Proceedings of ICEF2006
ASME Internal Combustion Engine Division 2006 Fall Technical Conference
November 5-8, 2006, Sacramento, California, USA

ICEF2006-1538

FLOW-THROUGH FILTER TECHNOLOGY FOR HEAVY DUTY DIESEL ENGINES

Pavel Farafontov, Shazam Williams, John Muter
DCL International Inc.,
P.O. Box 90,
Concord, Ontario, Canada, L4K 1B2

ABSTRACT

Reducing particulate emissions from diesel engines has become a major challenge for regions of Europe, Japan and the United States. Many mobile applications have been successfully addressed with passively regenerating wall flow filters. However stationary engines, locomotives and other large constant speed engines often require a different approach to particulate filtration. Flow-through filter technologies have merit for these applications due to their low maintenance requirements, tolerance to misfueling and suitability for engines with high specific PM emissions.

When considering the application of a particulate filter to any diesel engine the means of regeneration, or combustion of the accumulated soot, is of critical importance. In the case of filters which are regenerated through the use of a catalytic coating the duty cycle of the engine, and characteristics of the exhaust gas itself dictate the potential success or failure of the system. In many cases interruption of operation, whether due to insufficient regeneration rates, or for scheduled service to remove accumulated ash, is relatively more difficult to accept for locomotive and non-mobile engine operations. Locomotives, power generators and the like often accumulate large number of service hours between scheduled maintenance events and perform tasks where interruption of service can have costly consequences.

Details of an investigation into the suitability of a flow-through filter for heavy-duty constant speed engines are presented. Aspects of the design, including materials selection, catalyst coating and performance under various conditions are discussed. Results from CFD and micro-dilution tunnel particulate sampling of full-scale devices support the progressive refinement of the design.

INTRODUCTION

Reduction of particulate matter emissions from diesel powered locomotives and stationary engines has become of great interest to regulatory agencies. Regulatory standards for emissions on NOx, hydrocarbons and diesel particulate matter (DPM) have recently been approved [2,3].

A stationary engine is described by the US-EPA as an engine that is not mobile [1,2]. The final rule - New Source Performance Standards (NSPS) will reduce emissions by 90% from 2005 to 2015[2]. Stationary engine emissions are currently handled on a case-by-case basis and are dependent on air quality regulations of the region. In the near future, new stationary engines with less than 10 liters displacement per cylinder in the U.S. will be required to meet the EPA's non-highway DPM standard (Tables 1 and 2). Pre-2007 engines with less than 10 liters per cylinder will be required to meet the non-road Tier 1 emission standards [3].

Table 1: Stationary US EPA regulations [3]

Displacement (D)	**Power**	**Model Year**	**Emission Certification**
D < 10 liter per cylinder	≤ 3000 hp	2007+	Nonroad Tier 2/3-Tier 4
	> 3000 hp	2007-2010	Nonroad Tier 1
		2011+	Nonroad Tier 2- Tier 4
10 ≤ D < 30 liter per cylinder	All	2007+	Marine Tier 2(Cat. 2)

Table 2: US EPA Non-highway standards [3]

Organization	Emission Standards	Years	PM g/kWh	g/bhp-hr
U.S. EPA	Tier 2	2001-2006	0.6	0.45
	Tier 4	2008	0.3	0.22
		2013	0.03	0.022

Current and future legislation for locomotives is presented in Table 3. Locomotive engines can have lifetimes that exceed 40 years and contribute about 5 percent of diesel PM emissions from mobile sources in the U.S. Retrofitting of an after-treatment device on older engines would greatly accelerate PM reductions on the locomotive emissions inventory. The US-EPA regulation requires locomotive engines to meet Tier 0 standards when they are remanufactured. Engines are normally remanufactured 5 to 10 times during their service life. The regulations for stationary and locomotive engines tend to require significant PM reduction from new engines, and do not address the possibility of retrofitting older engines.

