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Optimizing crankcase ventilation for alternative fuels: addressing blow-by dilution and filtration

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

Alternative fuels significantly impact the design of crankcase ventilation systems, which are crucial not only for reliable, safe, and energy-efficient engine operation but also for reducing greenhouse gas emissions. Blow-by gases, when utilizing alternative fuels, can be highly toxic, corrosive, and explosive, presenting new challenges for engine design and operation. Effective crankcase ventilation systems are essential for preventing the escape of these harmful emissions. In response, legislation and technical standards are being updated to establish more stringent requirements for these systems, while the market demands cost-effective and space-saving solutions.

Crankcase ventilation systems must ensure efficient aerosol separation, maintain a stable vacuum under all engine conditions, and address the risks posed by changes in gas composition. The importance of leak-free, gas-tight system components is increasing. A purge air system may be used to dilute harmful crankcase gases, but such systems are not readily available and pose technical challenges, including increased total blow-by flow rates, composed of engine blow-by and dilution airflow.

Existing blow-by filters face performance deterioration under higher flow rates, resulting in increased pressure drop and reduced filtration efficiency. Increasing filter size to improve performance is often impractical due to space constraints. Instead, enhancing filter design and optimizing the ventilation setup present viable but challenging solutions. Additionally, particle-free purge air must be introduced in a way that dilutes crankcase aerosols effectively without generating or flushing out additional particles. Addressing these challenges requires a thorough understanding of blow-by aerosol formation, transportation, and separation.

This work expands this knowledge, tackles technical issues posed by alternative fuels, and proposes solutions for crankcase ventilation system design, including the optimal position for adding purge air. Quantitative analysis is based on aerosol concentrations and particle size distributions from optical particle counters. Comprehensive crankcase dilution experiments on a four-cylinder, 5.1-L diesel engine reveal that the location of particle-free air addition significantly impacts aerosol emissions. Adding air through the valve cover resulted in the expected dilution, while adding it between the oil sump and cylinder block did not reduce aerosol concentration. These findings are crucial for designing crankcase purge air systems and optimizing return paths for other gases, such as those from turbochargers.

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1 INTRODUCTION

During the operation of internal combustion engines (ICEs), a mixture of air, combustion gases, and fuel enters the crankcase through various pathways, with the primary sources being gas leakage past the piston rings and turbocharger seals [1]. These gases, commonly referred to as blow-by, are then loaded with oil droplets generated within the crankcase through mechanical processes (e.g., atomization) or thermal processes (e.g., condensation) [2]. To prevent the buildup of excessive pressure, it is essential to vent the blow-by gases from the crankcase.

Modern ICEs are typically equipped with closed crankcase ventilation systems [3], which vent blow-by gases into the intake air rather than releasing them into the environment. These systems serve two critical functions: aerosol separation and crankcase pressure control. To prevent fouling of intake air components and avoid abnormal combustion, a very high aerosol separation efficiency of over 99.5% (based on mass) is beneficial. Additionally, maintaining crankcase pressure typically a few millibars below atmospheric pressure is essential to prevent oil leakage and the release of harmful crankcase gases into the engine room.

While all ICEs are capable of venting blow-by gases, very few are equipped with systems to introduce particle-free air into the crankcase. However, with the growing shift toward renewable fuels, including hydrogen and methanol, the implementation of dilution / purge air systems has become increasingly necessary to prevent the formation of an explosive crankcase atmosphere. Additionally, the importance of ATEX-compliant crankcase ventilation systems is growing, as they play a critical role in mitigating the risk of explosions. The lower explosive limits (LEL) for hydrogen and methanol are 4% and 6%, respectively. Conventional methane has a comparable LEL of 5%. However, the explosion risk is lower with methane due to its significantly lower concentration in the air-fuel mixture, especially compared to hydrogen. This is because methane has a "higher calorific value" (molar) that is 3.1 and 1.2 times higher than hydrogen and gaseous methanol, respectively, requiring less fuel to achieve the same energy output.

