COGNIZANCE ’04 – Annual Technical Festival, IIT Roorkee,
19th to 21th March 2004,Roorkee (UA).

“IDEAZ”

DEPARTMENT OF MECHANICAL ENGINEERING

CATEGORY: THERMODYNAMICS & FLUID MECHANICS

Recent Advancements of Porous Medium Combustion Technology in IC Engines and a New Concept of Cogeneration in PM-Engine

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ABSTRACT

This paper presents the recent advancement and capabilities of porous medium combustion technology for energy efficient and environmentally safe operations in IC engine. A brief identification and survey of porous material (PM) used in this area is also presented with their operating and limiting parameters. Homogenization, 3D-thermal self-ignition, wide and dynamic power regulation, extremely low pollutant emissions, incorporation of porous medium in the cylinder head, open type- and closed type- PM-engines & their working and cogeneration concept are also discussed.

Keywords: Porous media PM, Combustion, Materials, Low emission, Cogeneration.

NOMENCLATURE

S_L = Laminar fellow velocity (m/s)
d_m = Equivalent Porous cavity Diameter (m)
c_p = Specific heat capacity of PM ($J\ Kg^{-1}\ K^{-1}$)
ρ = Density of PM (Kg/m^3)
θ = The heat conductivity of gas mixture ($W\ m^{-1}\ K^{-1}$)

1. INTRODUCTION TO THE CONCEPT OF POUROUS MEDIUM COMBUSTION.

Combustion is a basic phenomenon from which we derive out the energy in the form of heat and use it for different purposes. In the last two decades, efficiency of the system hardly got proper importance since understanding towards environment was also not very good. Its in this modern era, when energy decides the currency of the country and termed as the entity of dispute, wars are fought for it. Today energy is of prime importance. We are only concerned that if a fixed amount of fuel is burnt then the energy utilized from it must be approximately equivalent to its calorific value (or to maximize the exergy part) and drawing least impact on the environment. This is all because of the energy economics, which is on runway these days.

A very new and emerging area in the field of combustion is porous media (PM) combustion. Unlike conventional premixed combustion process, the porous burner technology does not operate with a free flame. Rather the combustion takes place in a three dimensionally arranged cavities of a porous and inert media, resulting in a totally different

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flame itself compared to conventional combustion process. There are few very obvious advantages associated in this type of combustion process which are: Wide infinitely variable dynamic power range of 1:20 compared to conventional state of the art burner which shows a power range of 1:3 only; High power density, i.e., burner and heat exchanger are about 10 times smaller in volume than conventional burner and heat exchanger units for comparable loads; Very low emission due to complete combustion (CO =< 7mg/KWh and NOx =< 30 mg/KWh) over the complete dynamic power range. The emissions are well below than the most stringent norms; and stable combustion for excess air.

