SMART CERAMIC MATERIALS FOR HOMOGENEOUS COMBUSTION IN INTERNAL COMBUSTION ENGINES – A REVIEW

by

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The advantages of using ceramics in advanced heat engines include increased fuel efficiency due to higher engine operating temperatures, more compact designs with lower capacity cooling system. Future internal combustion engines will be characterized by near zero emission level along with low specific fuel consumption. Homogenous combustion which realized inside the engine cylinder has the potential of providing near zero emission level with better fuel economy. However, the accomplishment of homogeneous combustion depends on the air flow structure inside the combustion chamber, fuel injection conditions and turbulence as well as ignition conditions. Various methods and procedures are being adopted to establish the homogeneous combustion inside the engine cylinder. In recent days, porous ceramic materials are being introduced inside the combustion chamber to achieve the homogeneous combustion. This paper investigates the desirable structures, types, and properties of such porous ceramic materials and their positive influence on the combustion process.

Key words: *porous ceramic material, internal combustion engine, homogeneous combustion*

Introduction

In internal combustion engines, ceramics are being considered in three general categories: discrete components in turbochargers for reciprocating engines, coatings and monolithic hot-section components in advanced diesel designs, and all-ceramic gas turbine engines. In the late 1980, when engine developers were working on the adiabatic combustion engine, advanced ceramics seemed to solve one of their main problems, which was to be able to run the engine without any oil – a necessity at the required high temperature level.

Compared with metals, ceramics have superior wear resistance, high-temperature strength, and chemical stability. Generally, they have lower thermal, electrical conductivities and also lower toughness. The lower toughness of ceramics (brittleness) causes them to fail suddenly when applied stress is sufficient to propagate cracks which originate at microscopic flaws (*e. g.*, cracks, voids or inclusions as small as 20 μm) in the material and this can occur at a stress value of 2069 MPa and above. The toughness of ceramics could be normally made higher through flaw size reduction. The unpredictable failure caused by poor control over flaw populations is the most serious handicap to the use of structural ceramics in load-bearing structures [1]. However with advanced ceramics, this difficulty can be overruled and they are now being predominantly used in the combustion chamber of reciprocating engines to achieve homogeneous combustion [2]. Researchers around the world are now focusing on the potential utilization of unique characteristics of ceramics for homogeneous combustion in internal combustion engines for fuel economy and emission reduction.

Homogeneous combustion

Introduction to homogenous combustion

Homogeneous combustion is defined as a process in which, a 3-D volumetric ignition of the homogeneous charge is followed by simultaneous heat release (no flame front) in the whole combustion chamber volume characterized by a homogeneous temperature field [3-5]. This is demonstrated in fig.1.

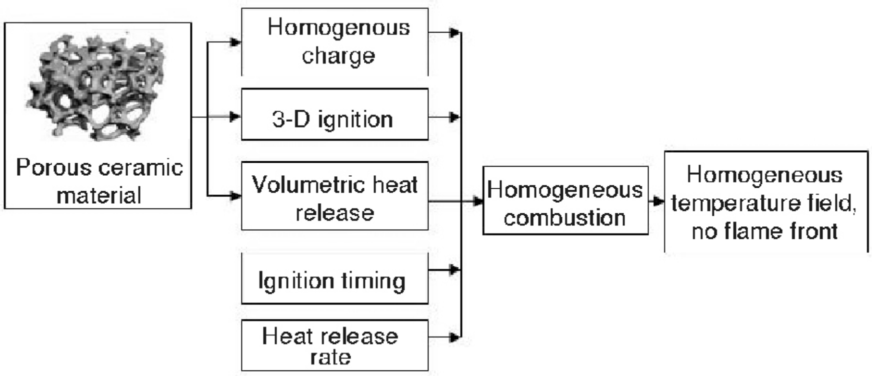

Figure 1. Definition of homogeneous combustion and the influence of porous ceramic materials on combustion

To realize a homogeneous combustion in a practical diesel engine, it is evident from the above definition that, in addition to the control of ignition timing and heat release rate; three necessary conditions namely homogeneous charge, 3-D ignition and volumetric heat release are to be effectively satisfied [3-5]. These three conditions are fulfilled with ease, by the introduction of porous ceramic materials inside the combustion chamber and utilizing their unique and specific characteristics [6] rather than employing other complex techniques such as variable compression ratio, variable induction temperature, variable exhaust gas recirculation, and variable valve actuation.

