

Improving surface characteristics of Porous medium reactor in diesel engine by Plasma technology.

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ABSTRACT - Applying Porous Medium (PM) as a heat reactor in diesel engine has been considered as a promising concept to approach a near-zero emission system. It takes full advantage of PM geometry and material characteristics to perform homogeneous combustion, therefore reduces significantly emission under all operational conditions. The surface characteristic of PM plays a key role in fuel vaporization process inside the combustion chamber. This paper summarizes the results of our recent effort in applying plasma technology to improve its surface characteristic. The research activities focused on preventing reactor surface from forming, sticking of soot and unburned liquid fuel. It helped to increase specific area, energy recirculation efficiency and enhance vaporization ability of fuel during injection process.

TECHNICAL PAPER - Porous medium (PM) was introduced as a reactor in Internal Combustion engine recently. With potential for homogeneous combustion under variable operational conditions, it is shown to be a key role for reducing NO_x and soot emission from engine, especially for diesel engine. Many studies have focused on this novel concept to prove its advantages in supporting mixture formation and combustion processes. The deep researches have been realized to explain the such questions as how is combustible mixture prepared effectively in porous medium volume, how do the geometry and thermal properties of porous medium effect to fuel injection process, fuel vaporization, energy recirculation in order to control the ignitability of the charge and 3D-thermal-ignition process, the very fundamental factors of homogenous combustion process (e.g. see references (1) to (4)).

Beside above studies, there is a lack of research concerning to surface characteristics of PM material. Under severe conditions inside the combustion chamber, these factors influence directly to thermal conductivity, specific area and durability of the reactor. One of these factors is wettability of activator surface by liquid fuel. This factor helps to form very thin layers of fuel on activator surface when fuel is injected into this volume. Therefore, fuel can be heated and vaporised easily and completely. Wettability enhances the specific surface area by restricting the formation of soot and unburned fuel on PM activator. Our approach for this work is to improve wettability of PM surface.

In this study, the treatment of PM surface using helium (He) and N₂O plasma generated by Radio Frequency (RF) plasma power supply was performed and the mechanism of interaction between the plasma and PM surface was discussed. We also purposed oxidation resistibility of activator surface after treatment.

THE CONCEPT OF DIESEL ENGINE WITH POROUS MEDIUM ACTIVATOR.

Principle

In this research, PM activator was mounted on the piston head as in Fig. 2 and 3. During intake and early compression stroke, there is not remarkable influence of PM thermal capacitor on thermodynamic condition inside the cylinder. The heat exchange process (between PM material and compressed air) increases with upward motion of piston. At the TDC, almost all the air is compressed and closed to PM volume. Near the TDC of compression stroke, fuel is injected into PM volume and spreaded widely by interaction with a large number of PM pore junctions ("self – homogenization"). A strong heat transferred from hot PM surface to liquid fuel makes fast and complete fuel vaporization. Very fast mixing with gaseous charge occurs and the combustible mixture is ignited in the whole PM volume. Amount of burned gases that trapped in PM volume defines accumulated energy for next cycle. The three fundamental conditions for a homogeneous combustion are satisfied : homogenization of charge in PM volume, 3D thermal self ignition and volumetric combustion with a homogeneous temperature. The principle of PM engine cycle is described as in Fig. 1.

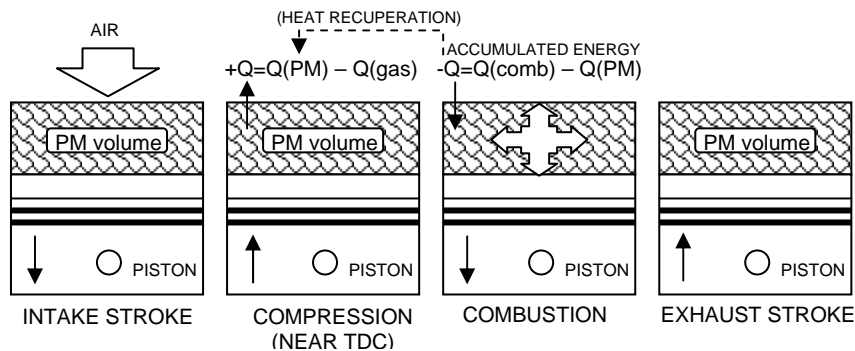


Fig. 1. Principle of PM engine cycle with PM on piston head.

