

A New Constant Dilution Ratio Concept for Vehicle and Engine Exhaust Particle Sampling

Leonidas Ntziachristos, Theodoros Tzamkiozis, Athanasios Mamakos and Zissis Samaras

University Thessaloniki, Greece

Copyright © 2008 SAE International

ABSTRACT

This paper presents a new concept of a partial flow sampling system (PFSS), involving a two-stage dilutor which operates at underpressure, while exhaust is sampled through a capillary. The sample flowrate is in the order of few cubic centimeters per minute. Due to the low flowrate, no tight fixation is required between the exhaust line and the capillary inlet. The dilutor may sample from an opening in the exhaust line which freely exhausts to ambient pressure. As a result, the PFSS operates at constant pressure conditions even upstream of diesel particle filters (DPF). A straightforward mathematical model is then developed to calculate the dilution ratio (DR), depending on the dilution air flowrate and the dilutor underpressure. The model is validated using CO₂ as a trace gas, and a very good agreement is demonstrated between the calculated and the measured DR values. After validation, the PFSS is combined with electrical aerosol detection devices to measure the exhaust particle concentration of a diesel engine operating at different steady-state modes. Also, the filtration efficiency of two particle filters is examined by respectively providing exhaust samples upstream and downstream of each filter. These applications demonstrate the stability and applicability of the PFSS combined with an aerosol instrument to measure the filtration efficiency of a DPF at low cost. Future applications of such configuration may include particle exhaust concentration measurements and on-board (portable) emission measurements.

INTRODUCTION

Constant Volume Sampling (CVS) has been designated for regulatory exhaust emission conditioning and sampling. It enables a relatively easy and accurate calculation of mass-based emission values since it provides a constant flowrate for the exhaust gas. On the other hand, CVS systems are quite expensive to build and operate, and require large facilities especially for heavy duty applications. The need to reduce the cost and space associated with CVS measurements led to the development of partial flow sampling systems (PFSS), even for regulatory measurements [1]. PFSS

are designed to draw only a portion of the exhaust stream which is then analyzed for pollutant concentration. There are two different main concepts for a PFSS, concerning the equivalence of the sample flowrate with the main exhaust flowrate. In one configuration the sample flowrate is adjusted in direct proportionality to the total exhaust flowrate, by an active control involving piezo valves (isokinetic systems). This process is equal to a downsized CVS but is still quite costly due to the need of an active flowrate control mechanism. In a second configuration, the PFSS draws a constant sample flowrate. This is the most economical sampling method but cannot be used to substitute the CVS procedure due to the lack of proportionality with the exhaust flowrate. However, it is regularly used when precise conditioning is required for the exhaust sample (dilution ratio, thermal treatment) and/or when real-time instrumentation is available [e.g. 2, 3].

One of the main limitations of constant-flowrate systems is that the exact flowrate depends on upstream exhaust conditions, namely static pressure and pressure pulsations, and temperature [4]. Hence, the flowrate deviates from its setting and the dilution ratio (DR) provided by such systems needs to be determined in real-time, usually with trace gas concentration measurements, such as CO₂ or NO_x. This becomes particularly necessary for large pressure differences, such as upstream of DPF. Even with such measurements, the sampling and conditioning significantly deviate from the initial settings, the measurement uncertainty increases due to the variable DR, while the calibration and the operation of the complete system becomes a tedious task [4].

This paper presents a new, simple concept of constant-flowrate PFSS, which leads to constant DR sampling, independently of exhaust gas pressure and pressure variations. This enables use of the system in variable pressure conditions, such as in exhaust lines equipped with diesel particle filters (DPFs) and when for example the DPF filtration efficiency needs to be determined. Due to the low cost, size, and power requirements, such a sampling system is also appropriate for on-board sampling applications. The paper presents the

operation characteristics and the DR calculation of a prototype PFSS developed and demonstrates its performance in exhaust particle sampling measurements.

EXPERIMENTAL

DILUTOR DESCRIPTION

Figure 1a presents a setup of the PFSS developed. This consists of two cascaded stages (primary and secondary), each comprising a capillary and a stabilization chamber. The sample is drawn by the primary capillary, due to the underpressure maintained in the stabilization chamber (capillary outlet). Dilution air enters the stabilization chamber through a throttling valve. The dilution air can be purified by means of a high efficiency particulate air (HEPA) filter for particle load, a charcoal scrubber for organic load and a silica gel dryer for water vapor. The sample flowrate depends only on the size of the capillary duct and the chamber underpressure. For a given size of the capillary, different DRs can be achieved by adjusting the underpressure in the stabilization chamber and/or the dilution air flowrate. The underpressure in the chamber may vary between a few millibars to several hundreds of millibars. Low underpressure is generally favorable to maintain the aerosol at close to ambient conditions.

