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DEVELOPMENT OF A PARTICULATE EMISSIONS MEASURING SYSTEM

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OCTOBER 2003

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BY

FAN SU, MALCOLM L. PAYNE AND MANUEL VASQUEZ

ENGINE SYSTEMS DEVELOPMENT CENTRE

OCTOBER 2003

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Since some of the accepted measures in the industry are imperial, metric measures are not always used in this report.

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16. Abstract

A portable particulate emissions measuring system (PEMS) for medium-speed diesel engines and diesel locomotives was developed at Engine Systems Development Centre Inc. (ESDC) in a cost shared project with the Transportation Development Centre of Transport Canada. The system consists of a raw exhaust probe and heated transfer line, dilution air filter module, dilution tunnel module, data acquisition (DAQ) module and filter weighing chamber and balance. The system was designed conforming to the U.S. EPA emissions standards for locomotives/locomotive engines (40CFR Part 92).

The system operation was validated by conducting evaluation tests for a fuel additive following the Simplified Fuel Additive Test (SFAT) procedure. Critical operating parameters of the PEMS could be properly maintained within limitations specified in the 40CFR Part 92. Similar particulate concentrations of diluted exhaust collected under same engine operating conditions revealed reliable repeatability of the particulate matter (PM) measurements. Trends of engine brake specific fuel consumption (BSFC) and exhaust emissions detected appeared to be consistent with that obtained from the SFAT project and other researchers' work with the same fuel additive.

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16. Résumé

Un système de mesure des émissions de particules (PEMS, pour *particulate emissions measuring system*) portable pour moteurs diesel à vitesse moyenne et locomotives diesel a été mis au point au Centre de développement de systèmes moteurs Inc. (ESDC), dans le cadre d'un projet à coûts partagés entre ESDC et le Centre de développement des transports de Transports Canada. Le système comprend une sonde d'échantillonnage de gaz d'échappement brut reliée à une ligne de transfert chauffée, un module de filtration de l'air de dilution, un tunnel de dilution, un module d'acquisition de données (DAQ) et une enceinte de pesée avec balance. Le système a été conçu en fonction des normes d'émissions de l'Environmental Protection Agency (EPA) des États-Unis pour les locomotives et les moteurs de locomotives (document 40 CFR, partie 92).

Le système a été validé au moyen d'essais d'évaluation répétés sur un additif pour carburants, menés conformément au protocole SFAT (essai simplifié des additifs pour carburants). Les paramètres d'exploitation critiques du PEMS ont pu être maintenus à l'intérieur des limites prescrites dans le document 40 CFR, partie 92. Les concentrations de particules mesurées dans l'échappement dilué, échantillonné dans les mêmes conditions d'exploitation du moteur, étaient semblables, révélant une bonne répétabilité des résultats de mesure des particules (PM). Les données de puissance au frein (BSFC, pour *brake specific fuel consumption*) et d'émissions détectées concordaient raisonnablement avec celles obtenues par le projet SFAT et par d'autres chercheurs avec le même additif pour carburants.

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EXECUTIVE SUMMARY

The objective of this work was to develop a portable particulate emissions measuring system (PEMS) for medium-speed diesel engines and locomotives at Engine Systems Development Centre Inc. (ESDC). The development process consisted of two steps:

Step I: System design and fabrication
Step II: System validation

A PEMS was developed in Step I based on requirements specified in the U.S. EPA locomotive/locomotive engine emissions standards (40CFR Part 92). The system consists of raw exhaust probe and heated transfer line, dilution air filters, dilution tunnel, particulate sampling sub-system, CO_2 measuring sub-system, data acquisition (DAQ) sub-system and weighing chamber and balance. By applying a "modular" concept, main components of the system were arranged in three modules (dilution air filter, dilution tunnel and DAQ), which could be moved and connected to the heated transfer line installed conveniently in each of ESDC's test cells. A weighing chamber was set-up in which particulate filters could be conditioned and weighed using a semi-micro balance. A program for determining particulate matter (PM) was also designed using MATLAB.

The system was validated in Step II by conducting repeated evaluation runs for a fuel additive following the Simplified Fuel Additive Test (SFAT) procedure. Critical operating parameters of the system such as particulate sampling zone temperature, heated transfer line wall temperature, Reynolds number of dilution air flow, etc. could be maintained to 40 CFR Part 92 specifications. Variation of particulate concentration measurements of the diluted exhaust for the single-cylinder research engine (SCRE) operating at full load was determined to be ±5% of mean value. Consistent fuel additive evaluation results (trend of emissions and brake specific fuel consumption changes) confirmed the reliability of conducting particulate emissions testing using the developed PEMS.

SOMMAIRE

Ce projet avait pour objectif de mettre au point un système de mesure des émissions de particules (PEMS, pour *particulate emissions measuring system*) portable pour moteurs diesel à vitesse moyenne et locomotives diesel, au Centre de développement de systèmes moteurs Inc. (ESDC). Les travaux se sont déroulés en deux phases :

Phase I : Conception et construction du système
Phase II : Validation du système

La phase I a consisté à mettre au point un PEMS inspiré des nouvelles normes d'émissions de l'Environmental Protection Agency (EPA) des États-Unis pour les moteurs de locomotives et les bcomotives, énoncées dans le document 40 CFR, partie 92. Le système comprend une sonde d'échantillonnage de gaz d'échappement brut reliée à une ligne de transfert chauffée, des filtres à air de dilution, un tunnel de dilution, un module d'échantillonnage des particules, un module de mesure du CO_2, un module d'acquisition des données (DAQ) et une enceinte de pesée avec balance. Le concept «modulaire» appliqué ici a permis de répartir les principaux éléments du système entre trois modules (filtre à air de dilution, tunnel de dilution et DAQ) mobiles pouvant être raccordés à la ligne de transfert chauffée, abouchée tour à tour avec l'une et l'autre des cellules d'essai de ESDC. Une enceinte de pesée a été aménagée, où les filtres à particules étaient conditionnés et pesés à l'aide d'une balance semi-micro. Un programme d'identification des particules a également été développé à l'aide de l'outil MATLAB.

