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. Homogeneous 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 homogeneous 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.

![Diagram of Homogeneous Combustion](image)

**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\textsubscript{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].

**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 NOx [5, 8, 26]. Additionally, there is strong cooling of the reaction zone and in consequence the thermal NOx 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 trans-
parity 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 and assists in the preparation of homogeneous charge [2].

![Figure 3. Typical volume distribution of a porous ceramic material for engine applications](image)

**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)](image)

**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 (Al₂O₃), silicon carbide (SiC), zirconium dioxide (ZrO₂), and silicon nitride (Si₃N₄) 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 (Y₂O₃) need to be added to the ZrO₂. Other stabilizers sometimes used are cerium oxide (CeO₂), scandium oxide (Sc₂O₃), or ytterbium oxide (Yb₂O₃).

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
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 aluminum 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 aluminum oxide suitable for mechanical applications especially in engine applications in the form of static mixer [1, 20]. The microstructure of aluminum 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].

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].

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])

<table>
<thead>
<tr>
<th>Material</th>
<th>Specification</th>
<th>Mean linear thermal expansion coefficient</th>
<th>Heat conductivity</th>
<th>Melting point</th>
<th>Application temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSZ</td>
<td>Partly stabilized zirconoxide</td>
<td>30-100 °C [10⁻⁶K⁻¹]</td>
<td>30-600 °C [10⁻⁶K⁻¹]</td>
<td>[Wm⁻¹K⁻¹]</td>
<td>°C</td>
</tr>
<tr>
<td>ATI</td>
<td>Aluminum titanate</td>
<td>5.0</td>
<td>1.5-3</td>
<td>2700</td>
<td>900-2400</td>
</tr>
<tr>
<td>AI₂O₃</td>
<td>Aluminum oxide 80%</td>
<td>5-7</td>
<td>6-8</td>
<td>10-16</td>
<td>2050</td>
</tr>
<tr>
<td>AI₂O₃</td>
<td>Aluminum oxide 86%</td>
<td>5.5-7.5</td>
<td>6-8</td>
<td>14-24</td>
<td>1400-1500</td>
</tr>
<tr>
<td>AI₂O₃</td>
<td>Aluminum oxide 95%</td>
<td>5-7</td>
<td>6-8</td>
<td>16-28</td>
<td>1400-1500</td>
</tr>
<tr>
<td>AI₂O₃</td>
<td>Aluminum oxide &gt; 95%</td>
<td>5-7</td>
<td>7-8</td>
<td>19-30</td>
<td>1400-1700</td>
</tr>
<tr>
<td>SSN</td>
<td>Sintered silicon nitride</td>
<td>2.5-3.5</td>
<td>15-45</td>
<td>1750</td>
<td></td>
</tr>
<tr>
<td>RBSN</td>
<td>Reaction bound silicon nitride</td>
<td>2.1-3</td>
<td>4-15</td>
<td>1100</td>
<td></td>
</tr>
<tr>
<td>HPSN</td>
<td>Hot forced silicon nitride</td>
<td>3.0-3.4</td>
<td>15-40</td>
<td>1400</td>
<td></td>
</tr>
<tr>
<td>AIN</td>
<td>Aluminum nitride</td>
<td>2.5-4</td>
<td>4.5-5</td>
<td>100-180</td>
<td>1750</td>
</tr>
<tr>
<td>SSIC</td>
<td>Pressureless sintered silicon carbide</td>
<td>4-4.8</td>
<td>40-120</td>
<td>2800*</td>
<td>1400-1750</td>
</tr>
<tr>
<td>SISIC</td>
<td>Silicon infiltrated silicon carbide</td>
<td>4.3-4.8</td>
<td>110-160</td>
<td>1380</td>
<td></td>
</tr>
<tr>
<td>HPSIC</td>
<td>Hot forced silicon carbide</td>
<td>3.9-4.8</td>
<td>80-145</td>
<td>1700</td>
<td></td>
</tr>
<tr>
<td>RSIC</td>
<td>Recrystallized silicon carbide</td>
<td>4.2</td>
<td>4.8</td>
<td>20</td>
<td>1600</td>
</tr>
<tr>
<td>NSIC</td>
<td>Nitride bound silicon carbide</td>
<td>4.2</td>
<td>4.8</td>
<td>14-15</td>
<td>1450</td>
</tr>
<tr>
<td>PS 1</td>
<td>Iron-chromium-aluminum alloy</td>
<td></td>
<td>13</td>
<td>1500</td>
<td>1400</td>
</tr>
</tbody>
</table>

* Dissociation starts at temperatures over 2000 °C

Influence of porous ceramic materials on homogeneous combustion

Silicon carbide foam and the corrugated structures made from Al₂O₃ fibers, ZrO₂ 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 vaporization 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.

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\textsubscript{x} in the range of 100-300 mg/kWh (with excess air factor, $\lambda = 1$-3.3) while the conventional engine produces NO\textsubscript{x} between 3000-5000 mg/kWh (with $\lambda = 4$-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 ($\lambda = 1$) 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\textsubscript{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 tem
perature 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 NOx 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.

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Authors’ affiliations:

K. Chidambaram (corresponding author)
Department of Automobile Engineering,
Sri Venkateswara College of Engineering
P. B. No. 3, Pennalur, Sriperumbudur
Tamil Nadu, India – 602 105
E-mail: tprial@yahoo.co.in

T. Packirisamy
Department of Mechanical Engineering,
College of Engineering, Anna University
Guindy, Chennai
Tamil Nadu, India – 600 025

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