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DEVELOPMENT AND CHARACTERIZATION OF A CONSTANT VOLUME SAMPLING FOR PM DIESEL ENGINES

ACHY, Acbal Rucas Andrade
SILVA, José Antonio dos Santos da
GONÇALVES, Walter Souza
DEMETINO, Geydison Gonzaga
Jass.mec@gmail.com
acbal.achy@gmail.com
waltersouzafilho@gmail.com
jdemetino@gmail.com

UFBA- Federal University of Bahia, Postgraduate Program in Mechatronics (PPGM/UFBA), Salvador, Brazil

SOARES JUNIOR, Luiz Carlos Simões
PINHEIRO, Vitor Ferreira
simoesc@gmail.com
vitordferreira@gmail.com

UFRB- Federal University of the Reconcavo of Bahia, LEI CETEC, Cruz das Almas, Brazil

REGIS, Ana Carla Dias
acdrigis@gmail.com
UFBA- Federal University of Bahia, LPQ IQ-UFBA, Salvador, Brazil

PEPE, Iuri Muniz
lapo.if@gmail.com
UFBA- Federal University of Bahia, LaPO IF-UFBA, Salvador, Brazil

Abstract. *Particulate matter (PM) emissions from diesel engines cause environmental damage (global warming, acid rain and atmospheric pollution) and damage to human health (cardiopulmonary and respiratory diseases). Mass emissions of PM are determined by the collection, dilution and storage of these particles by constant volume sampling (CVS) in accordance with the current legislation (NBR 14489). In this sense, the main objective of this work is to present the development and characterization of a CVS dilution tunnel for the collection of particles in diesel engines. The developed tunnel was evaluated from PM sampling tests emitted by the discharge of the diesel engine from an eight-cycle test bench with different loads. The collection filters were dried, packed and conditioned in a suitable environment, later weighed in a micro equilibrium analytical model (0.001 mg resolution). The results of the weighing indicated close values in the same load, showing robustness and repeatability of the system and visible difference of color and mass for different loads, showing reliability in the proposed system.*

Keywords: *CVS, Instrumentation, Particulate matter, Diesel engine*

1. INTRODUCTION

The emissions of exhaust gases to the atmosphere due to the combustion of diesel engines causes various damages to the environment and to the human health. During combustion, gaseous compounds such as hydrocarbons (HC) and carbon monoxide (CO), as well as nitrogen oxides (NO_x) and particles are released into the environment (Ferreira, 2013; Mollenhauer and Tschöcke, 2010). According to Park et al. (2012) the components of these gases are responsible for problems such as worsening global warming, acid rain and diseases in the human population.

Geller et al. (2006) argue that particulate matter (PM) has been receiving special attention because it can cause health problems such as cancer, respiratory irritation, respiratory distress, premature death with heart or lung failure. The problems may be associated with the small particle size, with mean aerodynamic diameter in the range of 0.01 to 0.25 μm. Guerreiro (2011) comments that particulate matter can agglomerates at different sites in the human respiratory system

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according to the size of these particles. The so-called large particles, which have an average diameter (d_p) between 2.5 and 10 μm (PM_{2.5} and PM₁₀), are deposited in the head region. Particles with a diameter of less than 2.5 μm (PM_{2.5}), called thin particles, are inhaled in the thoracic region (pulmonary airways or tracheobronchial region), in addition to the larynx. According to OMS (2014) data, several cities in Brazil have high emission levels of PM_{2.5}.

Particulate matter is defined as any material collected in the filters of the sampling system after the dilution of the crude exhaust gas from the engine with clean and filtered air at a temperature below 52° C (NBR 14489, 2000). The PM is formed in the combustion chamber from condensed hydrocarbons from the gas phase and they are housed in regions with low oxygen availability, in a very rich nucleus in the fuel spray (Martins, 2013).

