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PARTICULATE MATTER MEASUREMENT WITH AN IMPROVISED FULL-FLOW DILUTION TUNNEL

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Abstract

The gravimetric measurement of particulate matter emissions typically requires either a full-flow dilution tunnel with a Constant Volume Sampler, or a partial flow dilution tunnel with rather sophisticated controls. In many Czech laboratories, such setup is not available due to space, power and cost reasons. As an alternative, a low-cost sampler utilizing the laboratory main exhaust duct as an improvised full-flow dilution tunnel was considered, from which a sample was drawn through a single 47 mm filter, with the flow controlled by a low-cost rotameter. While such measurement might not be suitable for modern engines achieving emission levels of units mg/kWh, with much of this mass being volatile, a reasonable correlation has been observed for older engines emitting on the order of 0,1 g/kWh.

1. INTRODUCTION

Internal combustion engines, the prime mover of most motorized vehicles on the road today and the source of pleasure for many men, also produce, during their operation, many harmful substances, the bulk of which exits the engine via the exhaust system, to be released above roadways and potentially inhaled by other motorists, passerbys, residents of nearby buildings and denizens of various nearby establishments. Of the many substances emitted, ultrafine particles are viewed as having the highest potential negative effects on human health. The particles emitted by both positive and compression ignition engines are very small, from units to hundreds of nm (nanometers) in diameter [1,2]. Particles smaller than about one hundred nanometers (nanoparticles) readily deposit in human lungs [3], and have the ability to penetrate through cell membranes [4,5] into the blood, affecting respiratory, circulatory, and nervous systems and contributing to a variety of acute and chronic ailments [5,6]. In the Czech Republic, motorized vehicles are the largest source of particulate matter

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[7,8], with both total vehicle-km traveled and the fraction of particles emitted by the vehicles increasing [7,8].

With the advancements of new engine technologies, catalytic aftertreatment devices, and advanced motor fuels, many questions arise as to their effect on public health. For example, it is not clear whether technologies and fuels which reduce total mass of the particles emitted, have a commensurate effect on the decrease in the risk to human health, or worse, if they do not increase such risks.

As a part of EU-wide effort to develop a sound methodology to evaluate the effects of new fuels and technologies on human health, advanced chemical analyses [9] and toxicological assays [10] were carried on samples of particles collected from diesel engines operating on diesel fuel, biodiesel (a mixture of n-alkylesters of fatty acids), and non-esterified fuel-grade (and also food-grade) heated rapeseed oil. The facilitation of such tests required the collection of a relatively large mass of particulate matter, on the order of units to tens miligrams (mg) per sample. The traditional gravimetric measurement system allowed, however, only the collection of tens to hundreds of micrograms on 47-mm diameter filters. A novel approach of using high-volume samplers, operating at flow rates of hundreds to thousands of liters per minute, and collecting particles on much larger filters, was therefore adopted. Such large volumes cannot, however, be extracted from a partial-flow dilution tunnel. In the absence of a suitable full-flow dilution tunnel in the laboratory, the main exhaust duct, powered by a large centrifugal blower, was used as an improvised full-flow dilution tunnel. From this tunnel, samples were extracted on 150-mm diameter filters with Digitel high-volume samplers [10,11]; some of the results of the toxicological assays were reported in [10]. This sampling apparatus is shown in Fig. 1.

