11ICE-0279

Crankcase Sampling of PM from a Fired and Motored Compression Ignition Engine

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ABSTRACT

Crankcase emissions are a complex mixture of combustion products and aerosol generated from lubrication oil. The crankcase emissions contribute substantially to the total Particulate Matter (PM) emitted from an engine. Environment legislation demands that either the combustion and crankcase emissions are combined to give a total measurement, or the crankcase gases are re-circulated back into the engine. There is a lack of understanding regarding the physical processes that generate crankcase aerosols, with a paucity of information on the size/mass concentrations of particles present in the crankcase. In this study the PM crankcase emissions were measured from a fired and motored 4 cylinder compression ignition engine at a range of speeds and crankcase locations. A sequence of sampling equipment was used to characterise the emissions in the size range 5nm - 19 µm; Cambustion DMS500 fast particulate spectrometer, TSI Scanning Mobility Particle Sizer (SMPS), TSI^{TM} Condensation Particle Counter (CPC) and, TSI^{TM} Aerodynamic Particle Sizer (APS). The combination of the two test engines and range of sampling equipment provided new information on the generation and behavior of aerodynamic PM within an engine crankcase. Data is presented for the effect of controlled parameter changes on number distributions over the measured particle size range. A complex lognormal bimodal size distribution of sub micron accumulation mode particles was present in the crankcase of both engines at a low idle speed of 900rpm. At 1400rpm this complex distribution was not present. Increasing the engine load, on the fired engine, initially reduced the particle number concentration with a final significant increase in particle number concentration at 75% load. At 900 rpm 50% load there was a single strong peak at 32nm in the rocker cover however sampling from the push rod gallery and sump showed a strongly bimodal distribution with peaks at 32nm and 133nm. All other sampling data, from the fired engine, was consistent at each sampling location. The SMPS results, 15-665nm, on the motored engine showed location dependency, with the highest number concentration of particles present in the push rod gallery.

INTRODUCTION

Since 2007 the US Environmental Protection Agency (EPA), and more recently European legislation, has ruled if closed crankcase ventilation (CCV) is not used crankcase emissions must be added to tailpipe emissions giving a total emissions measurement. Crankcase emissions are a complex mixture of combustion products, including water vapor, un-burnt fuel and most significantly PM. Crankcase PM can contribute over 20% of the total PM emissions from an engine, whereas crankcase emissions of HC, NO_x and CO contribute only 3.7%, 0.1%, 1.3% respectively to the total engine emissions [Schmeichel et al 2007] [Clark & Tatli 2006]. Figure 1 illustrates the magnitude of the problem. Whilst efforts have been concentrated on tail pipe PM, the contribution of the crankcase PM has become more significant overall. Clark et al [2006] found that the engine lubrication oil contributed to approximately 50% of the PM emissions from the crankcase, the other 50% was associated with combustion emissions and wear of components. PM can be characterized by its particle size distribution, studies have found aerosols containing particles ranging from 50 nm to 10µm in diameter [Jaroszczyk et al 2006] [Dollmeyer et al 2007] [Tatli & Clark 2008].

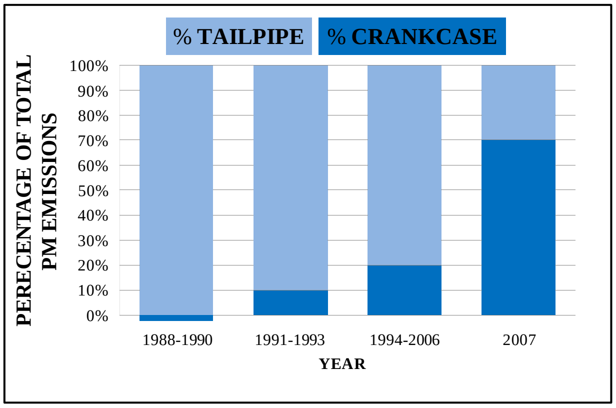

Figure 1 Crankcase emissions levels in diesel engines [Donaldson 2008]

Large particles, 10-20 µm, can be removed from the crankcase emissions using impaction separators in which the blow-by is forced through a rapid change in geometry; suspended oil particles cannot follow the flow path and are impacted onto a surface then drained away. With comprehensive knowledge of the aerodynamic particle loading an impaction separator device was developed at Loughborough university, [Long et al 2009], to control particles down to 1 µm. Removing sub-micron particles requires more restrictive geometry, this increases the back pressure on the crankcase and impaction becomes substantially more complicated to control. To achieve the desired filtration efficiency, filters become very complex, involving dynamic and consumable components.

The contribution of both combustion products and lubrication oil to engine emissions and control is of great concern however, there is research or literature explaining the generation and transport of PM through an engine crankcase. Research has focused on reducing the PM at the crankcase breather with few attempts to understand any sources of aerosol generation and oil atomization within the crankcase. This body of research provides a thorough investigation of the aerodynamic particles 5nm-19 µm present at a range of locations around the crankcase in both fired and motored Tier 2 compression ignition (CI) engines. The motored and fired engines were setup in parallel enabling the contribution of lubricant oil to crankcase PM emissions to be identified. Running with stable conditions the effect of changes to engine speed, load and oil temperature on the particle number distribution is presented.

EXPERIMENTAL TESTING

A fundamental study of PM emitted from the crankcase on both a fired and motored Tier 2 diesel engine was conducted at Loughborough University. The engine block and internal components within the crankcase were identical for both engines, full engine specifications and oil types are shown in the Appendix Tables 2-5. Three types of sampling equipment were used to characterize the crankcase PM emissions, these were, the Cambustion DMS500 MkII fast particulate spectrometer measuring particles 5nm - 1µm, the TSI SMPS and CPC measuring particles 15nm – 661nm and the APS measuring particles 0.542µm–19.81µm.

