

# International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 8, August 2015

## Review of Vehicle Emission Measurement and Sampling System

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**ABSTRACT:** The vehicle exhaust is considered as a significant source of anthropogenic emissions. The regulation authority all over the world is trying to limit the exhaust emission levels of the vehicles. Over the last few years, the measurement method has been changed and it is based on the gravimetric quantification of the mass of particulates collected on the filters. The particulate matters are the particles which are un-burnt carbon particles and ash particles due to incomplete combustion. The size of these particles is less than 100  $\mu\text{m}$ . Hence there are challenges in evaluation of its contribution to the air borne concentrations. This paper reviews how the exhaust emission measurement of the heavy duty vehicles and light vehicles are modified. The focus is on the newly evolving instrumentation and instrument based emission measurement methods for measuring the exhaust gases like carbon monoxide, carbon dioxide, nitrogen oxides and particulate matter. This concludes with the sampling requirements and future instrumentation for changing the innate characteristics of the exhaust emissions from today's and future vehicles.

**KEYWORDS:** Exhaust aerosol, Aerosol sampling, Dilution system, pollution and emissions.

### I. INTRODUCTION

The internal combustion engines operate by burning of fuel which produces exhaust emissions. These emissions are the major source for contributing to the environmental pollution. The green house gases like- methane, carbon dioxide, nitrous oxide and the other pollutants like- carbon monoxide, sulphur dioxide, nitrogen oxide and particulate matter are the major components. In the last few years large amount of research and the policy action has been taken to focus on exhaust emission and strict regulations and technical up gradation has resulted in reduction of the emissions from the tail pipe of the vehicle.

The leading countries are taking initiatives for launching the Particulate Measurement Program to develop accurate and sensitive measurement methodology. Therefore close involvement of the researchers in the Particulate Measurement Program discussion have enabled the measurement method to be capable of use by the automotive industries, legislators and the test centres. It is required that the testing of the vehicle should be recruited from the real world. Hence, this has been augmented for the on road emission measurement testing by regulations. This demands for the most robust measurement technique for the particulate matter emission, because the real environment is not suitable for complex and sensitive instruments used in the test centres. The new instruments which are now available in the world are required for the regular and periodic maintenance and inspection with appropriate sensitivity to check the function of the emission measurement systems for the modern vehicles. Therefore, such an application is required to be economical, lightweight, small in size and with less maintenance. In this we have discussed the dilution of the exhaust gas and the exhaust gas conditioning system used in vehicle exhaust emission testing.

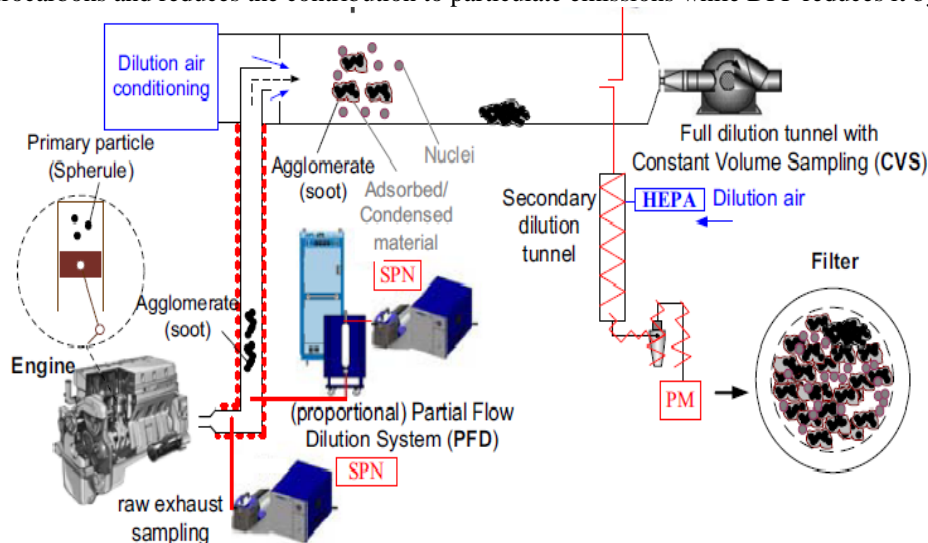
### II. EXHAUST GAS SAMPLING

The chemical and physical properties of the particulate matter changes continuously after their formation. An instant change occurs as the exhaust exits from the tail pipe and dilutes and cools in the atmosphere. The process is carried out in the testing laboratory by mixing of exhaust gases with clean ambient air within the dilution tunnel. There is significance in modifying the exhaust particulate matter properties by controlling the dilution process and therefore it affects the measurement.