Salient features of homogeneous combustion

(1) It provides up to 15% fuel savings, while meeting current emissions standards.
(2) The mode of operation is closer to the ideal Carnot cycle during compression and heat release.
(3) Overall lean operation leads to higher cycle efficiency.
(4) Homogeneous mixing of fuel and air leads to cleaner combustion with significant low peak temperatures, which in turn leads to lower nitric oxide (NO_x) emissions.

As the positive aspects of homogeneous combustion are numerous, engine researchers are now trying to establish the homogeneous combustion in internal combustion engines by putting various techniques into practice. In this aspect, the introduction of small ceramic materials in the form of porous media inside the combustion chamber has been found to be a promising technique and the selection of suitable ceramic materials for this purpose draws the attention of the researchers all around the world.

Features and requirements of porous ceramic materials for homogeneous combustion in engine applications

Numerous important parameters should be considered while selecting porous ceramic materials to realize the homogeneous combustion in internal combustion engines. In these parameters, the features that are directly related to the combustion and heat transfer processes are very important (*e. g.* specific surface area, flame propagation, heat transport properties, heat capacity and transparency for fluid flow). The pore structure, density, thermal resistance and mechanical properties of porous ceramic materials under high pressure and temperature are equally important for homogeneous combustion [2].

To support the engine combustion processes, the major features that must be possessed by the porous ceramic materials are depicted in fig. 2 [2, 7].

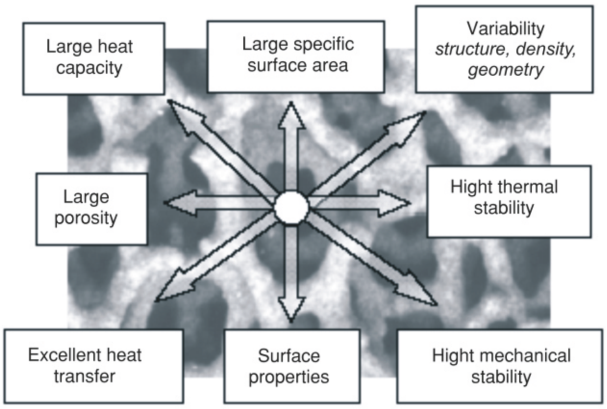

Figure 2. Main features of porous ceramic structures to support individual engine processes
(Courtesy: Miroslaw Weclas [2])

Features of porous ceramic materials for homogeneous combustion

Excellent heat transfer characteristics

The heat conductivity of ceramic material can be chosen of several orders of magnitude higher than that of gas mixture inside the cylinder. Even with a porosity of 95 percent, the overall conductivity will be 300-500 times higher than the gas mixture which results in 16 to 20 times higher combustion velocities. The high thermal conductivity of porous ceramic material contributes a better temperature distribution in axial and radial direction and accordingly cycle peak temperature will be eliminated which are the major contributors of NO_x [5, 8, 26]. Additionally, there is strong cooling of the reaction zone and in consequence the thermal NO_x formation is significantly reduced (low temperature combustion) [2].

Large porosity

Ceramic materials with porosity over about 80% are preferable for engine applications, since they provide transparency for gas and liquid flows as well as for flames. This transparency permits low pressure losses in fluid flow through the ceramic materials. Porosity can be deliberately generated through the appropriate selection of raw materials, the manufacturing process, and in some cases through the use of additives [5, 9, 10]. The volume distribution of typical porous ceramic material adopted for engine applications is shown in fig. 3.The pressure drop over the ceramic foams with different porosities (in ppi – pores per square inch) is shown in fig. 4. Large transparency permits low pressure losses in fluid (gas) flow through the porous ceramic material volume and assists in the preparation of homogeneous charge [2].