FIRED ENGINE

The fired engine PM was sampled using the Cambustion DMS500 MkII fast particulate spectrometer at three crankcase locations as shown in Figure 2; oil filler cap in the rocker cover, push rod gallery core plug and dipstick mounting hole in the sump. A sample was extracted from the crankcase into a 50mm length of Φ 8mm pipe. A k-type thermocouple was used to measure the sample temperature via a stainless steel t-junction, a second 50mm section of Φ 8mm copper pipe connected the t-junction to the Cambustion DMS500 heated line. Within the heated line the sample passed initially through a heated cyclone before the reaching the DMS500 fast particulate spectrometer. The engine exhaust was sampled separately as shown in Figure 3, a 250mm length of Φ 6mm stainless steel pipe was positioned in the centre of the exhaust flow.

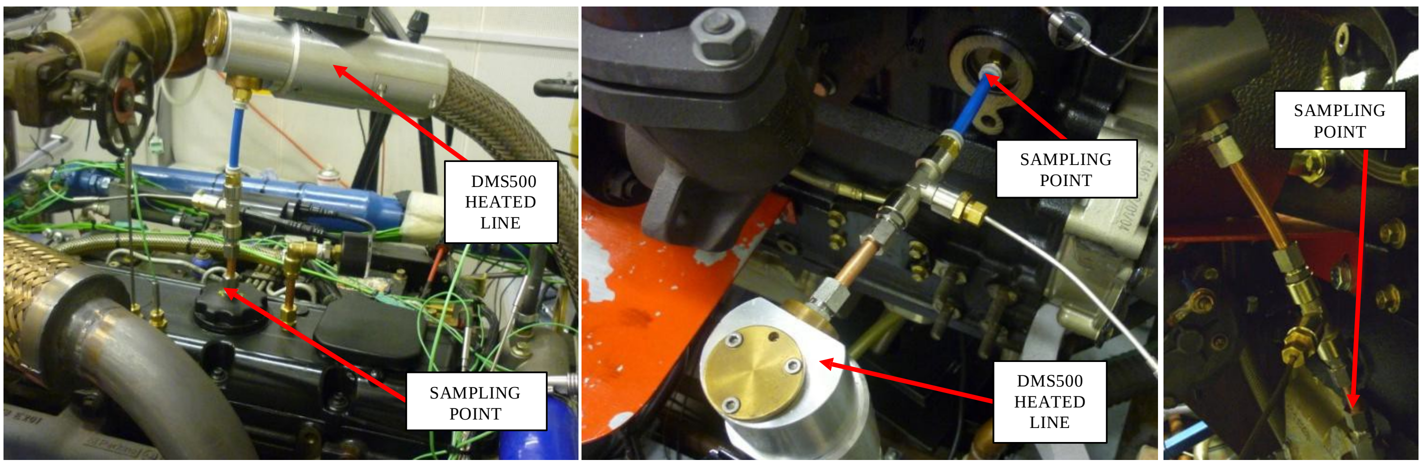

Figure 2 Fired engine DMS500 sampling points (a) rocker cover (b) push rod gallery core plug (c) sump dipstick mount

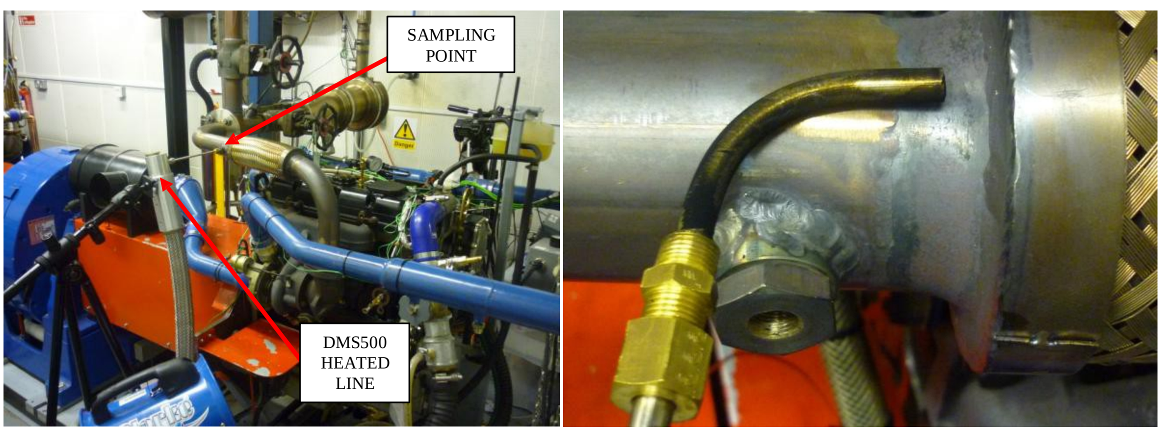

Figure 3 Fired engine (a) dynamometer and cell installation (b) exhaust sampling point

The fired engine was directly coupled to an eddy current dynamometer, within an engine test cell. Test were conducted at speeds of 900rpm and 1400rpm and loads of 0,25,50 and 75%. K-type thermocouple measurements were taken at the following locations: sump oil, post compressor air temperature, oil film above the push rod gallery, gas temperature at the top and bottom of the push rod gallery, the three sampling points and coolant temperature in the thermostat housing. The oil rail pressure was also monitored. A dynamometer control was used to fix the engine speed and load, the engine temperatures were stable before completing all steady state sampling tests.

The DMS500 has an integrated two-stage dilution system, primary dilution occurs at the sampling point in the heated line where compressed air is passed through a HEPA filter and then used to dilute the sample. Secondary high ratio dilution is applied using a rotating disc diluter, Figure 15 shows a schematic of the full dilution system. Both primary and secondary dilution was used on the DMS500 for fired engine crankcase PM emission measurement. A sample of 8 litres/min was extracted from the specific sampling point and diluted to an appropriate level, the DMS500 was calibrated to correct for dilution ratio. Additionally an AVL244 blow-by meter with two damping chambers was used to measure the blow-by flow rate.

