Pressure Drop Characteristic of Alumina-Zeolite Porous Ceramic Filter and Its Effects in Engine Performance

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***Abstract*-Ceramic open cell foam is proposed as an alternative structure in the automotive exhaust abatement system in the current work. Combination of zeolite and its interconnecting channels promote radial mixing and enhance turbulence which is highly desired in exhaust gas treatment. However, the associated pressure loss in the structure becomes a major limitation which may affect the overall engine performance. This paper addresses the pressure drop characteristic of alumina-zeolite porous ceramic (AZPC) filter and its effects towards engine performance. The filter employs polymeric sponge method to produce porous structure with a composition of 70 vol. % alumina and 30 vol. % of zeolite. Three filters were produced, namely the porous monolith, channelled porous monolith and cylindrical beads with the corresponding capacity for 1300 cc engine. Testing was conducted using a centrifugal blower having a flow rate up to 1224 m^3/hour. Pressure difference for the filters were measured and compared to that of commercially available honeycomb monolith catalytic converter. The filters were then tested in the actual 1300 cc engine to determine the engine performance. Results show that the filters' backpressure is within the 400 and 500 cells per square inch (cpsi) of honeycomb monolith and only deviates slightly from the existing catalytic converter. The AZPC filters depict high potential capability as the pollutant abatement in the automotive application.**

***Keywords*—Alumina-Zeolite Porous Ceramic (AZPC) Filter; Pressure Drop; Engine Performance; Catalytic Converter.**

I. Introduction

Porous ceramic filters have received particular attention in the development of diesel particulate filters and catalytic converters in the automotive industries. In addition to the outstanding high-temperature and chemical resistance afforded by the ceramic, it also offers a higher degree of porosity and larger surface area compared to the extruded honeycomb monoliths.

Existing catalytic converters consists of 1 to 2 mm diameter of channels resulting in the flow to become laminar. However, turbulence is preferred as it improves chemical reaction [1]. Open cell structure with interconnected channels offers relatively low-pressure drop, radial mixing and tortuous flow paths to encourage the turbulence [2].

Zeolites are the aluminosilicate members of the family of microporous solids known as molecular sieves which refers to the ability to selectively absorb molecules based primarily on a size exclusion process. Widely used as ion-exchange beds in water purification, molecule separation, catalysts and known for its potential in separation of specific gases. More than 150 zeolites have been synthesized and 48 naturally occurring zeolites are known [3]. Clinoptilolite is one of the natural zeolite used in this study.

In the exhaust treatment of automobiles, zeolites have received attention in improving the capability of catalytic converter in filtering the gases. Cu-ZSM-5 was used successfully in simultaneous oxidation of hydrocarbon (HC) and carbon monoxide (CO) and reduction of nitrogen oxide (NO_x) for 800 cc of petrol engine [4]. A catalyzed hydrocarbon trap using a metal-impregnated zeolite was found to be promising in improving the cold start of catalytic converter [5].

This paper presents the comparison of porous monolith, channelled porous monolith and cylindrical beads in terms of pressure drop. Comparison is made to the established correlation for 400 and 500 cells per square inch (cpsi) of the honeycomb monolith, typical commercial catalytic converter in the market. Further testing is conducted using the three types of porous ceramic filter in the actual vehicle of 1300 cc engine to measure its performance and emission. Comparison is made to the non-filter exhaust system of the vehicles. Results indicate the potential of alumina-zeolite porous ceramic filter in reducing the emission without largely affect the performance of the engine.

II. Methodology

A. *Preparation of Porous Ceramic Filter*

Porous ceramic filter was prepared using a polymeric sponge method with 90 % of alumina and natural zeolite (clinoptilolite) as the main mixture for slurry preparation. Ovalbumin and 10 % of water were added respectively as the carrier and binder for the ceramic slurry. The slurry was stirred until a uniform mixture was obtained. Additional binder was also added into the slurry composition. The next step was the impregnation of polyurethane sponge with the ceramic slurry. The sponge was compressed to remove air, immersed into the slurry and allowed to expand. This process was repeated to achieve the required loading. Excess slurry was needed to be removed from the sponge. Then the sponge was dried in a microwave oven before the sintering process commenced at 1350°C as shown in Fig. 1.

