

Recommended Practice for Partial Flow Dilution System Measurement of Particulate Matter (PM)

RATIONALE

The conventional test method for particulate matter (PM) measurement of vehicle and engine exhaust is the gravimetric type where a small fraction of the total diluted exhaust from a full flow dilution tunnel connected to a constant volume sampler (CVS) is sampled over pre-weighed 47 mm PTFE filters at a temperature of $47^{\circ}\text{C} \pm 5^{\circ}\text{C}$. In a full flow dilution tunnel, all the exhaust flow from the engine flows through the tunnel where it is diluted with ambient air. To cover a wide range of vehicle and engine sizes, either single or double dilution systems are permitted for certification. The accuracy of the total PM mass of the test depends on many parameters but the most significant seems to be the amount of dilution and the magnitude of the net mass of PM collected on the filter. Partial flow systems, which are an alternative method to full flow CVS systems, include the additional complexity in that the sample ratio needs to be carefully controlled proportionally to the varying exhaust flow under transient conditions. Partial flow systems have an advantage of allowing more PM mass to be collected on the filter if the sample ratio is optimized correctly for vehicle or engine being tested. The PM limit in the U.S. is set at 3 mg/mile for light duty vehicles and 0.01 g/bhp-hr for heavy duty engines. The California Air Resources Board (CARB) approved a new PM limit of 1 mg/mile for LD applications starting in 2025 as part of the ACC II regulation. At 1 mg/mile, the net mass of PM on the filters in full flow systems will be approaching tunnel background levels making partial flow systems more desirable as the net mass of PM on the filter can be higher. Partial flow PM measurement also has the advantage of using much smaller, lower cost equipment without the need for a large CVS and full flow dilution tunnel system. The aim of this document is to organize the information in an easy to read-and-follow document, describing in detail the components of partial flow systems with specifications and performance characteristics. It also includes best practices for PM measurement in partial flow mode for light duty and heavy duty applications.

FOREWORD

Gravimetric PM measurement procedures for full flow systems have existed for over 40 years, and over the same time period the certification limits have steadily decreased. The HD PM emission limits in 1991 were 0.25 g/bhp-hr, in 1994 the PM limit decreased to 0.10 g/bhp-hr, and in 2007, it decreased by an order of magnitude to 0.01 g/bhp-hr. The LD PM limit was at 0.2 g/mile in 1987, but the introduction of diesel particulate filters (DPF) in the mid 1980s allowed regulators to significantly lower the PM limit, which has been steadily decreasing ever since. The limit decreased to 0.08 g/mile in 1994, 0.04 g/mile in 1998, and 0.01 g/mile in 2006. More recently, trends to higher compression ratios, turbocharging, and downsizing resulted in a steady increase in production of gasoline direct injection (GDI) technologies to improve fuel economy and reduce greenhouse gas. PM emissions from GDI vehicles are approximately an order of magnitude higher than those from port fuel injection (PFI) vehicles. This upward trend in GDI production triggered the California Air Resources Board and the EPA to adopt, in 2017, a new LD PM limit of 0.003 g/mile on the Federal Test Procedure (FTP) cycle. Even though there has been over a 98% decrease in the limits over the past 30 years, CARB has already announced that the PM limit will be further reduced to 0.001 g/mile in 2025. These low limits are challenging in terms of measurement reliability and repeatability. The net weight on the filter is now in micrograms and small errors in filter weighing due to environmental control, human handling, static charge removal, or sampling system are magnified several hundred times by the sample ratio contributing to potentially large variability in PM mass. Partial flow systems offer an alternative to full flow dilution CVS tunnels, but the control of sample ratio based on transient exhaust flow places additional demands on the PM sampler equipment and operation.