MOTORED ENGINE

The motored engine sampling analysis was conducted using the TSI™ SMPS, CPC and the APS. The APS sample was diluted using a closed system aerosol diluter in increments of 20:1 or 100:1. A small sample of the aerosol is diluted with filtered air from the original sample, this maintains the sample elemental composition, temperature and relative humidity. The filtered air is reunited with the sample flow through a multi-hole mixing cone. Pressure gauges are used to monitor the aerosol path and total path flow rates. A valve on the filter side of the diluter can be used to adjust the pressure drop to match calibrated values. The engine was driven, by a 30 kW electric motor and controller, to a maximum speed of 900 rpm. The inducted cylinder volume was vented via the fuel injector and glow plug holes, Figure 4. A temperature controlled steady state crankcase flow was introduced below the piston skirt, the crankcase flow air temperature was kept at 110 °C. Sampling tests were conducted at crankcase flow rates of 40, 60, 80, 100, 150, 200 litres/min and speeds of 360, 600 and 900rpm. The engine coolant circuit was used to stabilize the engine temperature, and an external circuit was used to heat the engine oil, once at the specified temperature the oil was lifted into the engine sump and circulated around the engine.

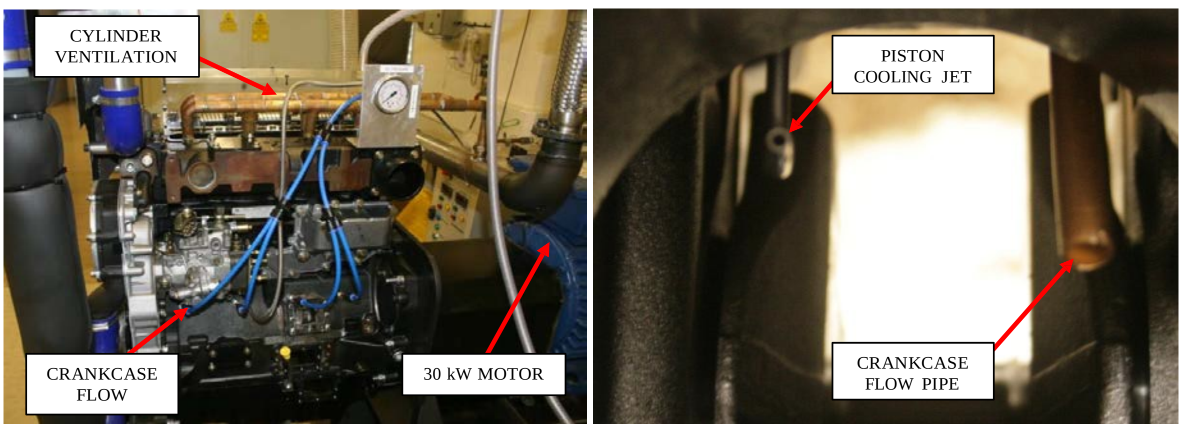

Figure 4 (a) Motored engine (b) copper injection pipe introducing crankcase flow

Again samples were taken from three locations around the crankcase of the engine: dipstick mounting hole, 100 mm down the push rod gallery and oil filler cap. The crankcase was fully vented via the specific sampling point, a 300mm length of Φ 8mm copper pipe was connected to the sampling point. The flow was then channeled into a 25mm rubber pipe before entering a Φ40mm stainless steel sampling pipe, samples were extracted from two 90° tappings in the centre of the sampling pipe connected to the APS (Φ20mm pipe) and SMPS (Φ10mm pipe). The remaining flow was vented to the extraction system.

RESULTS

REPEATABILITY

To assess the repeatability of the sampling equipment three sets of data were collected at each test point. Figure 5 shows the repeatability of the DMS500 results on the fired engine at a range of engine loads when sampling at a fast idle speed of 900rpm from the push rod gallery. The variation in peak number concentration from a mean value was approximately 15% for all engines loads, with a maximum of 27% at 75% load. Although the variation in number concentration is significant, the peak particle number concentration and trend across the measured particle size range is consistent. The data processing software was set to correct for dilution ratio, adjusting the dilution ratio was found to have no marked effect on the sampling results from the DMS500. Once the engine temperatures were stable sampling was conducted for 20 minutes. A typical contour plot is presented in Figure 6 and shows there is little fluctuation in the sampling equipment for stable engine conditions. The initial results showed good repeatability in both the size distribution and the contour plots over the test duration. To increase the range of test conditions the test duration was dropped to 15 minutes, then with continued repeatability 10 minutes, however three repeats were still completed for each test point to enable better assessment of the data. The SMPS and APS equipment used on the motored engine showed similar repeatability to that of the DMS500 for repeat tests at stable engine conditions.

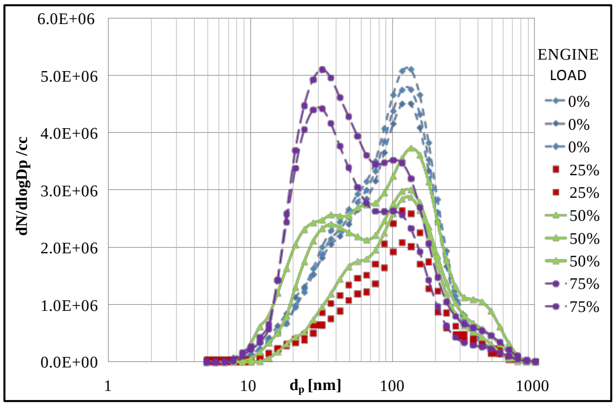

Figure 5 DMS500 size distribution of crankcase PM for varying engine load at 900 rpm sampling from the push rod gallery on the fired engine

