Challenges Related to the Measurement of Particle Emissions of Gasoline Direct Injection Engines Under Cold-start and Low-temperature Conditions

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Received on June 6, 2019

ABSTRACT: Particulate matter and – recently – particle number emissions from direct injection gasoline engines have already been regulated. The measurement techniques are well established for moderate temperature (23 ± 5 °C) but not for low temperature (e.g. -7 °C). Such an extended environmental condition has been enforced under real driving conditions but not yet for the laboratory testing. During development processes of engines and emission control systems, the testing at low temperature is of interest. This paper focuses on various challenges that need to be addressed for the developments with respect to engine calibrations and particle measurements under the extended environmental conditions.

KEY WORDS: environment, emissions, solid particle number, soot mass, low temperature testing, gasoline direct injection engines

1. Introduction

A Solid Particle Number (SPN) limit for light duty vehicles equipped with Gasoline Direct Injection (G-DI) engines was introduced in Europe at Euro 6 stage (September 2014) initially with a limit of 6 x 10¹² p/km and from September 2017 with 6 x 10¹¹ p/km aligned to the respective diesel light-duty vehicle limit [¹]. The SPN method was developed according to the findings of the Particle Measurement Programme [²] and came to enhance the established gravimetric method for determination of the Particulate Matter (PM) emissions. The latter was criticized on its suitability at low emission levels (e.g. engines equipped with a Diesel Particulate Filter (DPF) [³]) justifying the introduction of the SPN method to improve the sensitivity compared to the existing gravimetric PM method.

The sampling of the PM and the SPN for a certification test is conducted from a Constant Volume Sampling (CVS) tunnel. The vehicle is driven according to a predefined driving cycle on a vehicle test bench. The ambient temperature shall be from 20 °C to 30 °C (a so-called Type I test). A test at -7 °C for Carbon Monoxide and for Total Hydrocarbons – but not for particulates – is also conducted for gasoline vehicles [⁴].

Concerns have been raised that such a testing condition does not represent adequately the Real Driving Emissions (RDE) of a vehicle when it is driven on the road [⁵]. For this reason, RDE type approval vehicle test procedures based on Portable Emission Measurement System (PEMS) have been introduced for light duty vehicles [⁶].

The RDE regulation introduced extension of the vehicle operation outside the boundary conditions of laboratory testing. Such an extended testing condition includes high altitude (up to 1300 m) as well as ambient temperature from -7 °C to 35 °C. The experimental cost and time/effort of such RDE/PEMS tests can be reduced by building the corresponding cycles for laboratory testing [⁷]. Going one step further, the sampling for PM and SPN measurements can be conducted directly from the engine exhaust pipe (or by the vehicle tailpipe) – as is also done for the PEMS measurements [⁸] – instead of the CVS tunnel [⁹].

Extending such a methodology to sub-ambient temperature is not straightforward: engine and exhaust aftertreatment system developers should use driving protocols to ensure the engine is operated under the worst-case scenario in terms of the emissions. Measurement instruments are also in major concern since they need to be operated outside their regular operating conditions which cover those under the CVS testing. All these challenges are discussed in this paper.
2. Engine Development / Calibration for Cold-start Low-temperature Particle Emissions

The procedures for sampling, dilutions, and measurements of SPN emission of light-duty vehicles are described in United Nations Economic Commissions for Europe (UNECE) Regulation 83 [10].

With the introduction of RDE requirements, engine calibration efforts have increased substantially. As the first Euro 6b legislation still had the focus on laboratory cycle-based tests like New European Driving Cycle (NEDC) and Worldwide Harmonized Light Duty Test Cycle (WLTC) at 23 °C ambient temperature, the introduction of RDE has widened its requirements from -7 °C up to 35 °C. To be prepared for all possible driving maneuvers on the road during the RDE tests, an optimization of the complete engine map is necessary as shown in Fig. 1. A well-defined injection strategy and λ=1 operation over the entire engine map are the key factors for low gaseous and particulate emissions. Next steps are chassis dyno tests with the focus on RDE replacement cycles. By varying the ambient temperature, altitude, driving styles and vehicle weight, the RDE performance can be characterized early in the development process [11]. If the tests include extreme conditions (e.g. -7 °C and the very dynamic operation with the heaviest vehicle configuration), RDE road tests with the PEMS can be done as final validation without additional challenges of the vehicle development team.

