ANALYSIS OF INTERNAL COMBUSTION ENGINE WITH A NEW CONCEPT OF POROUS MEDIUM COMBUSTION FOR THE FUTURE CLEAN ENGINE

by

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At present, the emissions of internal combustion engine can only be improved by catalytic treatments of the exhaust gases. Such treatments, however, result in high costs and relatively low conversion efficiency. This suggests that a new combustion technique should be developed to yield improved primary combustion processes inside the engine with drastically reduced exhaust gas emissions. To fulfill all requirements, Dr. Franz Drust has proposed a new combustion concept to perform homogenous combustion in internal combustion engines. This concept used the porous medium combustion technique and is called "PM-engine". It is shown that the PM combustion technique can be applied to internal combustion engines. Theoretical considerations are presented for internal combustion engines, indicating that an overall improvement in thermal efficiency can be achieved for the PM-engine. This is explained and general performance of the new PM-engines is demonstrated for a single cylinder, water cooled, direct injection diesel engine. Verification of experiments at primary stage is described that were carried out as a part of the present study.

Key words: *porous medium combustion, internal combustion engine, future clean engine*

1. Introduction

In general, internal combustion (IC) reciprocating engines have reached a very advanced state of development, providing good overall performance and efficiency. In addition, continuous development, mainly in recent years, have resulted in considerable reduction in fuel consumption for both diesel and gasoline engines. Nearly all engine manufacturers have been successful in this field of development and further progress can be expected in the years ahead. In particular, the ongoing development of the direct injection (DI) concept still shows good potential to yield further reductions in fuel consumption. This concept also offers potential for the

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reduction of NO_x emission by applying exhaust gas recirculation (EGR) in the combustion region, both for stoichiometric and for lean-burn engine operating conditions. However, inevitable trade-offs limit the possibilities for reducing emissions substantially if the conventional mixture preparation and combustion techniques are maintained, because this results in a non-homogenous fuel-air ratio distribution in the combustion chamber and cause a regionally slow, incomplete, diffusionally controlled combustion. From this, non-homogenous temperature fields emerge and high level, engine-load-dependent emissions result that not only is difficult to control but can barely be reduced much further. This is outlined in the present paper and it is stressed that a new approach is needed to provide a better mixture preparation and/or improved combustion conditions. It has a claim that, without such a new approach, drastic reductions of emissions from IC engines cannot be obtained, that is the emission levels obtainable these days can only be reduced through improved and very costly catalytic treatments of the exhaust gases [1, 2]. Post-combustion treatments, however, have so far been insufficient and very limited in improving existing emission rates of IC engines [3, 4]. The new concept of controlled combustion in porous media, suggested in this paper for DI-IC engines, offers the potential to increase the engine efficiency.

Steady combustion in porous media is a subject of interest and a number of publications exist that describe the advantages of this combustion technique. The experiments carried out were demonstrative in nature and the results presented are intended as proof that the basic ideas put forward in this paper can be made to work in practice. Further research and development work is needed to yield PM-IC engines to drive cars. The present work show the potential of such development work to result in IC engines with very low emissions of NO_x, CO, and unburned hydrocarbons (UHC), and very low concentrations of soot. Post-combustion exhaust gas treatments might not be needed or may be employed to work towards a nearly zero emission IC engine [5]. In addition the new type of IC engine presented is very likely to yield higher efficiencies than existing models.

Overall requirements for a homogenous combustion

If talking about a homogenous combustion with controlled temperature level in combustion zone, it would be useful to define an idealized homogenous combustion conditions in IC engine. This process could be defined as 3-D-ignition of homogenous charge followed by a simultaneous heat release in the whole combustion chamber volume characterized by a homogenous temperature field. Additionally, the combustion temperature level should be lowered from the adiabatic one to reach the temperature (in the best case) below the normal NO_x formation. Of course, this process should not lower the engine cycle efficiency and the system has to be able to operate from very light to full load conditions [6].