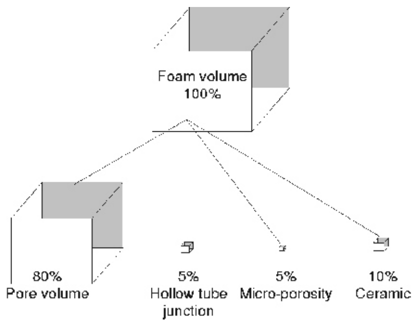

Figure 3. Typical volume distribution of a porous ceramic material for engine applications

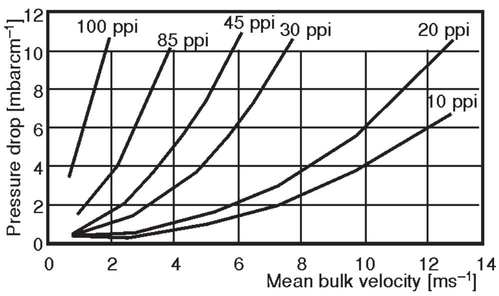

Figure 4. Pressure drop *vs.* mean bulk velocity (for different pore density of ceramic foams in engines)

Large specific surface area

Large specific surface area allows the porous ceramic material to be used effectively as a vaporizer. The fuel can thus be distributed over this surface, providing very thin wall films that can easily be heated and vaporized. This specific surface area depends on the pore density, its geometry and the basic structure used for manufacturing of ceramic material [2, 6, 10]. Ceramic materials with larger specific surface area are chosen for engine applications as they promotes vaporization of fuel that consequently ends with the preparation of homogeneous charge, which is the pre-requisite for homogeneous combustion [2].

High heat capacity

The heat capacity of the ceramic material should be chosen as high. Owing to this high heat capacity, high combustion stability can be achieved. Part of the heat released during the combustion process is accumulated inside the porous material resulting in a high temperature of the solid phase surface, which positively influences the cold start conditions [2, 6, 11, 13, 14].

High mechanical and thermal stability

It is one of the important features since the porous ceramic material is going to be operated under high temperature and pressure conditions. When the ceramic material is mounted on the piston top cavity, it will become a critical factor. Accelerations up to 500 of earth acceleration and large temperature gradients are usual. The ceramic must be stable enough to overcome these situations [2, 6].

Requirements of ceramic materials for engine applications

(1) Compactness: In automotive engines, the space inside the combustion chamber is limited. Therefore, the ceramic structure that is going to be introduced should be compact in size.
(2) Power turndown: The heat source has to allow the complete process to be operated in a wide range of power outputs.
(3) Multi-fuel capacity: For automotive applications, it is essential that the engine must be capable of running with a wide range of fuels such as gasoline, natural gas, hydrogen or even rapeseed oil, industrial gas oil, and rich methyl esters. Hence, it is essential that the porous ceramic structure must admit the burning of different gaseous and liquid fuels with consistent high performance.
(4) Emission output: The emission output of the resultant homogeneous combustion owing to the porous ceramic structure has to be very low over the complete dynamic power range and for a diversity of fuels [7, 16, 17]

Feasible porous ceramic materials, structures for homogeneous combustion

Ceramic materials

The material selection for porous ceramic structure to operate at elevated temperature is crucial, because of severe thermal and chemical stresses and the possibility of cracking. Thus the material selected for the purpose should be high temperature resistant. Number of studies have been carried out to identify the suitable materials, which can withstand the high temperature inside the combustion chamber and to provide satisfactory results. The ceramic materials such as aluminum oxide (Al_2O_3), silicon carbide (SiC), zirconium dioxide (ZrO_2), and silicon nitride (Si_3N_4) in the form of foam, lamellas or mixture structures are found to be appropriate for stated application [17, 22]

Zirconium oxide

Zirconium oxide occurs as monoclinic, tetragonal, and cubic crystal forms. This is shown in fig. 5. Densely sintered parts can be manufactured as cubic and/or tetragonal crystal forms. In order to stabilize these crystal structures, stabilizers such as magnesium oxide (MgO), calcium oxide (CaO) or yttrium oxide (Y_2O_3) need to be added to the ZrO_2. Other stabilizers sometimes used are cerium oxide (CeO_2), scandium oxide (Sc_2O_3), or ytterbium oxide (Yb_2O_3).