The collection and analysis of PM is carried out by means of a constant volume sampling (CVS) tunnel, according to the recommendations of the NBR-ABNT standards. The main function of this tunnel is to prevent condensation of the water in the collection system. The CVS tunnels can be classified into total flow dilution system and partial flow dilution system. In the total flow dilution system, the PM emission mass is determined from the total flow of the dilution air and the exhaust gas, whereas in the partial flow dilution system, the analysis is done from the partial flow of dilution air and exhaust gases (NBR 14489, 2000; Giechaskiel et al., 2014).

In this context, the objective of this work is to present the development and characterization of a partial dilution CVS for the collection of PM emitted by diesel engine discharges. Emission data collected can be used for researches on air quality and fuel quality.

2. MATERIALS AND METHODS

2.1. The Constant Volume Sampling (CVS) development and assembling

The particle dilution tunnel prototype for particulate material collection was designed, developed and assembled at the Energy and Instrumentation Laboratory of UFRB in order to meet the minimum requirements described in the recommendations of Brazilian MP Sampling standards, with low cost mechanical and electronic components that make up the system. For that, most of the electromechanical pieces were reused from other equipment. The system was separated into three main parts, the first one is the exhaust gas partial collection module, the second is the pure air dilution module and the last is the diluted gases collection module.

The exhaust gas partial collection module is composed of a flow control valve (1) installed in the discharge pipe of the testing engine, a collection tube (2) where an orifice plate flow sensor (3) and a temperature sensor (4) have been installed, the Fig. 1 shows an image of this module for better visualization. The knowledge of the gas flow was given by the interactive consultation to an off-line calibration table.

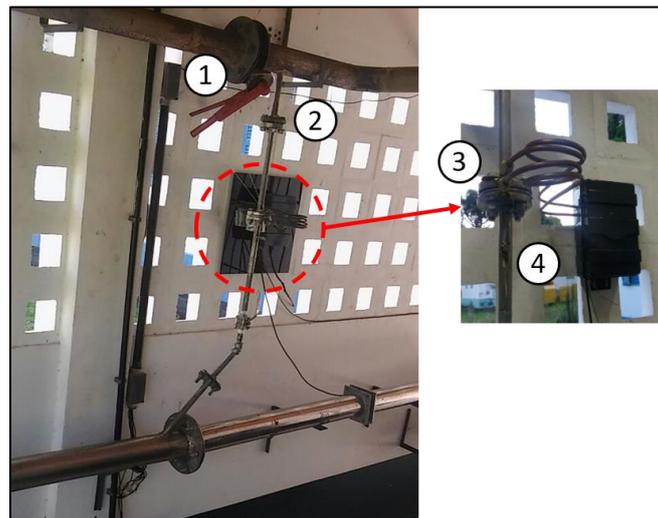


Figure 1. Images of the module for partial collection of exhausted gases.

The pure air dilution module is responsible for conditioning, treating and controlling the flow of fresh air used to dilute exhaust gases, it is composed by a frequency inverter, an axial fan, a filter folder and a flow sensor. The frequency inverter (5) controls the axial fan (6) which draws air from a filter holder (7). In this filter holder, there are three air filters, the first one for coarse particles, the second for thin particles and the last one is an absolute HEPA filter, with the capacity to remove up to 99.3% of air impurities. The flow of fresh air is measured by a turbine type flow sensor (8) installed in the fresh air line, the Fig. 2 shows the dilution air conditioning and control module.



Figure 2. Images of the module for partial collection of exhausted gases.

The last module of the CVS prototype is the dilute gas collection module, this subsystem is composed of a diluted gas outlet (9), a 47mm filter holder (10), a flow regulator rotameter type (11) and a vacuum pump (12). Part of the diluted gas that passes through the tunnel is collected by the vacuum pump with constant flow regulated by the flowmeter, through the microfilter that has the function of barring the microparticles of the diluted gas for further analysis, the Fig. 3 shows the MP collection module diluted by the particle dilution tunnel.

