

Investigation of Ultrasonic Flow Measurement for CVS Dilution Air Volume

Tim Nevius and Dario Rauker
Horiba Instruments Inc.

Masanobu Akita and Yoshinori Otsuki
Horiba Ltd.

Scott Porter and Michael Akard
Horiba Instruments Inc.

ABSTRACT

Direct measurement of dilution air volume in a Constant Volume emission sampling system may be used to calculate tailpipe exhaust volume, and the total dilution ratio in the CVS. A Remote Mixing Tee (RMT) often includes a subsonic venturi (SSV) flowmeter in series with the dilution air duct. The venturi meter results in a flow restriction and significant pressure drop in the dilution air pipe. An ultrasonic flow meter for a similar dilution air volume offers little flow restriction and negligible pressure drop in the air duct. In this investigation, an ultrasonic flow meter (UFM) replaces the subsonic venturi in a Remote Mixing Tee. The measurement uncertainty and accuracy of the UFM is determined by comparing the real time flow rates and integrated total dilution air volume from the UFM and the dilution air SSV in the RMT. Vehicle tests include FTP and NEDC test cycles with a 3.8L V6 reference vehicle. Initial results show SSV and Ultrasonic Flow dilution air volumes match within 0.5% uncertainty.

CITATION: Nevius, T., Rauker, D., Akita, M., Otsuki, Y. et al., "Investigation of Ultrasonic Flow Measurement for CVS Dilution Air Volume," *SAE Int. J. Engines* 10(4):2017, doi:10.4271/2017-01-0994.

INTRODUCTION

Direct measurement of dilution air volume in a Constant Volume emission sampling system (CVS) may be used to calculate tailpipe exhaust volume, and the total dilution ratio in the CVS. The performance of ultrasonic time-of-flight meters applied to engine exhaust dilution systems has proven feasible in demanding applications, including full-flow [1,3] and partial flow sampling systems [2,4]. A Remote Mixing Tee (RMT) dilutes and mixes exhaust gas with filtered ambient air, may include a subsonic venturi (SSV) flowmeter in series with the dilution air duct (Fig 1). The venturi meter results in a flow restriction [5] and significant pressure drop in the dilution air pipe. An ultrasonic flow meter for a similar RMT (Fig 2.) dilution air volume offers little flow restriction and negligible pressure drop in the air duct. Ultrasonic flowmeters (UFM) used in place of the usual venturi flow tubes [3] can reduce the size and cost of dilution air handling components in a CVS. Reducing flow restrictions in the CVS ducts can reduce the size and blower power required to operate a dilution tunnel.

The evaluation is performed in two phases, with the initial tests made with an ultrasonic exhaust flow meter (EXFM) and the mixing components of an RMT that are adapted to validate the overall UFM and RMT performance in a realistic emission test cell. The ultrasonic flow meter (UFM) is inserted in series with the CVS dilution air flow. The measurement uncertainty and accuracy of the UFM is determined

by comparing the real time flow rates and integrated total dilution air volume from the UFM and the dilution air SAO in the RMT. Comparisons are generated by performing FTP and NEDC tests with a 3.8L reference vehicle. Initial tests (Figure 9) suggest the UFM is heating the dilution air and affecting flow accuracy. Adjusting the UFM heaters to a set point of 42 C (~ambient + 20 C) improved the accuracy (Figure 9b) to an average 0.03%, where there is no statistical difference between the UFM and SSV dilution air volumes. This demonstrates the feasibility of constructing a Remote Mixing Tee with dilution air flow values determined by UFM.