The fuel concentration in the crankcase is significantly influenced not only by the type of fuel but also by the engine's operating conditions and the design of the fuel admission system. Generally, the highest fuel concentrations are observed in engines with fuel supply located upstream of the turbocharger, followed by those with port fuel injection. The lowest concentrations are found in engines utilizing direct fuel injection, due to the more efficient combustion process and reduced fuel bypass.

Given these facts, it is no surprise that the target crankcase dilution ratio of different engines varies significantly. Reported blow-by-to-dilution-air ratios range from 1:1 to 1:10 [4]. As the dilution ratio increases, oil mist separators must cope with higher flow rates, which has significant implications for the design of oil mist filters. To meet crankcase pressure, filtration efficiency, aerosol concentration, and filter lifespan requirements, the effectiveness of these filters must be enhanced, and/or larger dimensions may be necessary. Typically, the pressure drop of a given oil mist filter scales approximately linearly with flow rate, while filtration efficiency exhibits non-linear behavior. The aerosol concentration in the crankcase can also be influenced by the dilution flow rate and the precise location where the air is introduced. This is because the position of air addition affects the flow dynamics within the crankcase, potentially diluting or even flushing out additional particles from aerosol sources, which are primarily located in the lower compartment of the crankcase [5]. Filter lifespan depends on various factors including aerosol mass flow, aerosol composition, water concentration and temperature. Strategies to improve filter performance include optimizing space utilization, enhancing filter media composition, and implementing pre-separation techniques.

In addition to the crankcase explosion risk posed by certain alternative fuels, toxicity is a significant challenge, particularly with ammonia and methanol. The concentration of ammonia at which the gas becomes immediately harmful to life or health (IDLH) is 300 ppm, while for methanol, the IDLH is 6000 ppm. In crankcases, the concentration of these substances can far exceed these limits, as demonstrated by the CIMAC Paper [6], which reported ammonia concentrations in blow-by as high as 22,890 ppm. Crankcase purge air systems can help reduce this concentration. To prevent the release of harmful gases, ensuring the "gas-tightness" of crankcase ventilation systems is critical. One prerequisite for this is the use of materials that are compatible with the new fuels. Ammonia in particular poses a significant challenge, as it chemically attacks many common materials such as FKM and non-ferrous metals. Moreover, the pressure control system must be both robust and precise to maintain an underpressure in the crankcase. One effective solution for ammonia driven engines is the active extraction of blow-by using a blower, with the gas then being fed directly upstream of the SCR, as outlined in [7]. This approach not only ensures compliance with the 2024 DNV-RU-SHIP Pt.6 Ch.2 5.6.4 directive but also prevents ammonia-induced corrosion of components in the intake air path.

The growing importance of crankcase purge air systems, coupled with the lack of comprehensive literature on this topic, has motivated this research. One of the primary objectives of this study is to understand the effect of the dilution process on crankcase aerosol properties, which are crucial for the design of oil mist filters. A key focus is on examining how the location of dilution air introduction influences aerosol characteristics. Specifically, particle-free air was introduced either through the valve cover or between the oil sump and the cylinder block. Quantitative analysis was based on aerosol concentrations and particle size distributions (PSDs), measured using an optical particle counter. All experiments were conducted on a 4-cylinder, 5.1-liter diesel engine with 170 kW, operating at speeds of 1200 rpm and 2200 rpm, and loads of 0% (fired; idle), and 100%. The experiments were carried out at oil temperatures between 62 °C and 121 °C, with dilution flow rates of 50 L/min and 100 L/min.

2 EXPERIMENTAL METHODS AND PROCEDURES

This section details the optical particle counter (OPC) employed in this study to characterize crankcase aerosols. It also provides an overview of the engine specifications and test stand setup. It concludes with a description of the dilution procedure.