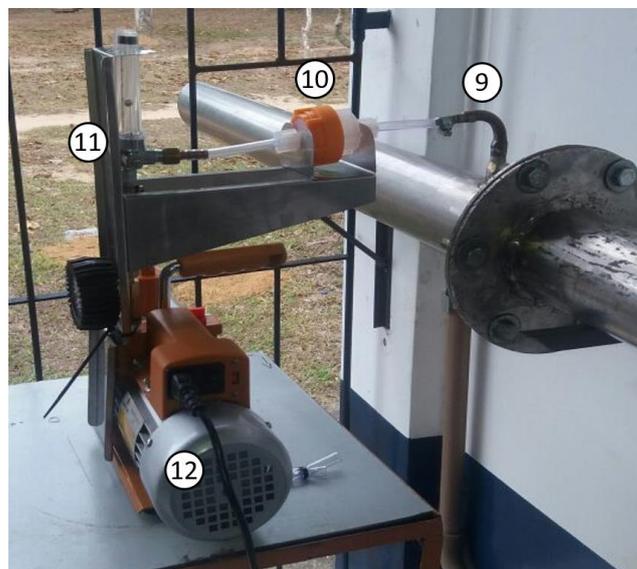


Figure 3. Image of the MP collection module.

The final prototype dimension is 4 meters long, the CVS was constructed by four 1-meter pieces with flange interconnector in order to make it portable, enabling them to be transported for PM sample and analysis of others internal compression (IC) engines.

2.2. Instrumentation

The dilution ratio is determined by means of two flowmeters that measure the exhausted gases and pure airflow. The exhausted gases flow sensor was an orifice plate type and the pure airflow sensor was a turbine-type.

The developed orifice plate sensor uses an orifice of 7.00 mm and was installed in a 16.80 mm nominal diameter pipe. The pressure difference is measured by a Motorola differential pressure sensor model MPX 5010DP. Since temperature directly influences the gas characteristics, a PT-100 temperature sensor was installed right after the pressure take-off.

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The calculation of exhaust gas flow is not a simple task, since it requires a series of previous knowledge about the typical composition of the exhaust gases, the portion of each gas type obtained by means of the combustion equation and the specific mass of each gas component. Starting from the Bernoulli equation and the continuity equation, the eq. 1 is obtained, it relates the volumetric flow rate, Q_v (m³/s) with the pressure difference in the flange taps.

$$Q_v = 1,1107CE\beta^2D^2\varepsilon\sqrt{\frac{\rho_1\Delta P}{\rho}} \quad (1)$$

The factor β is the ratio of the flange diameters (D) and the obstruction (d) given by eq. (2). The C is the discharge coefficient (dimensionless) introduced in the Bernoulli equation to correct the approximation problems due to friction, obtained by expression (3); E is the velocity factor of approximation, obtained by eq. (4)

$$\beta = \frac{d}{D} \quad (2)$$

$$C = 0,5959 + 0,0312\beta^{2,1} + 0,1840\beta^8 + 0,0029\beta^{2,5} \left(\frac{10^6}{Re_D}\right)^{0,75} \quad (3)$$

$$E = \frac{1}{\sqrt{1 - \beta^4}} \quad (4)$$

The term ε , called the "isentropic expansion factor", was included in eq. 1 because Bernoulli's equation deals only with incompressible fluids and in this case the operating fluid is compressible. This term is calculated by eq. (5) and is applied in cases of gas and vapor flow measurement with orifice plate-type sensors for pressure take-offs on the flange taps, corner flange taps and pipe taps (Delmée, 2003; Fraden, 2010).

$$\varepsilon = 1 - (0,41 + 0,35\beta^4) \frac{\Delta P}{kP_1} \quad (5)$$

The pure airflow was measured by a turbine-type sensor, built by a set of freely rotating propellers when airflows. A set of LED's is used as light source that illuminates a photodiode aligned with the propellers blades, when these propeller blades turns, the light beam is interrupted, the photodiode stops receiving light and its output voltage goes zero, otherwise it is one. The variation of the passage of the propellers on the LED beam can be correlated with the flow pure air.

