Feature Article

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Development of a High Temperature Exhaust Flowmeter for Diesel Emission Measurements.

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Direct measurement of engine exhaust volume is often required in determining vehicle or engine mass emissions. The most accurate exhaust flowmeters use ultrasonic transducers to measure exhaust gas velocity with 1% accuracy. Available ultrasonic exhaust meters are limited to exhaust gas temperatures of less than 400 degrees centigrade. These exhaust meters are not suitable for use with diesel engines, because the exhaust gas temperatures can exceed 600 degrees centigrade under heavy loads, or when Diesel Particulate Filter (DPF) regeneration occurs. A new type of ceramic ultrasonic transducer that is rated for exhaust gas temperatures greater than 600 degrees C is being developed. An ultrasonic exhaust flowmeter with these high-temperature transducers can be applied to diesel engine and emission tests without limitations for engine size or load.

Introduction

Internal combustion engine mass emissions can be quantified by measuring the gas concentration and the total exhaust volume, where the mass is equal to the gas concentration multiplied by the exhaust volume and density. The exhaust volume is normalized to standard temperature and pressure, and reported as standard cubic meters per minute (SCMM). Accurate emission measurement requires an exhaust flow measurement with 1% accuracy. Current technology[1] uses ultrasonic flow meter components to directly measure the exhaust gas velocity through an exhaust pipe. A schematic of an ultrasonic exhaust meter (Figure 1) shows the gas velocity determined by measuring the transit time for an ultrasonic pulse to travel upstream (T_1) and downstream (T_2) across the exhaust pipe. When the gas velocity is zero, the transit times are equal, where T_1 is equal to T_2. At increasing gas velocity, the difference in transit times will increase proportionally. It is necessary to correct for speed-of-sound, gas density, gas temperature, ultrasonic transducer delay time[2], and smaller second-order effects to deliver an accurate gas velocity and volume.

Gasoline internal combustion engine vehicles generate exhaust gas temperatures in the range of 100-400 °C. Exhaust temperatures of diesel engine can exceed 600 °C. The piezo-electric crystal in an ultrasonic transducer is limited to a maximum temperature of 250 °C, which is the Curie temperature of the crystal. Heating the crystal beyond the Curie temperature depolarizes the device and destroys its performance as an ultrasonic transducer. The ultrasonic transducers are inserted directly into the exhaust gas stream, so maintaining the piezo crystal element below the 250 °C temperature limit is a challenge when the exhaust gas is at a temperature of 400 to 600 °C.

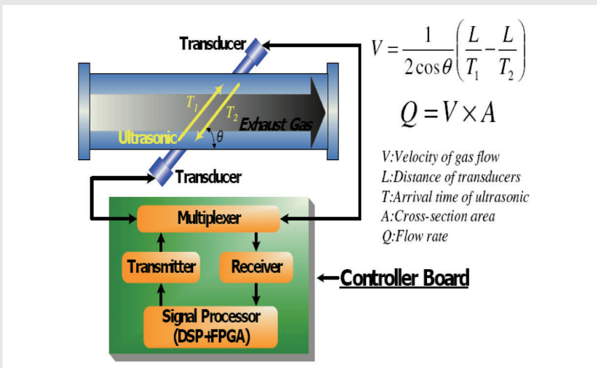

Figure 1 Outliine of an ultrasonic flowmeter

Description of the Present Exhaust Flow Meter

The HORIBA EXFM-1000 is an Exhaust Flow Meter that accurately measures exhaust flow-rate directly at the vehicle tailpipe. The EXFM-1000 is designed to be paired with a Bag Mini-Diluter. The EXFM and Bag Mini-Diluter is an alternative to Constant Volume Sampling (CVS) Techniques and provides the improvements necessary to address the testing of Partial Zero Emission Vehicle (PZEV) and Super Ultra-Low Emission Vehicle (SULEV) emissions.