According to this definition three steps of the mixture formation and combustion may be selected that define the ability of a given realistic engine to operate as a homogeneous combustion system:

– degree of charge homogenization,
– art of ignition, and
– homogeneity of combustion process and its temperature field (level).

Let us consider the conditions for mixture formation and charge homogenization in engine operating with a liquid fuel. There are two possible concepts to be realized in engine:

– liquid fuel is supplied directly to the combustion chamber resulting in two phase mixture – liquid-gas mixture, and

– already vaporized fuel is supplied to the combustion chamber resulting in a single phase mixture – gas-gas mixture.

The next factor conditioning the ability of the system for operating with a homogeneous combustion is the art of ignition. Here, four different ignition techniques may be selected, as shown in fig. 1:

– local ignition (*e. g.* spark plug),
– thermal self-ignition (*e. g.* compression ignition),
– controlled auto-ignition (*e. g.* low temperature chemical ignition), and
– 3-D thermal porous medium (PM) self-ignition (3-D-grid structure with a high surface temperature) [7].

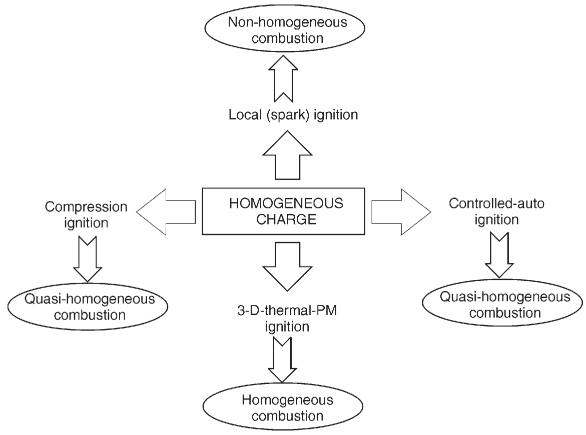


Figure 1. Possible model of combustion of homogeneous charge in engine

In the case of local ignition, a 3-D ignition required for defined homogeneous combustion can not be fulfilled. Additionally, if a lean-homogeneous charge is considered, the lean effective limit defines possible mixture composition that may be burned. This reduces potential of improving engine economy at part loads.

In the case of compression ignition (thermal self-ignition) system, a multi-point ignition can be achieved, and in ideal case a nearly volumetric ignition is possible, except the near-wall zones, if homogeneous, single-phase charge to be ignited. The only remaining question is how to control the timing of ignition and duration of combustion? By increasing amount of liquid injected in the cylinder a longer time is required for fuel distribution, its vaporization, and mixing with air. Such system is very sensitive to any non-homogeneity of the charge and to liquid phase that may be present in the cylinder [8]. To make this system practicable, it is necessary to look for the technique that makes the fuel supply and fuel vaporization processes independent of the cylinder conditions.

In case of low temperature chemical ignition which uses active radicals for controlled auto-ignition, the critical factor is the chemical activity of the fresh charge. In the systems known (especially two-stroke cycles) [9], the chemical activity of the charge is increased by trapping the burned gases. In the cylinder (even more than 80% of recirculation rate is required). The trapped exhaust gases reduces the volume available for fresh air reducing range of engine performance that could be achived.There is necessary to develop technique that could control the chemical activity of the fresh charge independently of the engine operational conditions [10].

The last considered ignition system has recently been proposed by Durst *et al.* [7-11].This system uses a 3-D structure of the PM for a volumetric ignition of the charge trapped in the PM-volume characterized by a homogeneous surface temperature higher than the ignition temperature. In this case the PM-volume defines the combustion chambers volume. Thermodynamically – the PM is here characterized by a high heat capacity and by a large specific surface area. As a model, we could consider the 3-D structure of the PM as a large number of "hot spots" homogeneously distributed throughout the combustion chamber volume. Because of this feature a thermally controlled 3-D-ignition can be achieved. Additionally, the PM controls the temperature level of the combustion chamber permitting the NO_x level control almost independently of the engine load or of the air to fuel ratio. It is clear, that none of considered systems with a free combustion in the cylinder may operate in a wide range of engine operational conditions with minimum of emissions. However, each individual system shows its advantages in a given range of the engine speed and loads.