The next process was the coating of filters with stanum (IV) oxide using dip-coating technique. The process generally involved 3 stages: immersion, dwell time and withdrawal. In the beginning, coating mixture was prepared where stanum (IV) oxide was dissolved in distilled water inside a dipping tank. This solution was allowed to settle from 2 to 3 hours before being used for the next process.

The filters were immersed in the solution at constant speed and remains fully immersed about 24 hours. Then it was gradually withdrawn before the drying process in the oven for 24 hours. At this stage, a layer was expected to be formed on the surface structure of the substrate.

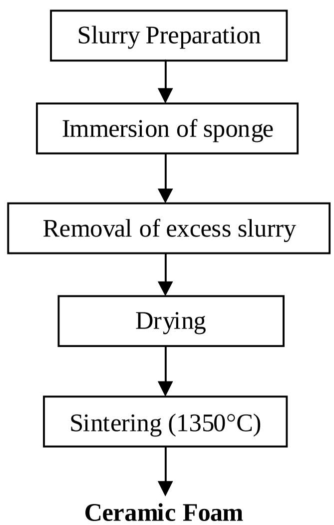

Figure 1. Preparation of AZPC filters

Fig. 2 shows the porous ceramic filter in two structures: porous monolith and channeled porous monolith. Channeled porous monolith is a modified structure of porous monolith by introducing 1 mm diameter penetrating the structure in order to reduce the pressure drop. Both types are assembled into 10 pieces to obtain the volume of 1300 cm^3 as in Table I. Fig. 3 depicts the cylindrical beads with the dimension of 13 mm of diameter and 8 mm height. It is arranged into an aluminium wire mesh and consists of 650 pieces of beads which also occupies the volume similar to the porous monolith. Table II summarizes the characteristics of the porous structure employed in this experiment.

Figure 2. Porous monolith (left) and channelled porous monolith (right)

Figure 3. Cylindrical beads (left) and cylindrical beads arranged in the casing (right)

TABLE I.

DIMENSION OF AZPC FILTERS

Structure	No. of parts	Volume (cc)	Dimension (mm)
Porous monolith	10	1300	100 x 15
Channelled porous monolith	10	1300	100 x 15
Cylindrical beads	650	1300	13 x 8

TABLE II.

SUMMARY OF PORE STRUCTURE

Mean cell diameter (μm)	Porosity (%)	Permeability (mDarcy)	BET surface area (m^2/g)
47.5	39	1712	230

B. *Experimental Setup*

Pressure drop measurement was performed in the experimental setup as indicated in Fig. 4. The blower used was a centrifugal type, Cowdray with a 25 hp motor and connected to a test section with the filter installed in its middle section. An inverter was deployed in the system to control the blower speed. The porous ceramic filter pressure drop across the filter was measured using pressure taps 12 mm before and after the filter in the canister. A pitot-static probe measured the air flow velocity at the inlet pipe before the test section. The measurement begins with the velocity of 12.7 m/s until 43.2 m/s. Pressure loss due to the filter was determined by the difference in static pressure obtained.

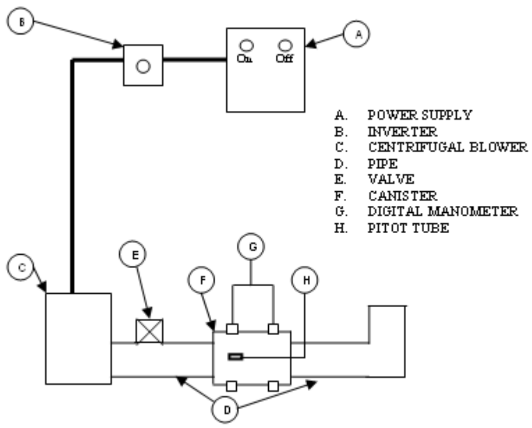

Figure 4. Schematic diagram of pressure drop test rig

C. Pressure Drop Test

This test involved the measurement of pressure drop across the filter for three configurations namely porous monolith, channeled porous monolith and cylindrical beads. Before the test was conducted, the experimental rig was checked and tested for any possible leakage of air. The porous ceramic filter was fitted into a canister equipped with the digital manometer and thermocouple. A canister consist of the filters was installed into the experimental rig of air pipeline. The pressure drop across the filter was investigated with different range of air mass flow rate controlled by the inverter.