Au cours de la deuxième phase, le système a été validé au moyen d'essais d'évaluation répétés sur un additif pour carburants, menés conformément au protocole SFAT (essai simplifié des additifs pour carburants). Les paramètres d'exploitation critiques du système, comme la température dans la zone d'échantillonnage des particules, la température des parois de la ligne de transfert chauffée, le nombre de Reynolds du débit d'air de dilution, etc., ont pu être maintenus à l'intérieur des limites prescrites dans le document 40 CFR, partie 92. Lors des essais mettant en jeu le moteur de recherche monocylindre (SCRE) fonctionnant à plein régime, les mesures de concentration des particules dans l'échappement dilué s'écartaient d'au plus $\pm$ 5% de la moyenne. La cohérence des résultats des essais d'évaluation de l'additif pour carburants (émissions et puissance au frein) a confirmé que le nouveau PEMS constitue un outil fiable pour la mesure des émissions de particules.

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GLOSSARY

AAR	Association of American Railroads
BSFC	Brake Specific Fuel Consumption
BSE	Brake Specific Emissions
CFR	Code of Federal Register (U.S.)
CO_2	Carbon dioxide
CO	Carbon monoxide
C_xH_y	Combustible
DAQ	Data Acquisition
ECOM	ECOM America, Ltd.
EMD	Electro-Motive Division of General Motors Corp.
EPA	Environmental Protection Agency (U.S.)
ESDC	Engine Systems Development Centre, Inc.
FS	Flow-velocity Signal
GE	General Electric Company
NO_x	Oxides of nitrogen
PEMS	Particulate Emissions Measuring System
PM	Particulate Matter
PS	Pressure Signal
Re	Reynolds number
R&D	Research and Development
RH	Relative Humidity
RP	Recommended Practice
SAE	SAE International
SCRE	Single-Cylinder Research Engine
SFAT	Simplified Fuel Additive Test
SD	Standard Deviation
SwRI	Southwest Research Institute
THC	Total Hydrocarbon
TS	Temperature Signal

1 INTRODUCTION

The Particulate Emissions Measuring System (PEMS) project was initiated mainly for two reasons:

1) With increasing public concern regarding the environment, more R&D and testing projects at ESDC involve emissions measurements for medium-speed diesel engines and locomotives. However, due to the absence of a measuring system, particulate matter (PM) emissions, an important part of diesel engine exhaust pollutants, could not be detected. The Simplified Fuel Additive Test (SFAT) project [1] is one method which aims to properly evaluate the claimed benefits of engine performance enhancing products (such as fuel additives and engine add-on devices) by suppliers at lower cost and reduced time than the AAR recommended practice RP 503. In the verification and validation phases of the SFAT project, gaseous and smoke emissions were measured using an electrochemical sensor based emissions analyzer and a BOSCH smoke meter respectively. By employing these analyzers, useful information can be provided to the user (i.e. the comparative engine performance with and without a product).

2) The U.S. Environment Protect Agency (EPA) locomotive and locomotive engine emissions standards (40CFR Part 92) [2] promulgated in April 1998 prompted the need to establish an emissions testing facility for locomotive compliance at ESDC. The test cells have to be fully equipped to provide test capabilities that cross the full spectrum of medium-speed diesel engine applications. To provide emissions compliance service, ESDC has been developing an emissions lab since February 2001. As a part of the work, a measuring system for particulate emissions must be established.

The project aims to develop a PEMS for medium-speed diesel engines and locomotives according to the US EPA for locomotive and locomotive engine emissions standards (40CFR Part 92). It was supported by Transport Development Centre of Transport Canada and began in January 2003. The PEMS development process consists of system design and fabrication and system validation

This final report contains an overview of system features and results obtained from three evaluation runs for a fuel additive. The system proved to be reliable and capable of performing R&D projects and locomotive emissions compliance tests at ESDC. Recommendations are also provided.

2 SYSTEM OVERVIEW

The particulate emissions measuring system includes a raw exhaust probe and heated transfer line, dilution air filters (primary, carbon and high efficiency particulate arrestance (HEPA) filter), dilution tunnel, particulate sampling sub-system, CO_2 measuring sub-system, data acquisition (DAQ) sub-system and weighing chamber and balance. A block diagram of the system is shown in Figure 1.