According to the adaptability of the combustion system to variable engine operational conditions for permitting the lowest emission combustion, four groups of combustion system are selected [12]:

– non-adaptive mono-mode combustion systems (*e. g.* MDI, GDI with a homogeneous charge or DI-diesel combustions systems),
– non-adaptive multi-mode combustion systems (*e. g*. GDI-system with stratified and homogeneous charges, DI-diesel with a homogeneous and non-homogeneous charge),
– ADAPTIVE (intelligent) multi-mode combustion systems (different ignition combustion modes may be realized in the same engine), and
– ADAPTIVE (intelligent) mono-mode combustion systems (combustion quality is independent of the engine load).

In the case of non-adaptive mono-mode combustion system, the combustion conditions are pre-defined by the mixture formation and ignition conditions. These conditions can not be changed and the optimum of emissions cannot be achieved under variable engine operational conditions.

Non-adaptive multi-mode combustion system are defined as systems operating under different mixture formation conditions (mostly with the same ignition mode), however, the switching between combustion modes is required to keep "the engine running" without permitting the optimum of emissions. In order to optimize engine emissions under variable engine operational conditions, it is necessary to develop new combustion systems that may satisfy one of the two following conditions:

– system that may change its combustion mode according to actual engine operational conditions to keep the optimum of emissions, *i. e.* ADAPTIVE (intelligent) multi-mode systems, and
– system that may operate independently of the engine operational conditions permitting optimum of emissions, *i. e*. ADAPTIVE (intelligent) mono-mode systems.

Initial combustion in creating of adaptive multi-mode combustion systems is given by applying of MDI concept proposed by Weclas [13]. Such systems may virtually be defined as systems that use different ignition and combustion condition to permit optimum of engine emissions under variable engine operational conditions. At least three part of engines operational map have to be considered: very light loads (ultra-lean charge), part loads (lean charge), and full loads (nearly stoichiometric charge). Here, the charge homogenization, art of ignition and combustion mode defines the quality of combustion process.

Adaptive mono-mode combustion system offers combustion quality to be independent of engine operational conditions, permitting homogeneous combustion process with controlled combustion temperature. A new concept of IC engine having such features with combustion in a porous medium has recently been proposed by Durst *et al*. [7-11].

Porous medium technology

The PM technology for IC engine means the utilization of specific features of a highly PM for supporting and controlling the mixture formation and combustion processes in IC engines. The employed specific features of PM are directly related to a very effective heat transfer and very fast flame propagation within the PM.

Most important features of PM are: high heat capacity, large specific surface area, excellent heat transport property (radiation conductivity), and transparency for fluid flow and flame propagation, variable pores size, pores density and pores structure, high thermal and mechanical resistance, and thermal shock resistance (tab. 1) [14, 15]. A close view of a magnified 3-D structure of SiC ceramic foam is given in fig. 2.

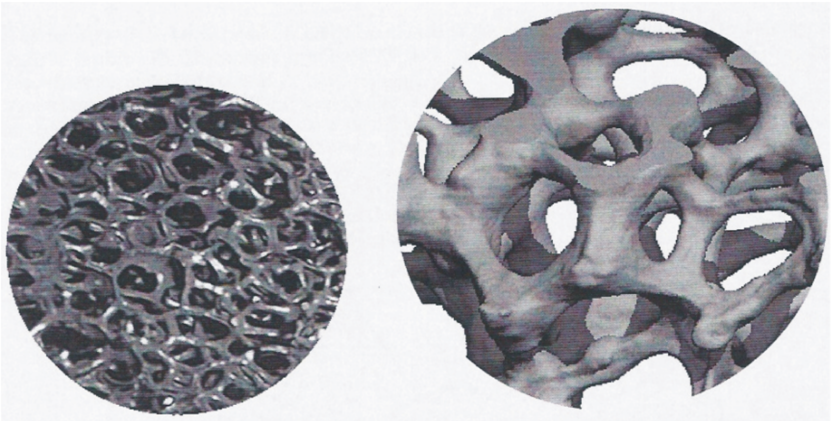


Figure 2. View of SiC foam structure (left); Reconstructed structure using computer tomography (right)