### III. PARTICULATE MATTER TRANSFER FROM ENGINE TO INSTRUMENT

In combustion chamber the primary particulates (10-30 nm size) is formed by the pyrolysis of fuel and lubricant in fuel rich area of combustion chamber. The concentration and size of these particles are depend on the operation condition, fuel and combustion process. In addition to this some lubricant and fuel molecules can be partly oxidized and can escape combustion releasing hydrocarbons (HC) in exhaust stream.

In diesel engines the soot burns up about 90-99% during the exhaust stroke as the soot gets oxidized by the excess air. By oxidation and fragmentation the soot growth by coagulation and shrinking leads to the lognormal shape with mean diameter of 40-80 nm. Soot are generally amorphous carbon which generate at low loads. But at high loads the soot can be graphitic like structure. They generally have bulk density of 1.8-2 gm/cm<sup>3</sup> because they have residual amount of hydrogen. Engine soot also have ash of zinc calcium and other elements which are contained in oil additives. To reduce particulate matter concentration in the cylinder includes improving miscibility of charge, optimizing injection duration and timing and injection pressure. Today, to control particulate emissions the after treatment devices are used and most often used is combination of DPF (Diesel particulate filter) and DOC (Diesel oxidation catalyst). The DOC oxidizes the hydrocarbons and reduces the contribution to particulate emissions while DPF reduces it by 90%.



**Fig.1** Particle transformation from engine to measurement location

In dilution tunnel (Partial flow or full flow) the exhaust gas is diluted with particle free, humidity and temperature controlled ambient air. During the process the semi-volatile gases, sulfates and organics are partition to the particulate phase, which depends on the species concentration and local temperature, for both of which are functions for dilution ratio. The dilution ratio is the ratio of air to exhaust gas. The partition occurs in the form of condensation and adsorption on the soot and as a nucleation of separate particles between 10-30 diameters. Excess condensation may change the structure of soot. Formation of its magnitude as well as separate nucleation mode depends on number of factors. These includes, the fuel and lubricant used, adsorption phenomena, the after treatment device used, the preconditioning of test and amount of soot present. This promotes the process of adsorption and condensation rather than nucleation.

Due to atmospheric dilution the nucleation mode may form under real driving condition in the wake of vehicle while verifying vehicle chase study. The simulation can be done of this nucleation mode in the laboratory. Due to the sensitivity of nucleation mode the exact characteristics will not be predicted. on the walls of sampling system the formation of heat release of the material was accumulated while doing laboratory testing on the nucleation mode.

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Corresponding to accumulation mode the EU decided to limit the number of particulate matter to avoid such sampling difficulties.

### IV. DILUTION SYSTEM

Under laboratory condition in the sampling particles the dilution is necessary to mimic up to some extent, and the exhaust particulates transforms in the environment air. To avoid the condensation of the exhaust constituents, proper dilution of the exhaust gas is necessary, especially water, on the sampling lines and the walls of the exhaust, thus the measurement accuracy is being improved. From the raw exhaust to the measuring range of particulate sensors, the dilution process reduces the temperature and concentration of the particles present in the exhaust gas. For the modern engines also with lower particulate emissions, the sampling done without dilution of exhaust will make adverse effect on the performance and durability of instruments. It is difficult to account for the variability and uncertainties during transport when it is continued to transformation and reaction among particulate species and gases. Therefore, the exhaust particulates are generally diluted to freeze the particle size before measurement. There are limited types of instruments which can sample and measure the particulate matter in hot raw exhaust. Hence, this process keeps the exhaust gases temperature slightly above the condensation and because of this the result does not measure the particulate matter as referred by the regulation.