Inlet and outlet static pressure was measured immediately using digital manometer of resolution 0.00l kPa. The working air temperature was also recorded. The pressure drop across the canister was obtained directly from the digital manometer. The flow rate was increased by controlling the inverter speed and the testing was repeated for thirteen different values of air mass flow rate. The same method was also repeated for other filters. The results of pressure drop were then compared to the correlation obtained by Makino et.al. [6] for honeycomb monolith as in (1):

$$\Delta P = 5.224 \times 10^{-2} \times \frac{L^{0.829}}{H.D.^{1.631}} \times \left(\frac{V}{O.F.A.}\right)^{1.405} \quad (1)$$

Where

L : length of channel in honeycomb monolith

H.D. : hydraulic diameter of the channel

V : air velocity

O.F.A: open frontal area

D. Engine Performance and Emission Test

The testing was conducted using a chassis dynamometer on a 1300 cc, 4-cylinder, 4-stroke water cooled gasoline engine (model 4G13). Engine performance, emission and pressure drop due to the presence of porous ceramic filter were measured using the equipment as shown schematically in Fig. 5. Gas emission analyzer was used to measure the emission from the engine. Three exhaust systems were tested which represented porous monolith, channeled porous monolith and cylindrical beads installed in a stainless steel casing. The volume of the filter was identical with the engine capacity of 1300 cm^3. The non-filter system was used as the comparison in terms of engine performance and emission.

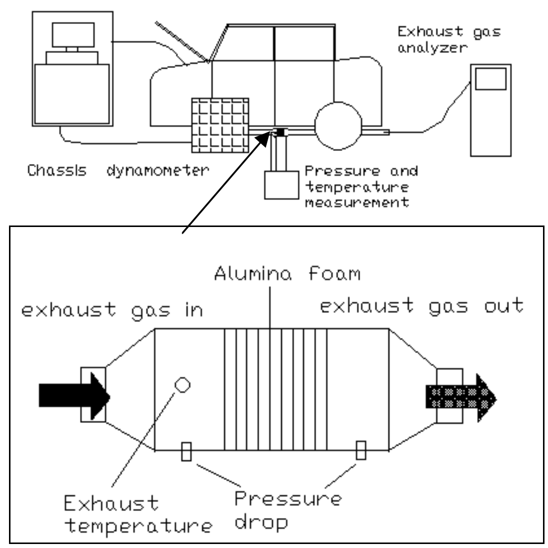

Figure 5. Schematic layout of the performance and emission testing layout (top); pressure and temperature measurement of AZPC filter (bottom)

The testing was conducted at constant load (maximum load) with 1500 rpm of engine speed (approximately 43 km/h road speed). Parameters of power, torque, CO and HC emissions and pressure drop between the porous ceramic filter were measured. The speed was progressively increased by 500 rpm (2000, 2500, 3000 and 3500 rpm) which is equivalent to the road speed of 58, 72, 87 and 101 km/h respectively. This testing procedure was applied for all three configurations of exhaust system.

III. RESULTS AND DISCUSSION

A. Pressure Drop Dependence on Different Filters Structure with Similar Volume

Two essential criteria in the development of filter in automotive application is the pressure loss and conversion efficiency. Pressure loss is critical as high back pressure will reduce the engine performance. On the other hand, conversion efficiency depends on the surface area for reaction to occur which is proportionate to pressure loss. Therefore, both criteria need to be balanced to fulfill its function as filtration exhaust gas without affecting engine performance.