In fully stabilized zirconium oxide, the high-temperature cubic structure is preserved even after cooling due to the addition of the other oxides into the crystal structure. Rapid increase in volume at elevated temperature, which is undesirable for technical applications, does not take place in fully stabilized zirconium oxide [18, 19, 24, 25].

Partially stabilized zirconium oxide is of great technical significance. At room temperature, the substance includes a coarse cubic phase with tetragonal regions. This state can be retained in a meta-stable form through appropriate process control or annealing techniques. This prevents transformation of the tetragonal phase to the monoclinic phase, and the

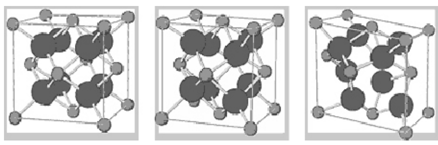

Figure 5. Zirconium oxide: cubic, tetragonal, and monoclinic crystal lattices *light spheres = Zr, dark spheres = O*

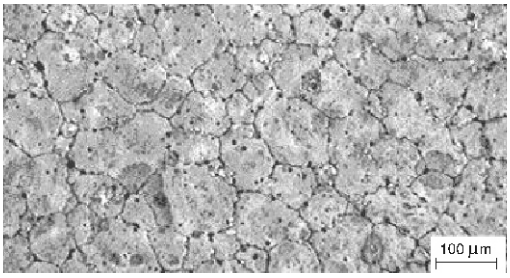

Figure 6. Microstructure of partially stabilized zirconium oxide
(Courtesy: Brevier Technische Keramik

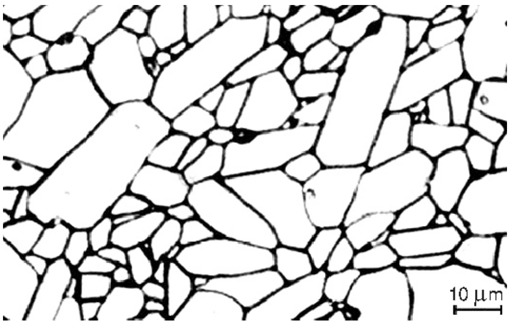

Figure 7. Microstructure of aluminium oxide ceramic (99.7%)
(Courtesy: Brevier Technische Keramik

Figure 8. Microstructure of coarse-grained SSIC (etched)
(Courtesy: Brevier Technische Keramik [20])

microstructure is "pre-stressed"; this is associated with an increase in strength and toughness. The microstructure of such a material is shown in fig. 6 [1, 17, 20, 21].

Aluminum oxide

Aluminum oxide which has the widest range of applications is characterized by its high strength, hardness, temperature stability, high wear and corrosion resistance. Synthetically manufactured materials with aluminium oxide contents ranging from 80% to more than 99% have been proven in practice. The outstanding values of bending strength, wear resistance and high temperature stability make the aluminium oxide suitable for mechanical applications especially in engine applications in the form of static mixer [1, 20].The microstructure of aluminium oxide ceramic is exposed in fig. 7.

Silicon carbide

Depending on the manufacturing technique, it is necessary to distinguish between self-bonded and second-phase bonded silicon carbide ceramics, as well as between open porous and dense types.

Open porous silicon carbide:
- silicate-bonded silicon carbide,
- recrystallized silicon carbide (RSIC), and
- nitride bonded silicon carbide (NSIC).

Dense silicon carbide:
- reaction bonded silicon carbide (RBSIC),
- silicon infiltrated silicon carbide (SISIC),
- sintered silicon carbide (SSIC), and
- hot pressed silicon carbide (HPSIC).

Out of the many silicon carbide types listed above, the sintered silicon carbide is found to be more suitable for combustion applications. Sintered silicon carbide is produced using very fine SiC powder containing sintering additives. It is processed using forming methods and sintered at 2000-2200 °C in an inert gas atmosphere. This is distinguished by high strength that stays nearly constant up to very high temperatures (approximately 1.600 °C), maintaining that strength over long periods [1, 17, 20, 21]. The microstructure of a sintered silicon carbide ceramic is shown in fig. 8.