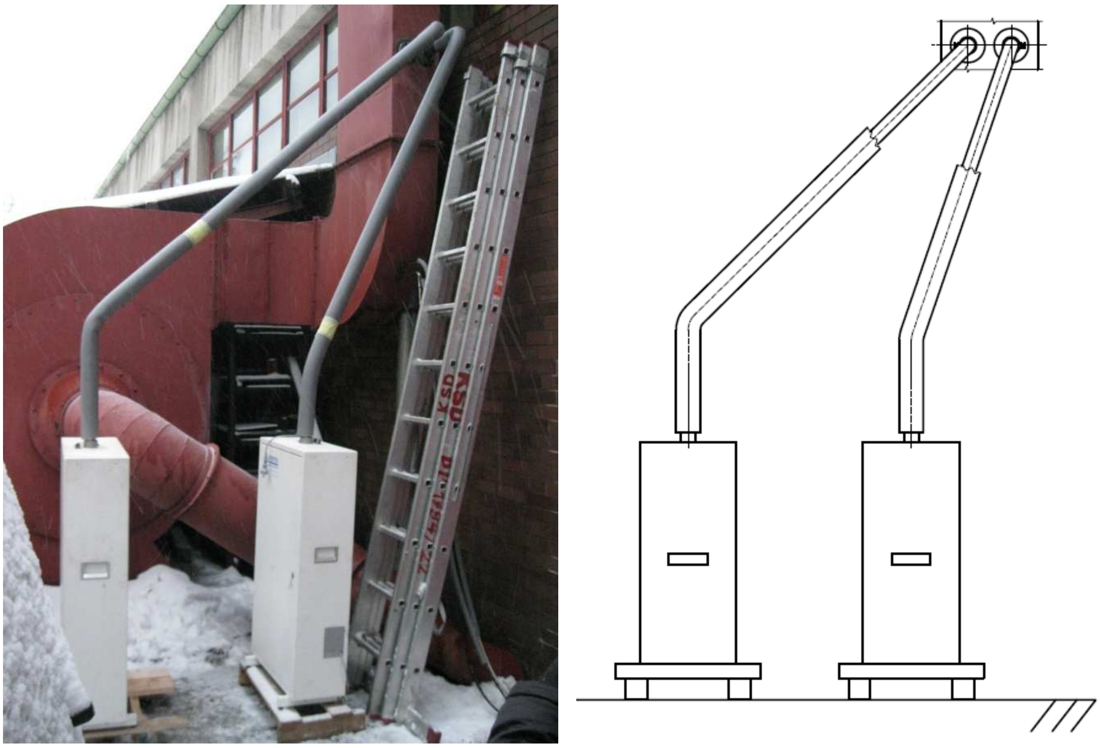

Figure 1: *Sampling of large quantities of particulate matter with two Digitel high-volume samplers from the laboratory main exhaust duct acting as an improvised full-flow dilution tunnel.*

As a part of the quality assurance of these assays, measurements were taken in order to validate the particle collection method using the improvised system, and to determine the particle losses in the improvised system. The results of CO_2 balance and gravimetric particulate mass comparison measurements are reported on in this paper.

An additional motivation for this work was to assess the feasibility of carrying on gravimetric particulate measurements using an improvised system in many Czech and Slovak laboratories which do not have a conventional full-flow dilution tunnel, neither do they have financial, space, power, and other resources to obtain such a system. To simultaneously meet this additional goal, the sampling from the full-flow tunnel was facilitated using inexpensive procedures and equipment.

2. EXPERIMENTAL

The experimental work was carried on four-cylinder, turbocharged, intercooled Zetor 1505 non-road tractor engine rated at 90 kW at 2200 rpm and 525 Nm at 1300-1500 rpm with an inline mechanical fuel injection pump, and on an experimental four-cylinder, turbocharger, intercooled Cummins ISBe4 highway engine informally rated at 185 hp (136 kW) at about 1800-2500 rpm and 520 ft-lb (705 Nm) at about 1300-1800 rpm.

The reference gravimetric particulate measurement were conducted with a Belasch system locally produced at the Technical University of Liberec (no summary reference describing the system and its parameters was found) utilizing a partial-flow dilution, with dilution ratio controlled by the user via (a) a butterfly valve in the engine exhaust system closing the exhaust and thus creating a backpressure upstream of the sampling point of the partial flow tunnel, (b) a quarter-turn plumbing valve in the raw exhaust transfer pipe from the engine exhaust system to the dilution tunnel, and (c) a variable speed drive of an electric motor driving a positive displacement pump extracting the diluted flow from the partial flow dilution tunnel. These three control elements were operated by hand based on the readings from a pair of non-dispersive infra-red analyzers measuring the concentrations of CO_2 in raw and diluted exhaust. The particulate matter emissions rates were determined using common procedures described in EHK 49, EHK 83 and ISO 8178 documents.