The turbine flow sensor calibration is a function of density and viscosity of the working fluid, besides the rotor (turbine) diameter and the angular frequency of the rotor (Francis, 2006), eq. 6 relates these parameters:

$$\left(\frac{Q}{fD^3}\right) = K \left(\frac{\rho f D^2}{\mu}\right) \quad (6)$$

Where Q is the flow rate of airflow in (m³/s); f is the frequency of the set of helices, ρ is the density of the fluid; D is the diameter of the vanes and μ is the viscosity of the fluid. The pure air was admitted from the atmosphere at room temperature and duly filtered.

A digital thermometer was installed nearby the particulate matter collection point to monitor temperature in the CVS, Tab. 1 presents information about the sensors and equipment used in the collection system.

Table1. Characteristics of the sensors and instruments used in the collection system.

Sensor/Instrument	Property Measures	Characteristics
Differential Pressure by Orifice Plate	exhaust gas flow	0 to 10 Kpa 0,2 to 4,7 V Output
Turbine	Pure air Flow	0 to 600 Hz
PT-100	Temperature of gases after flowmeter type orifice plate	Model: Minipa MT-455 Temperature range: -200°C ~ 1372°C Precision: -60°C ~ 1372°C ± (0.1%+1.0°C)

Digital thermometer	Temperature at the collection point of the CVS Tunnel	Model: Minipa MT-455 Temperature range: -200°C ~ 1372°C Precision: -60°C ~ 1372°C ± (0.1%+1.0°C)
oscilloscope	Monitor sensor input and output data	-

In order to keep the dilution ratio constant and the same in all tests, regardless of the applied torque and according to current norm, the input and output data were constantly monitored by an oscilloscope and a digital thermometer. These provided data for an iterative calibration table developed in the Microsoft Excel computer program, the Fig. 5 shows the table used to follow the tests.

INPUT DATA		OUTPUT DATA	
TEMPERATURE [°C]	190	VAZÃO DOS GASES [m3/h]	8,36
VOLTAGE [V _{ms}]	1,90	SETPOINT OF PURE AIR [m3/h]	125,4
DILUTION RATIO	1/15	SENSOR'S FREQUENCY [Hz]	389

TABELA DE CONSTANTES		TABELA DE VARIÁVEIS	
Beta constant	0,416666667	ΔP [Pa]	3647
E Constant	1,015419874	VELOCITY [m/s]	11,58
K Constant	1,4	N° DE REYNOLDS	1622,092343
TUBE'S DIAMETER [m]	0,0168	Massa específica corrigida com a temperatura [Kg/m ³]	0,832
SPECIFIC MASS [Kg/m ³]	0,850193051	COEFICIENTE DE DESCARGA	0,641237847
VISCITY [pa.s]	9,97503E-05	EXPANSION FACTOR	0,989563589
		WORK'S TEMPERATURE [K]	463,15

Figure 5. Dynamic table for fresh airflow adjustment as a function of the exhaust gas flow and its temperature.

2.3. Setup Experimental

The CVS characterization was performed by means of sample tests of a Diesel Engine (Maxxforce 229.4 MWM®) coupled to a Foucault dynamometer. The developed CVS is partial dilution type. The particle samples were evaluated by the gravimetric method, weighing the filters before and after test. The filters used in the collection are fiberglass type with pore size of 0.7 μm and 47 mm. A vacuum pump was used to extract a fraction of the diluted gases. The flow rate of the extraction pump was adjusted by a rotameter.