2.1 Aerosol measurement technique

The OPC used in this study is shown in Fig. 1. It consists of a Palas Promo 2000 H control unit and a Palas Welas 2070 HP sensor that has already been extensively validated for crankcase aerosol characterization [8]. The control unit provides a fixed sampling flow rate of 5 L/min. In this study, the OPC was not heated. The device was operated in the 0.3–17 µm size range with a resolution of 32 size channels per decade. Particle size distribution (PSD) graphs are based on a 3-point moving average, with each data point representing a 300 second measurement interval. OPC data are not corrected for dilution system particle losses, as the focus is on relative changes rather than absolute levels. Error bars are not shown to avoid cluttering the graphs. Besides, they have no impact on the conclusions drawn.

The OPC data processing software, PDAnalyze, includes several calibration curves for converting scattered light intensity to optical particle size. The calibration curve for paraffin oil, with a refractive index of 1.47 at STP, was used, as it closely matches the refractive index of engine oil.

The OPC sensor required regular cleaning and recalibration. Cleaning involves removing and wiping the optics of the sensor, while recalibration measures the particle time of flight (TOF) through the sensing volume. The TOF spectrum is used to correct for errors, such as coincidence events, and is sensitive to non-steady flow conditions, like pressure pulsations in an engine. Therefore, the recalibration was performed using the actual aerosol from the crankcase while the engine was turned off.

Figure 1. Optical particle counter (OPC) from Palas GmbH employed for crankcase aerosol characterization.

2.2 Engine characteristics and test stand

The engine used in this study is a medium-duty 4-cylinder, 5.1-liter diesel engine. It features a two-stage turbocharging system, delivers a nominal power of 170 kW at 2200 rpm, and provides a nominal torque of 900 Nm between 1200 rpm and 1600 rpm.

Key engine characteristics relevant to crankcase aerosol generation include the blow-by gas flow rate and the sump oil temperature, which depend significantly on the operating point of the engine. The flow rate ranged from 22 L/min to 81 L/min. This flow directly influences aerosol formation. Additionally, it affects particle transport speeds and dwell times in the crankcase, impacting particle-particle as well as particle-wall interactions and the resulting PSD. The sump oil temperature, in turn, ranged from 91 °C to 121 °C. It affects oil viscosity and vapor concentrations, influencing both mechanical and thermal aerosol generation.

For blow-by aerosol characterization, the test stand was equipped with an AVL blow-by meter (AVL 442.D/300) and the Palas OPC described in section 3.1. The device was connected to the engine via a custom 1:9 sampling and dilution system described in [8]. The OPC sampling flow rate was set to 0.56 L/min, with the sensor positioned directly above the sampling port to minimize particle losses. The crankcase aerosol was extracted directly from the space between the valve cover and the cylinder head, upstream of the crankcase ventilation inlet, in order to determine the actual raw aerosol concentration. The sampling position marked as "OPC REF" is shown in Fig. 2.

All experiments used Shell Rimula R6 LME (5W-30) synthetic lubricant oil. To eliminate the effects of oil aging on aerosol properties, the oil was pre-aged in the engine (24 hours at medium to high power output) and regularly replaced. The oil level was kept constant throughout all experiments to ensure consistent oil properties and prevent any influence on the blow-by aerosol spectra.

The engine's intake air was drawn from the test stand environment and conditioned by the engine's turbocharger and air intercooler. Cooling water was actively maintained at 90°C unless stated otherwise, while the engine's lubricant and cooling oil circulated in a closed-loop system, closely replicating the production model, except for an additional heat exchanger installed in the oil pan for improved temperature control.

Figure 2. Valve cover with ports for extracting aerosol "OPC REF" and adding purge air "HIGH".

2.3 Crankcase dilution procedure

The gas flow conditions within the crankcase are complex and heavily influenced by the specific engine design. Factors such as the flow properties of the blow-by that passes the piston rings, piston movement, and the rotation of engine shafts (e.g., crankshaft, camshaft) all contribute to a highly pulsatile, unsteady flow regime. The flow characteristics are not only dependent on the engine's operating point but also on the precise location within the crankcase. In this context, computational fluid dynamics (CFD) can be a powerful tool for identifying the optimal location for introducing purge air into the crankcase, helping to mitigate concentration peaks and reduce the risk of explosions. However, CFD analysis was not part of the scope of this study.