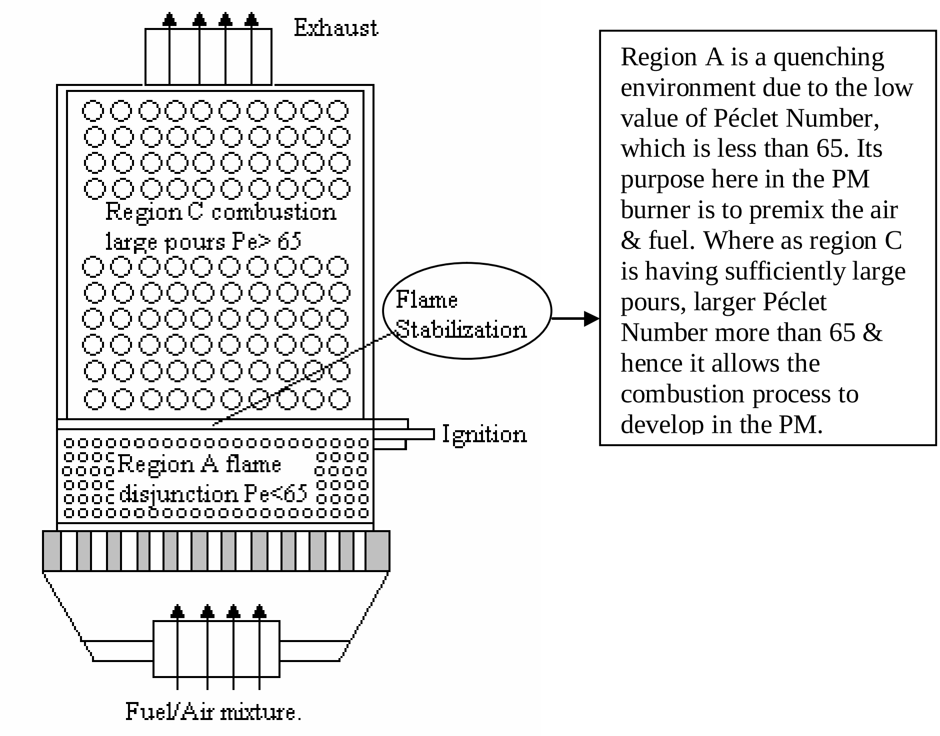

Figure 1.A. Typical schematic of porous

The combustion process is achieved in terms of power range, emission etc. The most important criterion for combustion is the critical pour size, which determines whether the combustion process would takes place in the porous media or not. If the size of the pours is too small or less than critical pour size the flame propagation will be prohibitive or quenched. If the dimension exceeds the critical pour size, flame propagation in the porous medium is possible. The critical pour size may be determined by modified expression of "Péclet Number" (P_e).

$$P_e = \frac{S_L * d_m * c_p * \rho}{\theta}$$

The combustion process is stabilized with a sudden change of the pore size corresponding to a change of the Péclet Number inside the combustion reactor. Body properties are chosen in such a way that flame propagation is not possible in region C, but in region A pour size is large enough to help develop the flame. These regions are shown in Figure 1.A.

2.0 APPLICATION OF PM-COMBUSTION TECHNOLOGY IN IC ENGINES

The advantages of low emission, high power modulation would further enhance suitability and efficiency of the process. Temperature control leads to lesser NOx formation. Heat transfer capability of PM is highly dependent on the type of material used for PM, the property of heat conduction increases as we go to the metal base PM. For fuel efficiency, power modulation is very necessary. PM burners are now designed for combined usage with conventional premixed industrial burners, wherein the combination of these two leads to greater range of power modulation. For conventional premixed industrial burners the modulation range is only **1:2.5** where as for PM burners it is up to **1:50**, so for a combined usage, power modulation of **1:50** can be achieved and it is without putting emissions at stake. Hence, at times when power requirements are very less, these burners are adjusted to very low fuel feed just to keep them alive.

Homogeneous combustion in IC engines can be achieved by a system proposed recently by (Drust et. al/Porous medium combustion in IC engines/315-334).the technique termed as 3D-thermal PM-self-ignition(3D-grid structure of a high temperature) and it uses a 3D-structured PM for volumetric ignition of homogeneous charge. The PM has homogeneous surface temperature over the most of the PM volume, higher than the ignition temperature. In this case the PM-volume defines the combustion chamber's volume. We could consider the PM volume as a large number of "hot spots" homogeneously distributed throughout the combustion chamber volume. This feature provides a thermally controlled 3D-ignition system. More over the PM controls the temperature level of the combustion chamber permitting the NOx level almost independent of the engine load or the A/F ratio.