Ceramic structures

Different porous structures have been tried inside the combustion chamber (on the piston top cavity) to enhance the individual engine processes and to achieve the homogeneous combustion. Range of ceramic materials in the form of static mixer, foam and high density wire packing has been attempted and been found to produce a realistic outcome. Those different forms are presented in fig. 9 [2].

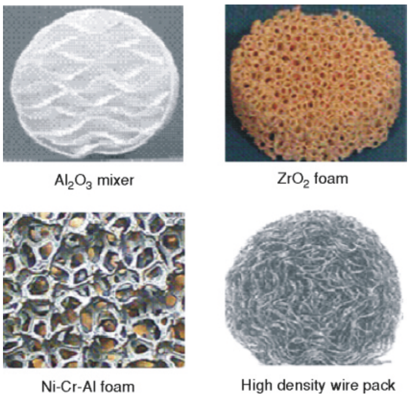

Figure 9. Different porous structures
(Courtesy: Miroslaw Weclas [2])

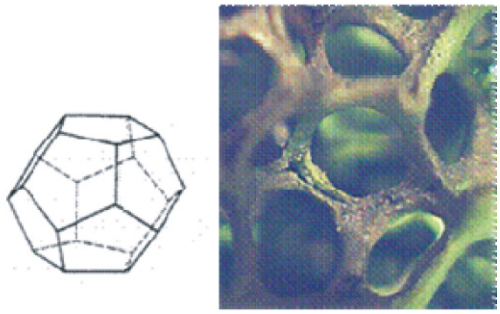

Figure 10. SiC foam structure
(Courtesy: Miroslaw Weclas [2])

If ceramic foam has been used, then the cells of ceramic foam would be idealized as a pentagonal dodecahedron. The edges of the dodecahedron are the struts of the ceramic foam. Typical example of SiC foam and its structure is shown in fig.10. The different pore densities for SiC foam is given in fig.11 [2]. It has been revealed from the literature that the ceramic foam with large porosity is preferable for engine applications since this makes the porous media transparent for gas flow, spray, and flame [3, 4, 6, 23].

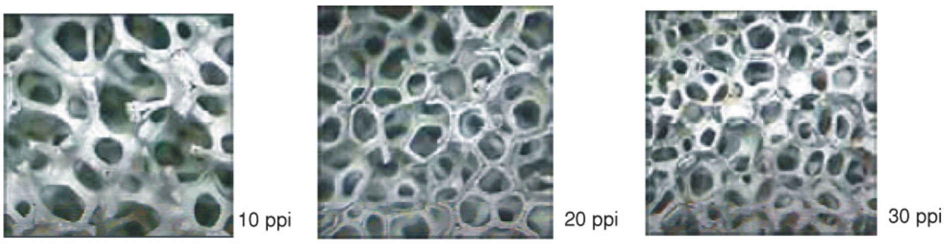

Figure 11. Different pore densities for SiC foam
(Courtesy: Miroslaw Weclas [2])

Thermal properties of porous ceramic materials to promote homogeneous combustion

The most important thermal properties of porous ceramic materials for internal combustion engine applications are given in tab.1.

Table 1. Thermal properties of porous ceramic materials (Courtesy: Miroslaw Weclas [2])