The Fig. 6 shows a flowchart of the system used to collect the particulate material, in the engine (1) during combustion there is formation of regions with particles created by the incomplete burning of the fuel that agglomerates forming larger particles (soot) in the exhaust pipe (2). A portion of these exhausted gases, restricted by the exhaust valve (3), is picked up by a stainless tube (4) which leads to the CVS, a blocking valve (5). In this tube was installed a orifice plate flow sensor (6) and a temperature sensor (7).

In the CVS (8) the fraction of exhaust gas collected is diluted with fresh air, simulating a PM capture process from the most persistent composites in the ambient air emitted by the diesel engine exhaust system. Finally, a vacuum pump (9) forces the passage of a fraction of the mixture in the CVS through a filter holder (10) capturing the MP that will later be weighed. The collection flow is regulated by a proportional valve control valve (11).

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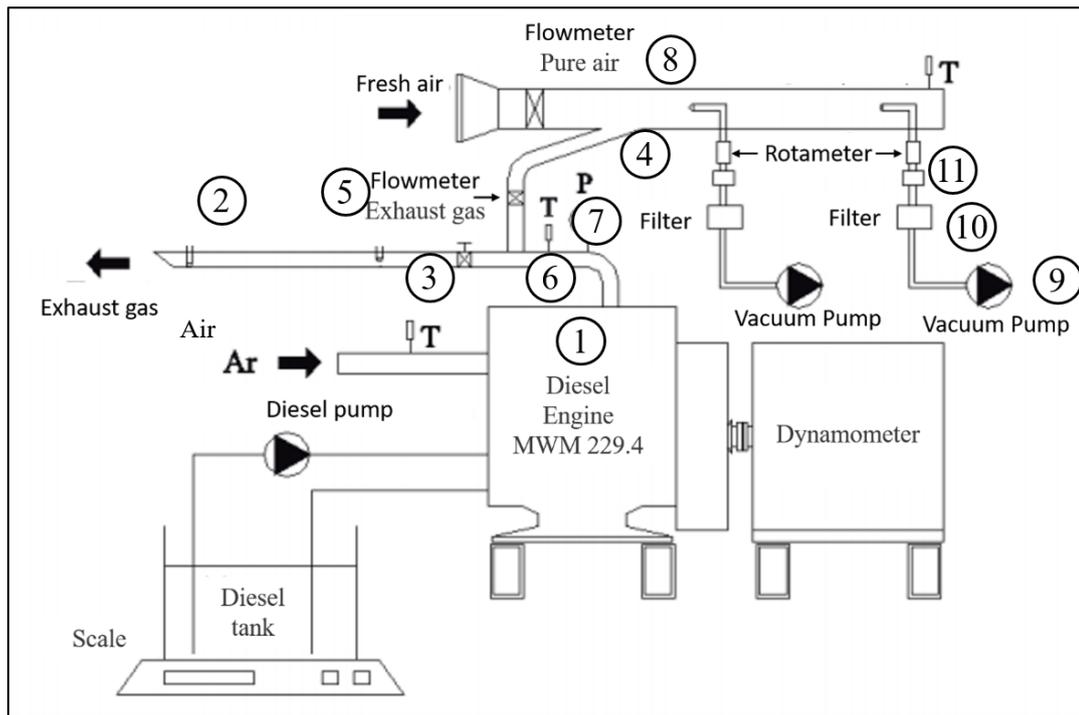


Figure 6: Flowchart of the particulate matter collection system using the CVS tunnel.

2.4. Collection tests

The experimental procedure starts with the CVS cleaning for removal of all soot deposited on the pipe wall. After that, the system was turned on for one hour with fresh air to collect the zero reference sample (Δ_{biasn1} , Δ_{biasn2} , ... Δ_{biasnN}). Once collected the blank samples, its weight difference was measured ($\# \Delta_{n1}$, $\# \Delta_{n2}$... $\# \Delta_{nN}$). The motor was turned on to warm up for 15 minutes, during this time the bypass valve remain closed. The motor speed was configured to 1800 RPM and two load conditions was studied, 120 Nm and 185 Nm. Eight test cycles were performed, four of them with a torque of 120Nm with collection time of 90 minutes and four with load of 185Nm with a duration of 45 minutes per test.