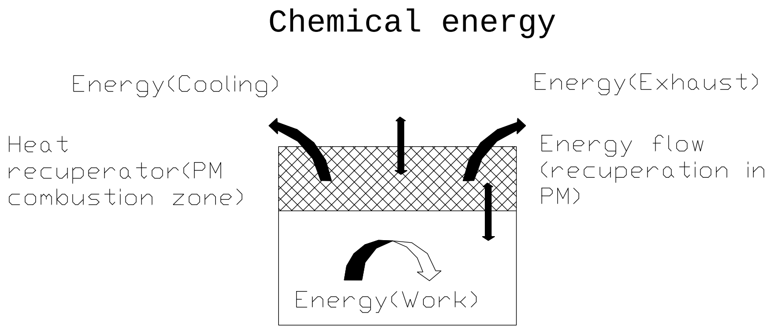

Figure 2.A. Energy components in PM-Engine

2.1 HOMOGENEOUS COMBUSTION

Homogeneous combustion in an IC engine is defined as a process characterized by a 3D-ignition of the homogeneous charge with simultaneous-volumetric-combustion, hence, ensuring a homogeneous temperature field. According to the definition given above, three steps of the mixture formation & combustion may be selected that define the ability of a given combustion system to operate as a homogeneous combustion system:

- Homogenization of charge.
- Ignition conditions.
- Combustion process & temperature field.

Four different ignition techniques may be selected:

- Local ignition (e.g., spark plug).
- Thermal self-ignition (e.g., compression ignition).
- Controlled auto-ignition (e.g., low temperature chemical ignition).

- 3D-thermal PM self-ignition (3D-grid-structure of a high temperature).

The last considered ignition system has been recently proposed by Durst and Welcas (3) and uses a 3D-structured porous medium (PM) for the volumetric ignition of homogeneous charge. The PM has homogeneous surface temperature over the most of the PM-volume, higher than the ignition temperature. In this case the PM-volume defines the combustion chamber volume. Thermodynamically speaking, the porous medium is here characterized by a high heat capacity and by a large specific surface area. As a model, we could consider the 3D-structure of the porous medium as a large number of “hot spots” homogeneously distributed throughout the combustion chamber volume. Because of this feature a thermally controlled 3D-ignition can be achieved. Additionally, the porous medium controls the temperature level of the combustion chamber permitting the NO_x level control almost independently of the engine load or of the (A/F) ratio. Let us consider the four possible combustion modes of a homogeneous charge:

- Homogeneous charge with local ignition.
- Homogeneous charge with compression ignition.
- Homogeneous charge with controlled auto-ignition.
- Homogeneous charge with 3D-thermal self-ignition in PM-volume.

In the case of local ignition we could not fulfill the requirements of the ignition defined for a homogeneous combustion. In this case a flame kernel will be followed a flame propagation in the combustion chamber. In the case of compression ignition a multi-point ignition can be achieved, except the near- wall areas. On one hand side, this process (if volumetric) would be related to very high-pressure gradients in the cylinder. On the other hand, any non-homogeneity of the charge, any hot spots in the combustion chamber, and colder area near the cylinder and piston walls will make the ignition process not controllable.

3.0 PRINCIPLE OF THE PM-ENGINE

The PM-engine is here defined as an internal combustion engine with the following processes realized in a porous medium: internal heat recuperation, fuel injection, fuel vaporization, mixing with air, homogenization of charge, 3D-thermal self-ignition followed by a homogeneous combustion.

PM-Engine may be classified with respect to the heat recuperation as:

- Engine with periodic contact between PM and working gas in cylinder (closed chamber).
- Engine with permanent contact between PM and working gas in cylinder (open chamber).

On the other hand, possible positioning of the PM-combustion chamber in engine can be used to design different engines:

- Cylinder head (PM is stationary).
- Cylinder (PM is stationary).
- Piston (PM moves with piston).

One of the most interesting features of PM-engine is its multi-fuel performance. Independently of the fuel used, this engine is a self-ignition engine characterized by its 3D-thermal ignition in porous medium. Finally, the PM-engine concept may be applied to both two- and four-stroke cycles.

3.1 PM-ENGINE WITH CLOSED CHAMBER

Let us start an analysis of the PM-engine cycle with a case of closed PM chamber, i.e., engine with a periodic contact between working gas and PM-heat recuperator (FIG. 3.1A). At the end of the expansion stroke the valve controlling timing of the PM-chamber closes and fuel is injected in the PM-volume. This volume represents in thermodynamic sense a low-pressure chamber and a long time is available for fuel injection and its vaporization in the PM. These processes may continue through exhaust, intake and compression strokes (SEE FIG. 3.1A).