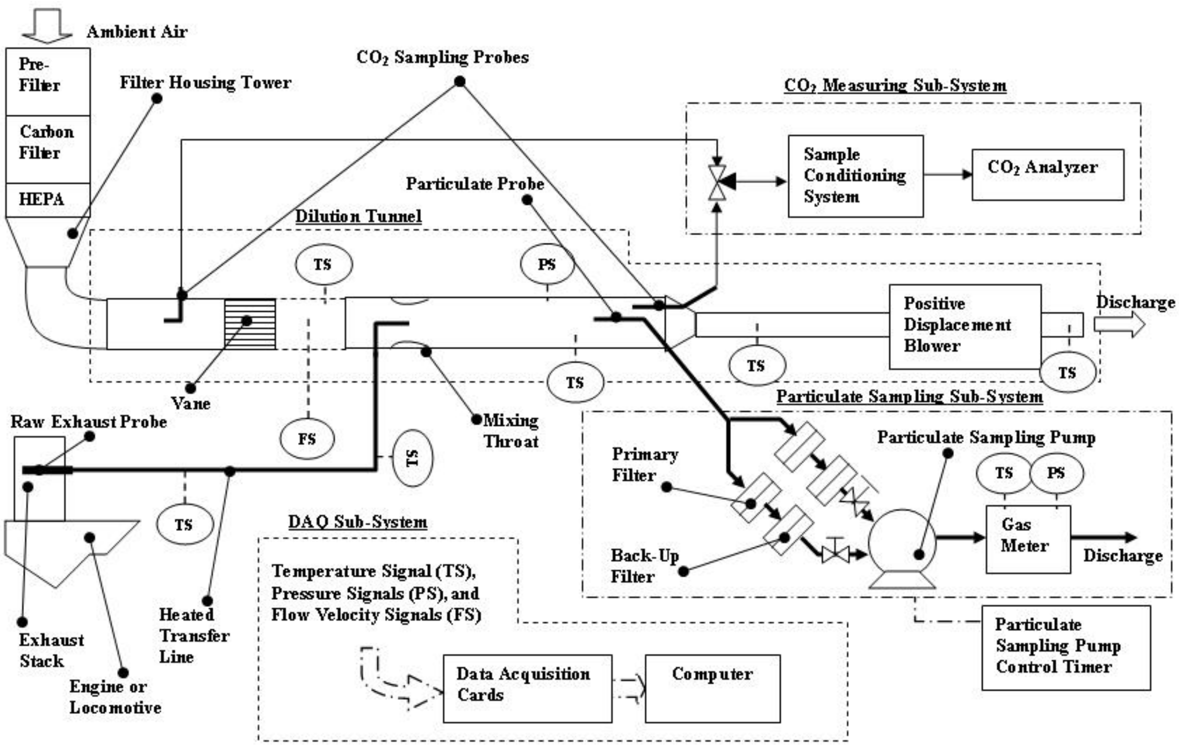

Figure 1: Block diagram of the particulate emissions measuring system

A positive displacement blower moves ambient air through dilution air filters, removing background particulates as the air passes into the dilution tunnel. By throttling the dilution air using a mixing throat, a small negative pressure is generated, which draws raw exhaust through a raw exhaust probe installed in the engine exhaust stack (or stack extension) and a heated transfer line to the dilution tunnel. Sufficient air volume and tunnel length cause turbulent flow and complete the mixing of raw exhaust and dilution air. A particulate sampling pump draws the diluted exhaust sample through a particulate probe, a primary filter and a back-up filter to collect particulate deposits. Following this, a gas-meter records the total sample volume. The CO_2 concentrations of the dilution air and the diluted exhaust are determined by passing samples through a CO_2 analyzer.

The blank and particulate sample filters are conditioned and weighed using a semi-micro balance located in a weighing chamber, in which temperature and relative humidity are maintained. The net weights of the filters (difference between the weight of blank filter and particulate sample filter) are used to determine the quantity of particulate matter.

To measure PM at different test cells of ESDC, the system's main components are arranged in modules: a dilution air filter module (pre-filter, carbon filter and HEPA filter), a dilution tunnel module (dilution tunnel, particulate sampling sub-system and CO_2 sampling probes), and a DAQ module (data acquisition sub-system and CO_2 measuring sub-system, heated transfer line temperature controllers, and a particulate sampling pump control timer). A photo of the modules is given in Figure 2.

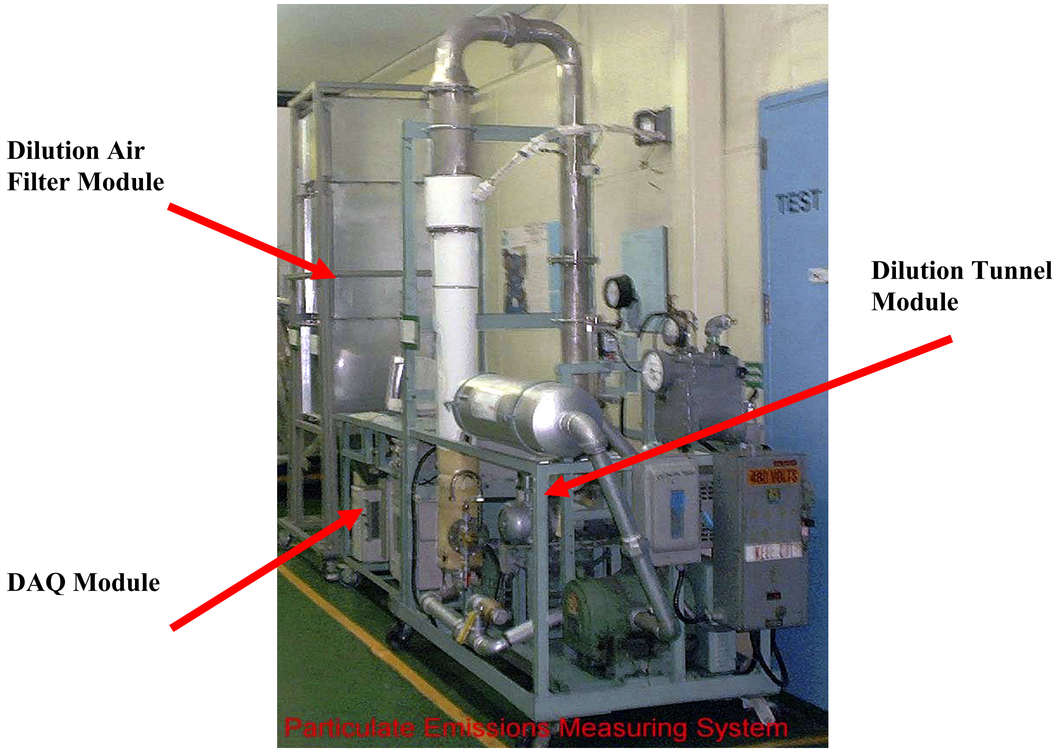

Figure 2: Particulate emissions measuring system

3 SYSTEM FEATURES

3.1 Raw Exhaust Probe and Heated Transfer Line

The raw exhaust probe is a straight, closed end, stainless steel multi-hole probe. It is installed in the engine exhaust stack (or stack extension) and extends across about 90% of the longest side of the stack. It faces away from the exhaust flow direction. The heated transfer line is warmed using rope heaters; it is covered by fiberglass insulation. The heated transfer line wall temperature is maintained above 191°C by a feed-back temperature signal from a K-type thermocouple and temperature controller installed on the DAQ module.