The low-cost particulate measurement system utilized the laboratory main exhaust duct serving all engine test stands, driven by a large centrifugal fan without controls, delivering the diluted exhaust above the roof of a four-story laboratory building. The sampling system consisted of (a) a 8-mm metal pipe inserted into the duct, (b) a flexible, conductive natural gas fuel line serving as a transfer line, (c) a stainless steel 47 mm diameter filter holder (Pall Life Sciences, USA), (d) a rotameter (Dwyer Instruments) and (e) a pair of diaphragm pumps taken from some old emissions analyzers and thus with no accompanying identification or documentation. The system was operated at nominal flow rate of 50 liters per minute. The emissions in g/kWh were calculated as the product of (a) the ratio of the tunnel flow to the filter flow, (b) the mass accumulated on the filter measured in grams, (c) the inverse of the work absorbed by the brake over the sampling period, measured in kWh (or for single-mode, steady-state tests, the inverse of the product of sampling time measured in hours and the average engine brake output measured in kW).

The flow rate through the tunnel was determined experimentally and was based on an assumption that all CO_2 emitted by the engine leaves the laboratory via this duct. (The assessment of the validity of this assumption is better left for the discussion section of this paper.) The CO_2 emitted by the engine was determined as the product of the intake air mass flow, measured by a thermal mass flow sensor (Model 620 S, Sierra Instruments, USA), and CO_2 concentrations, measured by a low-cost, portable, miniature multigas analyzer (VMK Praha), the verification of which was reported in detail previously [12,13]. Additional corrections were, of course, made for the discrepancy between molar flows in the intake and in the exhaust, determined from the CO_2 concentrations and carbon-to-hydrogen ratio of the fuel used, and for gas density, determined from the measured intake air temperature and barometric pressure; the formulas are not given here as these are common calculations for professionals in both engine testing and emissions measurement fields. The CO_2 flowing through the tunnel, determined as the product of the CO_2 concentration measured by the same analyzer and the total flow through the tunnel, was then iteratively adjusted to be the same as the flow of CO_2 from the engine.

All sampling was done on PallFlex T60A20 filters made of borosilicate glass fibers coated with fluorocarbons (Pall Life Sciences, USA). The filters were conditioned prior to weighing in a walk-in chamber maintained (solely by being in the right place in the building) nominally at 293 K (291-296 K) and nominally at 50% (40-60%) relative humidity. Generally, at least one blank filter was kept with the sample filters, and one or more blank filters were kept in the weighing chamber. The weights of these two types of blanks were continuously checked for drifts caused by unsteady temperature and humidity, impurities contaminating the scale, and other sources of measurement error. The filters were weighted on a scale with one microgram (1 ug) accuracy (Sartorius, Germany) located in the weighing chamber.

3. RESULTS AND DISCUSSION

The CO_2 measurement comparison is shown on Figure 2, where the CO_2 concentrations in the raw exhaust and in the dilution tunnel, and CO_2 flows in the tunnel and from the engine are plotted. Each set of measurements was taken from a different test: The reference measurement with the partial-flow system was conducted using the 13 modes of the ESC test, but run at four minutes per mode. The full-flow tunnel measurements were conducted during a modified ESC test, where the length of each mode was set to be proportional to the weight of the mode, in order to allow for uninterrupted, continuous sampling. A twenty-second transitional period was inserted between each two consecutive modes, and the length of the entire test was arbitrarily set to be 1000 seconds.

