being only stable when the agglomeration rate is low as per results shown in Figure 7. This relationship between particle number and particle mass emissions pattern gets changed after DPF out in comparison with the engine out. This characteristic and behaviour pattern between particle number and particle mass emission characteristics could be useful to work in areas of the after-treatment solution. No correlation was observed for PN with PM emissions in DPF out both for diesel and dual fuels. An increase of low reactivity fuel in diesel fuel leads to a very small particle number size due to a homogeneous mixture inside combustion. [Figure 7]

Diesel engine out emission contains large mass concentration from the exhaust as found during test data. From DOC out, due to the reduction of SOF part, the PN number is reduced from the engine out test data as shown in Figure 7. The best approach to control PM and PN is to increase low reactive fuel in dual fuel combustion.

### Conclusion

The experimental investigation on engine emission was performed to understand particle mass and particle size distribution with different compositions of dual fuel. Particle emissions from the engine out, DOC out, and DPF out are compared to understand the correlation among these. The PM emission and PN characteristics are studied with dual-fuel combustion. High-reactive diesel fuel is combined with low-reactive gasoline port injection. Test results show that the dual-fuel concept can escape from  $\text{NO}_x$ , a smoke trade-off, reducing both to near zero values but leading to the challenge of increasing HC and CO emissions. This analysis of particle mass and particle size experimental study was performed in a single operating condition. In the future, further studies need to be performed across all engine mode points to have similar emission trend.

1. An advantage to reducing  $\text{NO}_x$  and PM emissions with LTC combustion leads to an increase in HC and CO emissions. This can only be controlled through DOC with PGM contained as an after-treatment device. No SCR and DPF are required to meet BSVI with dual fuel.

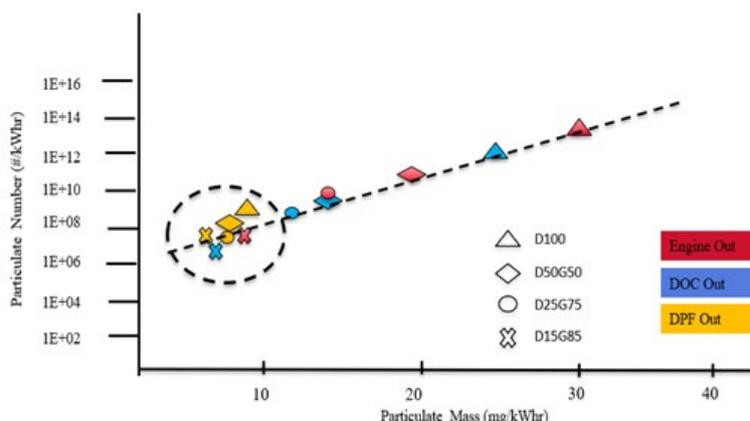


Figure 7: Correlation of Particle Mass and Particle Number with different dual fuel ratio.

All three DOCs with different PGM content can meet HC and CO emissions for BSVI norms limit. SOF content in exhaust gases has a direct relation with particle matter and number. Due to the increase of Pt contained in DOC, the particle size and particle number pattern trend are different with dual fuel ratio.

2. Diesel oxidation catalyst and its PGM content are critical to meet emission levels with dual fuel combustion. Particle mass can be reduced to 99% without DPF with dual-fuel (D15G85) and DOC3 with PGM loading of 20 g/cft<sup>3</sup>. Nobel material content (PGM) in DOC helps in the reduction of HC and CO emissions along with SOF content from emission. No significant impact was observed in particle number size distribution found with DOCs with an increase in Platinum content.

3. Subsequently, the increase in low reactive fuel (D15G85) and PGM content (DOC3) reflects a significant reduction in PM from 31 mg/kWhr to 2 mg/kWhr as per experimental data. This combination provided the optimised particle size distribution at 40 nm with different dual fuel ratios. In low-temperature combustion (dual fuel), to control HC and CO emissions selection of DOC and PGM content is most critical and important to meet emission standards.

4. High hydrocarbon content is observed reflecting a similar trend followed in SOF content with an increase of gasoline content from G50 to G85 with diesel fuel as a result of extremely low air/fuel ratios. An increase in the amount of gasoline fuel in the combustion chamber leads to unburnt hydrocarbon in form of liquid fuel which cannot fully burn before being discharged into the exhaust.

5. Particle mass and Particle Number show a linear correlation for engine out and DOC out condition emission with diesel and dual-fuel due to high particle mass emission from the engine out from the engine. This is due to the low agglomeration rate and high content of non-volatile fractions (soot) emissions from the engine out. Particle mass above 22 mg/kWhr showed linear behaviour with particle number.

6. Particle mass below 10 mg/kWhr displayed a nonlinear behaviour trend with respect to PN number after DPF out emissions. This is nonlinear due to significantly low PM and PN after high filtration efficiency of DPF. Due to the presence of semi-volatile particles from DPF out, the trend and correlation of particle number and particle mass will behave as chemical composition difference between particles mass as well as different size distributions.

7. An increase in the amount of gasoline in dual-fuel leads to a reduction of PM and PN as the mixture becomes a more homogeneous

fuel-air mixture resulting in low levels of PN emissions compared to D100 fuel. To meet BSVI emission norms, the limits of NO<sub>x</sub> (460 mg/kWhr) and PM (200 mg/kWhr) both SCR and DPF are not required in the after-treatment system with dual fuel combustion. DOC is only required to meet emission for BSVI emission with this low-temperature combustion technology using low and high reactive fuel having low cost after the treatment system.

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