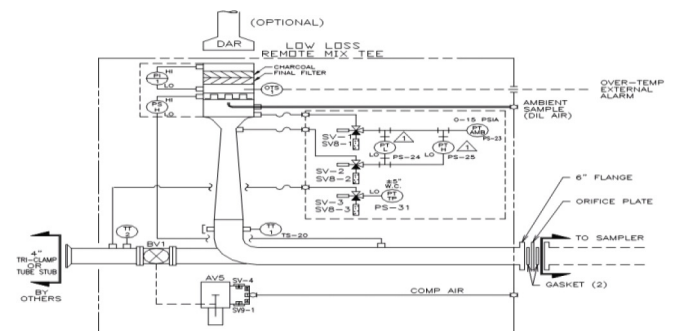


Figure 1. Schematic of a Remote Mixing Tee (RMT) including a subsonic venturi (SSV) in series with the dilution air duct.

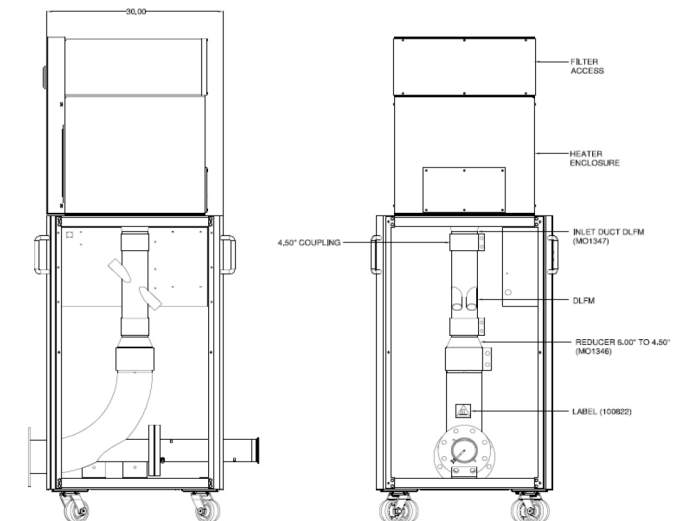


Figure 2. Mix-Tee with an Ultrasonic Dilution-Air Flow Meter (UFM)

EXPERIMENTAL SETUP

A chassis dynamometer emissions test cell forms the reference baseline of a Remote Mixing Tee (RMT) combined with a Constant Volume Sampling (CVS) tunnel which includes Critical Flow Venturis (CFV) and a blower. An ultrasonic exhaust flow meter (EXFM) is placed in series with the dilution-air supply (Fig 3.) such that direct comparisons are made between the RMT subsonic venturi dilution air volume and the ultrasonic flow meter dilution air volume. The specifications of the ultrasonic flow meter (UFM) are listed in Table 1. The maximum dilution-air volume is limited to 10 SCMM by the 3-inch (76mm) pipe diameter, this is adequate for many CVS emissions procedures with light-duty vehicles. The UFM and mix-tee pipe are detailed in Figures 4, 5, 6. The Mix-tee pipe is similar to that in a standard RMT (Fig1). The arrangement enables direct comparisons between the standard RMT and our prototype UFM mix-tee components.

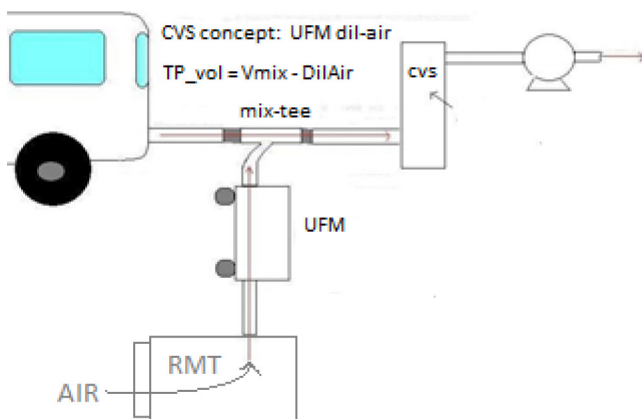


Figure 3. Chassis test cell configuration of a remote mix tee in series with a CVS.

Chassis Test Cell with a Remote Mix Tee



Figure 4. Configuration of the Ultrasonic Dilution Air Flow Meter test system in the chassis test cell. The conventional RMT (to the left of the ultrasonic flow meter) may be connected in series with the UFM to compare SSV and UFM dilution-air volume uncertainty.