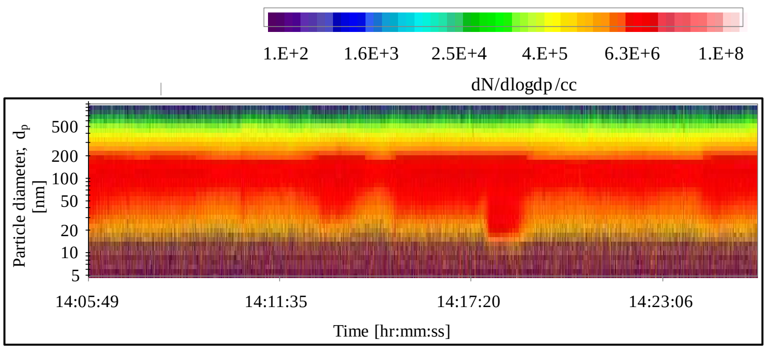

Figure 6 DMS500 contour plot at 900rpm 0% load sampling from the push rod gallery on the fired engine

LOAD VARIATION

Figure 5 highlights the significant effect of varying the engine load on the size distribution for the fired engine crankcase emissions when sampling from the push rod gallery, the push gallery gas temperatures at the tested engine loads are shown in Table 1. Initially with no load, and therefore the lowest blow-by rate, there is an approximate lognormal distribution of particles with a peak centred at 133 nm. In the size range d_p 10-100nm the particle number concentration is higher than expected for a single mode lognormal distribution. As load is applied there is an increased concentration of particles d_p 10-100nm, relative to d_p 100-1000nm, the size distribution is bimodal, this is most apparent at the higher load cases. At the highest tested load, 75%, the peak has shifted to 32nm, with a secondary peak remaining at 100 nm. The shift in peak particle diameter, caused by increased engine load, can be identified by comparing the contour plots of size distribution Figure 6 and Figure 7. At higher engine load, Figure 7, the size distribution is less stable over the twenty minute test duration, the size distribution is bimodal for the majority of the test.

The motored engine results show a similar trend to the fired engine, Figure 8. Using the crankcase flow rate as an equivalent of engine blow-by, increasing the crankcase flow rate causes the same shift in distribution over the measured particle size range. A single mode peak at 250nm shifts to a bimodal distribution with the largest peak in the range d_p 10-100nm, and a secondary smaller peak at 250 nm. Looking at the large particle size range measured by the APS, 0.5-4.5 µm, increasing the crankcase flow rate from 40 litres/min reduced the particle number concentration present in the rocker cover. No other strong trends were identified when sampling at other flow rates.

Table 1 Push rod gallery gas temperature for varying engine load at 900rpm on the fired engine

Engine Load	Push Rod Gallery Gas Temp [°C]
0%	64
25%	77
50%	78
75%	83

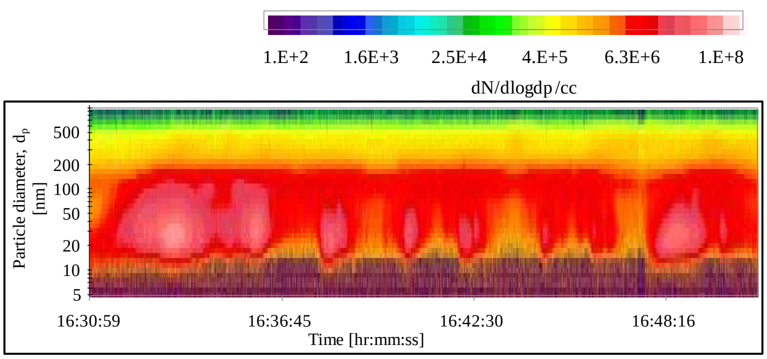

Figure 7 DMS500 contour plot at 900rpm 75% load sampling from the push rod gallery on the fired engine

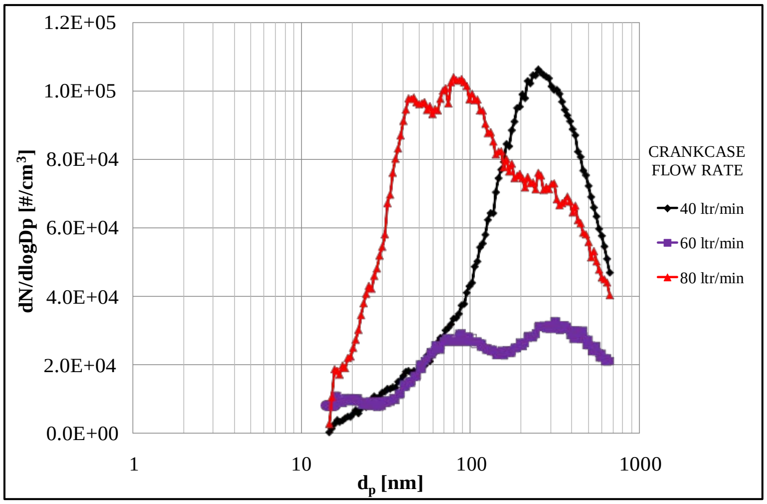

Figure 8 SMSP size distribution of crankcase PM for varying crankcase flow rate at 600 rpm sampling from the push rod gallery on the motored engine

LOCATION VARIATION

For the fired engine the complex bimodal size distribution is common for all three locations and measured engine loads at 900 rpm. A strong peak is found at 133nm for 0% and 25% load, shifting to a peak at 32nm for 75% load. A transitional stage was witnessed at 50% load Figure 9. When sampling from the sump and push rod gallery lower in the engine, the size distribution is strongly bimodal, with two prominent peaks. Sampling data from the rocker cover exhibited a single peak at 27 nm, falling within the existing common bimodal size distribution found in sump and push rod gallery. Variation in absolute number concentration was witnessed, as discussed in the repeatability section, making it difficult to identify any minor changes in concentration caused by changes in sampling location.

The motored engine sub micron particle sampling results indicate location dependency, with the most significant trend being an increase in number concentration emitted, Figure 10. The highest particle number concentration was found in the push rod gallery and the lowest particle number concentration was consistently in the sump. The distribution of particles is again lognormal and bimodal, with a single prominent peak occurring in the size range d_p 200 – 400 nm. Changing the sampling location had little effect on the number concentration and distribution of particles d_p 0.5-20 µm.