Table 3: Locomotive Emission Standards for the US (EPA) and Europe (UIC)[3,4]

Exhaust Emission Standards for Locomotives				
Year	EPA	g/kw-hr	UIC	g/kw-hr
Up to 2001	Tier 0	0.8	I	N/A
2002 to 2004	Tier 1	0.6	II	0.25
2005 and later	Tier 2	0.28	III (2008)	0.2

Wall-flow filter technology is being implemented on 2007 on-highway trucks with power ranges from 100 to 600 hp. The power range of a typical locomotive or stationary engine can be from 600 to greater than 4000 hp. Wall–flow devices only come in certain sizes and must be packaged in the exhaust line to accommodate many filters connected in parallel. This leads to problems of space requirements and uneven flow distribution and soot collection across the filters. These lead to problems when attempting to regenerate the filter.

Wall-flow technology is strongly dependent on the exhaust temperature to promote oxidation of the collected PM (or cause soot regeneration). On-highway wall flow technology uses external devices to raise the temperature to prevent excess soot build-up. The soot regeneration rate is further improved by the use of catalytic coatings on the filter or the addition of a NO_2 making catalyst upstream of the filter to reduce the regeneration temperature. Excess soot buildup in the filter can result in engine damage from excessive backpressure. In addition burn-off of the excess soot can result in a large amount of heat released that can cause physical damage to the filter channels resulting in engine backpressure problems. These types of devices are prone to ash accumulation in the channels. Removal of the ash build-up is needed on a periodic basis to maintain the filter efficiency and prevent backpressure build-up. This is not always possible on locomotive or stationary engines where maintenance intervals are less frequent. Clearly, wall-flow filter technology has its risks to the operation of the engine and a different approach is needed.

A solution to this problem is in the use of a new partial filter technology that better utilizes the filtration media and addresses the problems of wall-flow filtration technology. The design would have to reduce the risk of thermal runaway and excess backpressure build-up. The device should allow exhaust flow to bypass the filter media when the filter media is saturated with soot or ash. Thermal runaway is prevented by selection of a filter media that limits excess accumulation of soot and thus excessive heat release during soot combustion.

Partial flow devices have been demonstrated on on-highway engines [5,6]. PM trapping efficiency of these devices has been reported as high as 60% for on-highway vehicles while 90% can be achieved with wall-flow technologies. Although partial flow filters are not as efficient they alleviate the potential problems that can occur on locomotive and stationary engines.

This paper will discuss the novel design of a partial flow filter to address the above the issues. The objective of the design was to produce a non-blocking filter capable of 50% PM efficiency. The efficiency of a partial flow device is demonstrated with engine test data over the ISO 8178 steady state cycle.

NOMENCLATURE

EPA: U.S. Environmental Protection Agency
EU: European Union
CARB: California Air Resources Board
PM: Particular Matter
DPF: Diesel Particulate Filter
PFT: Partial Flow Technology
CFD: Computational fluid dynamics
ULSD: Ultra Low-Sulfur Diesel Fuel
SV: Space Velocity (1/h)
V: Inlet Velocity (m/s)

STRUCTURE AND DESIGN OF PFT FILTER BASED ON CFD SIMULATION

The PFT filter is constructed as a network of flow-through channels consisting of layers of corrugated metal foils and filter media (Fig. 1). The corrugated foils are formed into tapered trapezoidal ducts. A dynamic pressure gradient is created to force the exhaust flow through the filter media by alternating tapered ends of the foil on opposite sides of the filter media. The filter media and corrugated foils may be joined by brazing [10], welding or by mechanical techniques. An assembled device is shown in Figure 2. The trapped soot is combusted to carbon dioxide or carbon monoxide with a proprietary catalytic coating on the filter media and NO_2 from the engine or possibly a NO_2 making catalyst.