Instead, two distinct air inlet locations were selected for investigation: one in the lower compartment of the crankcase, referred to as "LOW," located just above the oil level (see Fig. 3), and another in the upper compartment between the valve cover and the cylinder head, referred to as "HIGH" (see Fig. 2). In this study, a controlled flow of particle-free air, with a relative humidity of less than 10% and a temperature of approximately 30 °C, was introduced at flow rates of either 50 L/min or 100 L/min.

The primary goal of this procedure was to assess the impact of dilution air on crankcase aerosol emissions. Depending on the location of the air inlet, the dilution could either reduce aerosol concentrations or potentially flush out additional particles. The measured PSDs were then compared with those obtained in the absence of added air. Additionally, the analysis included calculated PSDs based on the assumption of perfect dilution.

It is important to note that a separate investigation confirmed that the introduction of dilution air did not influence inertial particle losses in the riser ducts, which connect the lower and upper crankcase compartments, for particle sizes below approximately 5 µm.

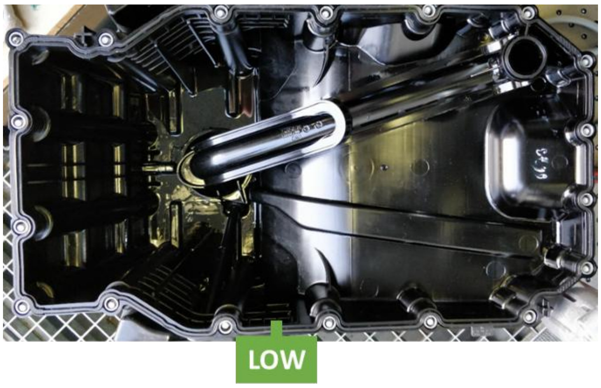

Figure 3. Oil pan with inlet for adding purge air "LOW" above oil level.

3 RESULTS AND DISCUSSION

The following subsections explore the effects of operating point, oil temperature, and dilution ratio on crankcase aerosol emissions, with dilution air introduced through the "LOW" or "HIGH" inlet.

3.1 Effects of dilution and operating point on crankcase emissions

The graphs presented below show PSDs with and without the addition of dilution air. On the left-hand side the air was added via the "HIGH" port and on the right-hand side via "LOW". The red curves represent the PSDs with dilution air, while the black curves represent the PSDs without dilution. In addition, the blue curves depict the PSDs without dilution, scaled by the ratio of blow-by flow to the sum of blow-by flow and dilution flow (dilution ratio).