Table 1. Properties of the material for comparison

Substance	Temperature [°C]	Thermal conductivity [$WM^{-1}°C^{-1}$]	Density ρ [kgm^{-3}]	Specific heat C [$kJkg^{-1}$]	Thermal diffusivity α $m^2[10^{-7}\mathbf{s}]^{-1}$
SiC	30	490	3156	0.68	2290
Al_2O_3	30	46	3970	0.76	150
Cu	30	386	8954	0.3831	11.23

Properties of the materials 16

The MDI system as described by Weclas [17] uses an internal energy for fuel vaporization and for controlling of active radicals produced from the fuel supplied to PM volume, independently of the engine load or speed. This system is a basis for creating an adaptive multi-mode combustion system, as proposed and described in this paper. A new kind of IC engine with a homogeneous combustion in a PM creates an adaptive mono-mode combustion system. Principles of MDI and PM engine combustion systems are shown in fig. 3. In both the cases the PM is used as a heat recuperator.

In MDI system the energy is taken from the burned gases during the expansion – exhaust period. In the PM engine the energy is directly taken from the combustion process per-

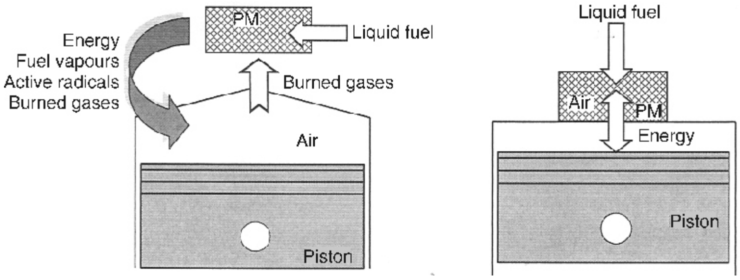


Figure 3. Principle of MDI (left) and PM-engine (right)

forming in PM-volume. In both situations, a liquid fuel is supplied to the PM where vaporizes under high temperatures conditions. The MDI system is characterized by a two steps mixture formation: a non-combustible mixture is formed in the PM volume, the latter a combustible mixture is formed in the cylinder.

Principle of the PM engine

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

The PM engine may be classified with respect to the heat recuperation as:

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

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

- cylinder heads (PM is stationary),
- cylinder (PM is stationary), and
- 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 characterized by its 3-D thermal ignition in PM. Finally, the PM engine concept may be applied to both two and four –stroke cycles. Owing to the differences in the thermodynamic conditions, the PM engine cycle has to be separately analyzed for closed and open chambers.

PM engine with closed chamber

A principle of the PM engine operating with a closed chamber, *i. e.* engine with a periodic contact between working gas and the PM heat recuperator is discussed below (fig. 4). At the end of the expansion stroke the valve controlling timing of the PM chamber closes and fuel may be injected in the PM volume. This chamber is a low-pressure chamber and a long time is available for fuel supply and its vaporization in the PM volume. These processes may continue through exhaust, intake and compression strokes (fig. 4). Near the top dead centre (TDC) of compression the valve in PM chamber opens and the compressed air flows from the cylinder to the hot PM containing fuel vapors. Very fast mixing of gaseous charge occurs and the resulting mixture is ignited in the whole PM volume. The resulting heat release process performs simulta-