3.2 Dilution Air Filter Module

This module is a filter housing tower with a quick air output connection. The pre-filter, carbon filter and HEPA filter are installed in three side access housings. The HEPA filter has an efficiency of 99.99% at 0.3 micron. Ambient air is filtered to remove background particulates prior to the dilution tunnel.

3.3 Dilution Tunnel Module

The dilution tunnel is constructed of a stainless steel tube with a 4.3-inch inside diameter. In the tunnel, dilution air flows through a mixing throat called a venture, generating a small negative pressure at the outlet of heated transfer line to draw exhaust into the tunnel. At the end of the tunnel, a positive displacement blower with 265 CFM capacity is employed to create turbulent air flow to complete the mixing of dilution air and the raw exhaust sample. To maintain the temperature of the diluted exhaust stream inside of the tunnel and prevent water condensation, the surface of the tunnel is thermally insulated. A vane stabilizes the dilution air flow before it passes through the mixing throat (Figure 1). Since dilution air temperature is required to be 20°C or greater, a rope heater is installed on the surface of a section between the vane and the air filter module for low ambient-temperature operations.

A particulate probe is installed facing upstream of the dilution air at approximately 43 inches downstream of the point where the exhaust enters the dilution tunnel. The distance from the particulate probe tip to filter holder inlet is about 20 inches. The diluted exhaust samples were drawn from the particulate probe mounted in the dilution tunnel via a high flow particulate sampling pump assembly with an operation control timer. The samples pass through the in-line primary filter (2.76 inches in diameter) and the back-up filter (2.76 inches in diameter) to collect particulate deposits prior to a gas meter, which records total gas sample volumes. The temperature and pressure of the gas sample at the gas meter is monitored using a thermocouple and a pressure transducer respectively.

The dilution factor, defined as a volumetric ratio of the dilution air to the raw exhaust sample, is calculated from CO_2 concentration in the dilution air and diluted exhaust samples. A diluted exhaust CO_2 sampling probe is installed facing upstream at a point where the dilution air and raw exhaust will mix, and a dilution air CO_2 sampling probe is located at a proper position between the vane and filters.

3.4 DAQ Module

Temperature, pressure and flow signals are transferred to the computer which monitors system operating conditions. Figure 3 shows a block diagram of the DAQ system.

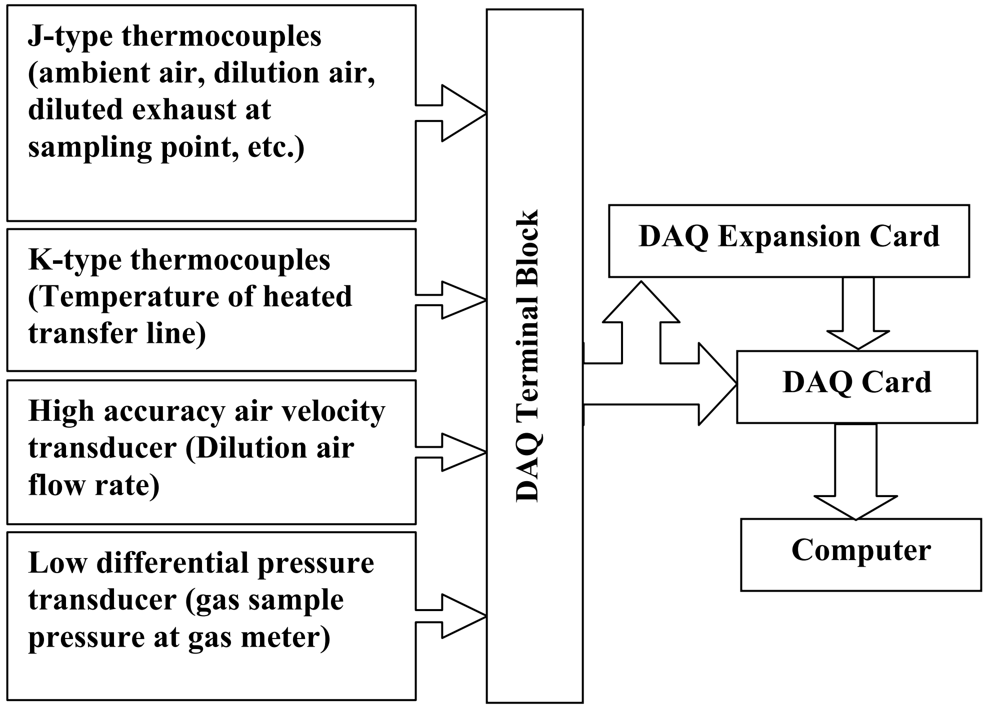

Figure 3: Block diagram of data acquisition sub-system

A program was designed using TestPoint application software. It has features for monitoring and recording data. Experimental data are recorded according to the designed schedule, and a simultaneous back-up is created every two seconds. A front panel of the program is displayed in Figure 4.

This module includes a CO_2 analyzer with an in-line sample conditioning system for CO_2 concentration measurements. A particulate sampling pump control timer is also included for convenient operation of particulate sampling.