The collection rate in the vacuum pump was 10 L/min, the dilution rate used was a fraction of exhausted gas for 15 fractions of pure air (1:15), value regulated by the exhaust gas flows and fresh air.

2.5. Sample filters preparation

The PM collection filters were dried in an oven for two hours at 120°C, then placed inside a desiccator for one hour in order to remove the remaining moisture. They were packed and conditioned in a silica gel environment until the pre-weighing procedure. The filters were then loaded for MP collection and the filters, now impregnated, were again weighed. The weighings were performed in an analytical model of micro-balance (0.001mg resolution) model MX-5, manufactured by Toledo (see Fig. 7). Masses measurement of clean and impregnated PM filters were performed at 24 ± 2 °C and relative humidity of 45 ± 2 %.



Figure 7: analytical micro balance used in the weighing process of PM.

3. RESULTS AND DISCUSSION

3.1. CVS sensors and actuators calibration

The turbine-type sensor calibration was done using an anemometer installed at the end of the first tubular section of the CVS, as shown in the diagram of the Fig. 8. The calibration procedure was to vary the frequency of the frequency inverter from 20 to 70 Hz by steps of 5 Hz, collect turbine propellers speed and correlate it with air velocity measured by the anemometer. The Fig. 9a shows the relation between turbine flow and frequency and Fig. 9b shows the relation between the frequency imposed by the frequency inverter and the measured airflow by the anemometer, the linear relationship is observed in both cases.

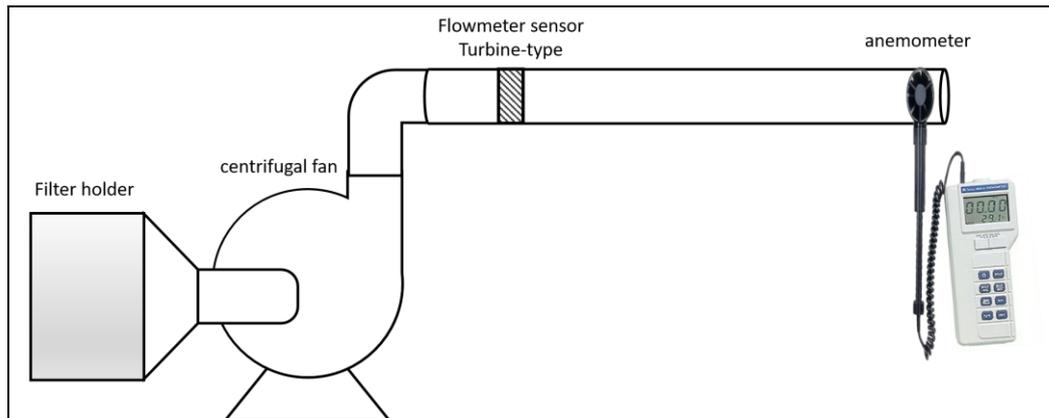


Figure 8. Calibration diagram of the pure air flow sensor.