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1. SCOPE

This recommended practice establishes test procedures and best practices for PM measurements under partial flow conditions. PFDS PM testing and certification is primarily used in heavy duty applications as described in 40 CFR Part 1065 because full flow sampling systems with a dilution tunnel and CVS can be very bulky for large heavy duty engines. 40 CFR Part 1066 also allows the use of partial flow systems for light duty applications in lieu of full flow systems. PFDS does not require the use of a CVS sampling system or a full flow dilution tunnel. This makes it easier and more convenient to perform PM measurement in smaller test cells that cannot fit a large CVS or a full flow dilution tunnel. This document describes the different components/specifications of LD and HD PFDS as well as the required quality checks necessary to ensure the integrity of the sampling system. It also addresses the many sampling options and calculations that are approved by the regulations. Correlation between partial and full flow systems will also be discussed.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J2943 Practice for Filter Weighing of Particulate Matter Emissions

2.1.2 Code of Federal Regulations (CFR) Publications

Available from the United States Government Printing Office, 732 North Capitol Street, NW, Washington, DC 20401, www.gpo.gov.

40 CFR Part 86 EPA, Control of Emissions from New and In-Use Highway Vehicles and Engines

40 CFR Part 1065 EPA, Engine-Testing Procedures

40 CFR Part 1066 EPA, Vehicle-Testing Procedures

2.1.3 ISO Publications

Copies of these documents are available online at <https://webstore.ansi.org/>.

ISO 8178-1:2020 Reciprocating Internal Combustion Engines – Exhaust Emission Measurement – Part 1: Test Bed Measurement Systems of Gaseous and Particulate Emissions

2.1.4 Publications Office of the European Union

Copies of these documents are available online at <https://op.europa.eu/en/web/about-us/fag>.

Regulation No 49 of the Economic Commission for Europe of the United Nations (UN/ECE). (2010). Uniform provisions concerning the measures to be taken against the emission of gaseous and particulate pollutants from compression-ignition engines for use in vehicles, and the emission of gaseous pollutants from positive-ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles. *Official Journal*, L 229, 1-138. [http://data.europa.eu/eli/reg/2010/49\(2\)/oj](http://data.europa.eu/eli/reg/2010/49(2)/oj).

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

Rahman, M., Rooney, R., and Nevius, T. (2018). *Partial flow dilution system with double dilution for PM sampling under transient test-cycles* (Report No. 2018-01-0643). SAE International. <https://doi.org/10.4271/2018-01-0643>.

Rahman, M., Rooney, R., Nevius, T., Otsuki, Y., Yoshida, T., Khan, Y., Mun Liew, C., and Basrur, C. (2020). *Single vs double stage partial flow dilution system: Automobile pm emission measurement* (Report No. 2020-01-0366). SAE International. <https://doi.org/10.4271/2020-01-0366>.

Otsuki, Y., Haruta, K., and Rahman, M. (2018). Diving flow-weighted sampling approach in partial flow dilution system for particulate emission measurement in internal combustion engine exhaust. (Paper No. 2018-01-0645). *SAE International Journal of Fuels and Lubricants*, 11(4), 483-494. <https://doi.org/10.4271/2018-01-0645>.

Khalek, I.A., et al. (2002). *Performance of partial flow sampling systems relative to full flow cvs for determination of, particulate emissions under steady-state and transient diesel engine operation* (Report No. 2002-01-1718). SAE International. <https://doi.org/10.4271/2002-01-1718>.

Khalek, I. (2005, August 21–25). *Update on 2007 diesel particulate measurement research (CRC Project E-66, Phase 1)* [Conference presentation]. 11th DEER Conference. Coordinating Research Council.

Khalek, I. (2005, August 21–25). *Update on 2007 diesel particulate measurement research (CRC Project E-66, Phase 2)* [Conference presentation]. 11th DEER Conference. Coordinating Research Council.

Johnson, K.C., et al. (n.d.). *Very low PM mass measurements* (Report No. CTC E-99). Coordinating Research Council.

Johnson, K.C., et al. (2017). *Very low pm mass measurements phase 2: Evaluation of partial flow dilution* (Report No. CTC E-99-2). Coordinating Research Council.