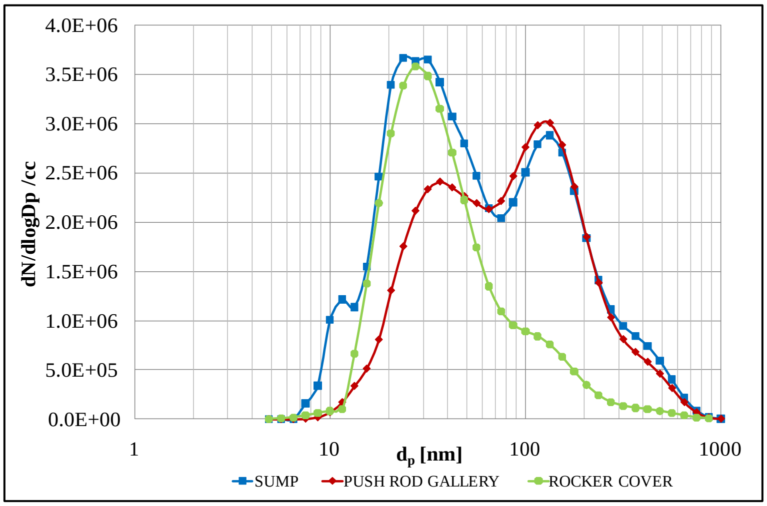

Figure 9 DMS500 size distribution of crankcase PM for varying sampling locations at 900 rpm and 50% load on the fired engine

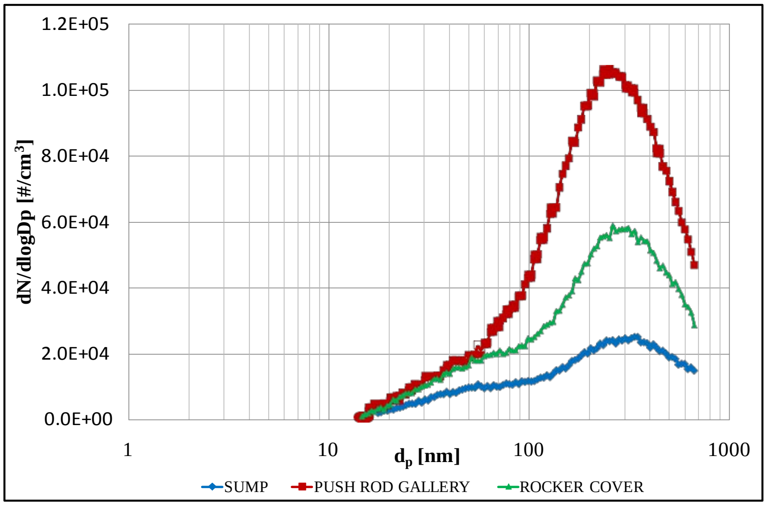

Figure 10 SMPS size distribution of crankcase PM for varying sampling locations at 600 rpm 40 litres/min crankcase flow on the motored engine

SPEED VARIATION

Increasing the engine speed had the most significant effect on the SMPS results from the motored engine, Figure 11. The increase in engine speed altered the bimodal distribution of particles most significantly between 600 and 900 rpm, a strong peak at 270 nm shifted to 76nm with the number concentration increasing by an order of magnitude. At 360 rpm there are peaks at 62 nm and 270 nm. A substantial increase in number concentration was also witnessed in the APS results however there was no change in the particle number distribution.

The effect of increasing the engine speed to the peak torque speed of 1400 rpm was examined on the fired engine. Figure 12 shows the load variation at 1400 rpm. Common for all three sampling locations, 0% - 50% load shows a bimodal distribution with a strong central peak around 133 nm , the peak then shifts to 178nm at 75% load. This trend is very different to that found at 900 rpm where the particle number distribution varied between each load. Generally the number concentration is largest at 75% load, with the 25% and 50% load curves falling under the 0% load curve.

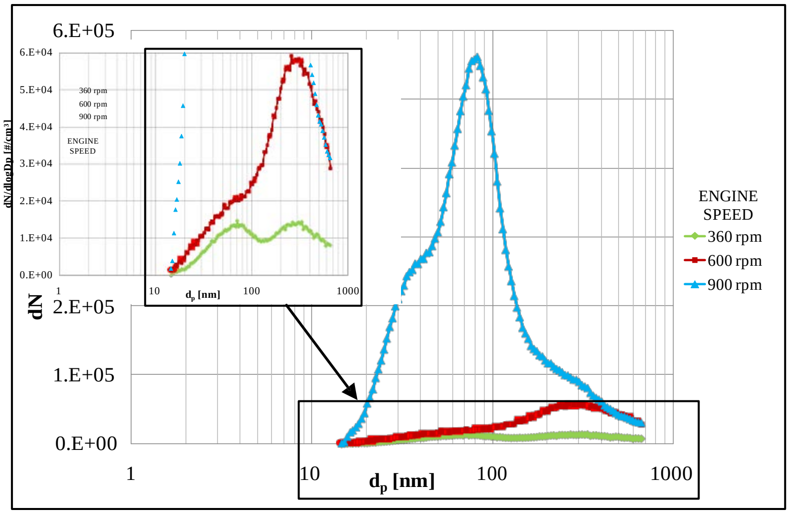

Figure 11 SMPS size distribution of crankcase PM for varying speed sampling from the rocker cover with 40 litres/min crankcase flow on the motored engine