Near the TDC of compression the valve in PM-chamber opens and the compressed air opens and the compressed air flows from the cylinder into the hot PM volume containing fuel vapors. Very fast mixing of the gaseous charge occurs and the resulting mixture is ignited in the whole PM volume.

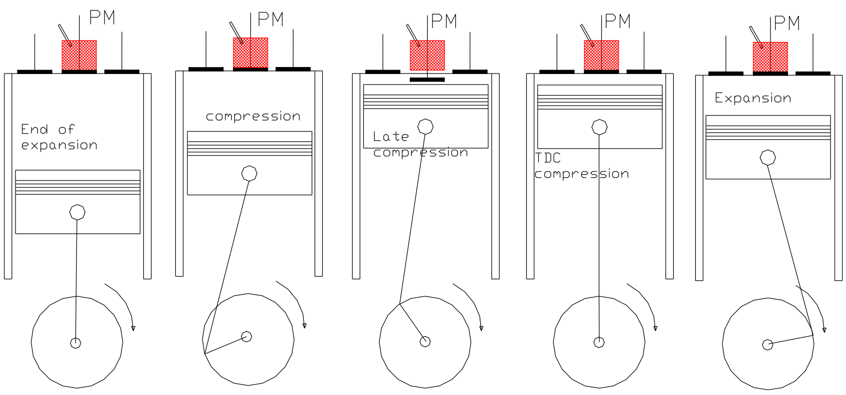

Figure 3.1.A. Principle of the PM-engine cycle with a closed PM chamber.

the resulting heat released process perform simultaneously in whole PM volume the three essential condition for homogeneous combustion are here fulfilled: Homogenization of charge in PM volume,3D-thermal self-ignition in PM and volumetric combustion with a homogeneous temperature field in PM volume. Additionally, the PM material deals as a heat capacitor and, hence, controls the combustion temperature.

3.2 PM-ENGINE WITH OPEN CHAMBER

Another possible realization of the PM engine is the combustion system characterized by a permanent contact between working gas and PM volume as schematically shown in (FIG. 3.2A). Here, it is assumed that the PM combustion chamber is mounted in the engine head. During the intake stroke there is a weak influence of the PM–heat capacitor on the in-cylinder air thermodynamic conditions. Also during the early compression stroke only a small amount of air is in contact with hot PM. The heat exchange process (non-isentropic compression) increases with continuing compression, and at the TDC the combustion air is closed in the PM volume. Near the TDC of compression the fuel is injected into the PM volume and very fast fuel vaporization and mixing with air occur in 3D-structure of the PM volume.

Again, the requested 3D-thermal self-ignition of the resulting mixture follows in PM volume together with the volumetric combustion characterized by a homogeneous temperature distribution in PM-combustion volume. Again, all necessary conditions for the homogeneous combustion are fulfilled in the PM-combustion chamber.

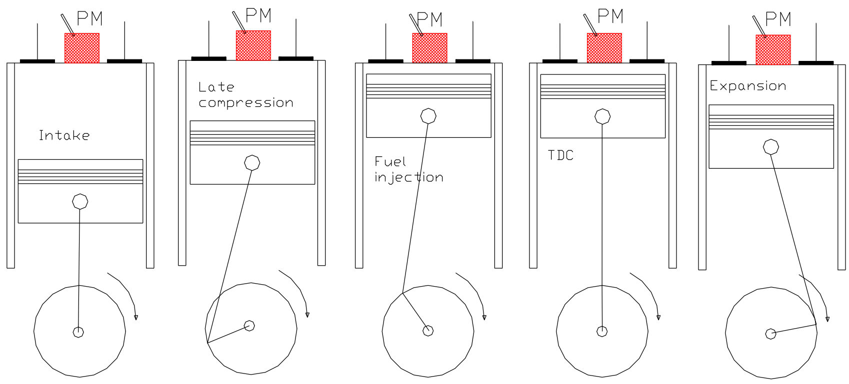

Figure 3.2.A. Principle of the PM-engine cycle with a open PM chamber.

