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Methodology for instantaneous average exhaust gas mass flow rate measurement

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ABSTRACT

This paper presents a new methodology for measurement of the instantaneous average exhaust mass flow rate in reciprocating internal combustion engines to be used to determinate real driving emissions on light duty vehicles, as part of a Portable Emission Measurement System (PEMS). Firstly a flow meter, named MIVECO flow meter, was designed based on a Pitot tube adapted to exhaust gases which are characterized by moisture and particle content, rapid changes in flow rate and chemical composition, pulsating and reverse flow at very low engine speed. Then, an off-line methodology was developed to calculate the instantaneous average flow, considering the "square root error" phenomenon. The paper includes the theoretical fundamentals, the developed flow meter specifications, the calibration tests, the description of the proposed off-line methodology and the results of the validation test carried out in a chassis dynamometer, where the validity of the mass flow meter and the methodology developed are demonstrated.

1. Introduction

Accurate measurement of the instantaneous average exhaust gas mass flow rate is necessary when motor vehicle mass emissions and fuel consumption factor are to be measured in real life [32]. The exhaust mass flow rate as well as the concentration of the gaseous pollutants (CO, HC, NO_x, etc.) emitted by an internal combustion engine are continuously changing as the torque and rotational speed of the engine changes due to the variability of the vehicle speed, road slope, acceleration, etc. [10,32].

The exhaust gas mass flow rate from reciprocating internal combustion engines has some characteristics that avoid the use of a conventional gas flow meters for its direct measurement, such as high concentration of condensable water vapour, particulate matter content, changes in the chemical composition and pulsating flow including reverse flow at very low engine speeds [13],[26,34,35,41].

For those reasons, most pollutant emissions measurement procedures used in standardized type approval tests are based in constant volume flow rate, either by using constant engine operating conditions or constant flow sampling techniques, such as the CVS (Constant Volume Sampling) testing procedures prescribed in worldwide accepted emission regulations. Also, in these testing procedures, the exhaust gases are diluted with fresh air to avoid water condensation, soot particles deposition and to damper flow pulsation [23,36,41,43]. Such CVS systems along with chassis dynamometer in the case of light duty vehicles and engine test bench in the case of heavy duty engines, can only measure the total amount of emissions in terms of mass emitted throughout the test [38]. The advantages are its easy implementation and that the repeatability is good enough, but they cannot give information about the time resolved influence of the different factors and they cannot conduct a modal analysis of pollutant formation in the real transient conditions of the engine. In some of these techniques, exhaust gas flow could be measured in real time in stationary engine test benches or chassis dynamometers, but it is not possible to use in on-board applications due to its size and heavy weight [36,41].

In the last 15 years different flow meters have been developed for direct exhaust gas flow measurement, such as ultrasonic, turbine, vortex type, and differential pressure flow meters [8,20–22,29,34–37,42]. Ultrasonic flow meters, are among the most effective to flow measure even if pulsating or backflow is present [29], but have some disadvantages because they are affected by the temperature, density and viscosity of the fluid [35,37]. Different techniques have been developed to overcome these problems like the work developed at the University of Leoben [16][17,18]

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and the flow meter developed by AVL [3,19].

Other flow metering devices such as turbine and vortex type flow meters have problems when dealing with pulsating flow [20], [21] because of the inertial effects and when used with high temperature gases [35]. Other flow meters such as those based on hot wire or hot plate anemometry are seriously affected by the deposition of particulate matter when exhaust gases are to be measured [20,35,39].

On the other hand, differential pressure flow meters, such as orifice plates, nozzles, venturi tubes, laminar flow elements or Pitot tubes, are currently the most widely used for on-board exhaust gas measurement because of its simplicity [25][28,29]. Differential pressure flow meters are based on the measurement of the pressure drop across a pipe restriction which is related to the flow speed by Bernoulli's equation, being this relation not a linear function [20] causing what is known as the mechanism of the “square root error” [29]. Therefore, the average volume flow rate is not represented by average differential pressure, so the average results obtained with these types of gas flow meters are seriously affected by the pulsation of the flow that causes huge errors [36]. The first differential pressure flow meter used successfully to measure exhaust gas flow in on-board testing conditions was the Annubar flow meter, recommended by the EPA, which is a multiport averaging Pitot type tube sensor [5,35]. Other differential pressure gas flow meters with different configurations have been developed for measuring the flow of recirculated exhaust gases in engines equipped with EGR such as the ones developed by Henderson et al. [12] and Colvin et al. [6].