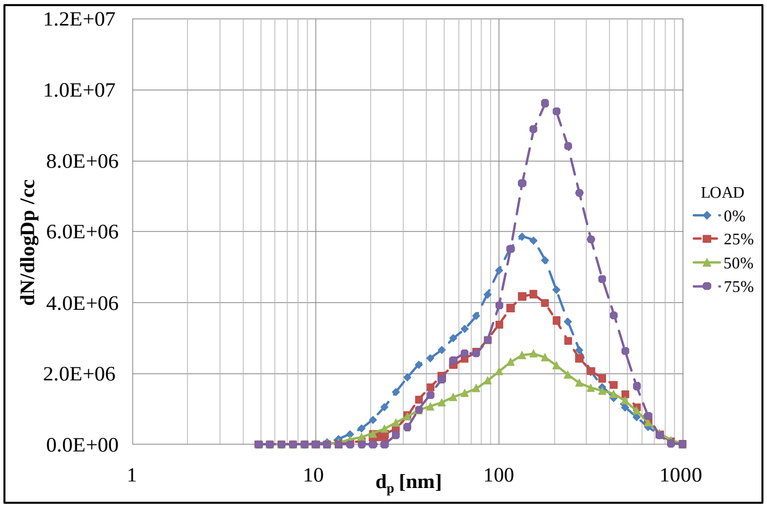

Figure 12 DMS500 size distribution of crankcase PM for varying load at 1400rpm sampling from the push rod gallery on the motored engine

CONTRIBUTION OF EXHAUST

The engine exhaust was sampled to investigate the magnitude and distribution of PM from combustion. This provides information on the contribution of the combustion products to the total crankcase emissions. Figure 13 shows the size number concentration of the exhaust emissions for varying load conditions at 1400rpm. The number size distribution is log-normal and bimodal at all measured engine loads; at 0% load there is a broad peak from d_p 27- 100nm. As load is applied to the engine the number concentration increases by a factor of six, the number size distribution remains bimodal, with a single strong peak around 100 nm and a large concentration of particles d_p 36-100nm.

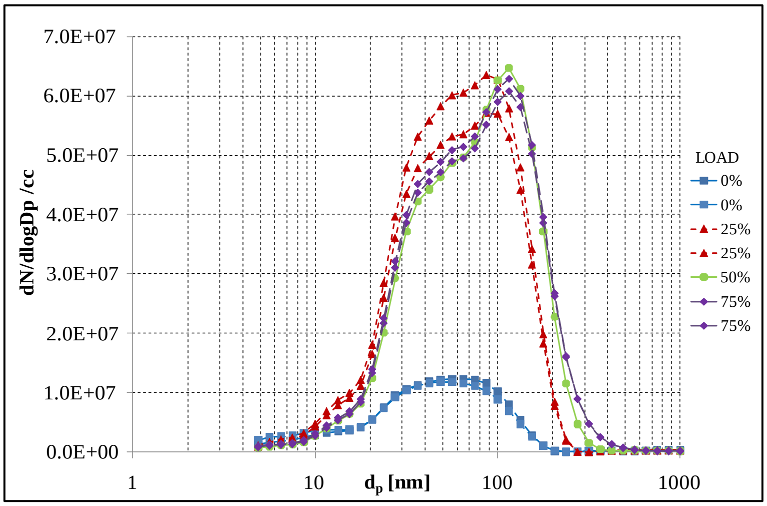

Figure 13 DMS500 size distribution of crankcase PM for varying load at 1400 rpm sampling from the exhaust on the fired engine

DISCUSSION

The work within this paper provides indication of the absolute levels of PM present within the crankcase, however the main objective was to understand the generation mechanisms and transport of PM by making controlled parameter changes. Many factors are known to effect the crankcase emissions; piston ring pack, valve stem seal and turbocharger oil seal design, engine wear and age, oil viscosity and age, crankcase and sampling point temperature and humidity. These parameters have been assumed to be approximately stable throughout all tests unless otherwise specified.

Figure 5 shows that, for the fired engine, the sub micron particle size number distribution shifts to a smaller particle diameter as load is applied at 900rpm. The peak number concentration shifts from 133nm at 0-50% load to 30nm at 75% load. This trend in size number distribution was also present in the motored engine when the crankcase flow rate was increased, Figure 8. The shift in sub micron particle size number distribution is only present at low engine speeds, 900rpm, and is consistent for all sampling locations. The only significant difference occurring at 50% load, Figure 9. At 50% load the sub micron size number distribution in the rocker cover showed a single peak at 27nm, which fell within the two peaks present at 27nm and 133nm in the push rod gallery and sump.

At higher engine loads the indicated mean effective pressure (imep) is higher, this will increase the flow rate of combustion products through the piston ring gap and, depending on the piston ring pack design and wear, may increase the leakage behind the piston rings. The intake boost pressure will also increase, potentially increasing the leakage past the turbo charger oil seals into the crankcase. These factors explain the increased blow-by flow rate that was witnessed at increased engine loads on the fired engine. The increased flow rate of gas through the crankcase has the potential to generate more aerodynamic oil particles, however this will not directly affect the generation of submicron particles that was witnessed. At the higher flow rates tested on the motored engine, there was no significant increase in aerodynamic particle number concentration measured using the APS, d_p 0.5-19µm.

There are two main mechanism of generating lubricant oil nanoparticles; evaporation from the surface of oil droplets and, evaporation and subsequent condensation of oil vapour. The motored engine enables the contribution of only lubrication oil to be identified. For increased crankcase flow rates, there is more thermal energy supplied to the crankcase therefore it could be expected that the sub micron particle number will increase substantially, however this was not seen, Figure 9. Increasing the engine speed though did increase the particle number concentration in the size range d_p 15nm – 1µm. The increased rotational velocity of engine components, most significantly the crankshaft, has been shown to increase the generation of particles down to 1µm, [Begg et al, 2010]. Increasing the engine speed increased the particle number concentration d_p 15-660nm. The increased rotational velocity of components and flow rate of air exhausted from the cylinder will increase the local surface temperatures throughout the engine providing additional thermal energy. The combination of these factors explains the increased sub micron particles witnessed in Figure 11. The significant effect of increased thermal energy present in the lubricant oil is clearly illustrated in Figure 14. Increasing the supplied lubricant oil temperature by 20°C increased the sub micron particle number concentration by a factor of 5, with no change in the submicron particle size number distribution.