Engine test with untreated PM activator

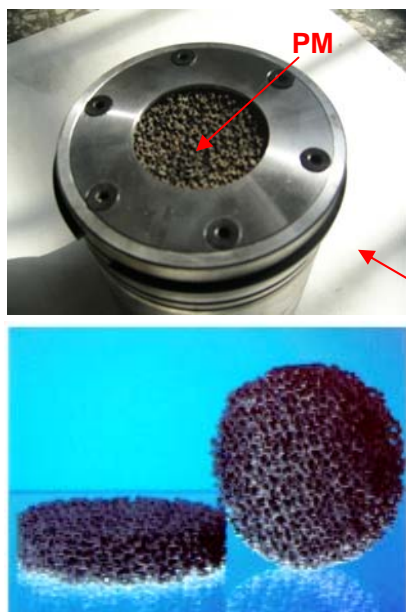


Fig. 2. View of piston head structure and PM.

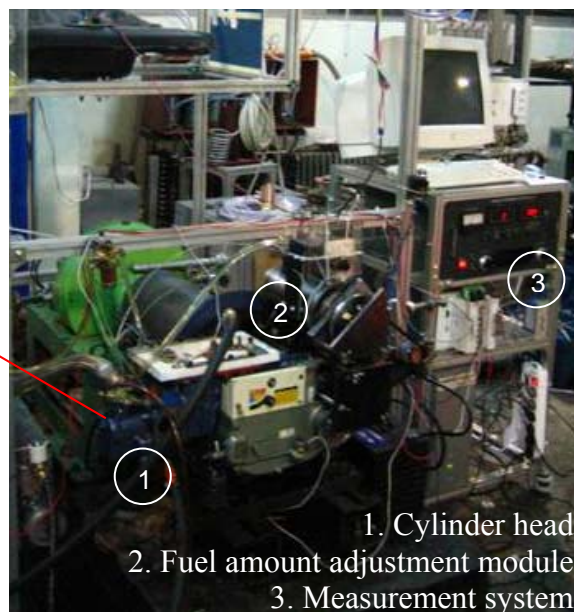


Fig. 3. View of engine test.

Table 1. Engine parameter (a), physical properties of PM activator (b)

Description	Specification	Material	SiC
Engine type	4 stroke-cycle, Water-cooled Diesel Engine	Porosity (%)	91,88
Bore X Stroke	95 X 95 (mm)	Connection density (per mm ³)	0.0311
Injection Type	Direct Injection	Density, ρ , kg/m ³	3200
Compression Ratio	18	Module elasticity, (E, GPa)	~100
Maximum Power	13/2400 (ps/rpm)	Theoretical strength, (GPa)	~10
Injection Timing	BTDC 22°	Experimental strength, σ_{exp} , GPa	~0.1
Piston Displacement	0.673l	Melting temperature, (T_{melt} , K)	2813
		Limit temperature, $T_{lim} \sim 0.8 * T_{melt}$, K	2250
		Heat capacity, (C_s , J/(kg*K))	270
		Thermal conductivity, (W/(m*K))	3
		Thermo diffusivity, (a_s , m ² /s)	$3.5 * 10^{-5}$

For the experiment with PM reactor, a single cylinder DI Diesel engine was adopted to operate as a PM engine (e.g. see Table 1). The PM reactor was mounted on the piston head as in Fig. 2. and Fig. 3. Fuel amount adjustment module was designed to keep engine work stably with variable factors from environment. We used Teledyne Analytical Instrument (model 9110AH) as analyzer for gases emission and National Instrument modules for measurement and control (for Fuel amount adjustment module).