Currently instrumentation technology and methods to measure exhaust gas mass flow, emission factors and consumption factors in real use (on-board) are considered mature [33]. Most of the commercially available Portable Emission Measurement Systems (PEMS) use Pitot type flow meters to measure instantaneous average exhaust gas flow in conjunction with electronic signal post-processing, because they are able to measure high-temperature fluids and are more effective in size and cost than other devices [4,25,28,31]. However, the precise measurement of the average mass flow rate of exhaust gases from an engine with a Pitot tube is a complex process in which it is necessary:

- to prevent clogging by moisture or particles through a suitable design of the sensing tube,
- to have a differential pressure sensor with high performance which is able to measure negative values,
- to synchronously measure the exhaust gases temperature and absolute pressure,
- to design a methodology,
- to have a powerful data logger and computation systems that allows the calculation of the average mass flow rate in real time, such as the Pitot type exhaust mass flow meter patented by Nakamura et al. [28].

In a Pitot type exhaust gas flow meter, the most expensive instrument is the differential pressure sensor because it needs high sensitivity, low reaction time, low hysteresis, low influence effects, low thermal errors, automatic zero adjustment and long term stability. It is due to the fact that in a Pitot-type flow meter the volume flow rate depends on the square root of the differential pressure; so small zero setting errors in the differential pressure measure, overcome in significant errors in the calculated volume flow rate. In addition, the measurement accuracy at very low flow rate strongly influences the calculation of the emissions and the fuel consumption factors in real urban traffic, where significant periods of time with the engine at idle are frequent [10].

Given the above, a Pitot-type flow meter and off-line methodology for measuring instantaneous average exhaust gas mass flow developed by the authors, are presented in this paper. The main advantage of the developed mass flow meter is that it uses standard specifications instruments and conventional data acquisition, processing and storage systems. The paper includes the theoretical fundamentals of the mass flow rate calculations and the specifications of the developed flow meter. The calibration procedures and tests results are also presented and discussed. The computation methodology for the instantaneous average flow measurement, designed especially when pulsating flow appears at very low engine speeds, is based on the fact that differential pressure waves can be approximated to a sine wave with a frequency equal to twice the engine speed for a four-stroke 4-cylinder engine.

2. Theoretical approach

2.1. Pulsating exhaust flow

Pulsating flow is a specific type of unsteady flow, where a more or less regular cyclic variation in flow velocity is superimposed on a constant time-averaged volume flow rate [27]. In an internal combustion engine, pulsating flow is due to the cyclic discharge of combustion gases through the exhaust valve that have a sequential lift movement. Two pressure waves are generated by the exhaust flow process: the first one, much more intense, is caused by the sudden opening of the exhaust valves during the blowdown period that creates a choked flow, the second one, less intense, occurs when the pistons move upward through the exhaust stroke. In addition, a small quantity of backflow of exhaust gas into the cylinder might occur during overlap periods and is largest at the lowest engine speeds and in Otto engines at part load.

The exhaust stroke pours a certain amount of gas in the exhaust pipe creating a flow wave that travels along the exhaust pipe to the open end, which is dampened by the fluid friction. The beginning of the exhaust valve opening creates also a shock wave that travels at a higher velocity to the exhaust tail pipe end. The pressure rise of the exhaust shock wave and the flow pulse depends on cylinder pressure at the end of the expansion stroke of the engine, which is a function of the engine type (Otto or diesel), the engine speed, the engine load and other engine designs and calibration parameters. The pressure waves propagate at a velocity slightly higher than the local speed of sound, through the entire exhaust system: exhaust manifold and pipes, catalytic converter and a muffler or silencer. Due to wave propagation phenomena, geometrical configuration of the exhaust system and frictional losses, pressure waves suffer reflection, refraction and attenuation and also interact with other waves in multi-cylinder engines [2] and reach the exhaust tail pipe end significantly dampened. The primary frequency of such pressure waves match up to the frequency of the exhaust processes of individual cylinders [14].

This means that the exhaust gas flow has a stationary component that varies with operating conditions changes of the engine and an oscillating higher frequency component that corresponds to the pressure wave described above. Then, for the instantaneous emission factors calculation of engines in real use, it is necessary to know the instantaneous averaged exhaust gas volume flow rate, obviating the oscillatory component that does not provide useful information. It has a higher frequency than load and speed changes of the engine. Therefore, although the volume flow rate of exhaust gas is a pulsating flow, for studies of emissions and consumption of an internal combustion engine, the average volume flow rate is of interest and has the advantage that it can be considered as a quasi – steady variable.

The average component of the exhaust flow (mass flow rate $\dot{m}_E$) for a four-stroke engine can be calculated as shown in Eq. (1). The