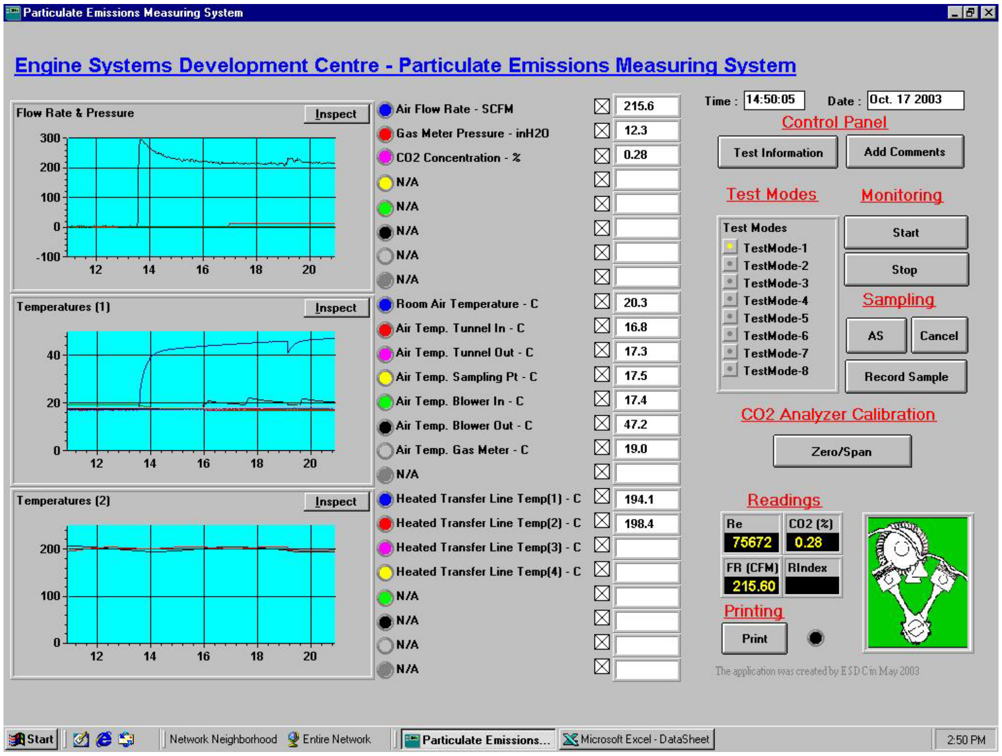

Figure 4: Front panel of the data acquisition program

3.5 Weighing Chamber and Balance

A weighing chamber was used to maintain required temperature and humidity during filter conditioning and weighing. The chamber controls relative humidity (RH) from 9~95% with an accuracy of ±2% at 22°C, and temperature from 0~50°C with an accuracy of ±1°C. A semi-micro balance with readability of 0.01mg and reproducibility of 0.02 mg is located inside of the chamber for weighing the filters. Filters remained in the weighing chamber at all times in covered but unsealed Petri dishes. The chamber sits on a marble table specially designed to minimize the influence of vibrations. A photo of the balance in the weighing chamber is shown in Figure 5.

Figure 5: Semi-micro balance in the weighing chamber

4 SYSTEM VALIDATION

Three repeated runs for performance evaluation of a fuel additive were conducted on a single-cylinder research engine at ESDC. The test objectives were:

- Verify system operating parameters, confirming to 40CFR Part 92 specifications.
- Validate results by comparing against the SFAT project and other researchers' work for the same fuel additive.

4.1 Evaluation Test Procedure and Data Analysis

The SFAT procedure was used to evaluate the effectiveness of engine performance-enhancing products, including fuel additives and fuel system add-on devices, for medium-speed diesel engine use. For each evaluation run, a baseline test was performed on standard #2 diesel fuel first, followed by a preconditioning period on additive-treated fuel prior to an additive-performance test. Procedure details are provided in [1].

Engine fuel consumption rate collected was converted to specific values. In calculating the brake-specific fuel consumption (BSFC), the following equation was used:

$$BSFC(g/hp\cdot hr)=\frac{FuelConsumptionRate(g/hr)}{CorrectedEngineBrakeHorsepower(hp)} \qquad (1)$$

The engine brake power was corrected to standard conditions considering intake air temperature, fuel temperature, fuel density, heating values of fuel and altitude effects.

The ECOM AC+ analyzer was used to measure gaseous emissions (CO, CO_2, NO_x and C_xH_y). Smoke and PM was measured using an AVL smoke meter and the PMES respectively. The measured raw emissions concentrations were converted to brake-specific values. In calculating the composite brake-specific emissions (BSEs), the following equation was used:

$$BSE(g/hp\cdot hr)=\frac{EmissionsRate(g/hr)}{IndicatedEngineBrakeHorsepower(hp)} \qquad (2)$$

The gaseous emissions rate, defined as mass exhaust emissions per hour, was calculated from measured emissions concentrations and the fuel consumption rate. The particulate emissions rate, defined as mass particulate emissions per hour, was calculated from particulate concentration of the diluted exhaust sample corrected for background, dilution factor and total exhaust flow rate. Detailed calculation methods can be found in section 92.132 of [2]. A MATLAB program with friendly user interface was developed to calculate all the specific emissions.

4.2 Test Results

4.2.1 System Operation Parameters

Some operating parameters were critical because of unstable emitted species that may alter through loss to surface, change in size distribution and perform chemical interactions at any time during a sampling, storage or weighing process. Therefore, they are specified in 40CFR Part 92. In the present work, all these operating parameters were collected using the DAQ system at beginning, mid-way and end of a particulate sampling period. To minimize random errors, three sets of data were collected for each baseline (or additive-performance) test. The operating parameters collected from the runs were compared to limiting specifications.

Heated transfer line temperature

Heated transfer line wall temperatures were measured using two K-type thermocouples at two different positions. They were plotted in terms of temperature versus test points (each particulate sampling included three test points (maximum) at the beginning, mid-way and end of the sample period) of the runs. As can be seen from the plot (Figure 6), they were maintained above 191°C during particulate sampling periods.