Table 1. Ultrasonic Flow Meter performance specifications. The UFM is a modified prototype EXFM adapted for Dilution Air testing.

Item	Specification
Pipe diameter	76 mm
Target Gas	Gasoline engine motor exhaust
Gas Temperature	Maximum 400C
Flow rate range	0.1 to 10.0 scmm
Accuracy	0.4 to 10.0 scmm, 1.0% of reading
Response Time	T90 less than 0.5 second
Pressure Loss	Less than 1.0 kPa at 10 scmm
Ambient Condition	5C to 40C, RH < 85%

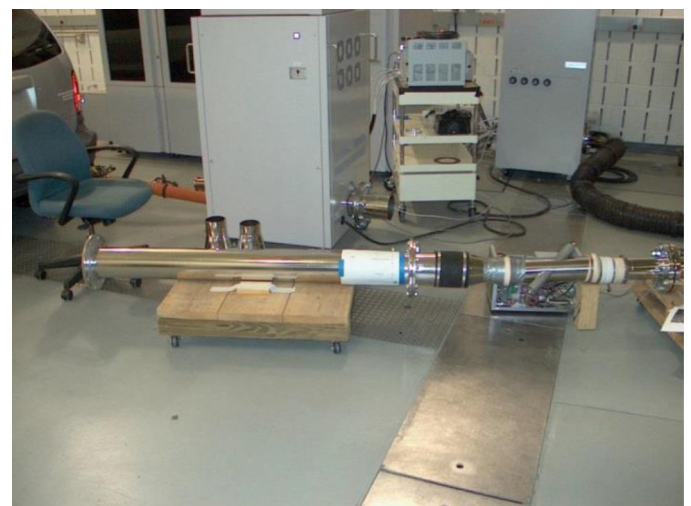


Figure 5. Ultrasonic flow meter in series with the Critical Flow Venturis and CVS tunnel. There is no connection to the RMT or vehicle.

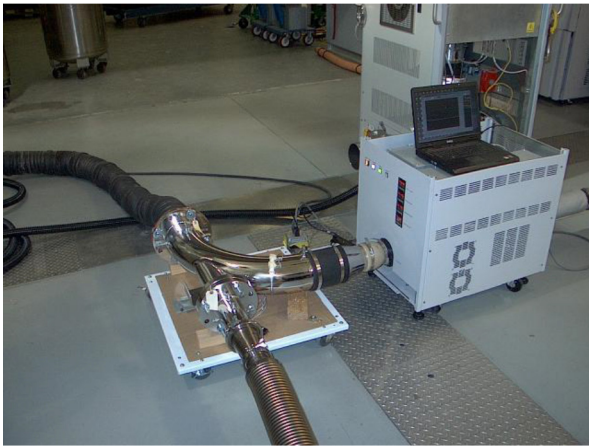


Figure 6. Configuration with UFM measuring total dilution air volume. The conventional RMT (background) is connected in series with the ultrasonic flow meter, as sketched in Figure 3.

Calibrations for all flow devices (SSV, CFV) are NIST traceable to calibration reports by the Colorado Engineering Experiment Station, Inc (CEESI). The EXFM and UFM are calibrated by the authors using the SSV and CFV for reference volumes. The uncertainty in flowrate is estimated at 0.5% of reading at the 95% confidence level. The volume comparisons show a match within uncertainty, which indicates there is no statistical difference between the CFV, SSV, and UFM meter readings.

Initial flow and volume comparisons of the SSV and CFV flowrates with the EXFM and UFM flowrates are performed with dilution-air alone under steady-state conditions. The UFM shows excellent correlation (Fig. 7) to the CVS volume from 2 to 9 SCMM, within 0.25% on average. There is no statistical difference between the UFM and CVS ambient dilution air flow rates in this equipment configuration.