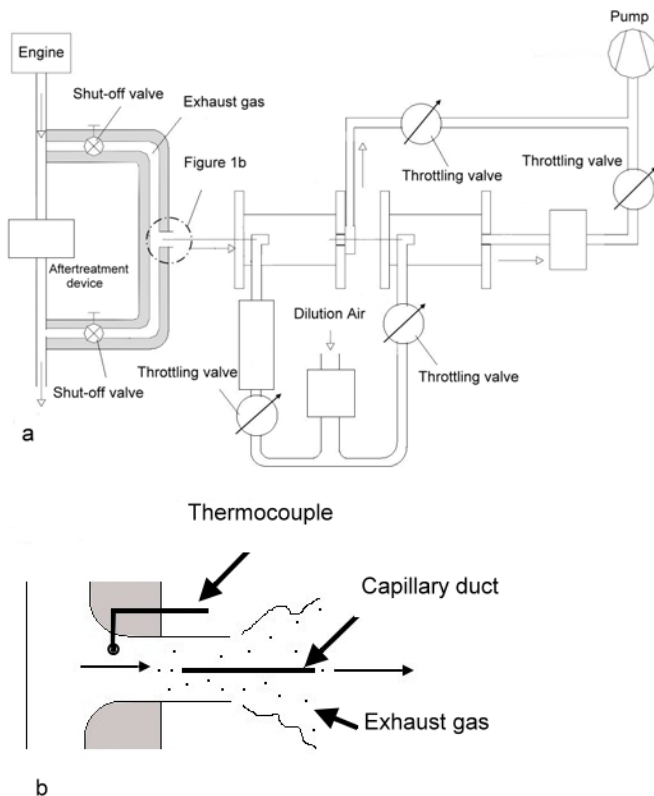


Figure 1: (a) Typical configuration of the PFSS, (b) Schematic of the connection of the primary capillary to the exhaust line.

The capillary diameter is in the order of half a millimeter, and the PFSS samples only a very small fraction of the

exhaust gas (less than 500 cm³/min). Figure 1b shows a schematic of the immersion of the primary capillary in the exhaust line. Due to the very small exhaust gas quantity sampled, no tight fixation between the capillary and the exhaust line is required. The capillary is fully surrounded by the exhaust gas which freely exhausts to ambient pressure, through an opening in the exhaust line. In this way, the capillary inlet is always exposed to exhaust gas of ambient pressure, regardless of the pressure of the gas in the exhaust line. The excess of exhaust gas (~1 l/min) is vented to the atmosphere outside of the measurement room. Since the inlet and outlet of the capillary are exposed to constant pressure conditions, the sample flowrate and, therefore, the DR remain constant during the measurement.

The two stages of the PFSS are identical in operation and geometry. The secondary capillary is immersed in the primary stabilization chamber and a flowrate between the primary and secondary chamber is established by maintaining a lower pressure in the secondary chamber. The secondary stage is not necessary for the PFSS operation but can be used to achieve a higher DR when this is required. The outlet of the secondary chamber can be connected to any aerosol instrument (e.g. a diffusion charger, an electrical low pressure impactor, etc.) to measure different aerosol properties. The instrument to be used should be tolerant to moderate underpressure operation.

Thermocouples are used inside each stabilization chamber to monitor the thermal conditioning of the aerosol sample before analysis. A third thermocouple is installed close to the primary capillary inlet to monitor the exhaust gas temperature at the sampling location. Figure 2 shows a prototype PFSS developed in this study.

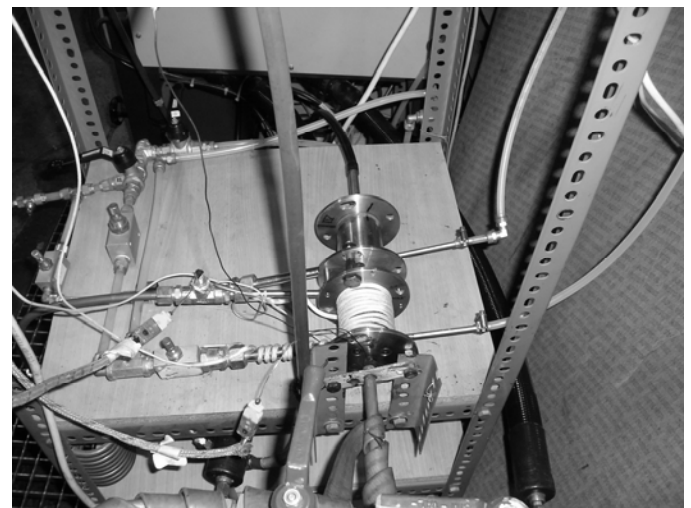


Figure 2: Photo of the prototype underpressure PFSS installed in the engine test cell.