Figure 2 shows the key components that make up an EXFM and BMD system. One of the critical factors for partial flow bag sampling is accurate measurement of the exhaust flow-rate. The exhaust flow meter is attached in series with the vehicle tailpipe, where it is directly exposed to the hot engine exhaust gases. Typical component temperatures in the flow meter are shown in Figure 3.

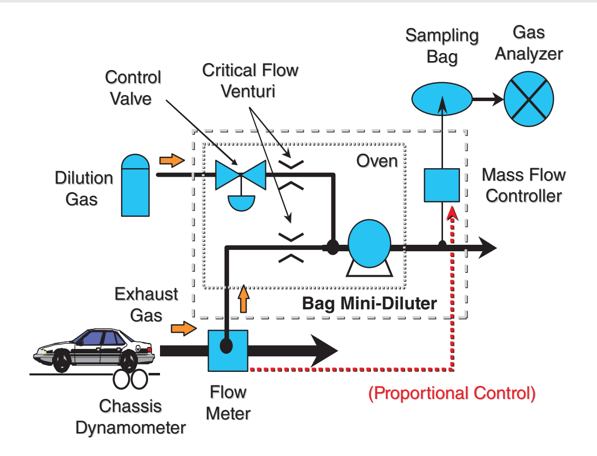

Figure 2 Exhaust flowmeter with Bag Mini-Diluter sampler.

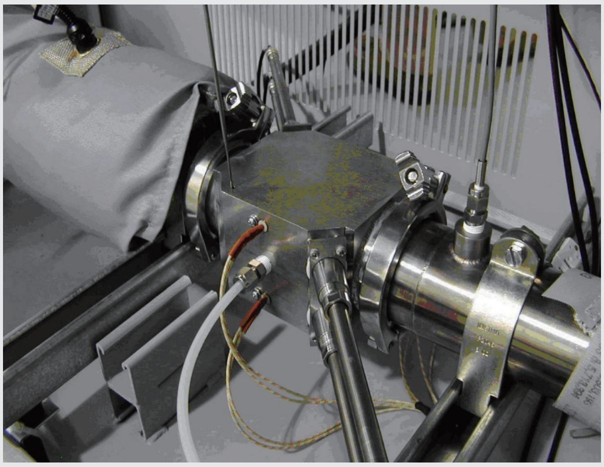

Figure 2b Exhaust Flow meter body, including 400 °C transducers, gas temperature and pressure probes.

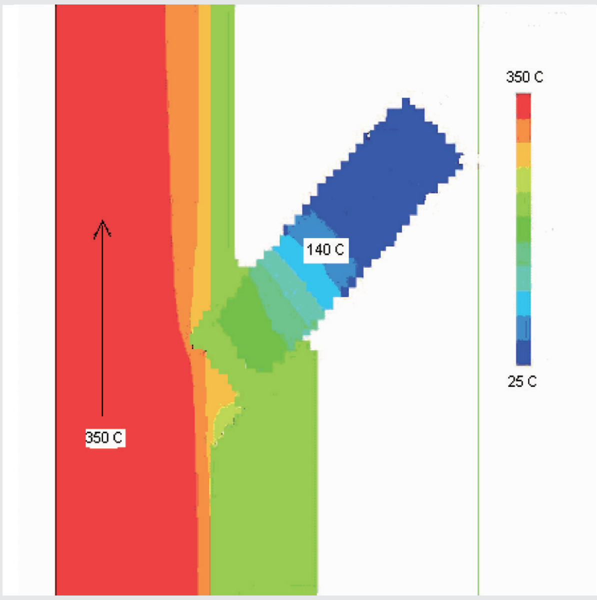

Figure 3 Exhaust Temperature profile for the 400 °C rated ultrasonic transducer. The internal transducer temperature is 141 °C, while the exhaust gas is at 350 °C.