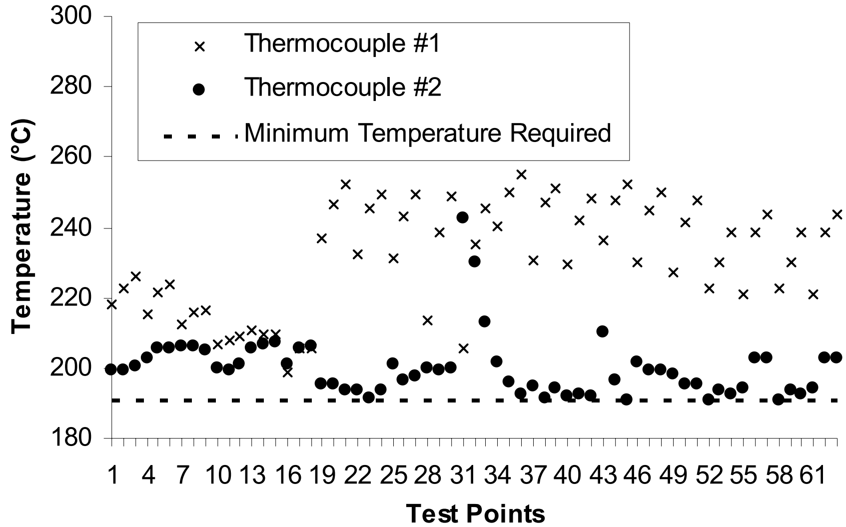

Figure 6: Wall temperature of the heated transfer line

Dilution air temperature

Dilution air temperature can be maintained above 20°C using an electrical heater and a temperature controller for tests conducted at all seasons. The subsequent test results shown in Figure 7 are in a range of 20~32°C.

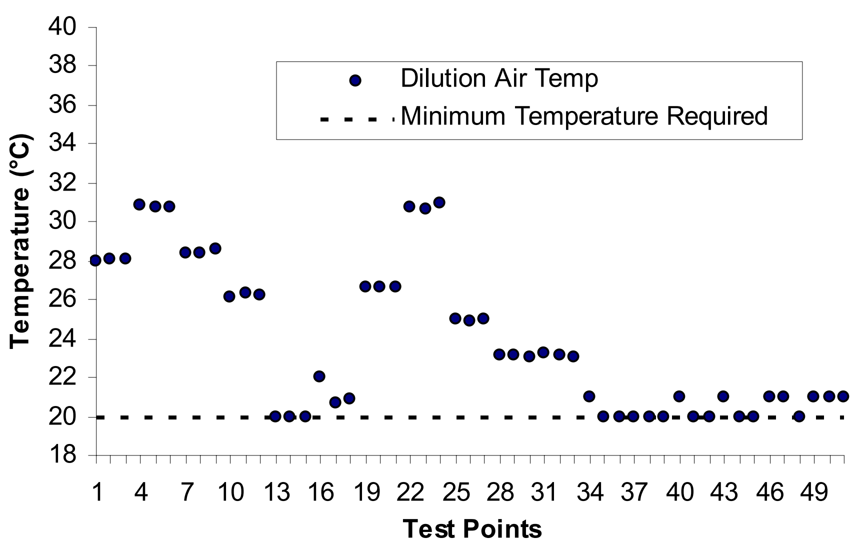

Figure 7: Dilution air temperature

Particulate sampling zone temperature

"Particulate sampling zone" refers to the area around the tip of the particulate probe. The temperatures in this area are displayed in Figure 8. Dilution air flow moved by the positive displacement blower was sufficient to maintain the diluted sample stream at a temperature less than 51.7°C (limit) at particulate sampling zone in the dilution tunnel.

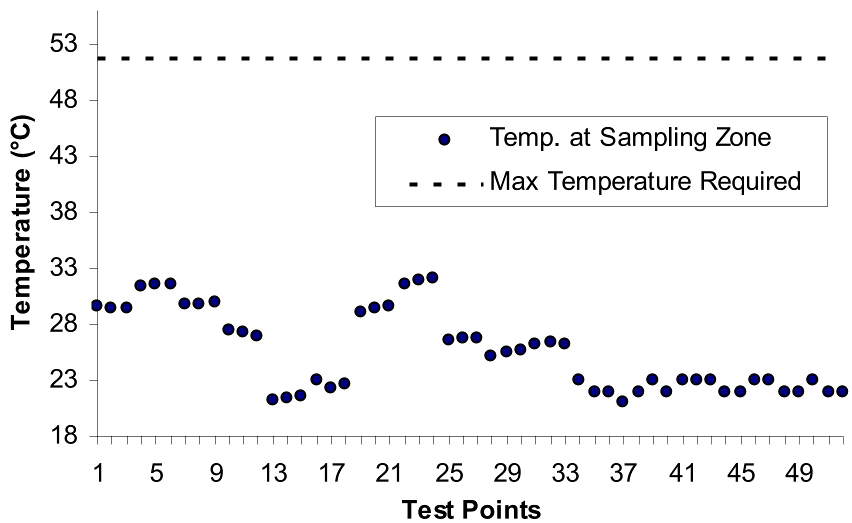

Figure 8: Particulate sampling zone temperature

Reynolds number

Dilution air flow Reynolds number was calculated according to this formula:

$$Re = \frac{\rho_a VD}{\mu_a} \qquad (3)$$

Where ρ_a is dilution air density, μ_a is dilution air dynamic viscosity, V is dilution air flow velocity, and D is dilution tunnel inside diameter.

Reynolds numbers were calculated from recorded dilution air flow rates (Figure 9). They were about 8.2E4±0.97%. Normally, to establish turbulence flow for complete mixing of dilution air and raw exhaust sample, the Reynolds number has to be greater than 4000.