DILUTION RATIO CALCULATION

The DR at each stabilization chamber is maintained constant by regulating the underpressure and the dilution air flowrate in the chamber. With reference to Figure 3, Eq. 1 provides the definition of the DR at each stage.

$$DR_i = \frac{Q_{i1} + Q_{i2}}{Q_{i1}} \quad \text{Eq. 1}$$

In Eq. 1, Q_{i1} is the sample flowrate through the capillary, Q_{i2} is the dilution air flowrate and $i = 1, 2$ denotes the primary (1) and the secondary (2) stabilization chambers, respectively.

Thus, the total DR of the system is given by the following equation.

$$DR_{total} = DR_1 \cdot DR_2 = \frac{Q_{11} + Q_{12}}{Q_{11}} \frac{Q_{21} + Q_{22}}{Q_{21}} \quad \text{Eq. 2}$$

The two flowrates Q_{i2} are set before the measurement and can be readily measured by a flowmeter. The Q_{i1} flowrates cannot be measured during sampling, due to the interference that any flowmeter would bring to the aerosol sample. However, both Q_{i1} can be calculated as a function of the pressure drop between the capillary inlets and outlets, at each chamber, respectively. The following assumptions were made to calculate the pressure drop in each capillary:

- The density of the flow throughout the capillary remains constant and equal to its value at the average temperature between inlet and outlet.
- The temperature at the outlet of the capillary is equal to the temperature of the stabilization chamber.
- The flow in the capillary is laminar fully-developed.
- The exhaust gas is a Newtonian fluid.
- The capillary duct has smooth walls.

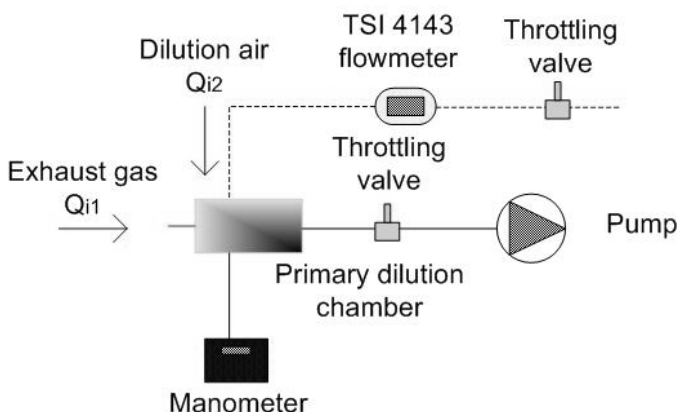


Figure 3: Model of the stabilization chamber.

A manometer (Figure 3) measures the total pressure difference between the stabilization chamber and the atmosphere. This is equal to the pressure drop of the sample flowrate through the capillary, which consists of three parts:

- Pressure drop at the inlet of the capillary due to sudden contraction of the streamlines.
- Pressure drop inside the capillary due to frictional losses.
- Pressure drop at the outlet of the capillary due to sudden expansion of the streamlines.

Pressure drop at capillary inlet

The sharp (almost 90°) bending of the streamlines is due to the very small diameter of the capillary compared to the size of the exhaust transfer pipe. For laminar flow, the losses in sudden contraction may be estimated for area ratios less than 0.2 by an equivalent additional pipe length L_e given in equation [5].

$$\frac{L_e}{D} = 0.3 + 0.04 Re \quad \text{Eq. 3}$$

D is the capillary diameter and Re is the Reynolds number in the capillary, defined in Eq. 4.

$$Re = \frac{\rho U D}{\mu} \quad \text{Eq. 4}$$

In Eq. 4 ρ , μ are the mean density and viscosity of the sample respectively (at the average temperature between inlet and outlet), and U is the mean velocity of the flowrate in the capillary. The density and viscosity values are gas properties and only depend on the sample chemical composition, at a constant temperature. Depending on the application of the PFSS, these values may be calculated for typical chemical compositions of exhaust gas from diesel or gasoline engines. Typical diesel exhaust (assuming $\lambda = 2$ and $C_{16}H_{34}$ as the sole diesel hydrocarbon) contains 6.6% CO_2 , 7.0% H_2O , 10.1% O_2 and 76.4% N_2 , while the pollutants concentration is too small to affect the physical properties of the sample. That is, three-atomic species are less than 15% of total exhaust and the sample properties are close to ambient air. Moderate deviation from this typical composition during the measurement is not expected to affect the model results. The composition of typical gasoline exhaust is more distant to ambient air. Assuming stoichiometric mixture and C_8H_{18} as gasoline leads to an exhaust sample consisting of 12.5% CO_2 , 14% H_2O and 73% N_2 . That is three-atomic species are more than 25% of the total sample and alter both the density and the viscosity of the mixture. However, since gasoline combustion is stoichiometric, the composition does not change during the measurement and can be compensated for.