To reach the Euro 6d particulate emission limits, a Gasoline Particulate Filter (GPF) is almost required. Removing solid particles by using a DPF is an established technology for diesel vehicles since years. Compared to the diesel engine, the gasoline engine shows a much higher sensitivity to high exhaust back pressure, which gains importance through the future requirement for its stoichiometric operation over the entire engine map. Thus, the trade-off between filtration efficiency and exhaust back pressure caused by the GPF becomes a key parameter for the gasoline engine.

Fig. 2 shows an overview of different GPF types with soot loadings of 0, 1 and 3 g/l [12]. In order to increase filtration efficiency of the GPFs, porosity and pore size of their walls must be reduced in principle so that they can capture soot in the exhaust in an efficient way, which also decreases their permeability. Therefore, the high filtration efficiency was inevitably associated with the high back pressure (the red and yellow areas in Fig. 2). However, current developments are leading to more favorable relationships – the green area in Fig. 2. The filtration efficiency of > 95 % is desirable for all the operation conditions to guarantee compliant particulate emission levels.

The largest challenge of the RDE tests is low-temperature testing. Low ambient temperature combined with increased engine load leads to high cold-start particulate emissions. In addition, dynamic driving has a major influence on the emissions. The particulate emission is widely varied by these factors. Fig. 3 schematically shows the relationship between ambient temperature and driving style right after the engine start. For example, a typical cold start at -30 °C under a very dynamic drive-off style could accumulate soot of up to 2 g on the GPF, whereas a cold start at -15 °C generates soot of only about 0.7 g on the GPF. At -30 °C the soot concentration measured by an AVL Micro Soot Sensor (MSS) may exhibit more than 1,000 mg/m³ which exceeds the measurement range of the instrument.
Fig. 3 A schematic showing a relationship between engine-out particulate emission and engine start temperature as well as driving behaviors.

3. Challenges for Measurement Instruments

This section describes challenges for particulate matter and particle number measurement instruments under low ambient temperature conditions.

The typical development process in most cases requires real-time instruments which collect sample gas from raw exhaust in order to obtain a time resolved signal of soot mass or particle number concentrations. Even though instruments like an AVL MSS and an AVL Particle Counter (APC) are capable of such an application, sampling raw exhaust instead of diluted one from the CVS tunnel can already be a challenge even at regular ambient temperatures (20-35 °C). Measurement uncertainties may be associated with such a method due to exhaust flow pressure pulsations, exhaust flow determination, misalignment of exhaust flow, particle concentration signals, and different particle loss mechanisms [9].

3.1. Particulate Matter Measurement Instruments

In contrast with an integral measurement of PM on a filter, the AVL MSS provides a real-time measurement signal of soot (black carbon) mass concentration [13]. This fraction represents the major part of the non-volatile PM and is of high interest on the engine developments since it is directly linked to incomplete combustion. A derivative of the AVL MSS is an AVL PM-PEMS which combines the AVL MSS with an integral filter measurement. It is often used in on-board applications because it is optimized for this purpose. Both devices are similar to each other in terms of the specified operating conditions.

The main challenge when using these devices in cold environments is to prevent condensation of water inside the sampling system. Therefore, it is obliged to use heated sampling lines in order to keep internal temperatures above the dew point. Based on experience, internal heaters of the device maintain the set temperatures under ambient temperatures of even slightly below 0 °C. For colder temperatures, some additional provisions must be taken. A layer of insulation around the device is necessary to prevent excessive heat loss. In addition, some insulation should wrap the heated sampling line for the same reason. Whenever a device shall be operated at ambient temperatures below 0 °C, it must be switched on before exposing it to the cold environments.

Fig. 4 shows the AVL PM-PEMS inside a rugged box with a layer of cotton-based insulation. This setup allowed it to run outdoor tests at -20 °C without suffering from internal water condensation.