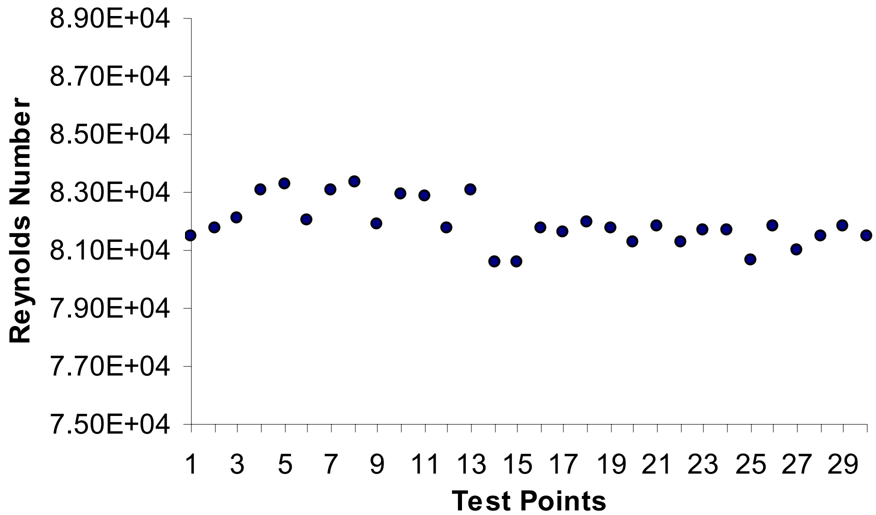

Figure 9: Dilution air flow Reynolds number

Gas meter inlet temperature variation

The gas temperatures at inlet of the gas meter were recorded and given in Figure 10. The temperature variation was 24.9±4.7°C, and could not be kept constant (±2.8°C) during the runs. Therefore, according to the 40CFR Part 92, the gas meter inlet condition (temperature and pressure) was monitored to correct the measured volume to standard conditions in the present project.

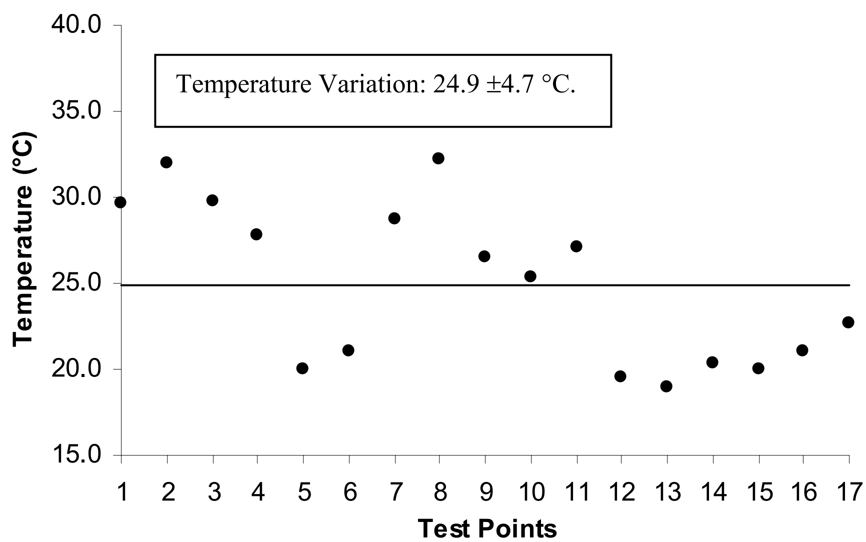

Figure 10: Gas meter inlet gas temperature

Face velocity of particulate sample across filters

Particulate sample flow rate can be adjusted depending on number (one or two) of filter sets (one set of filter means a primary and a back-up filter) to maintain a proper average face velocity across the filter (35~80cm/s). In the present runs, one set of filters is used and average filter face velocities are approximately 70±2cm/s.

Weighing chamber temperature and RH

Monitoring results of weighing chamber temperature and RH during filter conditioning and weighing period showed that temperature could be maintained at 22±2°C and RH at 45±5% at 29.8~30.5 inHg ambient air pressure. The EPA requires that weighing chamber temperature is maintained between 19 and 25°C, and RH is 45±8% during all filter conditioning and weighing.

Reference filters

Two reference filters (Filter1 and Filter2) were placed in the same general area as the sample filters. They were weighed at the same time as sample filter weighings. The average weight of reference filters changes between sample filter weighings less than ±1% of target normal filter loading (0.5 milligrams per 1075 square millimeters of stain area) (Figure 11). Therefore, all the sample filter weights were admissible use in determining the PM in this study.

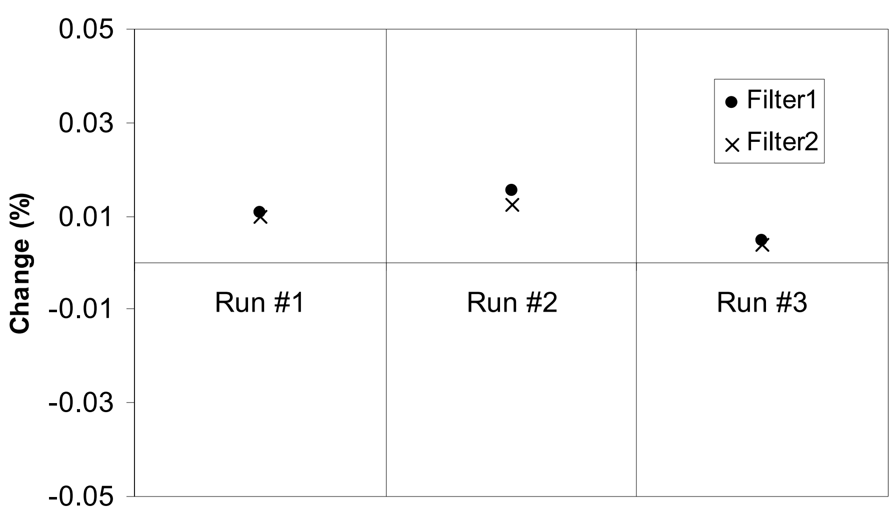

Figure 11: Reference filter weight changes over normal filter target loading

Repeatability of particulate concentration measurement

Particulate concentrations of diluted exhaust samples were calculated (Figure 12) from data collected at engine full load. Standard deviation (SD) of the concentrations was about ±5% of mean value. A reported SD of PM results from other engine research laboratory was approximately ±4.4% [3].