Flow Technology (n.d.). *UGF20 ultrasonic gas flowmeter: Installation, operation, and maintenance manual*.

3. DEFINITIONS

3.1 Abbreviations

CARB	California Air Resources Board
CFR	Code of Federal Regulations
CVS	Constant Volume Sampler
DR	Dilution Ratio
DVE	Direct Vehicle Exhaust Flow Meter
EPA	Environmental Protection Agency
FFV	Filter Face Velocity
HC	Hydrocarbons
HD	Heavy Duty
LD	Light Duty
OBD	On-Board Diagnostics
PFDS	Partial Flow Dilution System
PM	Particulate Matter

PN	Particle Number
RMC	Ramped Modal Cycle
SSV	Subsonic Venturi
VFM	Venturi Flow Meter

4. PFDS SYSTEM DESCRIPTION AND COMPONENTS

Particulate Matter (PM) is traditionally collected on filter media under simulated driving conditions in a laboratory using a full flow CVS system, where the total engine exhaust is diluted with HEPA filtered air. The flow rate and size of the CVS system are determined by the exhaust flow rate of the engine, among other parameters, in order to provide sufficient dilution. A full flow CVS may face challenges in the case of large heavy-duty and high horsepower engines due to high flow rate requirements, bigger footprint, and overall set-up/running cost. A second version of the full flow CVS uses a double dilution system where the whole exhaust flow is initially diluted by at least 2:1 and then a small sample of this diluted exhaust is sampled in the secondary tunnel with a second stage of dilution. The double dilution CVS is still a relatively large system. Partial Flow Dilution Systems (PFDS) are also allowed in the sampling of PM on filter media. In this case, only a part of the exhaust gas is extracted and diluted with HEPA filtered air, followed by flow through a smaller scale dilution tunnel. Because only a part of total exhaust gas (fixed quantity or proportional) is sampled, the PFDS can be used for a wide range of engine sizes. Language from 40 CFR Part 1065 and 1066 requires limits on DR, filter face velocity (FFV), and filter face temperatures for accurate PM sampling and measurement under transient test conditions. Lower DR (min 7:1) and higher FFV (up to 140 cm/sec) for LD applications are options to load a measurable amount of PM (preferably more than 100 µg) on the filter media. In addition, flow weighting can be applied in case of using a single filter to collect PM across multiple phases of the US-FTP test cycle. Some high horsepower engine testing requires higher DR and lower FFV to limit the amount of PM on the filter media (preferably less than 400 µg). Because of flow rate and dilution ratio limitations of a PFDS, it is difficult to maintain 40 CFR Part 1065 and 1066 requirements with a single dilution tunnel, especially for large HD engines. Therefore, a PFDS with second dilution tunnel is an option to meet the wide range of DR and FFV requirements for both LD vehicle and large HD engine testing.

4.1 PFDS System with Single Dilution Tunnel

Figure 1 shows an example flow diagram of a single tunnel PFDS configuration. Raw exhaust gas is introduced into the dilution zone through a sampling probe. HEPA filtered dilution air is added to create turbulence for better mixing after being cooled/heated by a chiller/heater. Moisture from the dilution air must be removed upstream of the dilution air flow meter. Total diluted gas is then passed through the tunnel to the PM sample filter. The flow rate through the PM sample filter is adjustable by a fast response piezo electric valve to obtain a wide range of FFV. The blower speed can be adjusted to obtain different filter face velocity, but, depending on the blower inertia, there may be delay to achieve the target FFV. Alternatively, a Venturi pump equipped with a fast response piezo electric valve that adjusts the driving force (compressed air) via PID loop involving a flow measurement can be employed. For a 47 mm filter, 40 CFR Part 1065 and 1066 recommend a maximum FFV of 100 cm/sec. However, the total flow rate can be adjusted to achieve a maximum FFV of 140 cm/sec on LD, if necessary, to collect more PM mass on the filter. Both the dilution air flow and the diluted exhaust flow must be measured on a real-time basis by high accuracy flow meters. The difference between the diluted exhaust flow (total flow) and the dilution airflow is the amount of raw exhaust gas introduced into the tunnel.