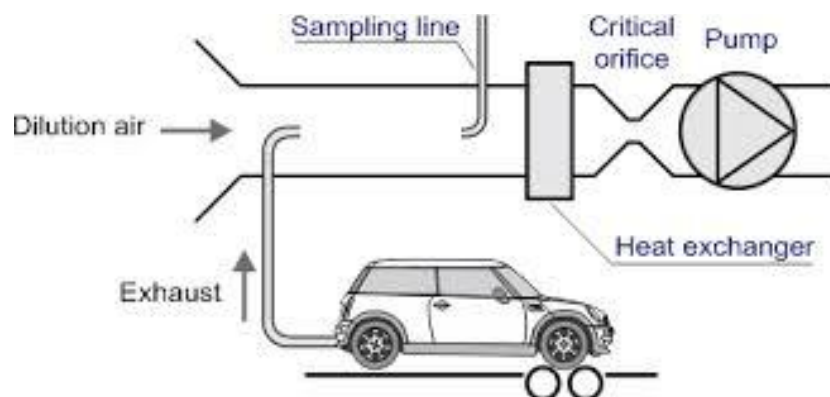


Fig.2 Layout of dilution system

### V. FULL DILUTION TUNNEL

Constant Volume Sampling (CVS) is the most common method used in the dilution of whole exhaust inside the tunnel. Since 1980s this method is required by the legislation. For the certification tests the CVS system procedure is having clear advantages. In the sample transport line the risk of condensation of water is eliminated or reduced by the dilution of exhaust gas. The fluctuation of temperature and pressure can be reduced by the stabilization of exhaust, which simplifies the sampling process. The entire flow rate is precisely measured and controlled. Even though CVS leads to variable dilution ratio over the transient driving cycle, the main advantage is that the mass per kilometer or emission rate in number is simply derived by scaling the measured value by ratio of sample flow rate to CVS.

The latest regulations have enforced that several exhaust parameters for exhaust conditioning to be considered otherwise it was left uncontrolled in Constant Volume Sampling. These parameters are usually operates at moderate dilution ratio (DR)  $< 10:1$ , and with no demand for heating the dilution air. Therefore, it will not allow to control the dilution and temperature independently. The concentration and temperature of the gas both varies with dilution ratio, and these are the factors which determine the partition of semi volatile substances between particle and gas phases. From the recent studies it is shown that due to less contribution from semi volatile materials there is reduction in Particulate Matter because of isothermal increase in Dilution Ratio. Later it is investigated that if there is increase of Dilution Ratio around 7:1 to 29:1 and subsequently the temperature of filter face shift from 45°C to 33°C then it increases the Particulate Matter by 25% over a neutral load and speed conditions. Due to this aspect the level of

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Particulate matter determined by Constant Volume Sampling is dependent on Dilution Ratio. In the inter laboratory comparison it is found that there is 20% of difference in Particulate Matter which are attributed in situations where outliers are excluded and the gaseous pollutants are agreed. To address this issue new regulation have been made in making efforts for improving the reproducibility between testing laboratories of different sites. If the Dilution is higher the there is a tough challenge to collect the sufficient amount of Particulate Matter for weighing. Since the mass of collected sample is comparable to the mass of gases which are absorbed by filters. To favour the determination of semi volatile Particulate matter higher Dilution ratio is preferred, but it is not clear that new particle formation is dependent on the Dilution Ratio which applies to filter based measurement. The formation of particles is totally dependent on the species concentration and cooling.

For the measurement variability the particle size distribution and the particle number concentration are more susceptible. For particulate matter sampling one can obtain the multitude for distribution of nucleation mode particles by using specialized sampling method, just by making modifications in the conditioning parameters in the limit permitted by reference method. These studies have shown that the dilution ratio, residence time for exhaust gas and temperature at the diluted conditions had main effects on size distribution. The high sensitivity of nucleation mode on these parameters made it possible that when it is specified to narrow limit then there is unexpected growth of the nucleation mode. There are uncertainties itself in Dilution Ratio, especially when it is high and it may increase variability of measurement, even though there is no particular shift takes place in nucleation mode.