4.0 COGENERATION IN PM-ENGINE

During ordinary operation of any engine approximately 70% of the heat value is lost due to practical and physical limitation. The concept of cogeneration now a day is quite established and implemented almost in every industry, where power requirement is accompanied by the industrial process heating (IPH). The term heat to power ratio is some how a very interesting topics of research, as in every industry the load matching is very important for proper utilization of heat energy. Generally it is seen that the dynamic range to which Q/W ratio can operate is limited due to certain parameters in working of any power generation cycle, typical values for certain established systems are given in the following table

Cogeneration system	**Q/W**	**Power output**
Back pressure Steam Turbine	**4.0-14.3**	**14-22 %**
Steam turbine	**2.0-10.0**	**22.0-40.0 %**
Gas turbine	**1.3-2.0**	**24-35 %**
Combined cycle	**1.0-1.7**	**34-40 %**
Ordinary reciprocating engine	**1.1-2.5**	**33-53 %**
PM-engine	**Yet to be explored**	**Yet to be explored**

Table 4.1.Efficiencies and dynamic power modulation of some established cogeneration technology.

Range of Q/W can be raised by incorporating certain mechanisms in above given systems like steam bleed or supplementary firing of fuel to match the IPH requirements. The concept synonymous to supplementary fuel firing can be used in PM-Engines here the advantage would be that the mechanical power output is also more for a fixed quantity of fuel. A typical schematic is shown in (FIG.4.A)

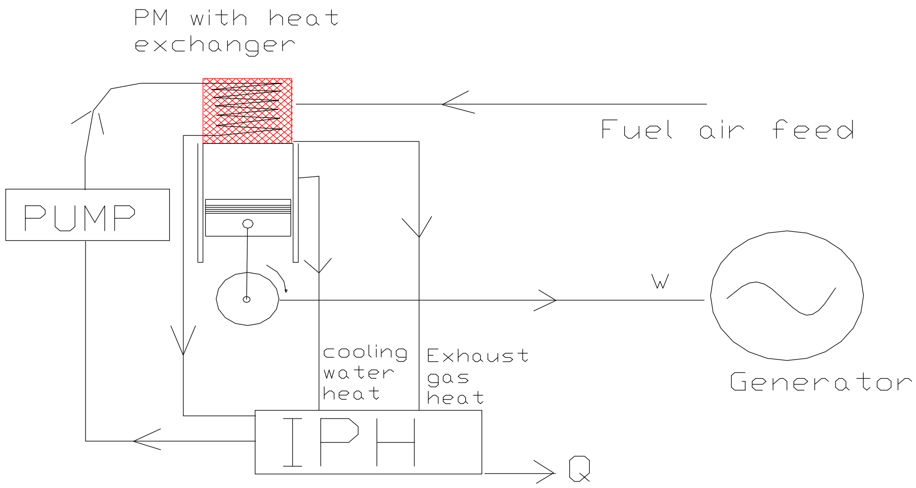

Figure 4. A. Principle of the PM-engine cycle with cogeneration.

This concept uses the energy of PM combustion to develop shaft power and also to make excess heat when its needed in the IPH a typical schematic above shows the basic working principle of this new concept. Logically if we are able to transfer heat in the finite time then the temperature of combustion chamber can be maintained and hence the operation of PM engine is unaffected from very lean F/A mixture to very high F/A mixture the power range and operational characteristic remains workable.