This system can be operated either at a fixed or proportional DR sampling mode. For fixed DR mode the dilution air flow remains constant together with the diluted exhaust flow rate (total flow). Therefore, the exhaust gas sample flow rate also remains constant, which results in a fixed DR. For proportional sampling mode, the total engine exhaust gas flow rate must be quantified, and an equivalent signal (analog/digital) must be fed back to the PFDS system. Regulations from 40 CFR Part 1065 allows to use the intake air flow and the fuel flow to calculate the exhaust flow rate. Receiving the exhaust flow signal, a fast response piezo-electric valve is adjusted to control the dilution airflow rate which, in turn, controls the sample flow rate proportional to the exhaust flow rate.

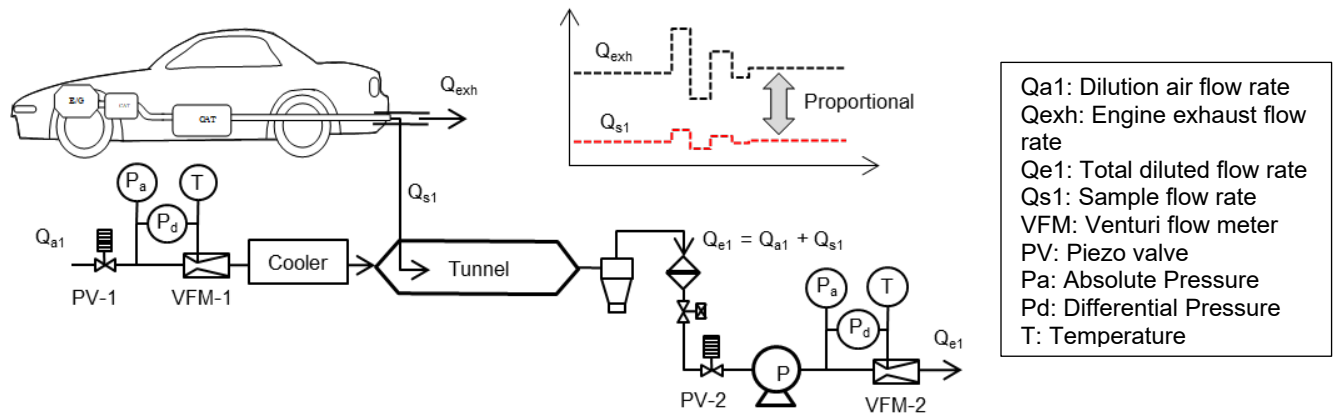


Figure 1 - Example of partial flow dilution system with single dilution configuration
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4.2 PFDS System with Double Dilution Tunnel

Figure 2 shows an example flow diagram of a double tunnel PFDS configuration. Two identical dilution tunnel configurations are employed in both first stage and second stage dilution. The system can be configured as single dilution tunnel or double dilution tunnel, where necessary. Raw exhaust gas is introduced into the first tunnel through a sampling probe by directing it downstream along the centerline of the tunnel. Dilution air can be added through a single point, or tangentially from multiple points, to create turbulence for better mixing. A portion of diluted gas from the first dilution tunnel is taken as the sample for further dilution in the second dilution tunnel with the remaining flow being bypassed. The flow rate of diluted gas in the second tunnel can be varied in the system to obtain a wide range of FFV. The system can operate under different control modes for dilution: proportional sampling mode (constant split ratio) and fixed DR mode (constant DR). Any PFDS must be configured to have an overall residence time of 1.0 to 5.5 seconds (depending on single or dual tunnel), as measured from the location of initial dilution air introduction to the location where PM is collected on the sample media, considering the total volume and system flow rate. The system must also meet 40 CFR Part 1065 and 1066 requirements.