PM engine test result

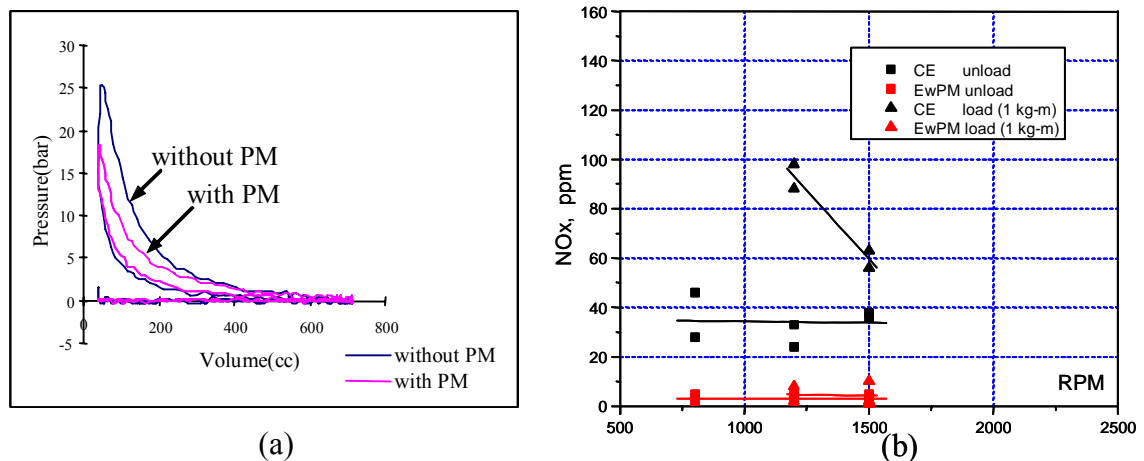


Fig. 4. (a) P-V diagram, (b) NOx emission with untreated PM reactor.

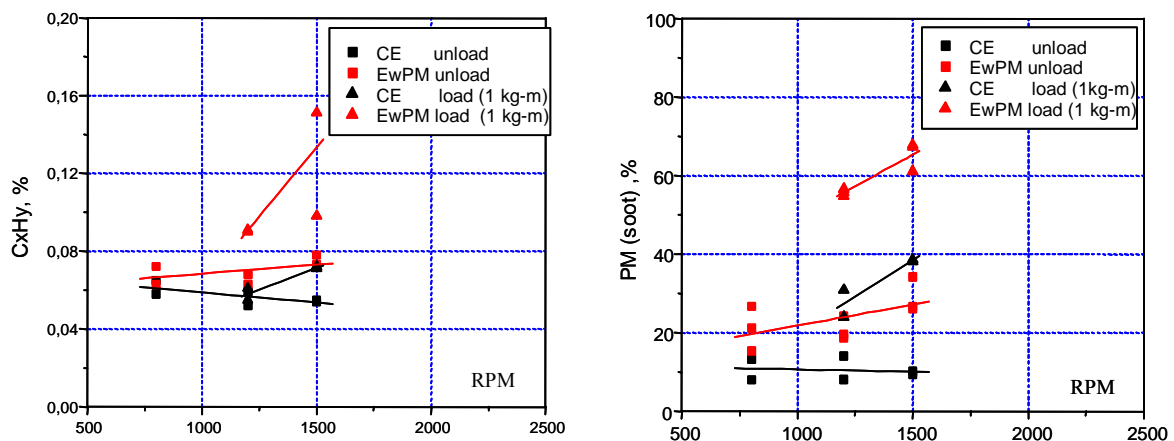


Fig. 5. CxHy and Soot

The first results (described in Fig. 4. and 5.) showed that NO_x was reduced significantly in case of using PM reactor. But decreasing the NO_x has occurred together with increasing of CO, the non burned fraction of C_xH_y and PM (solid particle components).

PM surface test result

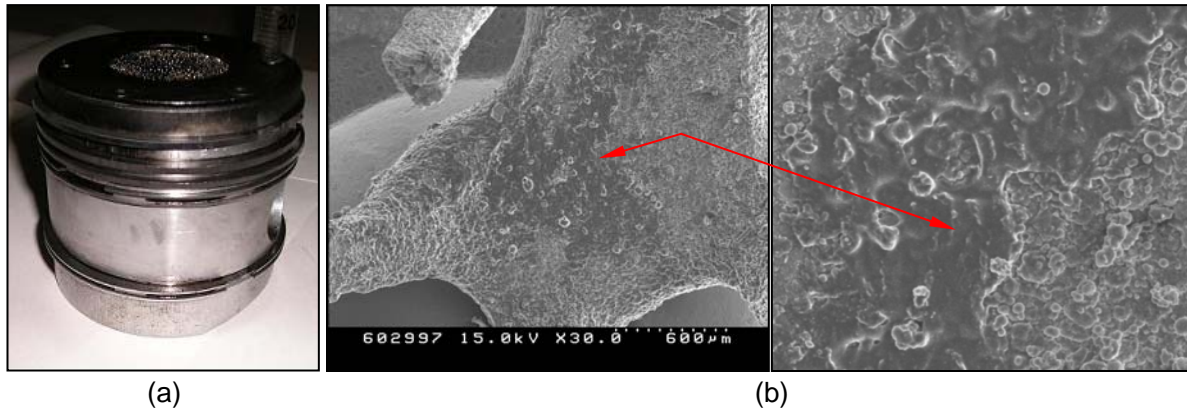


Fig. 6. Piston head (a), and liquid layer adhered on PM surface (b).