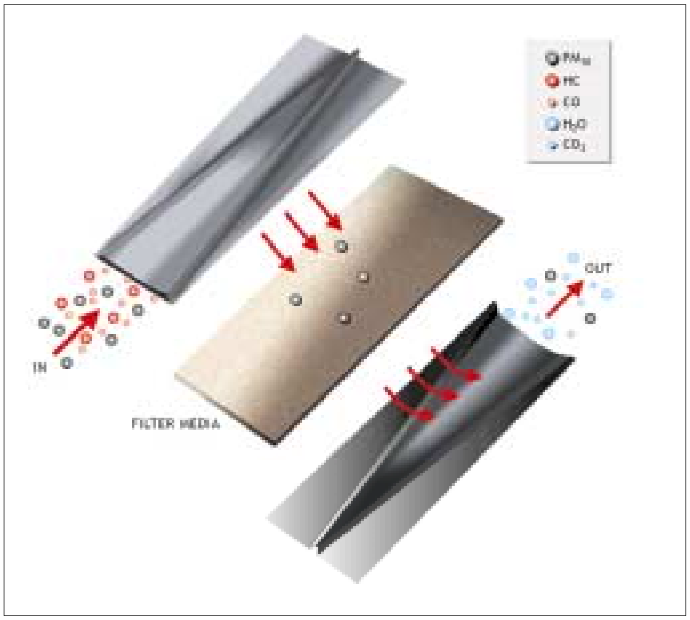

Fig 1: A cell of the main metal filter

Controlling the flow through the design is critical to improving the transit efficiency through the filter media [9]. The transit efficiency or flow efficiency through the filter media was identified to be dependent on the inlet flow velocity, duct geometry (duct height, taper ratio), device length and filter media resistance. The taper ratio is the width of the inlet duct to the width of the exit duct. Filter media resistance is a function of its density, thickness and porosity. Using CFD the design parameters were optimized and are discussed later.

A variety of metallic filter media were considered for use in the PFT [7,8]. Metallic filter media can be made from granules, fibers and filaments (wires). Many different configurations of media are available such as sintered wire mesh, metal foam and sintered fiber felt with differing pore sizes and porosities. Assortments of materials are available from stainless steel, Fe-Cr alloys and Ni-Cr alloys. The filter media (sintered fiber felt) was selected to withstand localized temperature gradients that would occur during regeneration of the trapped soot. High temperatures can cause oxidation of the metal media and weaken the structure. The media should be able to accept a catalytic coating. It must be suitable for forming and joining techniques such as brazing or welding. Other important parameters are soot collection properties such as porosity, pore size and strut or fiber thickness.

Fig. 2. Close-up view of PFT filter substrate showing the alternating tapered trapezoidal ducts and filtration media

CFD SIMULATION

Design parameter optimization was performed using Computational fluid dynamics (CFD) to simulate flow patterns through the PFT. The fluid flow analysis was performed using COSMOSFloWorks software. A single channel used for the simulation is constructed using Solidworks (Fig. 3) and used as a base case for parameter optimization of the transit efficiency.

$$Y = F(X1, X2, X3, X4, X5),$$

Where,

Y= Transit flow efficiency
X1= inlet flow velocity
X2= duct converging ratio
X3= duct height
X4= media thickness
X5= media resistance

Ultimately the criterion for design was to achieve greater than 90 % transit efficiency within a channel flow velocity of 2 to 20 m/s. These channel velocities were chosen based on sizing of existing devices such as diesel oxidation catalysts, and particulate filters. Transit efficiencies were investigated by changing the boundary conditions for the model (inlet velocity and outlet static pressure).

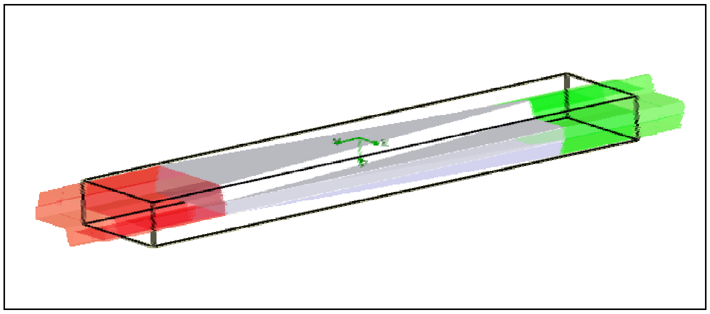

Fig. 3: One complete cell has inlet channel on one side of the media and an outlet channel on the other side.

One of the major parameters that affect transit efficiency is the taper ratio (Fig. 4). CFD results indicate that a taper ratio of 10:1 to 20:1 give values near or exceeding the criteria of 90%. Unfortunately, it does not appear that the lower limit of channel velocity can be met by only varying the taper ratio. The plateau for transit efficiency at any taper ratio occurs at the same critical velocity of ~14 m/s.