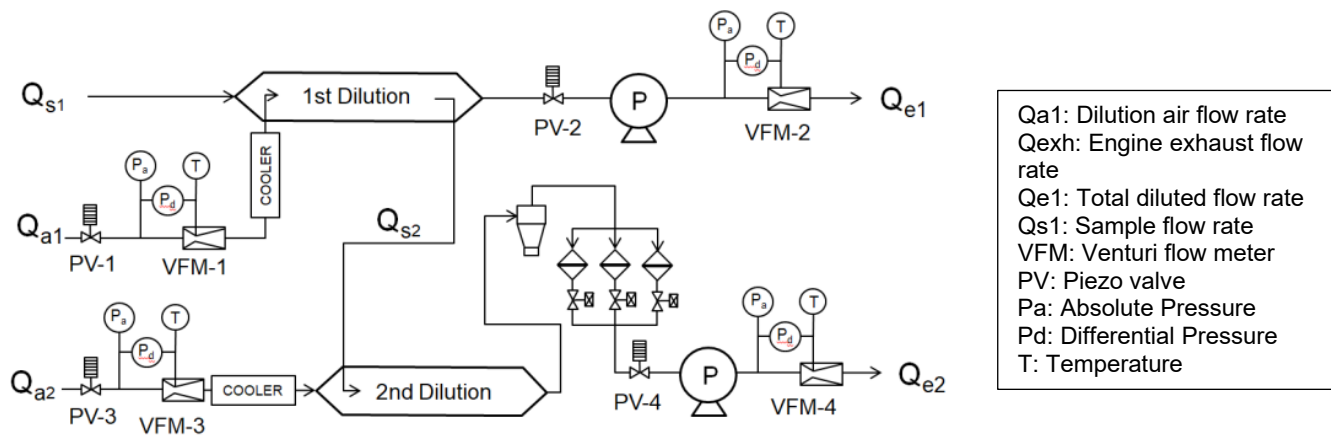


Figure 2 - Example partial flow dilution system with double dilution configuration
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In the first tunnel, the dilution air (Q_{a1}) and the bypass (Q_{e1}) flows are equal. Therefore, the sample flow into the first tunnel [Q_{s1}] will be equal to the sample flow into the second tunnel [Q_{s2}]. Flow balance in the first dilution tunnel is as follows:

Flow into PFDS = Flow out from PFDS

$$Q_{s1} + Q_{a1} = Q_{e1} + Q_{s2} \quad (\text{Eq. 1})$$

where:

Q_{s1} = Sample into the first dilution tunnel

Q_{a1} = Dilution air into the first dilution tunnel

Q_{e1} = Diluted gas from the first dilution tunnel

Q_{s2} = Sample into the second dilution tunnel

Flow balance in second dilution tunnel is as follows:

Flow into PFDS = Flow out from PFDS

$$Q_{s2} + Q_{a2} = Q_{e2} \quad (\text{Eq. 2})$$

where:

Q_{s2} = Sample into the second dilution tunnel

Q_{a2} = Dilution air into the second dilution tunnel

Q_{e2} = Diluted gas from the second dilution tunnel

The total DR is the multiple of the first DR and second DR.

$$\text{Total DR} = DR_1 \times DR_2 \quad (\text{Eq. 3})$$

where:

DR_1 = DR in first dilution tunnel

DR_2 = DR in second dilution tunnel

In a steady state test, fixed DR mode is used and the DR in the first dilution tunnel (DR_1) becomes equal to that of the second dilution tunnel (DR_2). In a transient test, the proportional sampling mode (constant split ratio) is used. Thus, the DR in the first dilution tunnel is not equal to that of the second dilution tunnel. However, the total DR still follows the calculation in Equation 3.