There are some evidences of unburned diesel oil layer adhered onto PM surface, Fig. 6b. This phenomenon is caused by unequal distribution of fuel over the activator surface. It is one of the reasons that causes uncompleted oil vaporization. It decreases effect of PM activator in forming high combustible mixture for homogenous combustion and heat exchanged between PM material and gases.

EXPERIMENTAL RESEARCH OF SURFACE TREATMENT

One of the key factors of porous structure is large inner surface area ($10^2 - 10^4$ /m depending on the pore size). This advantage allows PM to be used as effective vaporizer. Liquid fuel, when injected into PM volume, will be distributed widely over this surface, forming very thin wall films. By the strong heat from PM material, it could be easily heated and vaporised. The quality of vaporisation process and forming flammable mixture will be partially influenced by this specific surface area. Our experimental research showed that the wettability of diesel oil on PM surface could enhance the specific area and vaporization process. It also pointed out that, by improving wettability of PM surface, the contact angle between solid and liquid drop will be reduced. This result also directly restricts the bending phenomenon of flow when flowing through high porosity PM structure. So, it improves to some extent the efficiency of heat exchange between air-fuel and combustion speed.

Plasma treatment to enhance wettability and minimize oxidation

Comparative research of PM surface treatment was performed with two kinds of gases, an inert gas plasma such as helium (He) and an oxygen-containing plasma such as nitrous oxide - N₂O Plasma .

The experiment with He and N₂O were carried out separately at same condition. The N₂O (He) gas was flown into the chamber at about 750-2000 sccm. This chamber was kept at 100-400 °C and maintained at 4-9 Torr. A single RF power source (13.56 MHz, 1.4-5.7 W/ in²) was used to deliver 300W to the chamber. The substrate is exposed to plasma for 40 seconds.

After that, the specimens were subjected to O₂ plasma exposure for 30 minutes. The system is described in Fig. 7.

Table 2. Process regime using He, N₂O Plasma.

Parameter	Range	Preferred	More preferred
He, N ₂ O (sccm)	100-4000	500-2500	750-2000
Press. (Torr)	1-12	2-10	4-9
RF Power (W)	50-800	100-500	100-400
RF Power	0.7-11	1.4-7.2	1.4-5.7
Density (W/ in ²)			
Temp. (°C)	0-500	50-450	100-400
Spacing (mills)	200-700	300-600	300-500

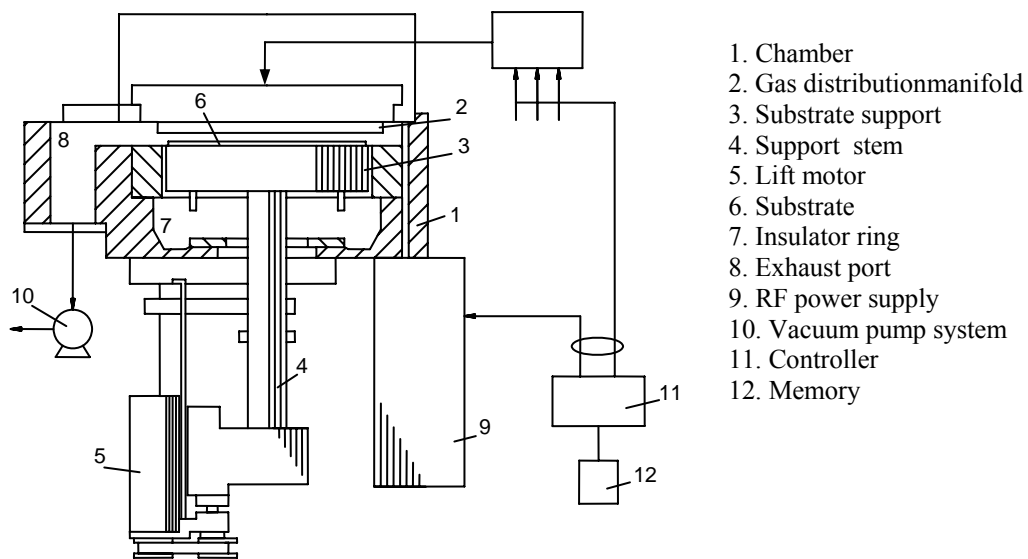


Fig. 7. Plasma treatment system.