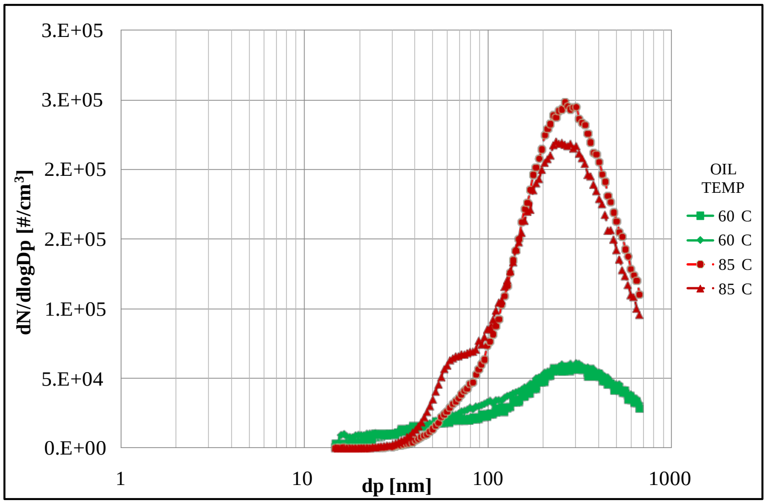

Figure 14 SMPS size distribution of crankcase PM for varying oil temperature at 600rpm sampling from the rocker cover 40 litres/min crankcase flow, motored engine

Again Figure 11 shows a shift in the peak sub micron size number distribution from 270nm to 76nm as the engine speed is increased from 600rpm to 900rpm. Data from the load comparison, at the rated speed of 1400rpm, on the fired engine also exhibited a shift in submicron size number distribution, Figure 12. The number concentration dropped as the load was applied up to 50%, at 75% the number concentration was highest and the peak of the bimodal distribution shifted from 133nm to 178nm. The changes in sub micron particle number concentration for increasing engine load, at 1400, can be attributed to both the increased blow-by levels and, particularly at 75% load, the increased thermal energy present. For increased engine load all the following parameters increased; the intake air temperature and pressure, the temperature of the combustion products and, the oil temperature. It is less clear why the sub micron particle number concentration dropped at 25% and 50% load.

The exhaust was sampled for changing engine load to isolate any contribution of the combustion products to the trends witnessed in the crankcase. Once load was applied to the fired engine the PM sampled from the exhaust did not change significantly for changing load. The sub micron size number distribution was log-normal and bimodal with a peak at 100nm spread to 36nm. Much higher levels of nucleation mode particles were expected, however they may not have been present due to the setup of the sampling point and, the level of dilution used. The sampling data from the exhaust explains why the magnitude of number concentration is much higher in the fired engine compared to the motored engine.

There is little published work on the size distribution of crankcase PM. Several studies have focused on reducing micron size particles using impaction separators, [Gokten et al 2008], however little data exist on submicron PM crankcase emissions. A comprehensive investigation of submicron crankcase PM was conducted by Tatli and Clark [2008] using a DMS500 on a range of engines pre- Tier 1 EPA regulations. This study found that the size distribution and number concentration of crankcase emissions differed substantially between four different engines. The main conclusions were; as the engine warmed up the crankcase PM number concentration reduced, for stable engine temperature the size number distributions were strongly bimodal. It is clear that the parameters effecting crankcase emissions are not well understood. The data collected in this study shows good agreement with both the particle diameters and number concentrations presents in the previous crankcase PM emissions studies. The data also quantifies the effect of controlled parameter changes on crankcase emissions.

CONCLUSIONS

A comprehensive PM sampling study has been conducted on the crankcase of both a fired and motored Tier 2 compression ignition engine, sampling particles from 5nm – 19 µm. A complex lognormal bimodal size distribution of sub micron accumulation mode particles was present in the crankcase of both engines at a low idle speed of 900rpm. At 1400rpm this complex distribution was not present. Increasing the engine load, on the fired engine, initially reduced the particle number concentration with a final significant increase in particle number concentration at 75% load. At 900 rpm 50% load there was a single strong peak at 32nm in the rocker cover however sampling from the push rod gallery and sump showed a strongly bimodal distribution with peaks at 32nm and 133nm. All other sampling data, from the fired engine, was consistent at each sampling location. The SMPS results, 15-665nm, on the motored engine showed location dependency, with the highest number concentration of particles present in the push rod gallery.

This experimental investigation has provided a new and novel insight into the distribution and transport of PM within the crankcase of a Tier 2 compression ignition engine. Controlled parameter changes have isolated potential mechanisms of PM generation. The measurement of aerodynamic PM is extremely difficult due to the sensitivity of the measurement equipment, and the complex behavior of the PM throughout the engine and within the sampling equipment itself.

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ACKNOWLEDGMENTS

All the experimental data has been collected at Loughborough University, the authors are extremely grateful for the technical support received. Thanks must also be extended to Perkins Engines Peterborough who supplied the test engines, additional test equipment, advice and consult.

DEFINITIONS/ABBREVIATIONS

APS	Aerodynamic Particle Sizer
CCV	Closed Crankcase Ventilation
CI	Compression Ignition
CPC	Condensation Particle Counter
DIL	Sample dilution
$\mathbf{d_p}$	Particle Diameter
EPA	Environmental Protection Agency
imep	Indicated mean effective pressure
PM	Particulate Matter
SMPS	Scanning Mobility Particle Sizer
Φ	Diameter

APPENDIX – ENGINE DATA

Table 2 Fired engine specification [Perkins]

Perkins 1104C-44TA General Data	
Number of Cylinders	4 vertical in-line
Bore and Stroke	105 mm x 127 mm
Displacement	4.4 litres
Aspiration	Turbocharged (air-to-air charge cooled)
Cycle	4 Stroke
Combustion System	Direct Injection
Compression Ratio	18.2:1
Rotation	Anti-clock wise viewed on fly wheel
Cooling System	Pressurised water
Dimensions	Length 663 mm Width 620 mm Height 810 mm
Dry Weight	306 kg
Lubricating Oil	10w-40
Fuel	Low Sulphur Diesel