5.0 MATERIALS USED FOR POROUS MEDIUM

Since this technology depends on high temperature resistant porous materials hence, identification and survey of such material is also necessary. The most important material and for porous burner are SiC (silicon carbide) foams as well as mixer-like structure made of Al_2O_3 fibers, ZrO_2 foams and C/ SiC structure. In some special application chromium-iron alloys and nickel base alloys are also used. Al_2O_3 and ZrO_2 are having different manufacturing properties these material can be used in temperature range of 1650 ^{o} C above, where as metals and SiC material do not fall in this category, hence they are used in comparatively low temperature applications. However they possess outstanding characteristic with regard to thermal shock, mechanical strength and heat transport capacity etc. The overall performance of a porous body is strongly dependent on combination of base material and porous structure itself. Aluminum oxide can be used to a process temperatures of 1950^{o}C, although the technical temperature limit is 1700^{o}C. Al_2O_3 – based materials show an intermediate heat conductivity ranging from 5W/(m K) at 1000^{o}C to about 30W/(m K) at 20^{o}C. Also Al_2O_3 shows an intermediate thermal expansion and an intermediate resistance to thermal shock and emissivity of 0.28 at 2000 ^{o} K. High quality SiC can be used to a maximum process temperature 1600^{o}C,a heat conductivity in rang of 20 W/(m K) at 1000 ^{o} C and 150 W/(m K) at 20^{o}C,a very good resistance to thermal shock and a very low thermal expansion and the overall emissivity at 2000^{o}K is about 0.8 to 0.9. Temperature resistant metal alloys may be used for temperature below 1250^{o}C. Their properties features a high heat conductivity ranging from 10 W/(m K) at 20^{o}C to about 28 W/(m K) at 1000 ^{o} C, extremely high thermal expansion and extremely good resistance to thermal shock. The emissivity of metals varies strongly with the surface finish and varies form 0.045 at 200 K to polished nickel of 0.5 in stainless steal. Solid Zirconia present a highest temperature resistance which ranges up to 2300 ^{o} C. Heat conductivity of solid Zirconia is hardly temperature dependant and in the range of 2 W/(m K) to 5 W/(m K). Good conduction and heat transport capacity, low radiations, and intermediate dispersion properties makes it quit suitable from high temperature application.

6.0 CONCLUSION AND FURTHER RECOMMENDATIONS

PM technology is very important due to its wide applicability in the field of energy efficiency. The properties inherited by it, like low emission, high power density or compactness of the systems and wide range of power modulation makes it a good alternative in places of conventional technologies. Selection of proper materials for any specific purpose would be achieved by the proper knowledge of such materials. Parameters like specific heat capacity, maximum temperature range, resistance to thermal shock and coefficient of thermal expansion etc. need to be known. This technology can be further applied to reciprocating engine power generation systems for load matching and to make a higher dynamic power range, hence higher overall efficiency.

7.0 REFERENCES

1. A Khaliq, Adil SMH, Tasmeem A. Khan "Prospective Utilization of Porous Medium Combustion Technology for Low Pollutant Emissions and High-Energy Efficiency Systems" Proceedings of International Conference on "Energy and Environment – Strategies for Sustainable Development". (ICEE-SSD), 23-24 January 2004, Jamia Millia Islamia New Delhi.

2. Babkin,V. S, Korzhavin, A. A, and Buner, V. A. (1991), "Propogation of premixed gaseous explosion flame in porous media combustion and flame", 87,PP.182-190

3. Drust F, Weclas.M, Mößbauer, S., "A New Concept of Porous Medium Combustion in IC Engines", Proceedings of the international symposium on "Recent Trends in Heat and Mass Transfer"6-8 January 2002, Indian Institute of Technology Guwahati

4. Durst, F.,Kesting, A., Mößbauer, S., Pickenacker, K., Pickenacker, O. and Trimis, D.,(1997a), "Der Porenbrennev-Konzept, Technik und Anwendungsgebiete, Gaswarme International,46(6) 300-307.

5. Durst, F. and Trimis, D., (1997a), "Combustion by free flame versus combustion reactors," 4th International conference on Technologies and combustion for a clean environment.

6. Hsu, P., Howell, J.R. and Matthews, R. D. (1993), "A numerical investigation of premixed combustion within porous inert media," Journal of heat transfer, 115,PP, 744-750