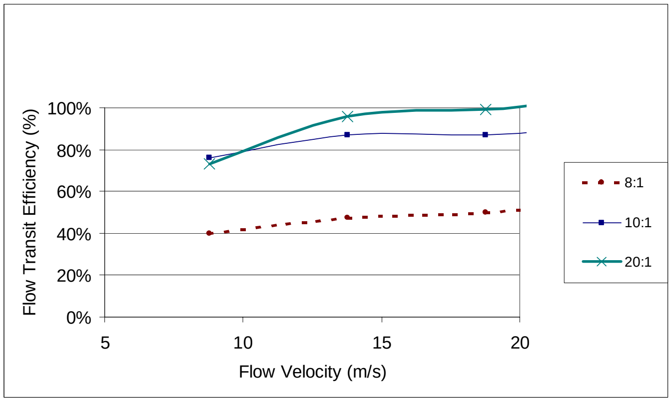

Fig. 4: Flow Transit Efficiency through the Filter media vs. Velocity. Effect of Taper Ratio (constant Duct geometry and Media properties)

Device filter efficiency is transit efficiency (Y) multiplied by the retention efficiency (Fig. 5). Retention efficiency is determined experimentally for each filter media (mass collected/exhaust residence time through media). The results reveal that the device has potential to meet the required efficiency within a reasonable size and velocity. As a result the CFD studies manufactured PFT filters were designed using velocity of about 10 m/s.

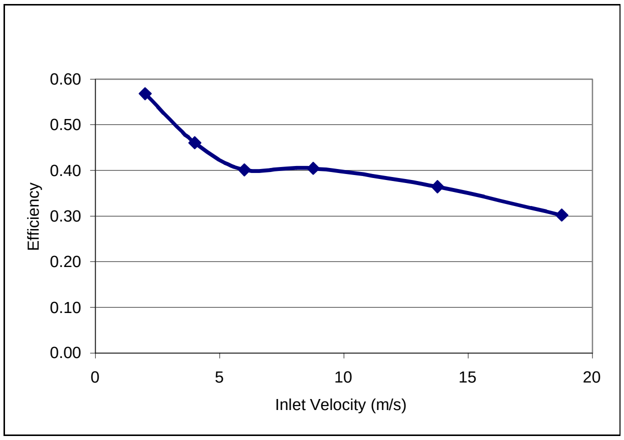

Fig. 5: Device filter Efficiency vs. Inlet Flow Velocity

ENGINE TEST PROCEDURE

Engine testing was used to get practical experience on manufactured PFT devices. The PFT devices (Fig. 6) were installed on a naturally aspirated diesel engine, 2.2L, 37 kW (n=2800 rpm). The engine was fuelled with ULSD fuel with a maximum sulphur content of 15 ppm. All devices were evaluated using the ISO 8178 C1 test cycle.

Fig. 6: Test Stand General View

PM mass reduction was evaluated with a Sierra BG-2 Micro-Dilution Test Stand. The sampling time was 70 to 600 sec on a 70mm filter to allow for measurable mass collect at the different modes. Particulate masses collected ranged between 0.4 to 2.7 mg. These mass values were normalized to the power rating of the mode.

The PFT filter parameters studied during the engine testing are shown in Table 4 and the ISO test cycle in Table 5.

Table 4. PFT filter's parameters during the experiment (D1>D2, V1<V2, SV1<SV2, SV1<<SV3).

Filter Diameter	Inlet Velocity V(m/s)	Coating	Media		Space Velocity SV(1/h)
			Structure	Thickness	
D1	V1	No	M1	THK 1	SV1
	V3	No	M1	THK 1	
		Yes		THK 1	
		No		THK2	
		No	M1	THK 1	SV3
D2	V2	No	M1	THK 1	SV2

Table 5. ISO 8178-C1 Test.

Mode	Engine Speed	Torque %	Time min	Speed rpm	Back Pressure "H2O	Exhaust Temp °C
1	Rated	100	18	2800	13.9	522
2	Rated	75	18	2800	11.7	386
3	Rated	50	18	2800	9.5	281
4	Rated	10	12	2800	7.9	172
5	Intermediate	100	12	1700	7.3	446
6	Intermediate	75	12	1700	6.7	310
7	Intermediate	50	12	1700	5.8	216
8	Low idle	0	18		3.9	89

RESULT AND DISCUSSION

Several different engine based tests were performed to evaluate device performance under different exhaust conditions and using different device parameters. The results of the experiments have shown that the filter configuration, dimensions, coating and other aspects influence the PM efficiency.