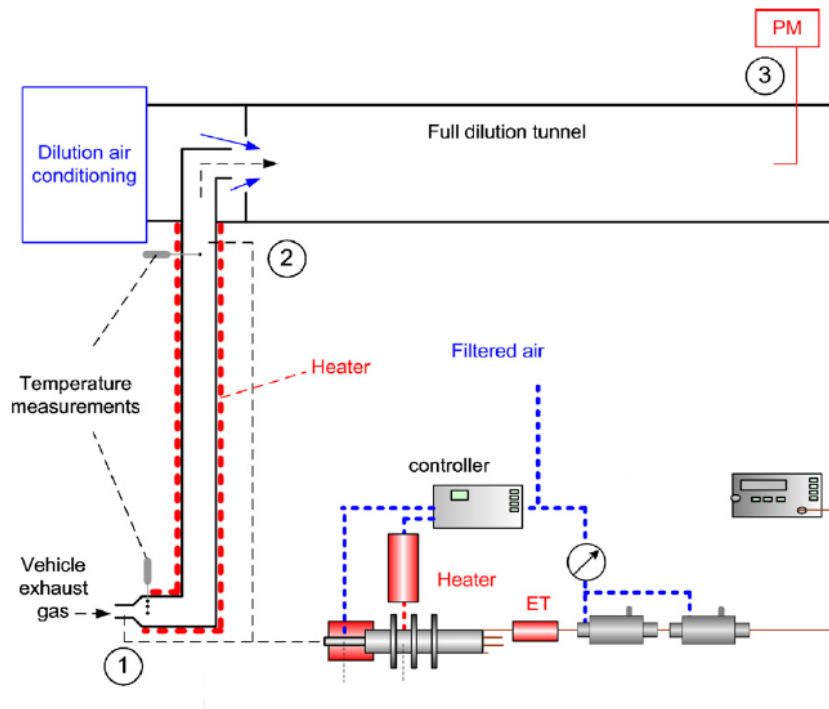


Fig.3 Layout of full dilution tunnel

The drawback of Constant Volume Sampling is the design and condition to the dilution tunnel inlet from the exhaust pipe transfer line can be complex artifact. Hence these artifacts generate by previous test on the transfer line surface of which thermal release of material is stored. During high speed portions and aggressive drive cycles these are more prevalent, where substantially the exhaust temperature increases. Mostly they occur in the portion upstream of the dilution point of the sampling line, where the exhaust gases are not being cooled. The best way to reduce the artifacts is in an appropriate conditioning cycle the transfer lines are kept short and cleaned. When testing of large engines is carried out the Constant Volume Sampling system has to be operated at higher flow rate because it dilutes and samples

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the entire exhaust from the engine. To achieve organic gases background and low particulate matter the latest Constant Volume Sampling system uses the hydrocarbon filters and High Efficiency Particle Air (HEPA). Therefore, Constant Volume Sampling systems are expensive and large in size. Constant Volume Sampling design and operations like - temperature control, residence timing and flow rate characteristics varies with other test facilities. The measurements which are conducted in different laboratories have limitation for reproducibility. Where the dilution is closer to the Constant Volume Sampling or the tail pipe for gasoline vehicles higher differences are expected.

## VI. PARTIAL FLOW DILUTION TUNNEL

The Partial Flow Dilution System is tested for Particulate Matter measurement to overcome the size problem and the expensiveness of the Full Flow Dilution System. These systems were applied for both light duty vehicles and heavy duty engines which was started in early 1980s. For the type approval of the heavy duty engines these system can be used for both transient and steady state cycles. To determine the particulate matter emission rates small amount of sample is diluted from the exhaust in this Partial Flow Dilution System. This system eliminates the large amount of air to be handled for diluting the exhaust gas flow. The main aspect in the system is to maintain the flow proportionality, even though performing the transient tests. To adjust the flow of gas in Partial Flow Dilution System a fast feedback system is required and measurement of total exhaust flow is to be done. From the fuel and air rates it is possible to determine the exhaust flow while performing engine testing applications. For recording the transient exhaust flow rate the ultrasonic exhaust flow meters is to be employed on the chassis dynamometer for light duty applications.

## VII. CONDITIONING SYSTEMS

The engine exhaust gas consist of condensed materials, adsorbed particles, liquid droplets and soot particles. For the regulations the Solid Particle Number (SPN) pertains to solid particles only. Most of the standards and regulations call for the measurement of Particulate matter for both liquid and solid particles, which should be particle diameter of  $< 2.5 \mu\text{m}$ . One of the most challenging task is to determine the partitioning between the particle phases and the gas components of the semi volatile particles. These things are mostly dependant on their vapour pressure, temperature, and pressure of particles concentrations. There are uncertainties in the Particulate matter measurements if the variations in partitioning are done. To improve the repeatability of measurement non volatile substances of particulate matter are focused by some applications. There are mainly three methods which are based on the principles of 1. Evaporation, 2. Adsorption, 3. Oxidation. These methods are mostly used to remove the semi volatile entities.

