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Sampling method for particle measurements of vehicle exhaust

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ABSTRACT

This paper describes a new sampling concept for particle emission measurements. The purpose is to produce repeatable and reproducible conditions for nucleation phenomena. The exhaust is sampled and instantaneously diluted by inserting a porous tube diluter inside the tailpipe. This is carried out in order to prevent uncontrolled sample transformations in sampling lines. The sampling system was tested in size distribution measurement of light duty diesel vehicle. The tests showed a clearly bimodal size distribution with distinguished nuclei and accumulation modes.

INTRODUCTION

The legislation on particle matter (PM) emissions from vehicles is conventionally based on mass measurements. In addition, there is a growing interest for particle size distribution measurements. The particle number size distribution measurements are a common practice in the vehicle emission research, even though they are not required by the current legislation. However, the legislative limits for the particle emissions are becoming increasingly strict [e.g. 1], which emphasises the role of particle sampling methods.

Recently, it has been argued that reliable and accurate particulate emission measurements of vehicles depends more on proper sampling and transport of the sample than on measurement instruments themselves. The vehicle exhaust is a dynamic mixture of carbonaceous particles, i.e. soot, volatile hydrocarbons, sulphur compounds, water vapour etc. Uncontrolled dilution and transport of this mixture may cause unintentional transformations [2,3]. Moreover, concentrations of different compounds can change the dynamics of the mixture. For example, there is evidence that reducing the concentration of soot particles in vehicle exhaust may increase the number of nucleated particles in measured samples [4].

The condensable hydrocarbons present in the vehicle exhaust may form particles or condense on existing particles during dilution. Amann and Siegla [5] reported the fraction of the hydrocarbons to be 10-30 % of the total particle matter in diesel light-duty cars. Moreover, these compounds can condense on sampling lines or diluters and be subsequently released during episodes of prolonged high exhaust temperature. Maricq et al. [6] found the sampling line artifacts overwhelm the exhaust particle matter concentrations for a gasoline engine measured after a diesel engine in the same test bench.

In addition to hydrocarbons, soot particles can be lost in sampling lines by deposition. These deposited particles may re-entrain and cause an unexpected coarse particle mode in particle size distribution [7,8]. The origin of the coarse particles may be in the exhaust system of the vehicle or in the sampling lines.

The objective of this study has been to construct and test a new sampling system.

The system was designed to produce repeatable and reproducible conditions for nucleation phenomena. The system is based on simultaneous sampling and dilution of the exhaust gas flow. This method has been applied for combustion studies earlier [e.g. 9]. This paper describes the design principles of the device and discusses reasons for the compromises in sampling. Finally, a test result of a vehicle exhaust dilution is presented.

DESIGN PRINCIPLES AND DISCUSSION

The purpose of the new dilution method was to dilute the sample in a manner that maximum nucleation of the sulphur compounds and hydrocarbon vapour is achieved and simultaneously particle losses in the sampling system are minimised. During controlled cooling in the diluter, compounds with tendency to form new ultrafine particles nucleate. As a consequence, particles existing prior to sampling may be distinguished from particles forming during dilution by their size. The nucleated new particles form a nuclei mode, which can be defined as smaller than 50 nm, and the soot based carbonaceous particles form an accumulation mode, which can be defined as 50-1000 nm.

Kittelson and Abdul-Khalek [10] experimented values to create a high nucleation rate in exhaust sampling. Values adapted from their work are shown in Table 1.

Table 1. Variables used in order to maximise nucleation in a sampling system.

Variable	Unit	Value
Dilution ratio	-	10-20
Residence time	s	1 or 1.5
Dilution air temperature	°C	30-50
Relative humidity	%	Controlled

In a porous tube diluter, the dilution air is introduced at the tip of the sampling probe within the tailpipe. The dilution air flows through a porous tube and mixes with the sample gas [11]. Most of the dilution gas flows through the tip of the probe to improve mixing in the probe. The rest of the dilution gas is introduced through small pores along the probe in order to minimise losses inside the probe. Simultaneously, the dilution air is cooled with an external cooler and with cooling agent jacket around the probe. This jacket is designed to maintain the dilution gas temperature below 50°C even during transient testing. In Figure 1, operation principle of the porous tube diluter is presented. In addition, the cross section of the probe is presented with a detail on a heat exchanger surface.

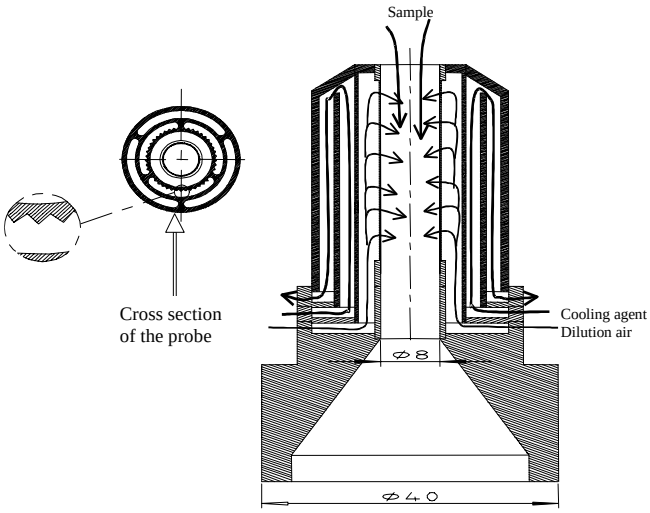

Figure 1. Operational principle of the porous tube diluter (not in scale).