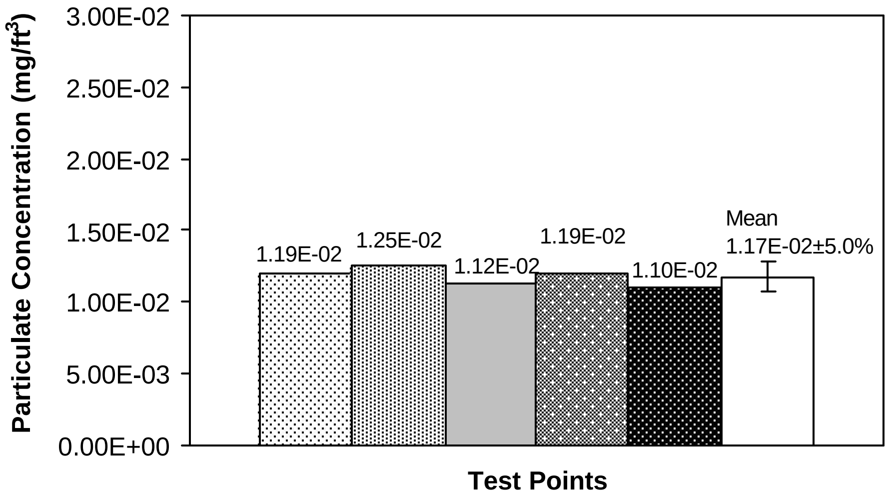

Figure 12: Repeatability of particulate concentration measurements of diluted exhaust

4.2.2 Fuel Additive Evaluation Results

The fuel additive evaluation results are summarized in Table 1. Results from different runs showed similar trends on BSFC and emission changes due to additive use.

When the results were compared to those obtained from SFAT project and Southwest Research Institute (SwRI) for the same fuel additive, similar trends on BSFC, NO_x, CO and THC from additive use was found (Table 2). Normally, diesel particulate emissions result from incomplete combustion of fuel hydrocarbon, and are partially contributed by lubricating oil. In this test, incomplete combustion dominated PM emissions. Therefore, the additive reduced baseline THC and PM emissions. An observed trend of PM increases was observed in SwRI's results, and was attributed to combustion of lubricating oil, since lubricating-oil derived components dominate PM emissions from two-stroke EMD engines [4].

Table 1: Summary of fuel additive evaluation results

		BSFC (g/kW-hr)	Gaseous Emissions (g/hp-hr)			PM (g/hp-hr)	Smoke (BOSCH)
			CO	NO_x	THC		
ER1[1]	B[2]	244.0	2.2	11.0	1.49	0.13	0.50
	P[3]	240.0	2.0	12.0	1.47	0.12	0.45
	Change (%)	-1.64	-9.1	9.1	-1.3	-7.7	-10.0
ER2	B	243.1	1.9	11.2	1.45	0.11	NA[4]
	P	240.0	1.8	11.8	1.41	0.10	NA
	Change (%)	-1.30	-5.3	5.4	-2.8	-9.1	NA
ER3	B	242.7	1.8	14.7	1.46	0.11	NA
	P	239.0	1.7	15.2	1.45	0.10	NA
	Change (%)	-1.52	-5.6	3.4	-0.7	-9.1	NA

Note: (1) ER: Evaluation Run; (2) B: Baseline; (3) P: Performance; (4) NA: Instrument is not available.

Table 2: Comparison of the fuel additive evaluation results[1]

	Present Results	SFAT Project	SwRI
Test Engine	SCRE	SCRE	EMD12-645E3B
Test Procedure	SFAT	SFAT	RP-503
BSFC	D[2]	D	D
CO	D	D	D
NO_x	I[3]	I	I
THC	D	NA[4]	D
PM	D	NA	I
Smoke	D	D	NA

Note: (1) The trend of changes of test results are compared here, however, the changes may not be significant due to experimental repeatability and errors. (2) D: Decreased due to the additive. (3) I: Increased due to the additive. (4) NA: not available

5 CONCLUSIONS

This project aimed to develop a particulate emissions measuring system conforming to EPA 40CFR Part 92 specifications for medium-speed diesel engine and locomotive emissions testing conducted at ESDC's test facility. The development process was divided into two steps: system design and fabrication, and system validation (by performing evaluation runs for a fuel additive). The following conclusions were made:

a. A PEMS consisting of a raw exhaust probe and heated transfer line, dilution air filter module (air filters), dilution tunnel module (dilution tunnel, particulate sampling sub-system and CO_2 sampling probes), DAQ module (data acquisition sub-system and CO_2 measuring sub-system, heated transfer line temperature controllers, and a particulate sampling pump control timer) and weighing chamber and balance was configured according to specifications described in the 40CFR Part 92. The system is portable and can be set-up conveniently for particulate emissions testing at different test cells at ESDC.

b. Evaluation runs for a fuel additive were conducted to validate the PEMS. Critical system operating parameters, such as heated transfer line temperature, dilution air flow Reynolds number, temperature at particulate sampling zone, face velocity across particulate filters, filter conditioning temperature and relative humidity etc., were properly maintained within limiting specifications. It was also determined that the standard deviation of particulate concentration measurements of diluted exhaust is about ±5% of mean value for the SCRE when operating at full load.

c. Validation results demonstrated that the particulate emissions measuring system is a reliable tool for conducting R&D and emissions compliance projects at ESDC.

6 RECOMMENDATIONS

The particulate measuring system was applied on ESDC's single-cylinder research engine in the present project. To better understand the features of the system for actual locomotive PM measurements, it is recommended that emissions tests on a GE/EMD diesel engine powered locomotive be conducted.

REFERENCES

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