Material	Specification	Mean linear thermal expansion coefficient		Heat conductivity	Melting point	Application temperature
		30-100 °C [$10^{-6}K^{-1}$]	30-600 °C [$10^{-6}K^{-1}$]	[$Wm^{-1}K^{-1}$]	[°C]	[°C]
PSZ	Partly stabilized zironoxide		9-13	1.2-3	2700	900-2400
ATI	Aluminum titanate		5.0	1.5-3		900-1600
Al_2O_3	Aluminum oxide 80%	5-7	6-8	10-16	2050	1400-1500
Al_2O_3	Aluminum oxide 86%	5.5-7.5	6-8	14-24		1400-1500
Al_2O_3	Aluminum oxide 95%	5-7	6-8	16-28		1400-1500
Al_2O_3	Aluminum oxide > 95%	5-7	7-8	19-30		1400-1700
SSN	Sintered silicon nitride		2.5-3.5	15-45		1750
RBSN	Reaction bound silicon nitride		2.1-3	4-15		1100
HPSN	Hot forced silicon nitride		3.0-3.4	15-40		1400
AIN	Aluminum nitride	2.5-4	4.5-5	100-180		1750
SSIC	Pressureless sintered silicon carbide		4-4,8	40-120	2800*	1400-1750
SISIC	Silicon infiltrated silicon carbide		4.3-4.8	110-160		1380
HPSIC	Hot forced silicon carbide		3.9-4.8	80-145		1700
RSIC	Recrystallized silicon carbide	4.2	4.8	20		1600
NSIC	Nitride bound silicon carbide	4.2	4.8	14-15		1450
PS 1	Iron-chromium--aluminum alloy			13	1500	1400

* Dissociation starts at temperatures over 2000 °C

Influence of porous ceramic materials on homogeneous combustion

Silicon carbide foam and the corrugated structures made from Al_2O_3 fibers, ZrO_2 foam, and C/SiC composite ceramics are introduced in the combustion chamber either in the cylinder clearance volume, cylinder head or on piston top. This cause eddies, flow separation, unification of air fuel mixture together with augmentation of the radiation and thermal conduction. Thus, the individual in-cylinder requirements for homogeneous combustion are fulfilled by the porous ceramic structures that are introduced inside the engine cylinder. The individual engine processes supported by these ceramic structures are depicted in fig.12 [3].

Energy recirculation in the form of hot burned gases recirculation considerably influences thermodynamic properties of the charge in the cylinder and control the ignitability of the charge. The unique features of liquid jet distribution and homogenization throughout the porous ceramic material volume is very attractive for fast mixture formation. Combination of large heat capacity, large specific surface areas with excellent heat transfer of ceramic material make the liquid fuel vapourization very fast and complete. The flow inside the 3-D structures allows very effective mixing and homogenization [12]. When the temperature of ceramic material is equal to ignition temperature under certain thermodynamic properties and mixture composition, there is a new kind of ignition called flameless combustion (homogeneous combustion) created automatically in the combustion chamber volume. Due to inherent characteristics of ceramic materials, the heat is released under controlled temperature [2-4]. This ceramic material could be well accommodated in any of the following engine locations: cylinder head, inside the cylinder, and piston top cavity [2, 27]. A single cylinder direct injection diesel engine cylinder head fitted with ceramic material in space between the valve spaces is shown in fig. 13. The engine is provided with common rail direct injection and the high pressure fuel pump is externally powered.

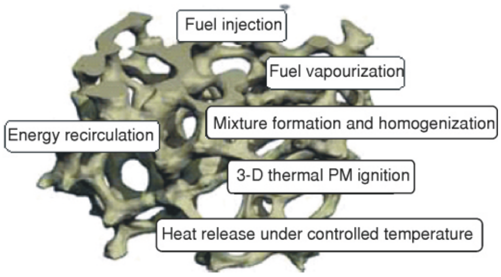

Figure 12. Individual engine processes supported by ceramic structures
(Courtesy: Miroslaw Weclas [3])

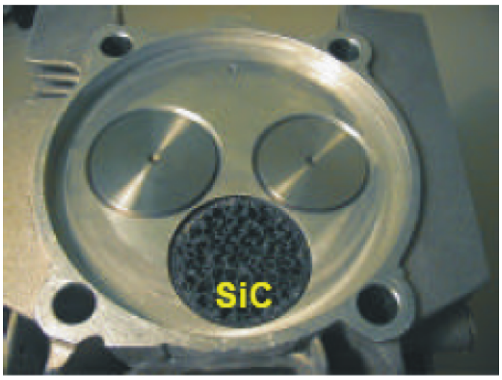

Figure 13. View of engine head with SiC ceramic material mounted in space between valves
(Courtesy: F. Durst, [5])