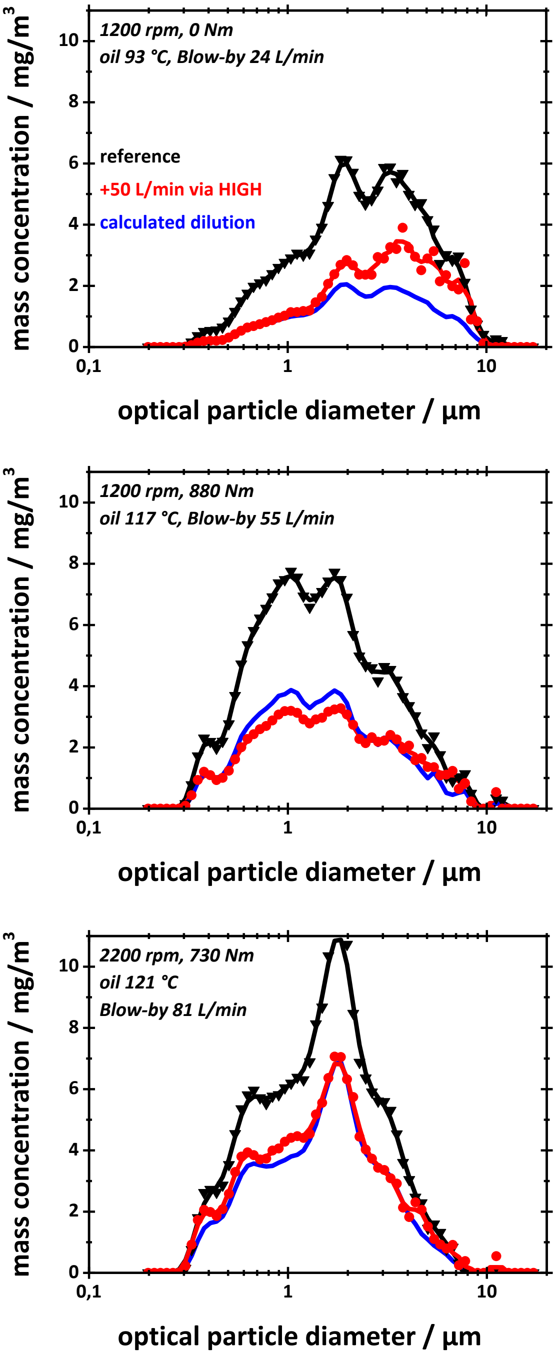

Figure 4. Blow-by aerosol PSDs with and without the addition of 50 L/min of dilution air to the crankcase from above “HIGH” at three engine operating points. Aerosol was sampled from the reference measuring position “OPC REF”.

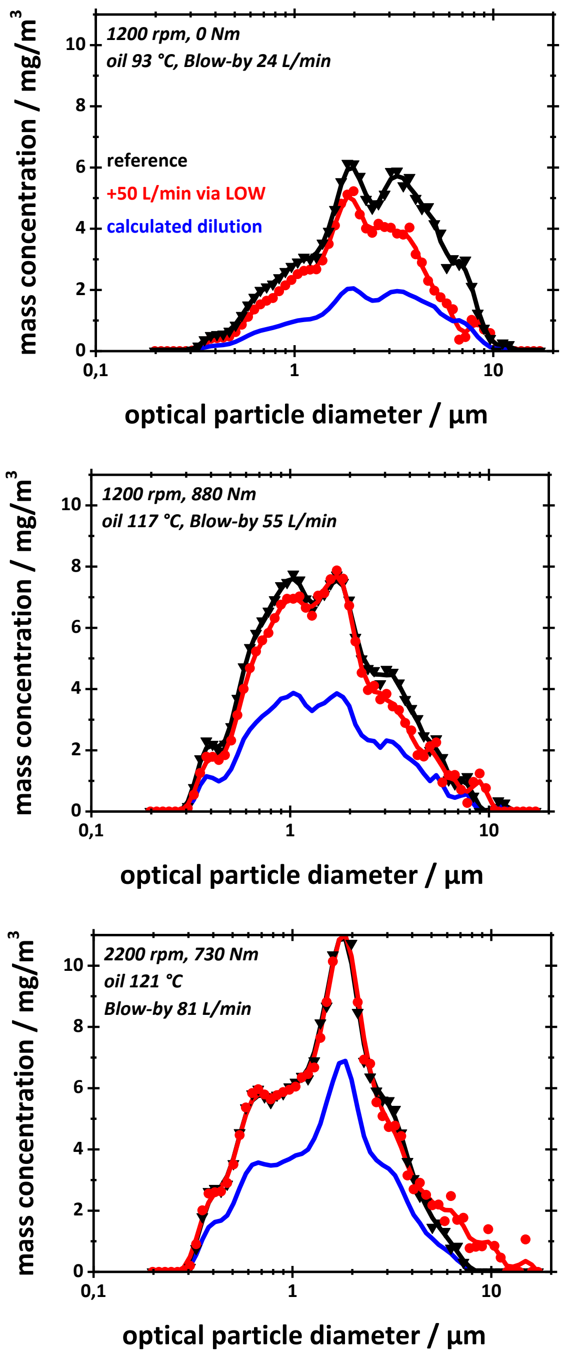

Figure 5. Blow-by aerosol PSDs with and without the addition of 50 L/min of dilution air to the crankcase from below “LOW” at three engine operating points. Aerosol was sampled from the reference measuring position “OPC REF”.