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Fig. 4 An AVL PM-PEMS installed inside an insulated box.

For even lower temperatures, a heated box for the device is required. In a test cell the device can be placed outside the cooled test chamber by using an extended heated sampling line. In this case, some protection of the sampling line might also be necessary.

Another important factor is proper dilution of the sample gas. The dilution takes place close to the sample point in a heated dilution cell (120 °C). For gasoline application, the dilution ratio of at least 6 must be used. This will suppress the condensation of water.

Especially for cold start experiments, condensation and icing of water on especially the parts exposed to undiluted exhaust – a sampling probe, a pressure reduction unit etc. – are a common issue. A permanent active heating of these areas can be very difficult or even impossible. Prior to any cold start tests, the sampling system and the probe should be purged completely in order to keep them dry. It is advisable to turn around the sampling probe to face downstream the exhaust flow. This will reduce the risk of sucking water spray into the sampling line. Pre-heating of the affected areas can also help to prevent the ice formation.
3.2. Particle Number Measurement Instruments

3.2.1. Legislation Requirements

The sampling, dilution, and measurement of SPN emission of light-duty vehicles are prescribed in accordance with UNECE Regulation 83 [10].

The sampling is performed from a CVS system where the whole exhaust is mixed and diluted with filtered ambient air. The Particle Transfer System, which consists of a sampling probe and of a transfer tube in an internal diameter of ≥ 8 mm, shall be designed so that the sample flow in it has a Reynolds number of < 1700 and a residence time of ≤ 3 s.

The diluted sample gas is introduced into a Volatile Particle Remover (VPR) system. The scope of the VPR is diluting and heating the sample gas in order to remove the volatile particles and to reduce its particle concentration below the upper limit of a single count mode of a Particle Number Counter (PNC). Thus, it allows only the solid particles to reach the PNC. The VPR consists of a two-stage dilution system and of an Evaporation Tube (ET) between them. The Particle Number Dilution 1 (PND1) shall heat the sample gas at temperature of ≥ 150 °C and ≤ 400 °C, and dilute it by more than 10 times. The ET temperature shall be controlled in a range of 300 °C to 400 °C and higher than the PND1 temperature. The (recommended) dilution range of the Particle Number Dilution 2 (PND2) shall be between 10 and 15. It should ensure the particle concentration after the second dilution is in a range of the single count mode and temperature of the sample gas at the PNC inlet is < 35 °C.

The PNC shall have a linear response and counting accuracy of ± 10 % up to the upper threshold of the PNC single count mode against a traceable standard. The counting efficiencies of particles in electrical mobility diameter of 23 ± 1 nm and 41 ± 1 nm are 50 ± 12 % and > 90 %, respectively.

3.2.2. Challenges Under Low Ambient Temperatures

Extending the already demanding raw exhaust application under low ambient temperature conditions requires careful selection of the material and of the sampling options used to transfer the exhaust sample gas to the inlet of the PND1. The reason is condensation of water at first, which may occur in the sampling lines, since the sample is undiluted and there may be some cold spots in the lines, especially during a cold-start test. Water absorbs the particles. It influences the PN measurement values and the repeatability of the SPN method. Water can also remain in the device itself and corrodes its components. The second reason is the thermophoretic particle losses caused by high temperature of the exhaust when it is transferred inside cold tubes. Estimation of such losses showed that using an unheated tube (the wall temperature of 30 °C) for sampling of raw exhaust instead of a tube heated at the wall temperature of 150 °C can contribute to 15 % higher particle losses [14]. For these reasons, it is highly recommended that the sampling tubes used to transfer the exhaust sample gas from the engine exhaust pipe to the PND1 should be actively heated. Cold spots on the transfer tubes should be avoided.

When it comes to low-temperature testing with the SPN measurement instrument itself, two main parts should be taken into account from the viewpoint of the regulation requirements: (a) the dilution system (known also as the VPR) and (b) the PNC. Both parts incorporate heating components and control their temperatures within the specific limits.