Fig. 6 depicts pressure drop per unit length against air velocity for three types of filters. The graph shows the modified structure and cylindrical beads present lower pressure drop from 2 to 14 % compared to the porous monolith structure. Comparison is made to the correlation obtained by Makino *et.al.* [6]. Two honeycomb monolith structures with different cell density are calculated to obtain pressure drop for 400 and 500 cpsi. It is clear that an increase of cell density raises the pressure drop of the filter system. Comparison to the experimental values of porous ceramic filter indicates the pressure loss is acceptable as it lies between 400 to 500 cpsi which has been widely used in the market.

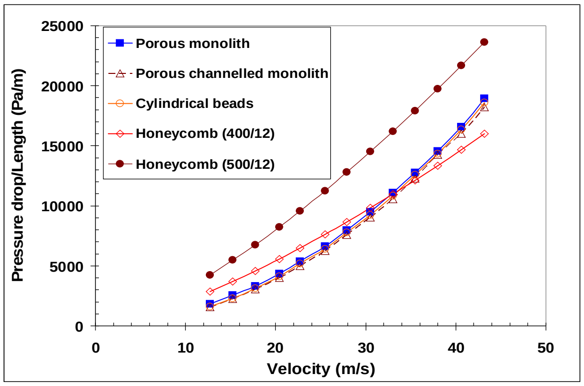

Figure 6. Pressure drop per unit length of different AZPC filters in comparison with honeycomb monolith

B. *Engine and Emission Performance*

Performance of the engine in terms of power for all configurations is shown in Fig. 7. Power loss from the engine using porous monolith is the highest (3.3 to 9.4 % - average is 6 %) compared to channelled porous monolith (1 to 6.2 % - average is 2.7 %) and cylindrical beads (0.8 to 3.2 % - average 1.3 %). The result indicates the potential of cylindrical beads in filtration activities while minimizing power loss up to 1.3 %.

Similar trend is seen for torque measurement. In Fig. 8, comparison of torque shows channelled porous monolith is close to non-filter system as the deviation ranging from 1.6 to 6.9 % (3.7 % average). As for cylindrical beads, the deviation ranges from 1.2 to 3.9 % (3.4 % average). Both results of power and torque produced are consistent as cylindrical beads manage to minimize torque loss up to 3.4 %.

Pressure drop due to the presence of porous monolith, channelled porous monolith and cylindrical beads is shown in Fig. 9. In the exhaust system, high pressure drop across the length of the catalyst could reduce engine performance. The result of 32 % average pressure drop reduction from the porous monolith exhibit the effectiveness of introducing channels to the existing porous ceramic filter. However, cylindrical beads show more improvement in pressure drop as the average pressure drop reduction average is 81 %. The result is consistent with the power and torque measurement in Fig. 7 and 8.

Fig. 10 and 11 represent the normalized form of CO and HC emission. The results are plotted as normalized emission by dividing emission concentration of the tested configuration to the concentration emitted in the non-filter system (if the value is larger than 1.0, then the emission is higher than the emission from non-filter system and vice versa).

Effectiveness of porous monolith channelled porous monolith and cylindrical beads is measured compared to the non-filter system. All filters display typical trend in emission reduction from 1500 to 3500 rpm of engine speed. However, channelled porous monolith performs better at lower range engine speed (1500 to 2500 rpm).

Overall results show cylindrical beads is preferred in terms of engine performance and pressure drop. In the view of emission reduction, channelled porous monolith is better in HC emission.