Generally, the following outcomes are possible from adding dilution air: First, the aerosol concentration could be reduced ("diluted"), causing the PSD without dilution (black curve) to drop to the level of the blue curve, meaning the red and blue curves will coincide. Alternatively, the additional air flow could flush out more particles toward the sampling point, offsetting the dilution and keeping the concentration relatively unchanged, and thus higher than the blue curve. In this case, the red curve will be similar to the black curve.

Fig. 4 displays results with dilution air added from the "HIGH" inlet, while Fig. 5 shows results for dilution air introduced from the "LOW" inlet. Three engine operating points were tested: 1200 rpm at 0 Nm, 1200 rpm at 880 Nm, and 2200 rpm at 740 Nm (nominal power).

In Fig. 4, the red curves generally align with the blue curves, indicating that dilution from above, near to the inlet of the crankcase ventilation system, reduces aerosol concentrations as expected. In contrast, in Fig. 5, the red curves tend to align with the black curves, suggesting less dilution. This agreement is especially strong for intermediate and high engine loads. For micron and submicron particles, the addition of dry air from above results in a reduction in concentration proportional to the dilution factor. This strongly suggests that submicron particles predominantly originate from the lower crankcase region and are diluted before reaching the OPC probe. Introducing dilution air at the "HIGH" location would effectively reduce crankcase emissions and reduce the demand on the oil mist filter. Regarding supermicron particles, concentrations were sometimes higher than expected from dilution, particularly at 1200 rpm and 0 Nm. This suggests that the added air flow may flush larger particles from the upper crankcase, transporting them to the sampling point.

When dilution air was introduced from below, "LOW" (see Fig. 5), the concentration of micron and submicron particles in the range of 0.3 µm to 5.0 µm remained largely unchanged across all operating points. This indicates that the dilution effect is counterbalanced by the introduction of additional particles. These particles may either preexist in the lower crankcase and are only entrained by the added air, or they may form due to vapor condensation. Both scenarios are plausible, especially when the dilution air mixes with the aerosol-laden blow-by in the turbulent flow field created by piston movement and crankshaft rotation. Additionally, the added air flow is heated and becomes saturated with oil vapor. The particles are then carried through the riser ducts to the upper crankcase regions and to the OPC probe. No significant inertial particle losses in the riser ducts were observed in the data.

3.2 Effects of dilution and oil temperature on crankcase emissions

A key question that remains to be addressed is whether the additional particles observed during dilution via "LOW" are formed by the condensation of oil vapor. To investigate this, an experiment was conducted at a reduced oil temperature of 62 °C, where the saturation vapor concentration is minimal. This was achieved by lowering the cooling water temperature and activating the oil pan cooler. All other experimental conditions followed the same protocol as in the previous measurements. The results from these OPC measurements are presented in Fig. 6.