Highly accurate Venturi Flow Meters (VFMs) or Laminar Flow Elements (LFE) are typically used to measure flows on a real-time basis. The diluted exhaust flow rate is kept constant by controlling a piezo valve while the pump is running at constant speed continuously. By this method it is possible to avoid the response delay due to pump inertia. The dilution air is also controlled by another piezo valve to obtain faster transient response. However, the delay time (T_d) due to tunnel buffer volume may need improvement in the form of the predictive control method. Gas transformation time is not necessary for the predictive control method. The parameter to be corrected is the response time of flow control at the sample probe tip which is typically less than 0.3 second. This method records the exhaust-gas flow rate of the test engine in the tunnel system before the actual PM measurement begins. The actual PM measurement is performed using the recorded flow data by reading the data 0.5 or 1 second in advance of the engine test cycle in order to compensate for the system delay time. The predictive control is an option for PFD systems with long response times especially when the exhaust flow meter response is very slow.

4.3 Flow Meters (VFM)

Highly accurate VFMs or LFEs are commonly used to measure flows in PFDSs on a real-time basis. Subsonic venturis (SSVs) are commonly employed in the VFMs. VFMs have minimal errors in flow measurement caused by differences in the physical densities or thermal capacity variations of the different gaseous components contained in the sample. The density of diluted engine exhaust gas ($DR > 5$) is nearly constant and virtually identical to that of air and, thus, cause negligible measurement variability in the VFM. The flow rate measurement is based on the proportional relationship of the gas velocity and the square root of the differential pressure caused by two different velocities of the gas pressure at the inlet and the pressure at the venturi throat. Because the calculation relies on the square root of the differential pressure, measurements using a VFM are more accurate at higher flow rates.

LFE flow meters are also highly accurate and also used to measure flows in PFDSs on a real-time basis. LFE flow rate is based on viscosity, whereby frictional drag of individual molecules in the flow created by interaction with the pipe material produces a pressure drop. LFE flow exhibits a linear relationship with pressure drop as expressed by the Hagen-Poiseuille equation. The linear relationship results in a comparatively high turn down ratio and thus a much larger range of flow measurement.

4.4 Filter Media and Loading Specifications

Table 1 shows the filter material, diameter, stain diameter, and collection efficiencies required for different countries/regulations. CFR Part 1065 highly recommends the use of a pure PTFE filter material that does not have any flowthrough support bonded to the back and has an overall thickness of $40 \mu\text{m} \pm 20 \mu\text{m}$. An inert polymer ring may be bonded to the periphery of the filter material for support and for sealing between the filter cassette parts. It is recommended that the maximum PM loading on the filter be less than $400 \mu\text{g}$ with a minimum filtration efficiency of 99.7%. Assuming a 38 mm diameter filter stain area and a PM filter loading exceeding $400 \mu\text{g}$, a minimum initial collection efficiency of 98% is required.

Table 1 - Filter material, diameter, stain diameter, and collection efficiencies

Regulation	US	EU: On-Highway	EU: Non-Road
Filter Medium	PTFE	PTFE	PTFE
Filter Diameter	46.5 mm $\pm$ 0.6 mm	46.5 mm $\pm$ 0.6 mm	46.5 mm $\pm$ 0.6 mm
Stain Diameter	≥ 38 mm	≥ 38 mm	≥ 37 mm
Collection Efficiency	$\geq 99.7\%$ ⁽¹⁾	$\geq 99\%$	$\geq 99.7\%$ ⁽¹⁾

⁽¹⁾ Minimum 98% collection efficiency for net PM mass on the filter exceeds $400 \mu\text{g}$.