The first test was designed to examine the filter efficiency as a function of time to study if steady state exhaust conditions resulted in stable PM efficiency (Fig. 7). The device efficiency was about 50% over the three-hour test period.

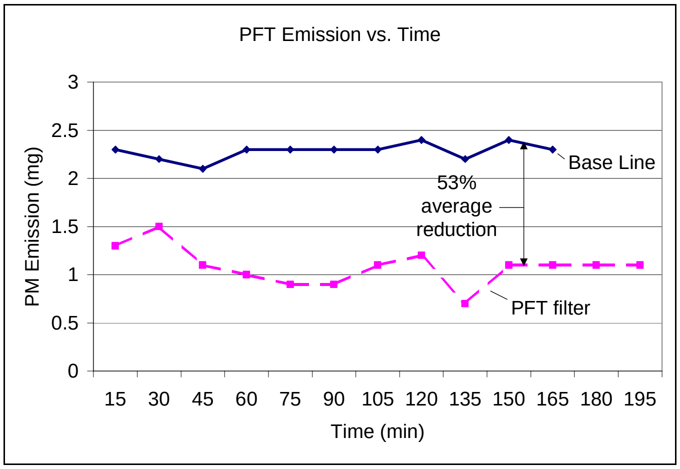

Fig. 7: PFT PM Emission vs. Time (Mode 2, Exhaust Temp-386°C)

A second experiment compared two different devices under identical engine conditions (Fig. 8). The two devices were of different diameters resulting in different internal velocities. The objective was to determine if the internal velocity influenced the PM efficiency. It was observed the device shows low sensitivity to internal velocity, the variation is 10% based on device efficiency.

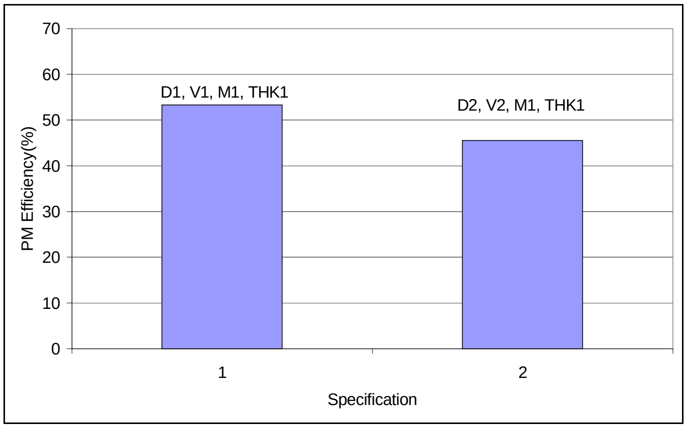

Fig. 8: Device PM Efficiency vs. Exhaust Flow Velocity through the Device. Mode 2 ULSD

The third test compares the effect of catalytic coating on the device. Catalytic coating proved beneficial to PM reduction efficiency. This promotes higher reaction rates at lower exhaust temperatures. According to the data obtained through the experiment, catalyst coating can improve filter efficiency by 20% (Fig. 9).

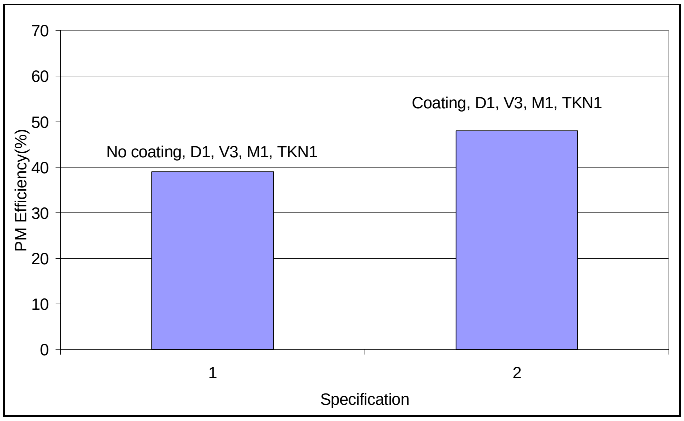

Fig. 9: PM Device Filters Efficiency vs. Coating. Mode 2 ULSD

The fourth test compared two different media thickness (Fig.10). The thicker media with longer residence time demonstrated better PM reduction efficiency under the same conditions.