In Figure 2, mounting of the porous tube primary diluter to the tailpipe is shown. The probe samples directly from the tailpipe with a sample flow rate of 10 lpm. The excess exhaust gas can be transferred to additional analyses in, e.g., dilution tunnel. In this case, the dilution ratio can be confirmed by simultaneous measurements of the CO_2 concentration in the exhaust gas and in the diluted sample.

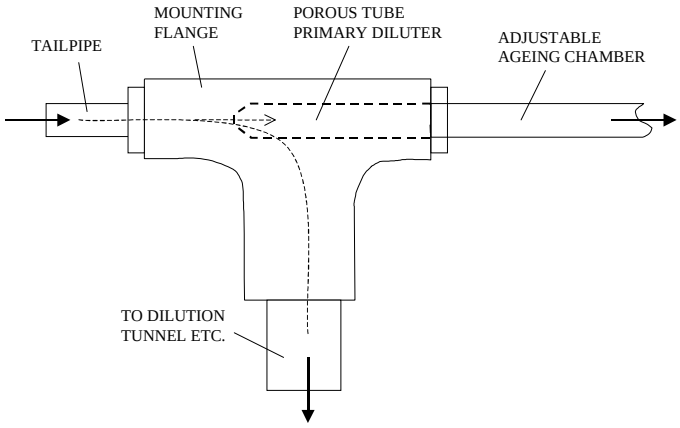

Figure 2. Mounting of the porous tube primary diluter in the tailpipe.

A number of ideas have been presented on adjusting the probe tip to match the exhaust gas flow velocity by altering the sample flow rate [e.g.12,13] or by changing dimensions of the tip continuously [e.g.14,15,16]. In our method, we chose to keep the sample flow rate as well as the probe dimensions constant. This was done since the particles smaller than 1 µm are practically insensitive to percent of isokinteic sampling [e.g. 17] and since moving parts in the tip of the probe may cause entrainment of particles attached to the tip.

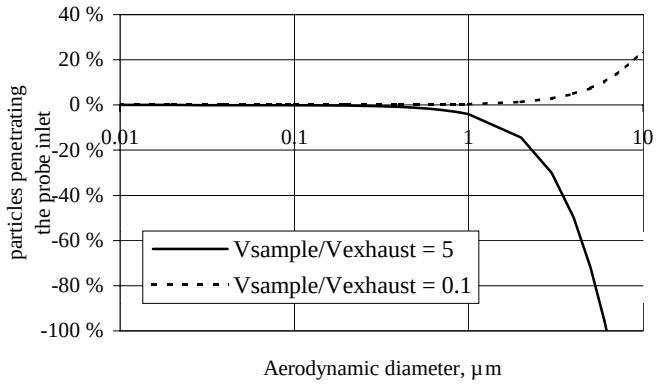

Figure 3. Particles penetrating the sampling probe inlet during sampling with velocity ratios 5 and 0.1.

Figure 3. shows particle penetration in an isoaxial sampling inlet as a function of particle size. The results are calculated according to Hinds [17] for a 3 m/s sampling flow velocity in a 0.6 and 30 m/s exhaust flow velocity. As stated earlier, the losses for particles smaller than 1 µm are negligible in flow rates applicable for vehicle sampling conditions.

In order to obtain proper residence time in the diluter, an ageing chamber was introduced. This ageing chamber is a tubular volume with an adjustable length (Fig. 2). Since the flow rate in the sampling system is constant, turbulent flow was selected in order to minimise artifacts caused by different residence times along the tube radius [18]. On the other hand, since the diffusion losses increase while the chamber length increases, the flow velocity was set as small as possible for turbulent flow (Re=Vd/v=4000, where V is the gas velocity, d is the tube diameter and v is the kinematic viscosity of the gas) [19]. In Figure 4, particle residence times for laminar and a turbulent tube flows are shown. The figure is presented as a probability of a gas volume to travel through the system in an optimum residence time for laminar flow and for Re = 4000. The laminar flow velocity is determined by the Hagen-Poiseuille equation

$$\frac{V_r}{V_{\max}} = \left(1 - \frac{r}{R}\right)^2$$

and the turbulent flow velocity by the Blasius equation

$$\frac{V_r}{V_{\max}} = \left(\frac{R - r}{R}\right)^{1/n}$$

where R is the tube radius
V(r) is the flow velocity in position r
Vmax is maximum velocity in the tube
n=6 for Re=4000