4.5 Mixing of Dilution Air and Exhaust

Introduce raw exhaust into the tunnel by directing it downstream along the centerline of the tunnel. If dilution takes place directly from the exhaust stack, the end of the exhaust stack is the start of the dilution tunnel. A fraction of dilution air may be introduced radially from the tunnel's inner surface to minimize exhaust interaction with the tunnel walls. A typical turbulent mixing zone is shown in Figure 3. The system may be configured with turbulence generators, such as orifice plates or fins to achieve good mixing. A minimum Reynolds number ($Re^\#$) of 4000 for the diluted exhaust stream is recommended, where $Re^\#$ is based on the inside diameter of the dilution tunnel.

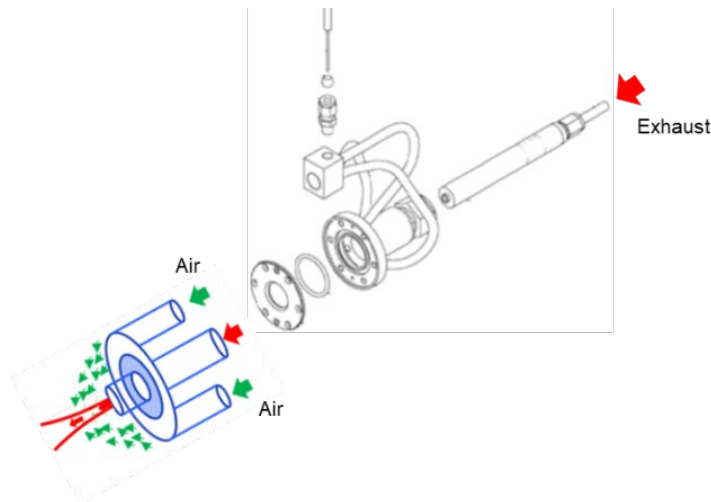


Figure 3 - A typical turbulent mixing dilution tunnel

4.6 Sample Probe

A single opening at the end probe can be used for PM sampling. PM probes should be oriented to directly face the flow. When a deflector/hat probe is used, pre-classifiers cannot be used. The inside diameter of PM probes should be sized according to isokinetic sampling at the expected mean flow rate. The location of sample probe is recommended to be co-axial with the exhaust stack, if possible. A CFR compliant probe must be less than 26 cm in length from probe inlet to the mixing point. The probe should be fabricated with 300 series stainless steel for dilute applications and raw exhaust applications or any nonreactive material that can tolerate the exhaust temperatures. It is recommended that the inner surface of transfer lines be electrically conductive and grounded. At a minimum, the transfer tube must be insulated to limit heat transfer prior to dilution. Active heating of transfer lines or tubes is also recommended to prevent condensation due to heat transfer loss.

4.7 PM Transfer Lines

4.7.1 Transfer Line Specification

Minimize the length of all transfer lines by locating the PFDS as close to probes as practical. Minimize the number of bends in transfer lines and maximize the radius of any unavoidable bend. Avoid using 90 degree elbows, tees, and cross-fittings in transfer lines. Where such connections and fittings are necessary, take steps, using good engineering judgment, to meet the temperature tolerances. This may involve measuring temperature at various locations within transfer lines and fittings. Use heated transfer lines to minimize temperature differences between transfer lines and exhaust constituents. Use transfer lines that are inert with respect to PM and are electrically conductive on the inside surfaces. Using PM transfer lines made of 300 series stainless steel is recommended. Electrically ground the inside surface of PM transfer lines.

4.7.2 PM Transfer Lines per CFR Part 1065

CFR Part 1065 requires diluting the PM samples at least once upstream of the transfer lines. Full-flow and partial-flow dilution are both allowed for sample dilution immediately downstream of a PM probe. In the case of partial-flow dilution, CFR Part 1065 recommends the length of the probe to be as short as possible with a maximum permitted 26 cm of insulated length between the end of the probe and the dilution stage.

4.7.3 PM Transfer Lines per ECE R-49

The ECE R-49 requires that the exhaust transfer tube be as short as possible but with a maximum length of 0.26 m if insulated for 80% of the total length, as measured between the end of the probe and the dilution stage. The insulation shall be done with material with a maximum thermal conductivity of 0.05 W/mK with a radial insulation thickness corresponding to the diameter of the probe.

