

Influence of Exhaust Gas Composition on Measured Total and Exhaust Flow Using a CVS with Critical Flow Venturi and Smooth Approach Orifice

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ABSTRACT

The Constant Volume Sampler (CVS) is often used to dilute automotive exhaust with ambient air for measurement of emissions from light duty vehicles. A CVS is traditionally equipped with Critical Flow Venturi (CFV) to control and measure total flow. If the CVS is equipped with a Smooth Approach Orifice (SAO) to measure dilution air flow, the exhaust flow of the vehicle can be calculated as the difference between dilution and total flow. Calibration of the CVS and SAO is routinely done using ambient air, but carbon dioxide (CO₂) and water vapor in diluted exhaust have an influence on the flow through the CFV. In current US emission legislation the provisions to include water vapor is added. However, if this is done then the effect of carbon dioxide (CO₂) in exhaust has not been considered. Further on, when using the CVS to measure exhaust flow, only the CFV will be affected by the diluted exhaust gas composition. The measurement of dilution air will still be unaffected and thus will the resulting exhaust flow be influenced by the unbalanced conditions of the CFV compared to the SAO. Even though the effect of gas composition on flow may be small for the CFV, the influence will be much larger on measured exhaust flow since this is calculated from the difference of two large flows. This paper presents how measurements on exhaust flow are influenced by diluted exhaust gas with different composition. The results are then compared with theoretical studies, and differences are discussed.

CITATION: Berg, O. and Simonson, L., "Influence of Exhaust Gas Composition on Measured Total and Exhaust Flow Using a CVS with Critical Flow Venturi and Smooth Approach Orifice," *SAE Int. J. Engines* 10(4):2017, doi:10.4271/2017-01-0995.

INTRODUCTION

The CVS have been used since the 60's to dilute exhaust using ambient air for measurement of gaseous emissions from light duty vehicles and trucks. The addition of a particle tunnel made it possible to also measure particle mass. Through the years, several enhancements have been made to the system like the possibility to use Proportional Ambient Sampling [1] and Bag Mini-Diluter [2,3]. There have also been development of special provisions for testing of hybrid and plug-in hybrid vehicles where the total exhaust is much less and comes intermittent compared to conventional vehicles [4]. There are today several legal descriptions of the CVS, most notable are for the US, the Code of Federal Regulation (CFR) title 40 part 1066 and for other countries, the UNECE Regulation 83 which is being replaced by GTR15 (World Light Test Procedure).

However, considering the total use of a typical OEM emission test cell, the number of dedicated certification tests according to strict legal requirements, are often low. Even though these test are very much in focus, the majority number of tests are run for development purposes to reach legal emissions levels. During development, not only absolute levels are of importance but also when and how much emissions are released from the vehicle while running the drive cycle. This can be done either by recording the second-by-second diluted emissions or by measuring the exhaust flow and instantaneous undiluted exhaust. Integrating diluted emissions has two general drawbacks, which are the longer time response and lack of detailed

resolution. The other method rely on exhaust flow measurement, which traditionally has been difficult due to high temperature and pulsations. However, today there are the possibility to use direct exhaust flow meters which typically use ultrasonic sensors, or as described here, a mounted SAO to measure the dilution flow of the CVS and then calculate the exhaust flow by the subtraction of dilution flow from total flow. This method also need some technique to time align the measurement of emissions using different types of analyzers and the total exhaust flow. Work have been done to enhance time alignment even further by modelling transport times, mixing and diffusion within the exhaust pipe e.g. [5]. This paper shows that when using a SAO and CFV method, the CFV is also affected by the composition of the diluted exhaust and thus influencing the measurement of exhaust flow.

THEORETICAL DESCRIPTION OF CRITICAL FLOW VENTURI AND EXHAUST FLOW MEASUREMENTS

The calibration of the critical flow venturi of a given diameter is traditionally done by measuring the flow of ambient air through the venturi using a reference SAO or Laminar Flow Element while increasing the pressure ratio across the venturi. At a certain point, typically at a pressure ratio of around 0.93, will the flow decrease and thus deviate from the constant flow at lower pressure ratios. This is the point where the venturi no longer is running critical and this point

is often called the ‘knee’. The calibration coefficient C1 is then calculated from the mean volume flow rate (Q_{cal}) when running critical using the simplified formula:

$$C1 = Q_{cal} \cdot \frac{\sqrt{T_k}}{P_{abs}} \quad (1)$$

Where P_{abs} is the absolute pressure before the venturi and T_k the temperature. The flow at these conditions is then only dependent on the pressure and temperature of the gas prior to the venturi and thus assuming air as reference for density, heat capacity etc. However, in this simplified view where C1 is a constant, several aspects have been neglected of which the most important is the speed of sound and how that changes with gas composition. As a gasoline vehicle follows the drive trace during an emission test the exhaust flow will be high during accelerations and steady-state driving while being low during idle and decelerations or even going down to zero during engine shutoff (start/stop). As the total diluted flow is always constant in the CVS, the concentration of exhaust will vary during the test with high concentration at high exhaust flow. This variation of exhaust concentration will affect the flow going through the venturi. The main effects comes from varying concentration of water and CO_2 . For instance in figure 1, we can see how measured exhaust flow is changing while driving the FTP75 drive cycle:

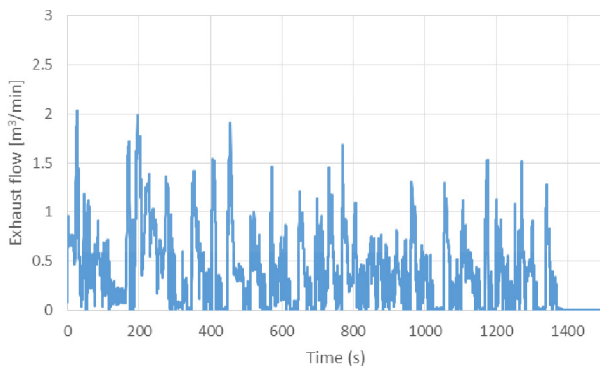


Figure 1. Measured exhaust volume flow rate during an FTP75.

However, the reported volume flow (Q) from the CVS is only calculated with the formula:

$$Q = C1 \cdot \frac{P_{abs}}{\sqrt{T_k}} \quad (2)$$

It does not compensate for anything other than changes in pressure and temperature while the conditions from the original calibration is included in the C1 factor. In general the above mentioned flow influences on the venturi are small, typically < 0.5% and thus its' influence on legislative bag measurements is also small.

If the CVS also is equipped with an SAO to measure dilution air, the exhaust flow can be calculated by subtracting dilution air from total flow. To compensate for any differences between the SAO and the venturi and to make this measurement more accurate, since it is a subtraction of two large numbers, a flow calibration is done prior to each test by adjusting the SAO to the CFV flow. This is often done by

a gain constant. This calibration is using air only. The difference between the SAO and the CFV for these kind of calibrations are typically below 1%. However, as the vehicle is running and the conditions of the diluted exhaust through CFV are changing, the actual flow through the CFV will deviate from the flow as calculated by the simplified formula above. The SAO, on the other hand, remains unaffected as only air pass through it but it will in reality measure the actual flow of the CFV minus the exhaust flow rate. This means that the calculated exhaust flow rate while running an emission test will have an error dependent on the difference in flow between the CFV having air going through it or diluted exhaust. For example, at a total constant exhaust flow where the CO_2 concentration is shifting, the CVS measured exhaust flow will also shift.

The classical way to calculate mass flow through a critical venturi is done by the equation 3.

$$m = C_d A \sqrt{k \rho P \left(\frac{2}{k+1} \right)^{\frac{k+1}{k-1}}} \quad (3)$$

Where:

m : mass flow rate

C_d : discharge coefficient

A : area of the hole

k : heat capacity ratio $k = c_p/c_v$

ρ : gas density before venturi

P : absolute pressure

In these calculations, density was calculated using the formula for ideal gases, except for CO_2 for which the density was increased by 0.45% due to its' non-ideal behavior. On a typical total CVS volume flow of 9 m³/min, the influence of different gas composition on the venturi can be calculated using the above formula by first calculating the total mixture density and specific heat ratio before using equation 3.

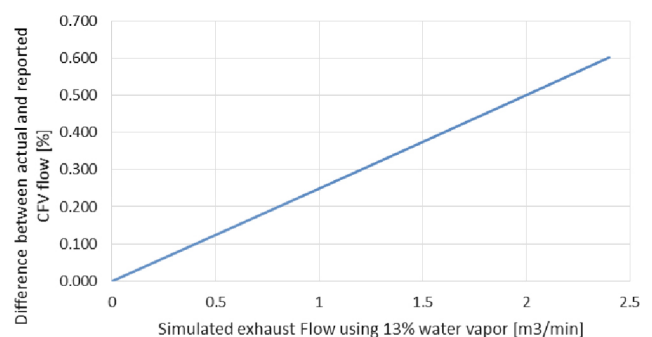


Figure 2. Calculation of venturi flow for different simulated exhaust flow rates with water vapor only.