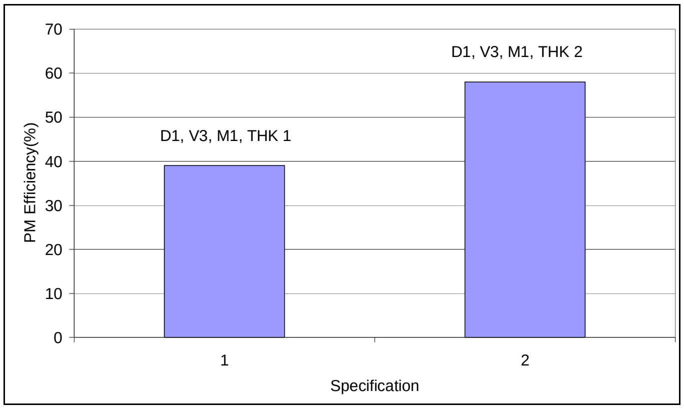

Fig. 10: PM Device Efficiency vs. Thickness (THK2>THK1). Mode 2 ULSD

The fifth test compares similar devices under identical exhaust conditions but at different space velocities (Fig. 11). The space velocity (Ratio of exhaust gas flow/total volume of the device, where total volume uses the inner diameter and the length of the device) has the largest effect on the PM efficiency.

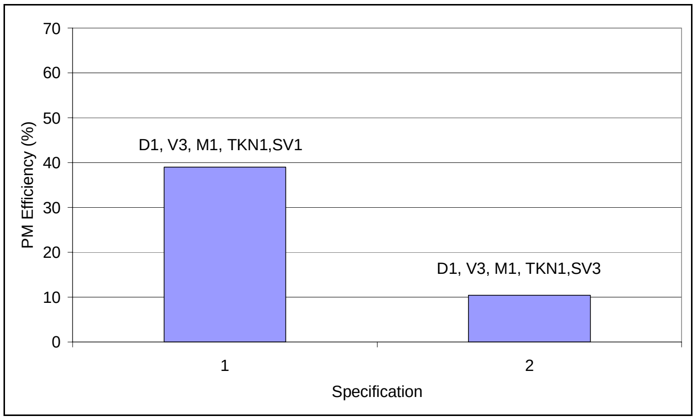

Fig. 11: PM Device Efficiency vs. Space Velocity (Length).

The final test is a complete ISO 8178 C1 test cycle that gives information on individual modal performance (Fig. 12). The different speeds and loads result in different exhaust temperatures and flow rates. The cycle weighted PM efficiency was 58 % with the lowest modal efficiency being 40% and the highest 78%. As demonstrated in the previous test exhaust flow rate did not strongly influence the PM efficiency. At exhaust temperatures of greater than 500°C, direct combustion of carbon dominated the regeneration of the filter media. At moderate temperatures (250 to 350°C), the regeneration of carbon on the filter media was promoted by primarily the NO_2 in the engine exhaust. At low temperatures the combination of carbon storage within the media and soluble organic fraction oxidation resulted in the observed PM reduction.

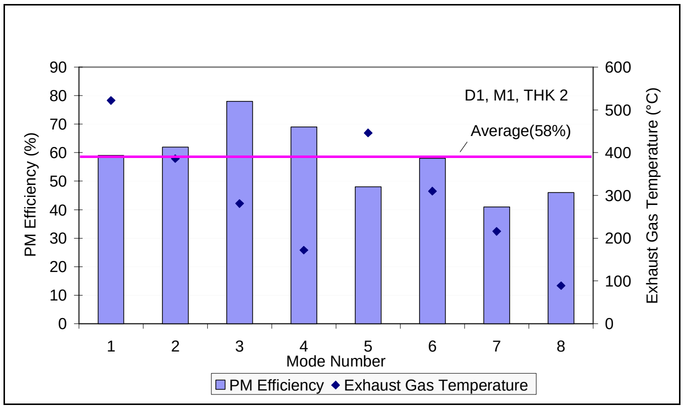

Fig. 12: ISO 8178-C1 Test. Device PM Efficiency and Exhaust Gas Temperature vs. Mode number.