The EXFM-1000 flowmeter is flow calibrated using a NIST traceable calibration system. The accuracy specifications for an Exhaust Flowmeter are <1% at flows greater than 15 scfm, <2% for 5-15 scfm, and <5% for flows less than 5 scfm. The EXFM-1000 has an average flow error of about 0.2% (Figure 4).

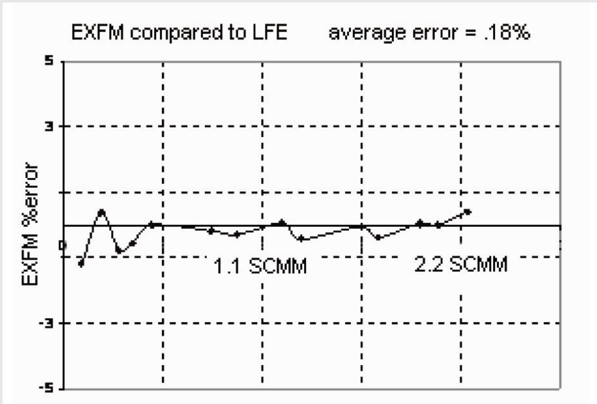

Figure 4 Percent Error plot for the Linear Flow Element (LFE) flow audit. Error limits are <5% error from .1-.15 scmm, <2% error from .15-.5 scmm, and <1% error at flows greater than .5 scmm.

A test vehicle (3.8L V6 gasoline engine) was used to evaluate the Exhaust Flow meter and BMD. The test procedure included an EPA Federal Test Protocol (FTP), followed by a Highway Fuel Economy (HWFE) test and a high-speed (US06) test. The FTP simulates low-speed urban driving. The Highway Fuel Economy test simulates highway driving, and the US06 test simulates aggressive driving and acceleration with speeds up to 85 mph.

Results were evaluated by comparing CO_2 mass emissions in grams per mile between the BMD and a reference CVS for each test. Because tailpipe CO_2 concentration is essentially constant during a test cycle, we can estimate that errors in mass are proportional to errors in total exhaust flow over a test. The EXFM-1000 matched the CVS within 0.5% to 1% for all CO_2 mass emission tests. The maximum exhaust gas temperature for these tests is about 180 °C for the FTP, 280 °C for the HWFE, and 400 °C for the US06 test. This demonstrates that the exhaust flowmeter accurately measures the exhaust volume for a gasoline engine at temperatures up to 400 °C.

Improvement of the Flow Meter

Description of the High Temperature Ultrasonic Transducer

When a heavy duty diesel (HDD) emission is tested, the emissions are measured from not the tail pipe of vehicle but engine directly.

Diesel engine emission tests often result in exhaust gas temperatures greater than the 400 °C possible with the EXFM-1000. The goal for a diesel exhaust flowmeter is to increase the temperature rating to 600 °C. The ultrasonic transducer has been the limiting component, so much of the development effort involves the design of high-temperature transducers.

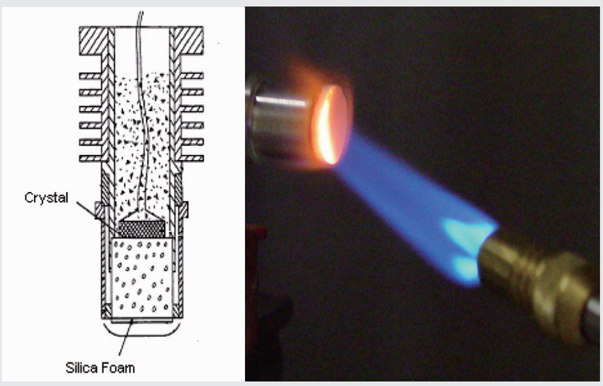

Figure 5 Ceramic high-temperature transducer. The drawing shows the silica foam buffer between the ultrasonic crystal element and the transducer tip. The adjacent picture shows a transducer exposed to gas temperatures of about 1000 °C. The crystal element remained below 250 °C during this test, and the transducer still functioned. However, the signal intensity was reduced even after cooling. Also, we realized the signal processing of the ultrasonic pulse waveform is more difficult than under current temperature range (<400 °C) because of the temperature characteristic of the piezo-electric crystal.