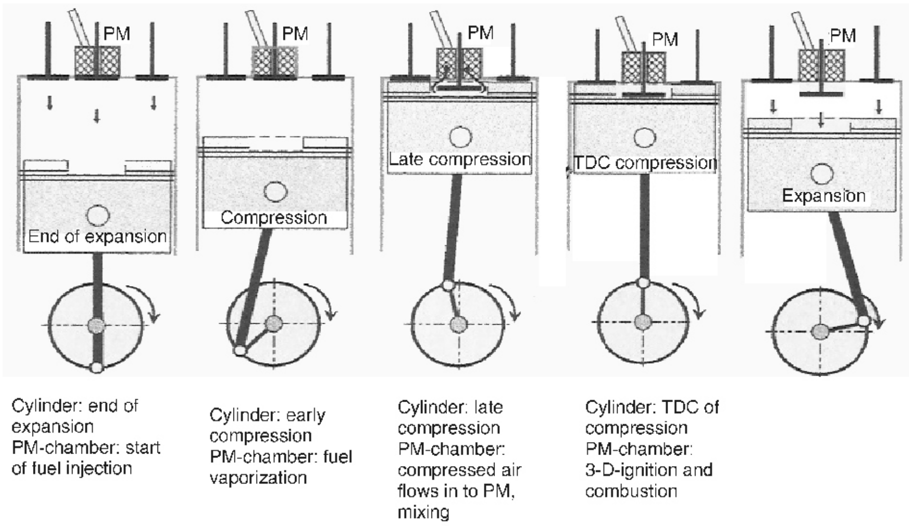


Figure 4. Principle of PM engine with a closed chamber

neously in the whole PM volume. Three necessary conditions for a homogeneous combustion are here fulfilled: homoge- nizations of charge in PM volume, 3-D-thermal self-ignition and a volumetric combustion with a homogeneous temperature field in PM volume. Additionally, the PM deals as heat capacitor and controls the combustion temperatures level in PM combustion chamber.

PM engine with open chamber

Scheme of engine operating with an open chamber is presented in fig. 5. During the compression stroke the cylinder charge is forced into the porous medium located in the cylinder