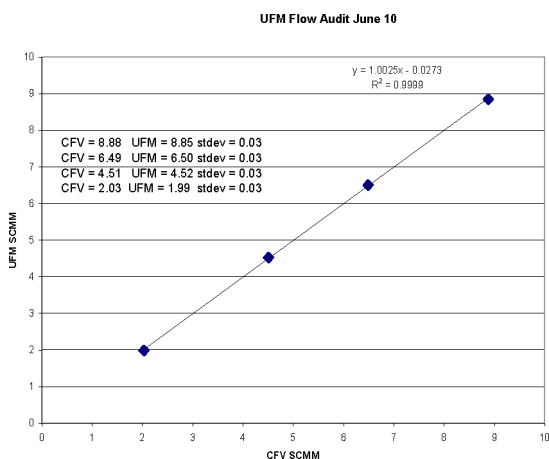


Figure 7. UFM (spool temperature set point = 42 C) matches CVS within 0.25% on average. There is no statistical difference between the UFM and CVS ambient dilution air flow rates.

EVALUATION OF TRANSIENT DILUTION AIR VOLUMES

With steady-state dilution air-flow equivalence proven, the UFM is challenged with typical Light-Duty Vehicle (LDV) transient exhaust emission tests, specifically EPA Federal Test Procedure (FTP) (Fig. 8) and European NEDC (Fig. 8b). The dilute CVS volume (V_{mix}) selected for the reference 3.8L V6 vehicle is 9 SCMM. The vehicle tailpipe exhaust volume is given by

$$\text{Tailpipe_volume} = V_{mix} - \text{Dilution_Air}$$

(1)

The UFM and Dilution-Air SAO are connected in series (Fig. 3) and data is logged in parallel over the vehicle tests. The integrated total volumes for the UFM and SAO over transient tests are shown in Figure 9. The average difference between the UFM and the SAO volume is 0.71 SCM or 0.43%. This is a reasonable correlation, however the standard deviation is greater than the steady-state result. Further analysis suggested the UFM configuration was heating the dilution-air, which resulted in a small temperature bias. The modified EXFM was designed to directly measure engine exhaust, and included pipes and transducers heated above 70 degrees C to eliminate condensation. While this is optimal for raw exhaust gases, there is no danger of condensation when measuring dilution air. The UFM temperature offset is shown in Fig 9a. This was corrected by reducing the UFM spool temperature to 42C, and the transient vehicle tests were repeated, with improved results (Fig 9b). The average difference between the UFM and SAO volume is 0.02 SCM, or 0.03%. This is consistent with the steady-state correlation with a difference of 0.03 SCM between the UFM and CVS.

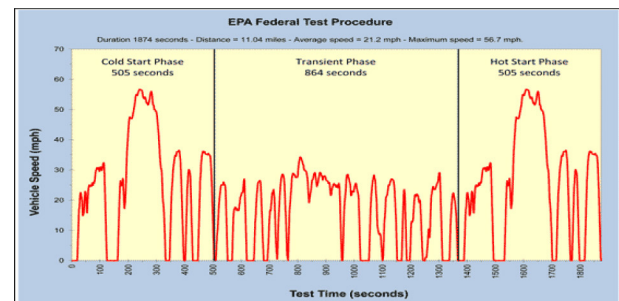


Figure 8. FTP75 dynamometer speed trace.

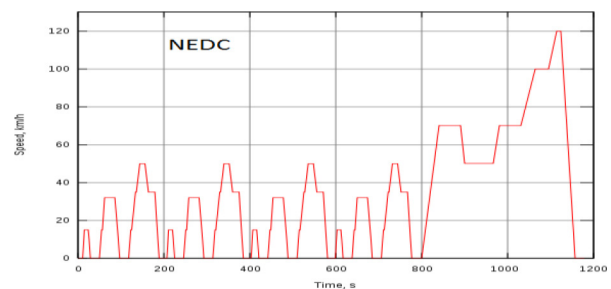


Figure 8b. New European Drive Cycle dynamometer speed trace.