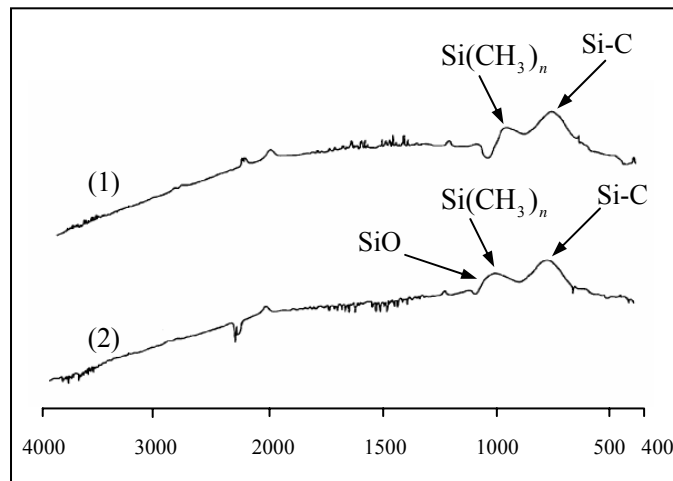


Fig. 8. FTIR analysis of SiC treated with He (1) and N₂O plasma (2).

Fig. 8. shows the bonding structure of treated SiC layer after treatment with He (1), and with N₂O (2). As can be seen, the He plasma has unremarkable effect on the composition and bonding structure of the specimen. It also showed no appreciable effect from O₂ plasma

exposure. From line (2), the N₂O plasma treatment alters the bonding structure of specimen, especially with Si – O bonding. There appears no major difference in bonding structure between specimen treated by N₂O plasma and after subsequent O₂ plasma exposure.

The results confirm that the He plasma does not significantly affect the composition of SiC layer as N₂O plasma treatment does. And it is supposed that the reaction of oxygen from N₂O with SiC surface to form a Si – O and C – O bonding will reduce dangling bonds and improves the wettability and oxidation resistance.

Table 3. ESCA/XPS of bonding structural change.

Sample	Si – C	C – C, C – H	C – O	O = C – O
Base	69	30	1	–
He Plasma	68	29	3	–
N ₂ O Plasma surface	–	78	20	2
N ₂ O Plasma bulk	84	16	–	–

Table 3. shows data of Electron Spectroscopy for Chemical Analysis/ X-Ray (ESCA/XPS) analysis report detailing the chemical bonding structure. The results show that the bonding structure does not change much with He plasma treatment. However, the SiC surface composition is modified with the N₂O plasma treatment resulting in the increase of C – C and C – O bonds to passivate the Si dangling bonds. It is well known that the polarity of C = O double bond is more intense than that of C – O bond. So, the rise in C = O bond plays the most important role in decreasing contact angle and improving the wettability on SiC surface (e.g. see references (7)).

Experiment of oxidation resistance

Two PM specimens were treated with He and N₂O plasma according to previous conditions. Another one was left untreated as a comparison specimen. The substrate was exposed to the plasma for about 20 seconds. Thickness measurements were taken before and after while ashing process with used an oxygen plasma to remove a photoresist layer. Experiment results were shown in Table 4.

Table 4. Thickness of specimens after treatment (Å).

Sample Sic	Thickness before ashing			Thickness after ashing		
	Oxide layer	SiC layer	Total	Oxide layer	SiC layer	Total
Base untreated layer	40	2895	2935	191	2874	3065
He Plasma	0	3108	3108	60	3008	3068
N ₂ O Plasma surface	210	2821	3821	255	2673	2928

A large increase in the layer thickness from oxidation can affect the characteristics of the overall layer, by increasing the dielectric constant or decreasing the ability of a barrier layer to resist metal diffusion. Thus, it is desirable to minimize any increase in the oxidized layer thickness. From Table 4., the oxide layer thickness of untreated SiC layer increases 150 Å

(from 40 to 191 Å). In contrast, the oxide layer thickness of the SiC layer treated with He plasma increases only 60 Å (from 0 to 60 Å) and 45 Å with N₂O plasma treatment. The test result shows that the treated SiC layer resist oxidation from ashing about 300% more than the untreated SiC layer.

Engine test with treated PM activator

After treatment with N₂O plasma, PM activator was installed again onto piston head and the engine test was performed with same as previous condition.

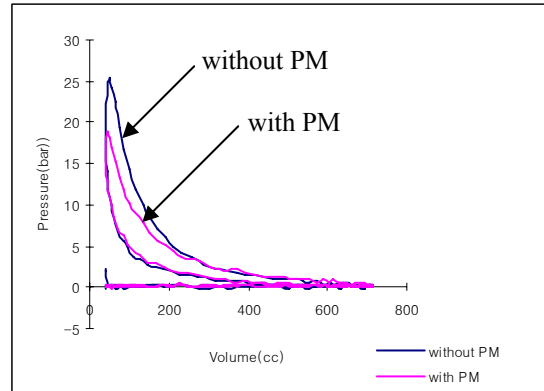


Fig. 9. P-V diagram with PM reactor after treatment.