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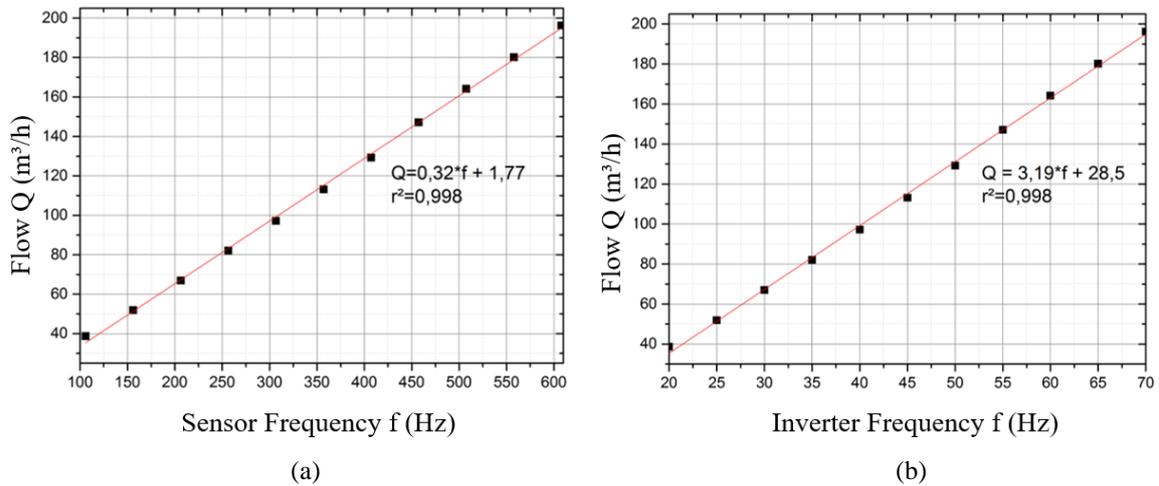


Figure 9. Sensor calibration curve airflow in (a) and inverter frequency and airflow in (b).

The exhaust gas flow sensor calibration was performed in two different steps. The first step provided the relationship between pressure difference and output voltage. The pressure sensor was installed in the bottom of a graduated one-meter pipe filled every 10 centimeters of water column, the sensor output voltage was recorded, according to the graph of the Fig. 10 (a). The second calibration step was to impose a controlled and variable flow rate on the orifice plate sensor and record the pressure sensor output voltage values (graph of Fig. 10 (b)), these calibrations were performed with air at room temperature (30 °C) and humidity at 65%. For the final exhaust gas flow determination, eq. 1 was used to adjust the calculation taking into account the system temperature variations.

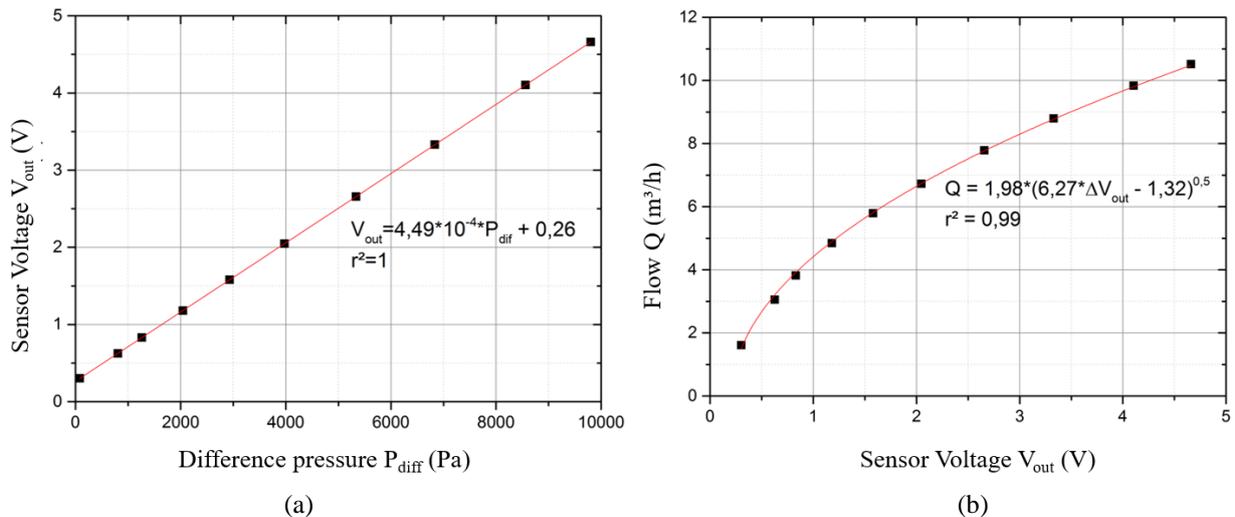


Figure 10. (a) Calibration of the output voltage in relation to the differential pressure of the sensor and in (b) the flow in relation to the output voltage of the flow sensor per orifice plate.