The overall particulate matter measurements results have shown a high fraction of unsuccessful measurements. Notably pitiful were the measurements with the partial-flow dilution reference system, on which several malfunctions were found, such as introduction of leakage into CO_2 analyzer inlet, introduction of leakage into the filter sampling system, complete blockage of a sampling system, misalignment of filter holder components resulting in the perforation of the filter, and an occasional inability to maintain a constant dilution ratio. Further, the irreproducible and unknown settings of the two operator controlled valves and the cooling of the transfer pipe with water have probably resulted in differences in aerosol dynamics, which were beyond the ability of the authors to explore. The experimental system, where the filters were installed by the operators outside, was subjected to operator-related errors, such as contamination of the filters via contact with surrounding objects, dropping filters on the ground, abrasion of filters during manipulation, and contamination of filter media with falling snow or rain (a frequent problem given the local climate). Other sources of error were losses of the exhaust into the laboratory from leaky exhaust systems, causing a loss of some of the emitted particles, but also causing an increase due to the previously emitted particles "stored" in the laboratory from which the "dilution air" was taken.

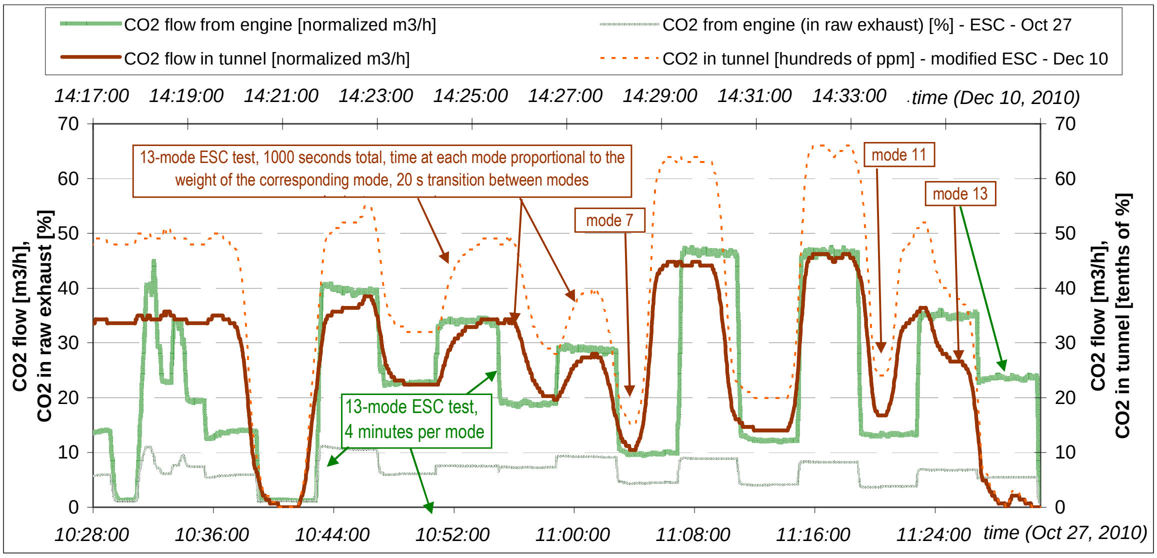

Figure 2: *Comparison between CO_2 flows at the engine and in the full-flow dilution tunnel during two different ESC tests.*

The test-to-test variance of the measurements on the Cummins engine appeared to be on the order of tens of percent, and thus to be too high for a meaningful use of this system as a reference. Therefore, only data on the Zetor engine, and of those, only data absent of known errors noted in the test records, are reported on in Figure 3.

The differences between the two methods are generally around 10% or lower, with some values being higher – in this case, April 27, 2011 measurements for a mixture of 10% butanol and 90% of rapeseed oil at 25% engine load (112 Nm), where the particle mass is dominated by volatile fraction, which is much more sensitive to various measurement artefacts than elemental carbon (black carbon, soot) which dominates diesel operation at high loads. Similar differences were, however, observed between two measurements done with the partial flow system each done with a different filter holder. And differences on the order of 10% are also apparent among tests done at the same conditions, but at different times (diesel fuel at full load, rapeseed oil at full load).