Table. 5. Emission test result.

Heat activator	rpm	Load, Kg - m	NO _x , (ppm)	CO, (ppm)	C _x H _y , %	PM, %
Without PM	1200	0	24-33	245-290	0.052-0.059	8.1-14.1
Untreated			2-5	150-255	0.063-0.068	18.6-24.2
Treated			2-4	147-239	0.058-0.059	16.99-22.3
Without PM	1200	1	88-98	330-350	0.055-0.061	24-30.8
Untreated			2-8	440-810	0.090-0.091	54.6-55.7
Treated			2-8	440-807	0.083-0.087	54-55.2
Without PM	1500	0	36-38	330	0.054-0.058	9.3-10.2
Untreated			1-5	345-420	0.073-0.078	26.1-34.2
Treated			1-6	333-410	0.07-0.075	26.5-35
Without PM	1500	1	63-56	620-700	0.071-0.072	38.2-38.6
Untreated			1-10	1020-1900	0.098-0.151	61.1-67.8
Treated			1-10	995-1805	0.092-0.105	58.3-65.2

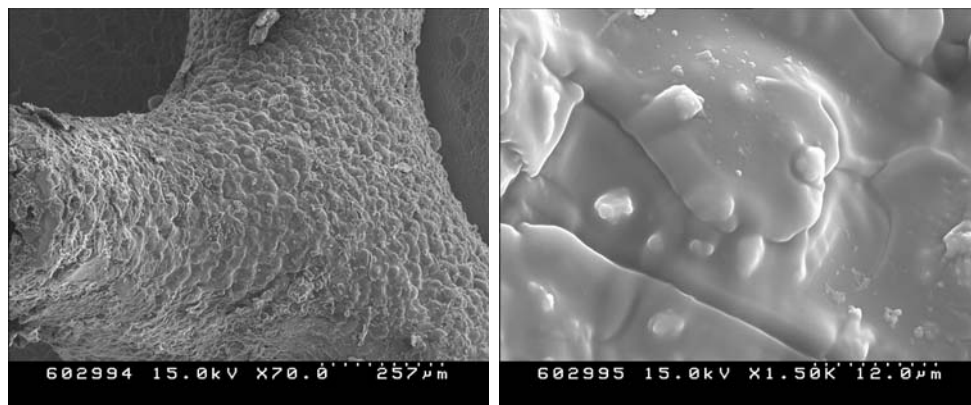


Fig. 10. Surface of treated PM after engine test.

RESULT AND CONCLUSION

Power of engine and emission is respectively described in Fig. 9. and Table. 5. There are desirable changes in engine performance. The engine generated power was increased 2% compared to engine with untreated PM activator. Emission was reduced but still higher than which coming from engine without activator. In other research, we found that the way we mounted PM activator and injection timing (turbulence created by cavity and injection angle, blue regions in Fig. 11.) influenced to emission. However, in this work, surface treatment by plasma proved its effect on PM (SiC) surface in order to improve engine performance and activator durability.

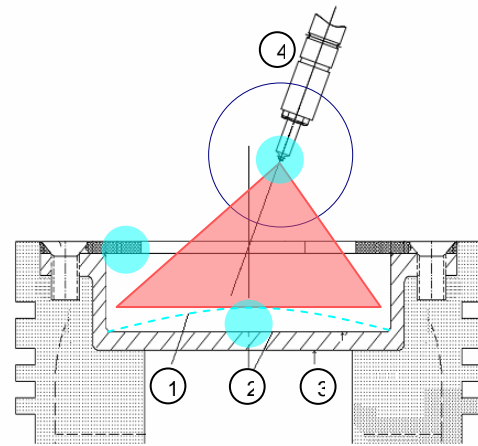
Fig. 10. shows the picture of treated PM surface layer after engine testing. There is no evidence of unburned oil adhered onto it. Visually, plasma treatment modifies PM surface to enhance spreading equally over activator and therefore minimizes sticking of unburned oil on this activator.

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1. Porous media heat activator
2. Thermal insulator
3. Steel cap for porous activator
4. Injector

Fig. 11. Structure of piston head and relative position of PM volume with injector at injection timing