Not more than 1 m in length, if heated above 150 °C for 90% of the total length, as measured between the end of the probe and the dilution stage. It shall be equal to or greater than the probe diameter, but not more than 25 mm in diameter, and exiting on the centerline of the dilution tunnel and pointing downstream.

4.8 PM Pre-Classifiers

Use a PM pre-classifier to remove large-diameter particles. The PM pre-classifier may be either an inertial impactor or a cyclonic separator. It must be constructed of 300 series stainless steel. The pre-classifier must be rated to remove at least 50% of PM at an aerodynamic diameter of 10 µm and no more than 1% of PM at an aerodynamic diameter of 1 µm over the range of flow rates used. Follow the pre-classifier manufacturer's instructions for any periodic servicing that may be necessary to prevent a buildup of PM. Install the pre-classifier in the dilution system downstream of the last dilution stage. Configure the pre-classifier outlet with a means of bypassing any PM sample media so the pre-classifier flow may be stabilized before starting a test. Locate PM sample media within 75 cm downstream of the pre-classifier's exit..

4.9 Filter Holder

To minimize turbulent deposition and to deposit PM evenly on a filter, use a filter holder with a 12.5 degree (from center) divergent cone angle to transition from the transfer line inside diameter to the exposed diameter of the filter face. Use 300 series stainless steel for this transition. The filter holder temperature should be maintained at 47 °C ± 5 °C.

4.10 High Pressure Sampling Unit/Sample Probe

PFD sampling for certification measurements is made only post aftertreatment where the pressure is at or near ambient, and thus usually within the operating specifications of PFD samplers. Modern aftertreatment systems create high back pressure at engine-out sampling locations. Sampling of exhaust gas under high pressure, such as sampling at a location upstream of the DPF/GPF or of exhaust gas from turbocharged and supercharged engines high-pressure fluctuation, can affect the sample flow accuracy within the PFDS. Sampling under pressures higher than 40 to 50 kPa above ambient presents challenges to most PFD samplers, primarily due to over sampling relative to proportionality with respect to the exhaust flow signal. Sampling outside of this constraint would primarily be undertaken in R & D efforts and thus should be approached with caution.

Although PFD devices differ somewhat on the maximum pressure at the sample point for varying reasons, the basic dilution scheme among them is similar to that described within this document. In short, accurate dilution as a function of exhaust flow proportionality relies on constant total flow and varying dilution flow (as a function of exhaust flow) with the actual exhaust sample being the difference of these two flows, commonly known as “makeup flow.” This “makeup flow” is driven by the pressure differential between the sample inlet and the pressure drop created by the demand of the total flow pump and the dilution flow pressure. When the pressure at the inlet increases, the total pressure drop at the inlet of the PFD increases resulting in a higher sample flow (makeup flow) into the PFD.

Thus, sampling under high pressure requires a high-pressure sampling device. There are different types of devices commonly used for high-pressure sampling, as described in the following sections. Figure 4 shows high-pressure sampling using a special probe. A special sampling probe with some degree of capillary effect can be used to minimize the sample pressure and pulsation. A sudden enlargement in probe diameter can minimize the pressure and pulsation. This is effective up to limited exhaust pressure and pulsation. Higher exhaust pressure and pulsation requires specially designed high-pressure sampling units.

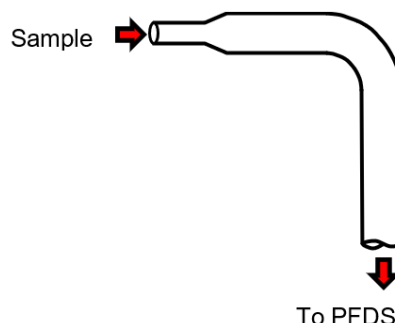


Figure 4 - A typical high-pressure sampling probe