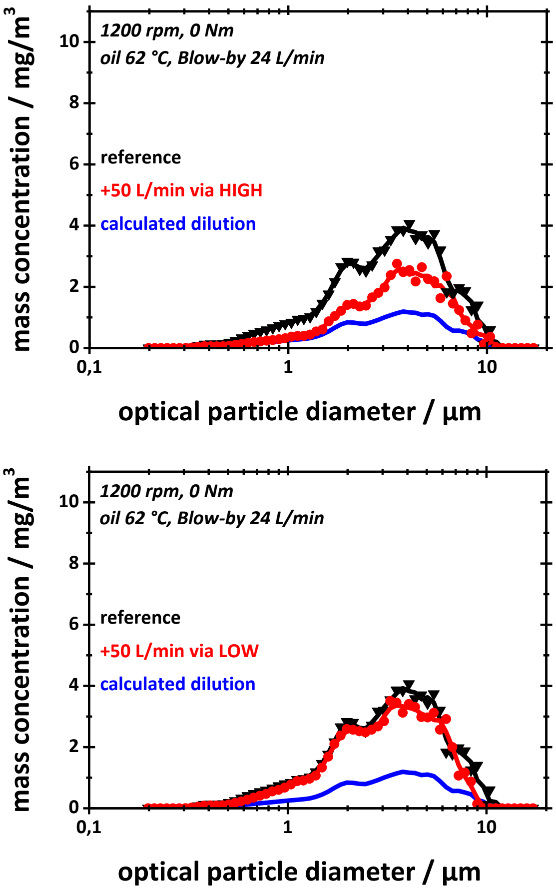

Figure 6. Blow-by aerosol PSDs with and without the addition of 50 L/min of dilution air to the crankcase from below "LOW" and above "HIGH" at 1200 rpm and 0 Nm. Aerosol was sampled from the reference measuring position "OPC REF". Oil temperature was reduced to 62 °C.

At the reduced oil temperature, where oil vapor generation and hot-spot temperatures are relatively low, and oil viscosity is relatively high, crankcase aerosol concentrations decreased but no significant change in system behavior was observed. As in previous tests, the introduction of dilution air to the upper crankcase compartment did result in a reduction of aerosol concentration proportional to the dilution factor. In contrast, when the same amount of air was added to the lower crankcase, the particle concentrations remained unchanged. Given the low temperatures, condensation of oil vapor can be ruled out as a contributing factor. These findings suggest that mechanically generated particles are being flushed out from the lower crankcase compartment when dilution air is introduced there.

3.3 Effect of dilution ratio on crankcase emissions

An additional investigation was conducted to examine the effect of the dilution ratio, which was increased from approximately 1:2 in the previous experiments to 1:4. This test was performed while operating the engine at 1200 rpm and 0 Nm. The goal was to determine whether dilution would occur or if additional particles would be flushed out when more dilution air was introduced through the "LOW" position.

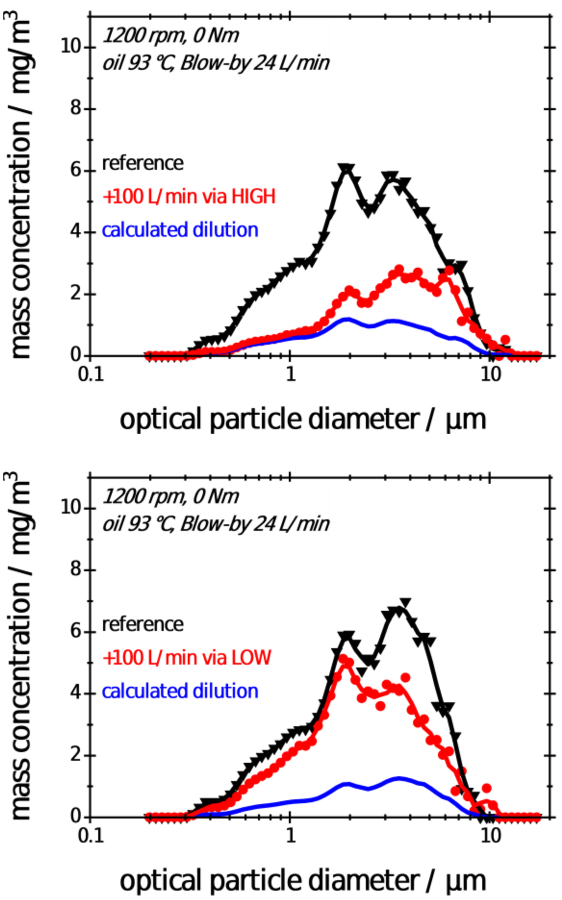

Figure 7. Blow-by aerosol PSDs with and without the addition of 100 L/min of dilution air to the crankcase from below "LOW" and above "HIGH" at 1200 rpm and 0 Nm. Aerosol was sampled from the reference measuring position "OPC REF".