The performance and emission assessments conducted on the modified engine shows that even under the same operating conditions, the engine under investigation is producing NO_x in the range of 100-300 mg/kWh (with excess air factor, λ = 1-3.3) while the conventional engine produces NO_x between 3000-5000 mg/kWh (with λ = 4-7). The CO emissions from the modified engine is less than 1000 mg/kWh whilst the conventional engine has typical CO emissions of 5-6 g/kWh [5, 6]. It reveals that CO emission could be reduced by a factor of 5 comparing to a conventional engine. The modified engine also shows a considerable reduction in soot even when the engine is operated with no excess air (λ = 1) due to homogeneous mixing of fuel with air inside the combustion chamber [5].

Summary and concluding remarks

There is no doubt the future of the internal combustion engine is related to homogeneous combustion process in a wide range of engine operational condition due to its potential for a near zero combustion emission (especially NO_x and soot) as well as high cycle efficiency. This paper investigates the potential realization of homogeneous combustion with controlled temperature in the porous ceramic material independent of the engine operational conditions. The temperature control is determined by the heat recuperation by the porous ceramic material. Constant temperature and the corresponding cylinder pressure distribution are responsible for high cycle efficiency and low combustion noise as compared to conventional engines.

From the experimental tests, it has been established that all processes (gas flow, fuel injection, spatial distribution, vaporization, homogenization, ignition, and combustion) can be controlled or positively influenced with the help of porous ceramic structures/ceramic foams. The first experiments on porous ceramic material implemented engine reveal that the measured NO_x and CO emissions were substantially lower than conventional engine. The soot reduction was also significant even when the engine was operated with no excess air. The combustion noise was also reduced due to quite running of the modified engine [5].

The optimization of thermal, mechanical properties of ceramic materials, the appropriate choice of pore structure and the proper selection of pore density for particular application draws the attention of researchers all around the world. The development of entirely new materials and structures exclusively relevant to engine combustion processes is still under progress.

References

[1] ***, U. S. Congress, New Structural Materials Technologies: Opportunities for the Use of Advanced Ceramics and Composites – A Technical Memorandum, Office of Technology Assessment, OTA-TM-E-32, U. S. Government Printing Office, Washington DC, USA, 1986
[2] Weclas, M., Potential of Porous Medium Combustion Technology as Applied to Internal Combustion Engines, Sonderdruck Schriftenreihe der Georg-Simon-Ohm-Fachhochschule Nürnberg, Germany, Nr. 32 (2001), ISSN 1616-0762
[3] Weclas, M., Strategy for Intelligent Internal Combustion Engine with Homogeneous Combustion in Cylinder, Sonderdruck Schriftenreihe der Georg-Simon-Ohm-Fachhochschule Nürnberg, Germany, Nr. 26 (2001), ISSN 1616-0762
[4] Kannan, C., Tamilporai, P., Porous Medium Combustion in Diesel Engine with Biodiesel Blends – Future Low Emission Engine – A Review, *i-Manager's Journal on Future Engineering and Technology, 3* (2008), 3, pp. 27-38
[5] Durst, F., Weclas, M., A New Concept of IC Engine with Homogeneous Combustion in a Porous Medium, *Proceedings*, 5th International Symposium on Diagnostics and Modeling of Combustion in IC Engines, Comodia 2001, Nagoya, Japan, 2001, pp. 467-472
[6] Durst, F., Weclas, M., A New Type of Internal Combustion Engine Based on the Porous Medium Combustion Technique, *Proc. Instn Mech Engrs, 215* (2001), Part D, pp. 63-81
[7] Durst, F., Trimis, D., Zero Emission Engine – A Novel Steam Engine for Automotive Applications, *Proceedings*, 5th International Symposium on Diagnostics and Modeling of Combustion in IC Engines, Comodia 2001, Nagoya, Japan, 2001, pp. 473-478
[8] Macek, J., Polasek, M., Porous Medium Combustion in Engines May Contribute to Lower NO_x Emissions, Joesef Bozek Research Center, Czech Technical University, Prague, Czech Republic, Paper code: F02V147
[9] Trimis, D., Durst, F., Combustion in Porous Medium – Advances and Applications, *Combust. Sci. Technol., 121* (1996), 1-6, pp. 153-168
[10] Viskanta, R., Interaction of Combustion and Heat Transfer in Porous Inert Media, *Transport Phenom. Combust., 1* (1996), pp. 64-87
[11] Sathe, S. B., *et al.*, An Experimental and Theoretical Study of Porous Radiant Burner Performance, *Proceedings,* 23rd Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Penn., USA, 1990, pp. 1011-1018
[12] Andersen, F., *et al.*, Ceramic Fiber Plates as Flame Holders, *Proceedings* (Ed. R. Finch), Conference on Ceramics in Energy Applications, Sheffield, UK, 1990, pp. 69-78
[13] Min, D. K, Yoo, Y. D, Shin, H. D., Heat Transfer in a Porous Material Having Reaction Zone, *Proceedings* (Ed. L. S. Fletcher), ASME–JSME Thermal and Fluids Engineering Conference, Seoul, South Korea 1998, pp. 1.316-1.322