Table 3 Fired engine oil specification [Castrol]

Oil Type	SAE 10W-40		
Manufacturer	Castrol		
Name	Magnatec Diesel 10W-40 B3		
Test	**Method(s)**	**Unit**	**Typical**
Density @ 15°C	ASTM D4052	Relative	0.871
Viscosity, 100°C	ASTM D445	mm^2/s	14.3
Viscosity, 40°C	ASTM D445	mm^2/s	95.5
Viscosity, CCS-25C (10W)	ASTM D5293	cP	6195
Ash, Sulphated	ASTM D874	% *wt*	1
Total Base Number, TBN	ASTM D2896	mg KOH/g	8.1
Pour Point	ASTM D97	°C	-33

Table 4 Motored engine specification [Perkins]

Perkins 1104C-44	
General Data	
Number of Cylinders	4 in-line
Bore and Stroke	105 mm x 127 mm
Displacement	4.4 litres
Aspiration	Natural
Cycle	4 Stroke
Combustion System	Direct Injection
Compression Ratio	19.3:1
Rotation	Anti-clock wise viewed on fly wheel
Cooling System	Pressurised water
Dimensions	Length 663 mm Width 470 mm Height 812 mm
Dry Weight	357 kg
Lubricating Oil	5w-30

Table 5 Motored engine oil specification [Castrol]

Oil Type	SAE 5W-30		
Manufacturer	Castrol		
Name	Magnatec 5W-30 A3/B4		
Test	**Method(s)**	**Unit**	**Typical**
Density @ 15°C	ASTM D4052	g/ml	0.85
Viscosity, 100°C	ASTM D445	mm^2/s	11.43
Viscosity, CCS-30C (5W)	ASTM D5293	cP	5860
Viscosity Index	ASTM D2270	None	169
Flash Point, PMCC	ASTM D93	°C	200
Ash, Sulphated	ASTM D874	% *wt*	1.22
Total Base Number, TBN	ASTM D2896	mg KOH/g	11.26
Pour Point	ASTM D97	°C	-42

APPENDIX – DMS500

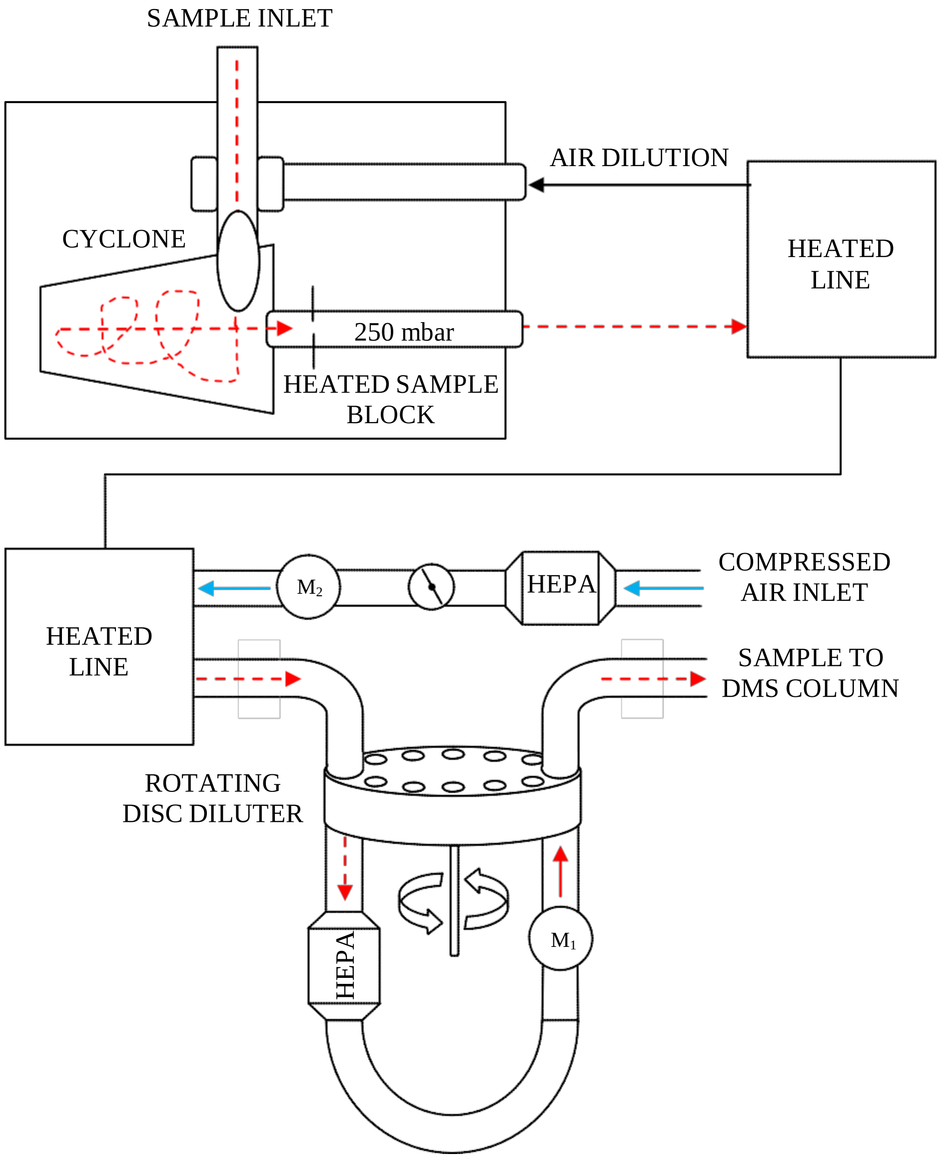

Figure 15 Cambustion DMS500 Sample Dilution [Cambustion]