The VPR has a PND1 and an ET heated at a demand temperature with a tolerance of ±10 °C. It should be ensured that there is enough power to maintain the temperatures of the components within the limits when it is operated under low ambient temperatures. Fig. 5 shows the temperature evolution of main components of an APC during its operation under ambient temperature conditions from -30 °C to +45 °C (the blue dash line in Fig. 5). In this experiment, the maximum temperature gradient from -30 °C to +45 °C was approximately 2 °C/min. The APC is a device designed to measure the SPN emissions of vehicles in compliance with the UNECE R83 requirements [15]. The APC was installed inside a trolley with an air conditioning system. The conditioning trolley can either heat or cool the APC cabinet in dependence of the ambient temperature conditions. During the experiment, the ET and PND1 temperatures were kept within their demand values and range (350 ± 10 °C and 150 ± 10 °C, respectively) even in the ambient temperature of -30 °C and +45 °C within the temperature gradient of 2 °C/min.
The cut-off size of a PNC is adjusted by temperature difference (ΔT) of a working fluid (usually alcohol) between condenser and saturator. The ΔT dominates the growth rate of the particles, which means it determines the PNC’s counting efficiency \(^{[16]}\). To ensure the stability of the counting efficiency curve of the PNC, the temperatures of the condenser, saturator and optics should be controlled accurately irrespective of the ambient temperatures. Fig. 6 illustrates the temperature evolution of main components of an AVL Condensation Particle Counter (CPC) as well as the ambient temperatures (the blue dash line in Fig. 6) which is the same as that in Fig. 5. The temperatures of the condenser, saturator and optics, which are crucial for the counting efficiency, were well-controlled at their demand values of approximately 32 °C, 38 °C and 42 °C, respectively, even in the ambient temperature of -30 °C and +45 °C within the temperature gradient of 2 °C/min.

Fig. 6 A temperature evolution of main components of an AVL CPC under extended ambient temperature conditions.

4. Experimental Investigation of Particle Number Measurements Under Low Ambient Temperature

In this session the effect of low ambient temperature on SPN emissions of a G-DI light-duty vehicle is presented. Fig. 7 presents the experimental layout. A 1.8 L G-DI vehicle was tested at a chassis dyno bench over an RDE cycle. The vehicle was equipped with a Three-Way Catalyst (TWC) at a close-coupled position and with a GPF at an Under-Floor (UF) position. Two APCs were installed upstream and downstream of the GPF (Engine Out - EO and TailPipe - TP, respectively) to measure each SPN concentration. The RDE cycle was implemented two times identically under different ambient temperatures of 23 °C and -7 °C, respectively.

Fig. 9 shows cumulative SPN emissions at EO / TP and 23 °C / -7 °C, respectively, which are normalized by a total value of the SPN emission at EO / 23 °C over the RDE cycle. The EO SPN emission at 23 °C rapidly increased at the cold-start phase (over the first 300 s of the RDE cycle), which reached approximately 1/3 of its total value. The one at -7 °C drastically increased over the cold-start part similar to that at EO / 23 °C, which attained about 1/2 of its total value. Such a rapid increase at the cold-start phase especially under low ambient temperature is attributed to incomplete combustion due to e.g. a fuel injection strategy (fuel enrichment). It leads to firstly high amount of soot particles and subsequently of SPN emissions. Similar SPN emission behavior over the cold-start phase at -7 °C has been reported by other studies \(^{[17, 18]}\). On the other hand, the TP SPN emissions at both 23 °C and -7 °C were significantly lower than those at the EO position thanks to the GPF. The TP SPN emission at 23 °C was negligible over the RDE cycle. The one at -7 °C was slightly observed at the cold-start phase when the EO SPN emission drastically increased. After the cold-start phase, it did not further increase more.
Fig. 8 Cumulative profiles of SPN emissions at engine out and tailpipe positions under ambient temperatures of 23 °C and -7 °C, respectively. Each value is normalized by a total value of the SPN emission at engine out / 23 °C over the RDE cycle.