[14] Hanamura, K., Chae, J. O., Echigo, R., Stabilization of Radiation Controlled Flame in a Highly Porous Medium, *Proceedings* (Ed. J. R. Lloyd), ASME/JSME Thermal Engineering, Maui, Hawaii, USA, 1991, pp. 175-180
[15] Itaya,Y., *et al*., Combustion Characteristics of a Liquid Fuel in a Porous Burner, *Proceedings* (Ed. L. S. Fletcher), ASME/JSME Thermal Engineering Conference, Maui, Hawaii, USA, 1995, pp. 99-104
[16] Xiong, T. Y., Viskanta, R., A Basic Study of a Porous-Matrix Combustor Heater, *Proceedings* (Ed. E. R. Ellul), Energy-Sources Technology Conference and Exhibition on Foss. Fuel Combust., Houston, Tex., USA, 1992, Vol. 39, pp. 31-39
[17] Pickenacker, O., *et al.*, Innovative Ceramic Materials for Porous-Medium Burners, *Interceram, 48* (1999), 5-6, pp. 1-12
[18] Aldinger, F., Baumard, J. F, Advanced Ceramic Materials: Basic Research Viewpoint, Max-Planck--Institit für Metallforschnung, Germany
[19] Fanzott, S. M., Technical Ceramics, Raw Materials, Characteristics and Field of Application, Verlag Moderne Industrie, 1987, Landsberg, Germany
[20] ***, Ceramics Technical Brevier, Association of the Ceramic Industry e. V., Fahner Verlag, ISBN 3-924158-77-0
[21] Barry Carter, C., Grant Norton, M., Ceramic Materials – Science and Engineering, Springer-Verlag, 2007, ISBN: 0387462708
[22] Pantangi, V. K., Subhash, C. M., Combustion of Gaseous Hydrocarbon Fuels within Porous Media – A Review, *Advances in Energy Research*, 2006, pp. 454-461
[23] Kamal, M. M., Mohamad, A. A., Combustion in Porous Media, *Proceedings IMechE*, Part A: *J. Power and Energy, 220* (2006), 5, pp.487-508
[24] Bhargava, A. K., Engineering Materials: Polymers, Ceramics and Composites, Prentice Hall of India, ISBN 81-203-2583-4, 2004, pp. 147-223
[25] Askeland, D., R., Phule, P. P., The Science and Engineering of Materials, 4th ed., Thomson Asia Pvt. Ltd, 2003, ISBN 981-243-855-6, pp. 625-659
[26] Yamane, K., Ueda, A., Shimamoto, Y., Influence of Physical and Chemical Properties of Biodiesel Fuel on Injection, Combustion and Exhaust Emission Characteristics in a DI-CI Engine, 5th International Symposium on Diagnostics and Modeling of Combustion in IC Engines, Comodia, 2001, Nagoya, Japan, pp. 402-409
[27] Le Duc Chien, Chae Jae Ou, Kwak Yong Hwan, Improving Surface Characteristics of Porous Medium Reactor in Diesel Engine by Plasma Technology, Korea, Paper code: F2006SC27

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