The curve describing the relationship between the voltage difference (Δv) and the air flow (Q) in the volumetric flow sensor (Fig. 10 (b)) must be corrected by calibration to meet the ambient conditions of each test, the best fit is $Q(\Delta v_{out}) = A\sqrt{B\Delta v_{out} + C}$. During the CVS particulate sampling tests, the coefficients A, B and C are adjusted using the correction table shown in figure 5 according to the operating temperature, this is necessary since temperature variation changes gas density, Reynolds number and gas expansion coefficient that could implies in false measurements.

3.2. Results of particulate collection tests

In order to validate the developed equipment two different torques were chosen, one at 120 Nm and the other at 185 Nm for the same rotation speed (1800 RPM) to carry out PM collection campaign, using the diesel engine and the dynamometric bench. According to Yao et al (2007); Surawski et al. 2009 and Zhang et al. 2009, total particulate matter tends to increase with increasing load on the motor shaft for the same rotation and the same type of fuel because a larger

load requires a higher fuel consumption which generates larger PM product (g/kWh), on the other hand the same tends to decrease because at high loads the diesel engine is more efficient.

All three continuous and sequential collections were performed for the rotation torque x load, at similar climatic characteristics. The final compilation of the particulate material collections of the zero reference samples and for filters masses measurements are presented in Tab. 2.

Table 2. Compilation of the collection tests performed

Result for 1800@120Nm		Result for 1800@185Nm	
Sample n1 (g)	0.000701	Sample n1' (g)	0.000514
Sample n2 (g)	0.000776	Sample n2' (g)	0.000479
Sample n3 (g)	0.000745	Sample n3' (g)	0.000463
Méd (\bar{a})	0.000741	Méd (\bar{a})	0.000485
DesvPad (S)	0.000031	DesvPad (S)	0.000021
Variance (S^2)	9.5385E-10	Variance (S^2)	4.4862E-10
CoefVar (C_v)	4.2%	CoefVar (C_v)	4.4%
ErroPad (ϵ)	0.0000178	ErroPad (ϵ)	0.0000122
MP (mg/h)	0.423	MP (mg/h)	0.647
Sampler period (h)	1.75	Sampler period (h)	0.75
Error	5.4%	Error	5.9%

Tab. 2 shows low standard deviation for PM produced at 120Nm (0.000031 g) and 185Nm (0.000021 g) loads, as well as low variance (respectively 9.5385E-10 g² and 4.4862E-10 g²) and low PM coefficient of variation (4.2% -4.4%). The global measurement error was lower than 10% (5.4% - 5.9%), these values shows low measurement variability, which demonstrates the robustness of the built system. In addition, the weighing results showed close values for the same load, this indicates that the tunnel constructed has good repeatability.

4. CONCLUSIONS

This work presents the description of a transportable system for particulate matter collection and analysis of internal combustion engines. The system allows comparative evaluation of particulates emission for different levels of loads in the motor axis at different rotations for different fuel types.

The developed partial flow constant volume particle collection tunnel has low cost when compared with the commercial systems for the same purpose.

The validation of the CVS prototype was done first by sensors and actuators calibration and then its fully evaluation was obtained through a test campaign choosing a fixed speed and two different loads after six PM collections.

The tests were based on weighing strategy and the results indicated that the system has good repeatability, different samples collected at same test conditions showing similar results within 10% precision. In tests with different loads the PM samples had different weights. The analysis of the weighings showed low values dispersion, ensuring the equipment is trustworthy and suitable for its purpose.

5. ACKNOWLEDGEMENTS

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