The majority of the PM was produced in Modes 1 and 5, both high load and high temperature modes (Fig. 13). Higher PM efficiency at these modes may be possible by improving the effectiveness of the catalyst coating or device design to optimize PM reduction.

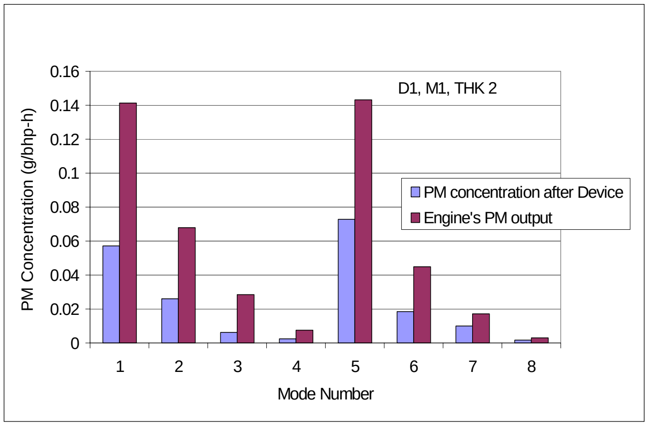

Fig. 13: ISO 8178-C1 Test. Engine's PM output and PM concentration after Device.

CONCLUSION

Partial flow Technology (PFT) devices were designed and manufactured based on CFD results and investigated using a natural aspirated diesel engine (2.2L). The following conclusions were made:

1. 58% PM efficiency was observed on the ISO 8178 C1 test. The best result (78%) was achieved at Mode 3.
2. Mode 1 and 5 are the largest contributors to the overall cycle PM emissions. Optimization should focus on these modes.
3. The devices showed stable PM efficiency throughout the testing regime.
4. The devices show modest influence of exhaust flow rate on PM efficiency.
5. A catalytic coating demonstrated a strongly positive effect on the measure of PM efficiency.
6. Space Velocity had a significant effect on measured PM efficiency

Based on these conclusions it is reasonable to expect that PFT devices will have merit for stationary and locomotive type engines, but further investigations are needed. Useful reductions in particulate matter meeting the objective of 50% have been achieved under conditions typical of these types of engines. Future work will address the potential for blocking of the PM filter during unfavorable operating conditions.

ACKNOWLEDGMENTS

The authors would like to thank Bob Sarna for fabricating the samples, Mojghan Naseri for coating the samples, Henry Liu for performing the CFD analysis and Kamal Chowdhury and Darek Bialasz for performing the experiments.

REFERENCES

1. "Emission Regulations for Stationary and Mobile Engines." EPA420-F-02-034.

2. "Standards of Performance for Stationary Compression Ignition Internal combustion Engine". EPA-HQ-QAR-2005-0029, FRL-RIN 2060-AM82.

3. DieselNet: Diesel Exhaust Emission Standards: http://www.dieselnet.com/standards/

4. Final Emissions Standards for Locomotives', EPA420-F-97-48.

5. Jacobs, T., Chatterjee, S., Conway, R., Walker, A., Kramer, J., Klaus, M. -H., "Development of Partial Filter Technology for HDD Retrofit", SAE Technical Paper 2006-01-0213.

6. SAE Seminar "Advanced Diesel Particulate Filtration System" Detroit, 19-20 May 2005.

7. Purchas, D., Sutherland, K., "Handbook of Filter Media", 2nd Edition, New York, 2002.

8. Dickenson T.C., "Filters and Filtration Handbook", 4th Edition, New York 2004.

9. Mayer, A., "Definition, Measurement and Filtration of Ultra fine Solid Particles Emitted by Diesel Engines", ATW-EMPA-Symposium 19th April 2002.

10. Leone, E.A, Rabinkin, A., Sarna, B. 'Microstructure of Thin-Gauge Austenic and Ferritic Stainless Steel Joints Brazed Using Metglas® Amorphous Foil', Welding in the World, Vol. 50, n° 1/2, 2006.