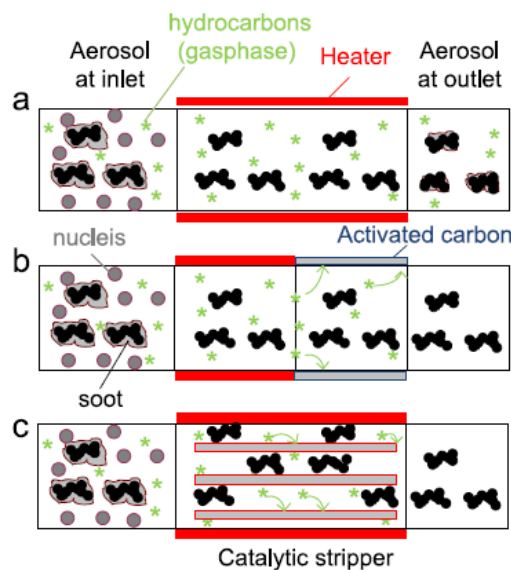


Fig.4 a. Evaporation, b. Adsorption, c. Oxidation.



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## VIII. MATCHING METHODS WITH MEASURING INSTRUMENTS

It is investigated that many aspect of certification, development, engine research and production requires the information regarding particulate matter emissions. There is a need to match the best possible combination of the instruments used in the system design. The considerations for the measurement of exhaust emission of the vehicle and the choice of instruments for the same is as follows:

1. Detection limit: For specific application the suitability of the instruments is determined by concentration detection limit and the size range.
2. Robustness: The system or subsystem of the measuring method should be continued to perform the task even though the existence of failure.
3. Accuracy: The system should be accurate to the accepted reference value which is compared with average value or single value. Systematic error and random errors should be analytically solved with the time reference.
4. Cost: This is very important factor for any system design. The cost for assembling and integrating the instruments should be less. The instrument used for engine testing should be low maintenance.
5. User friendly: The design of system should be easy to use for specific applications.
6. Representativeness: The universally accepted aging condition and real world dilution should be adopted for the measurement of SPN and particulate matter.

These considerations are given importance is dependent on the specific application. For example, the accuracy and representativeness is given more importance for cost effectiveness and type approval of the vehicle. The table below shows the selection criteria for the application of engine testing to type approval for the particulate matter measurement methods. Original detection limit of the manufacturers are listed in the table for the specific instruments. One column is for the real time measurement for the instrument. The next column is for the requirement of the dilution of exhaust gas with instruments. The dilution column also suggests whether to protect the instrument from high temperature or condensation.

## IX. CONCLUSION

The aim of the study was to put together the information describing the sampling system and advanced emission measurement technique that can be used for the low level emissions of today's regulations. The study for the design of emission measurement system is done and various methods and techniques are matched with instruments used in the design. The study also looked parallel in to two main aspects such as sampling system and dilution system for the measurement of particulate matter.

The sampling procedure and dilution procedure are adopting number of configurations with different instruments. For the measurement in steady state cycles it includes full flow dilution for particulate matter and gaseous pollutants both, raw exhaust sampling for gaseous and for particulates partial flow dilution technique. The measurement in transient cycle it includes the partial flow dilution with technical service approval and full flow dilution for both particulate matter emissions and gaseous pollutants. The full flow constant volume system is considered idle for the approval granted to the measurement systems. But in transient cycle the partial flow system is not having detailed specifications for the raw exhaust measurement.

This study has summarized the measurement instruments and sampling system which are available for the measurement of Solid particle Number (SPN) and Particulate matter (PM). The study reviews current methods such as gravimetric test, mobility spectrometers, constant volume sampling and partial flow dilution tunnel. Various instruments were compared with each other and their matching methods in the system. The study gives platform for the researchers to rethink on the new designs for exhaust emission measurement. The study gives enforcement to portable emission measurement system and advanced sampling methods for aerosol measurement from internal combustion engines. The high time resolution measurement is necessary for understanding the particles formation from the combustion engine hence the design reviewed here can be very crucial for such studies. There is a need for more research to be done in this area to identify particularities and problems arising in the measurement system.

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