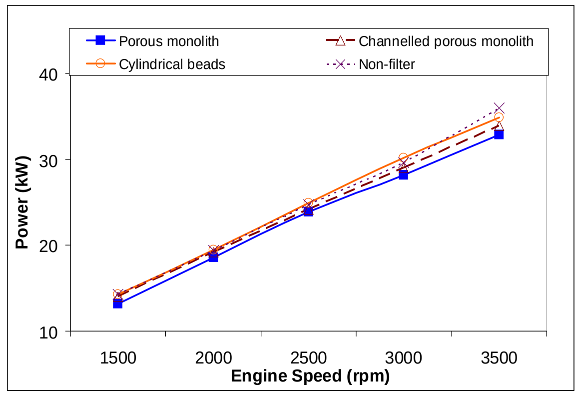

Figure 7. Engine power per unit length of different AZPC filters in comparison with non-filter system

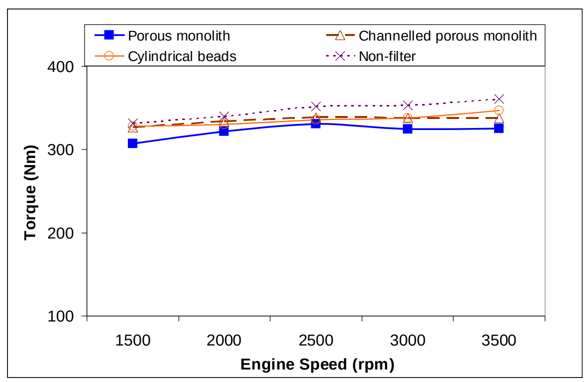

Figure 8. Torque of different AZPC filters in comparison with non-filter system

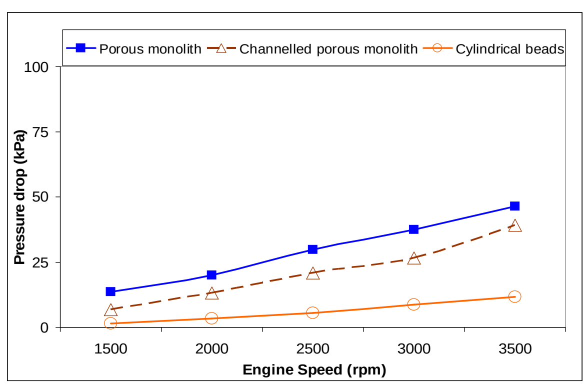

Figure 9. Pressure drop of different AZPC filters

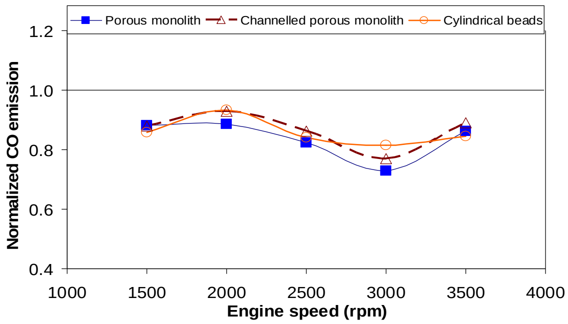

Figure 10. : Normalized CO emission of AZPC filters

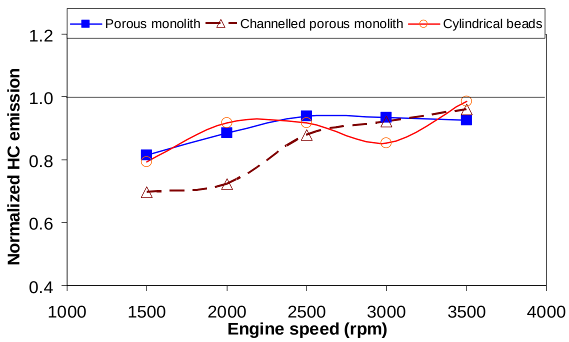

Figure 11. Normalized HC emission of AZPC filters

IV. Conclusion

The results of performance test demonstrated only minimum losses of power for porous monolith, channelled porous monolith and cylindrical beads compared to non-filter system. However, power loss from the engine can be reduced down to 3.7 % by introducing channels to the channelled porous monolith but cylindrical beads gives the lowest power losses from the engine. In term of emission, the AZPC filters can improve especially channelled porous monolith in HC emission. Overall results indicate the potential of CO and HC emission reduction with the application of AZPC filters coated with stanum (IV) oxide in the exhaust system of the engine.

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