Fig. 7 shows a similar pattern to previous observations, with little to no dilution when air was added through the lower inlet and perfect dilution of submicron particles when air was added via the "HIGH" position. These results highlight the lower engine compartment as the primary source of blow-by aerosols (especially in the submicron range).

Even with a dilution ratio of 1:4, aerosol concentrations were not significantly reduced when air was introduced to the "LOW" position. However, this position is expected to effectively reduce the risk of explosion, as the added air would lower gas concentrations over a larger region of the crankcase compared to adding air near the crankcase ventilation inlet.

From these findings, we can conclude that engines with similar behavior would place significant demands on the crankcase ventilation system. Specifically, the aerosol mass flow entering the system would increase in proportion to the dilution factor, requiring highly efficient and effective oil mist filters.

4 CONCLUSIONS

This study explored the impact of dilution air on crankcase aerosol emissions, offering valuable insights for optimizing crankcase ventilation systems, particularly for engines operating on alternative fuels. Fuels including hydrogen, methanol, and ammonia introduce unique challenges – particularly in terms of toxicity, corrosion, and explosion risks – placing high demands on crankcase ventilation systems. These systems must not only ensure optimal filtration efficiency and maintain ideal crankcase pressure but also mitigate the risks associated with harmful blow-by gases. In this regard, dedicated crankcase dilution systems may be essential.

Key findings of this study emphasize the significant role of the dilution air introduction location in controlling aerosol emissions. The results clearly show that adding dilution air through the "HIGH" position, near the inlet to the crankcase ventilation system, led to the anticipated dilution effect, resulting in a reduction of aerosol concentration in the upper compartment of the crankcase. In contrast, introducing dilution air through the "LOW" position, near the oil sump, did not significantly reduce aerosol concentrations. Instead, this procedure tended to flush out mechanically generated particles from the lower compartment, maintaining constant concentration levels, particularly for submicron particles.

The study also examined the effects of various engine operating conditions, including oil temperature and dilution ratio, on aerosol emissions. Lowering the oil temperature did not lead to significant changes in the system's behavior, ruling out condensation as a key factor in the generation of additional particles. Furthermore, increasing the dilution ratio from 1:2 to 1:4 at low load conditions revealed that even higher dilution flows through the "LOW" inlet did not result in a reduction in aerosol concentration, further supporting the conclusion that the lower engine compartment is the primary source of aerosol.

The implications of these findings are twofold. First, assuming other engines behave similarly when dilution air is introduced, crankcase ventilation systems must be designed to cope with higher flow rates and increased aerosol mass flows to effectively control emissions. Second, strategically placing the return paths for gases near the crankcase ventilation inlet could significantly reduce aerosol concentration by preventing the flushing out of additional particles – particularly beneficial for the turbocharger return path. However, this location is not suitable for introducing dilution air, as it would not distribute evenly throughout the crankcase, thus failing to fully mitigate the risk of explosion.

To reduce the demands on crankcase ventilation and dilution systems, measures should be implemented within the engine to minimize blow-by flow rates. These measures include optimizing piston ring design, turbocharger shaft seals, and valve stem seals. Additionally, minimizing the amount of fuel entering the crankcase can be achieved through improved fuel injection and combustion optimization. Finally, optimizing engine oil properties is essential to reduce the formation of aerosol in the crankcase. This can be accomplished by lowering oil volatility, either through enhanced oil formulation or by reducing oil temperature.

5 ABBREVIATIONS

Table 1. List of abbreviations.

Abbreviation	Description
ATEX	atmosphères explosives
CFD	computational fluid dynamics
ICE	Internal combustion engine
IDLH	immediately harmful to life or health
LEL	lower explosive limit
OPC	optical particle counter
PSD	particle size distribution
STP	standard temperature and pressure
TOF	time of flight

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