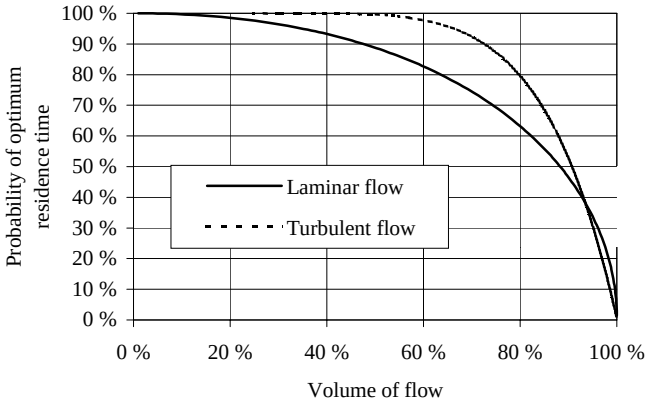

Figure 4. Particle residence time distribution for laminar and turbulent tube flows.

Fir example, only about 15 % of the sample volume reaches an optimum residence time with laminar flow, whereas with turbulent flow about 55 % of the sample has the optimum residence time.

During the tests, dilution air flow and temperature were monitored. The dilution air temperature was used as a control input for the cooling agent flow rate. In addition, the exhaust temperature and pressure as well as the cooling agent outlet and the sample temperatures were recorded.

RESULTS AND CONCLUSIONS

The properties tested prior to the exhaust experiments were the pressure drops in the dilution air channels and in the porous tube as well as the cooling efficiency. The tests showed pressure drops less than 0.05 bar in the tubing. The cooling efficiency was tested by inserting the probe section of the sampling device into a 600°C furnace. During this test, the cooling air temperature remained less than 20°C at a 70 % cooling capacity. Thus, we concluded that the mechanical construction of the device was acceptable.

The dilution experiment was carried out with EURO 2 light duty diesel vehicle with 50 km/h speed and 7 kW load at EMPA, Switzerland. The exhaust measurements were carried out directly from the tailpipe outlet. The dilution ratio was about 10, cooling air temperature about 15°C and relative humidity about 4 %.

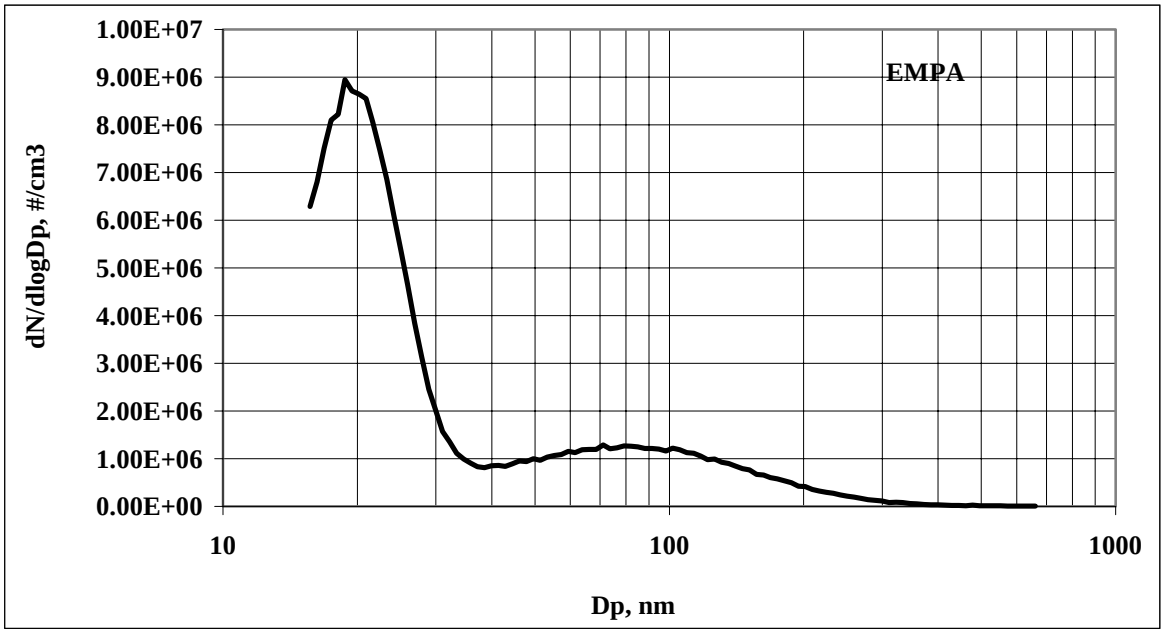

Figure 5. Particle number size distribution for the test with a EURO 2 light duty diesel vehicle with 50 km/h speed and 7 kW load.

As depicted in Figure 5. the particle number size distribution is clearly bimodal. The nuclei mode is clearly distinguished from the soot mode, as set for design criteria. The nuclei mode peaks at about 20 nm and the soot mode at about 80 nm. These values correspond to measurement results obtained from similar cars in earlier studies at steady state tests.

The question remains, whether the results of sampling ought to present the exhaust characteristics as they exit the tailpipe or to simulate the atmosphere as the exhaust mixes in the conditions outside the tailpipe. However, with the presented method, the exhaust characteristics could be transformed intentionally.

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