Fig. 8 depicts differences of each total SPN emission normalized by the EO SPN emission at 23 °C. These results represent an average over the whole RDE areas (urban, rural and highway). The EO SPN emission at -7 °C increased in total by a factor of 2.6 compared to that of EO SPN at 23 °C. In the cases of the GPF equipment, it reduced the EO SPN emissions by 99 % and by 97 % compared to those at 23 °C and at -7 °C, respectively, which were in compliance with the Euro 6d SPN emission limits [11]. It is found that the GPF captured the solid particles in an efficient way and the SPN emission at -7 °C attained the compliance limits even though the EO SPN emission increased by a factor of 2.6 due to the low ambient temperature. Honeycomb-structured particulate filters made by a porous media have a trade-off relationship between filtration efficiency and pressure drop [19]. Accumulated soot inside the filters contributes to an increase of the filtration efficiency. The soot particles firstly deposit inside porous walls of the filters, which is a so-called deep-bed filtration, and then the filtration efficiency reaches almost 100 % after the soot cake is formed on the walls (a cake filtration) [20]. The deposited soot simultaneously induces the additional pressure drop [20]. Thus, the trade-off relationship of the filters can be seen as usual [21]. It can be possible that the recent advanced emission afttreatment system including a GPF enables G-DI vehicles to comply with the Euro 6d limits.

5. Conclusion

After the introduction of RDE light-duty vehicle testing with a PEMS under extended environmental conditions (-7 °C to 35 °C), engine and emission control system developments focus on laboratory testing. Dynamic driving protocols especially under low ambient temperatures are the key for G-DI vehicle and GPF calibrations in terms of particulate emissions. This paper discussed challenges that need to be addressed with respect to engine calibration and particulate (PM/SPN) measurements under extended environmental conditions.

Requirements of instruments for PM/SPN measurements at engine out or tailpipe position under low ambient temperatures were presented in terms of sampling and diluting the raw exhaust as well as the measurements. Devices of an AVL MSS and an APC can be operated under low ambient temperature conditions with options like insulations/heaters and a conditioning trolley, respectively. A meticulous care should be taken to avoid condensation of water in all sampling lines as well as instrument bodies themselves. Note that the devices should be powered on and off at regular ambient temperatures (10-35 °C) to keep enough temperatures of each component to avoid the condensation when the ambient temperature changes around a boundary of 0 °C.

An experimental investigation of SPN emission of a G-DI vehicle equipped with a GPF over an RDE cycle under different ambient temperatures revealed that the emission at an engine out position under -7 °C was 2.6 times higher than that under 23 °C. However, the state-of-the-art emission afttreatment system ensured that the emission was in compliance with the Euro 6d limits even under -7 °C.
Acknowledgement

Part of the work reported here is part of the UPGRADE project which received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 724036. The authors would like to thank the partners within the UPGRADE project consortium for their assistance and permission to publish this content.

This paper is written based on a proceeding presented at JSAE 2019 Annual Congress.

Abbreviations

| Abbreviation | Description                                      |
|--------------|--------------------------------------------------|
| APC          | AVL Particle Counter                              |
| CPC          | Condensation Particle Counter                     |
| CVS          | Constant Volume Sampling                         |
| DPF          | Diesel Particulate Filter                        |
| EO           | Engine Out                                        |
| ET           | Evaporation Tube                                 |
| G-DI         | Gasoline Direct Injection                        |
| GPF          | Gasoline Particulate Filter                       |
| MSS          | AVL Micro Soot Sensor                             |
| NEDC         | New European Driving Cycle                       |
| PEMS         | Portable Emission Measurement Systems            |
| PM           | Particulate Matter                                |
| PNC          | Particle Number Counter                           |
| PND          | Particle Number Dilution                          |
| RDE          | Real Driving Emissions                            |
| SPN          | Solid Particle Number                             |
| TWC          | Three Way Catalyst                                |
| UF           | Under-Floor                                       |
| UNECE        | United Nations Economic Commissions for Europe    |
| VPR          | Volatile Particle Remover                         |
| WLTC         | Worldwide Harmonized Light Duty Test Cycle        |
| ΔT           | Temperature Difference                            |

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