The high-temperature transducer[3, 4] has a silica-foam buffer (Figure 5) between the piezo crystal element and the face of the device. Exceptionally low thermal conductivity maintains the crystal temperature at less than 200 °C while the gas temperature at the face can exceed 600 °C.

This construction technique results in a transducer that maintains the piezo crystal below the Curie point. However, the buffer material also attenuates the ultrasonic signal strength by 20-40 decibels. This means we have an ultrasonic transducer that tolerates high temperatures, but the reduced signal level results in a low signal-to-noise ratio that yields noisy velocity measurements.

Description of the electronic controller for the high-temperature transducer

A high-performance electronic controller (Figure 6) is under development for optimal performance of the ceramic ultrasonic transducers. The controller requires high-speed analog and digital circuitry, including a dedicated digital signal processor. The signal processor is capable of performing 150 million floating point calculations per second, which allows the use of complex noise reduction algorithms. This controller compensates for the increased noise and reduced signal levels observed at high gas temperatures. The ceramic ultrasonic transducers, when combined with this controller results in an exhaust flowmeter that operates at higher temperatures than was previously possible.

Conclusion

An EXFM-1000 has been refitted with the DSP controller and high-temperature ultrasonic transducers. The previously described 3.6L V6 test vehicle validated the new hardware over the 100 °C to 400 °C exhaust temperature range. Preliminary results indicate that the high temperature ultrasonic transducers have extended the exhaust gas temperature rating to 500 °C, where the reduced ultrasonic signal levels limit the measurement accuracy.

Ceramic transducer showed us the possibility of the durability against more than 400 °C.

It is believed that the noisy signal can be significantly improved by applying the digital signal processor. It is expected that the development of improved signal

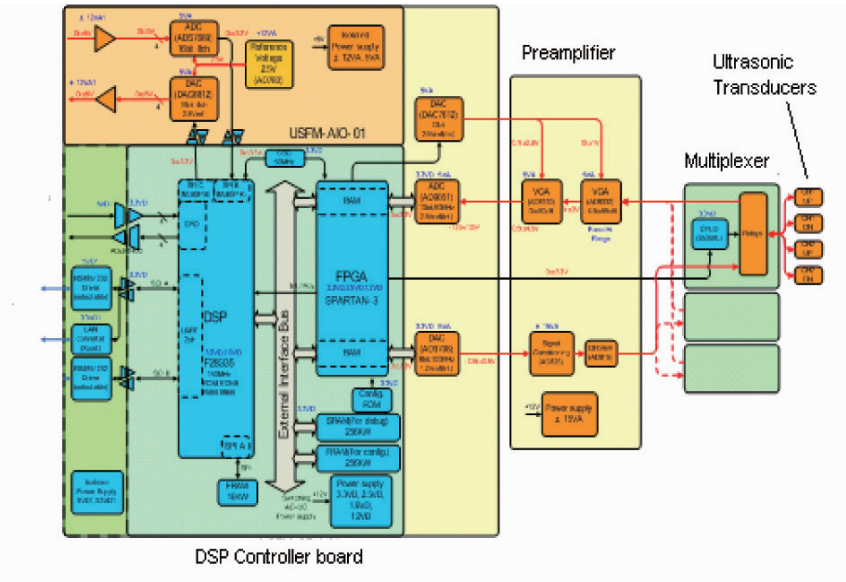

Figure 6 Ultrasonic Controller Diagram

processing algorithms is as necessary to a high temperature flowmeter as the development of the high temperature ultrasonic transducers.

After the upper temperature limit of the flowmeter exceeds 600 °C, it can be applied to diesel engine and emission tests without limitations for engine size or load.

Also, it has a possibility to measure not only vehicle emission but also gasoline engine exhaust directly.

References

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