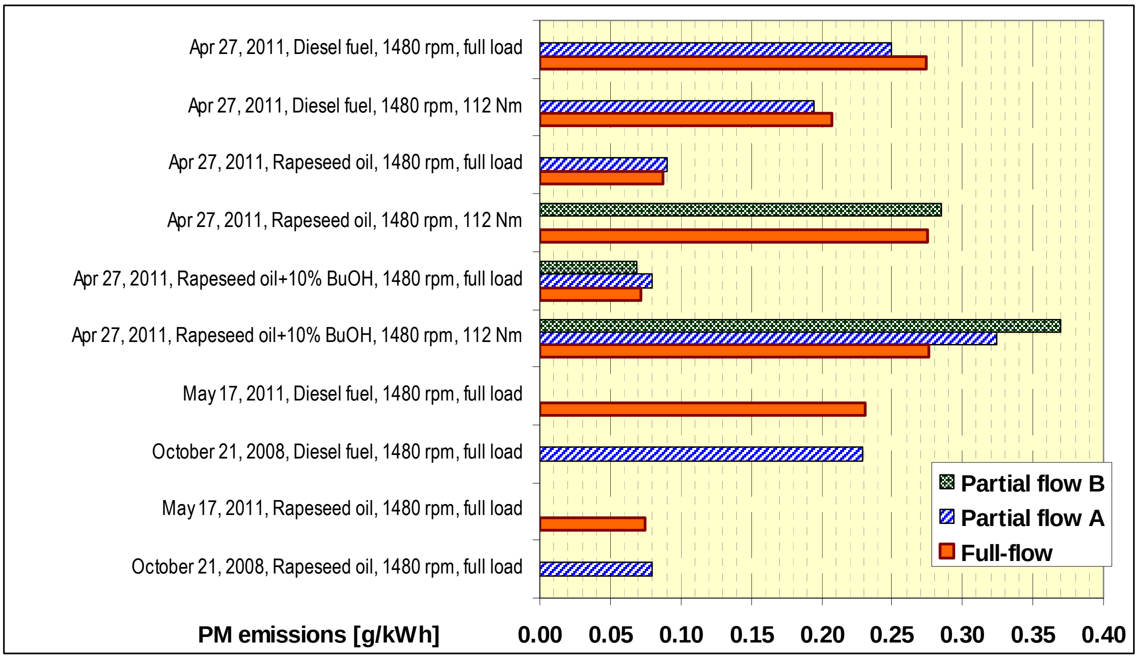

Figure 3: *Comparison of gravimetric measurement of particulate matter between the partial-flow and the experimental improvised full-flow sampling systems.*

Overall, it appears that the general particulate matter measurement uncertainty of the laboratory is around 10-20%, and that absent a gross measurement error (filter damage, sampling system malfunction), the difference between the particle mass measured by the reference system and sampling from the improvised full-flow dilution system with the improvised apparatus appears to be within this range for the Zetor engine. Given uncertainties associated with the simplified system such as in CO_2 concentrations and sample flow measurements, and due to exhaust leakages and temperature and barometric pressure variances, this can be considered a success. For the Cummins engine, with PM emissions of 0.02-0.04 g/kWh, a reliable reference measurement was not available, and therefore the differences were not assessed.

4. CONCLUSIONS AND IMPLICATIONS

The difference between the experimental full-flow and reference partial flow dilution system and the repeatability of both systems were in the 10-20% range. Such repeatability seems to be generally in the same range as the repeatability of PM measurements in many laboratories, and therefore, might be considered acceptable for most measurements, at least on engines with emission levels comparable to those reported on in here. Major improvements to the repeatability would, on the other hand, require considerable investments throughout the laboratory, which would likely be a subject to diminishing returns.

The first implication of these findings is that it is unlikely that major PM mass losses exist in the improvised full-flow sampling system. The second implication is that a low-cost, improvised sampling from an exhaust duct – which can be easily constructed or is already present in most "low-tech" laboratories – might be used at least for indicative gravimetric PM measurements at least for engines with suitable emission levels.

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