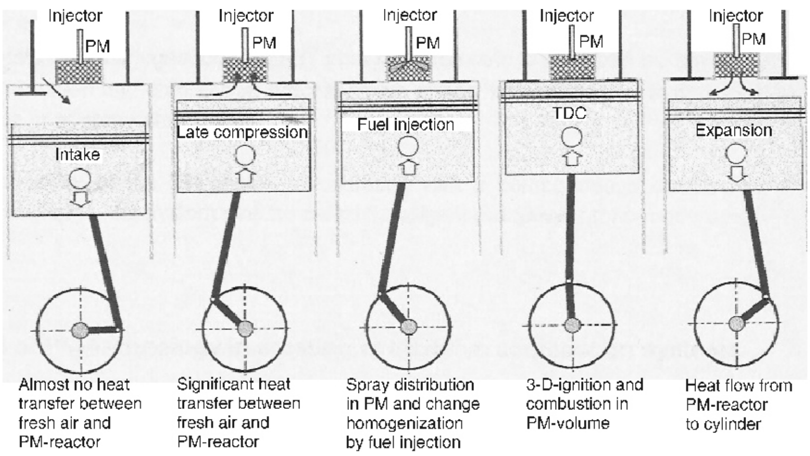


Figure 5. Principle of PM engine with an open chamber

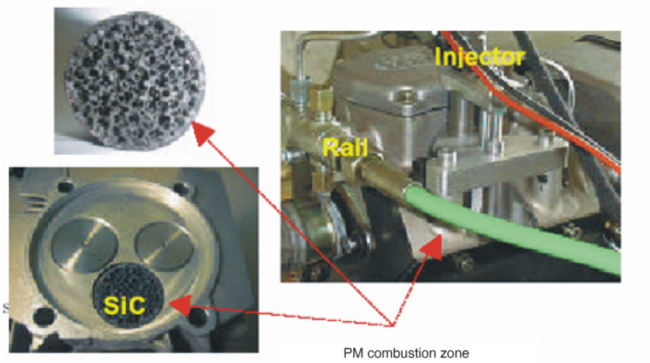


Figure 6. View of PM engine head with SiC reactor

head (fig. 6) and the gas receives additional heat, causing its temperature to rise during compression. Near the TDC of compression the fuel is injected into the PM volume by a conventional DI-diesel nozzle. The high temperature inside the PM processing a high specific surface area and a high heat capacitance, lead to rapid furl vaporization. Finally, strong gas motion again acts to mix the vaporized fuel and air, producing a nearly homogeneous mixture for ignition. At TDC the temperature of the gas can be considered to be approximately equal to that of the PM, which maintains roughly the combustion temperature of the previous cycles. It can be considered to be higher than the gas temperature of a conventional engine, with equal compression ratio, prior to ignition. Because of the way in which the fuel is injected, ignition occurs only in the PM medium and the resulting in heat released in the PM volume, only. Hence, the entire combustion process can be considered to be limited to the PM, *i. e.* no free flame is present in the volume of the cylinder. In this phase of the combustion process the enthalpy is utilized to increase the internal energy of the cylinder charge.

Part of the energy is diverted into the PM to be used in the next cycle for charge heating and fuel vaporization. As a consequence of the complete vaporization and effective mixing processes, the combustion quality in the PM is only weakly dependent on the spray atomization characteristics, *i. e.* the process is only weakly dependent on engine load. Again, all necessary conditions for a homogeneous combustion are fulfilled in the PM combustion volume. A practical realization of the PM engine concept has been described by Durst and Weclas.

Main feature of the PM engine concept are the following:

- very low NO_x emission level due to homogeneous combustion and controlled temperature in the PM combustion zone,
- it is possible to (almost) eliminate the soot formation,
- theoretically higher than conventional engine cycle efficiency due to similarity to the Carnot cycle,
- very low combustion noise due to significantly reduced pressure peaks,
- nearly constant and homogeneous combustion temperature field,
- very fast combustion,
- multi-fuel systems,
- may operate with homogeneous charge from stoichiometric to very lean mixture compositions, and
- mixture formation and combustion processes are almost independent of in-cylinder flow structure, of turbulence or of spray atomization.

Owing to the ability of the PM engine of operating with a homogeneous combustion at all required optional conditions, the system may be called "intelligent" (adaptive) mono-mode combustion system".

Potential of PM technology in creating of adaptive combustion system

There are two different criteria selected here for analysis of the combustion system:

- potential for homogenization of the combustion process, and
- potential for operating with charge composition from very lean to nearly-stoichiometric.

Three combustion systems are compared in this analysis: conventional DI systems, PM-engine and MDI-system (mixture formation with charge homogenization, ignition and combustion processes).

In DI-system large-scale in-cylinder flow structures (*e. g.* swirl, tumble) are responsible for mixture formation and charge homogenization being dependent on the engine speed and load. In conventional GDI system four groups of engine processes are selected for this analysis: gas flow processes, fuel injection a large-scale gas motion [18] is responsible for charge stratification. Not less important is the turbulence generated in the cylinder. Flow separations in the valve gap define the discharge conditions in to the cylinder and formation of a recirculation zone under the valve [8-19].

These problems do not exist in PM-engine, where the system is divided in two parts: free volume of the cylinder and PM volume. While processes of mixture formation and combustion are performed in the PM-volume, no large-scale flow structure is required in PM-engine. Also the intake generated turbulence is not important, while a small scale motions are generated during the gas flow in a PM. If the gas is pushed into the PM-volume a strong heat transfer from a solid phase of PM and gas is observed together with a spatial homogenization of the gas in the PM-volume. In this case it is assumed that the temperature is homogeneous throughout the PM-volume.

Different role plays a PM in MDI system. Here, large-scale flow structure in the cylinder may be important for homogenization of gaseous charge. Very important are processes of gas flow between cylinder and PM-chamber, and corresponding heat transfer from burned gases to PM solid phase. Advantageous is a strong turbulization of the cylinder charge during gas discharging from PM to the cylinder volume.

Another critical aspect of conventional DI combustion systems is fuel injection. In this case liquid fuel is present in the cylinder. Most critical parameters are: injection timing, spray atomization and spray geometry. Fuel injection in DI system is responsible for mixture formation and charge stratification or charge homogenization, depending on the combustion system.

Quite different situation is observed in two other systems that use a PM technology. In the PM-engine the liquid fuel is injected directly in to PM-volume and fuel atomization and spray geometry are not critical. A self-homogenization process in PM-volume is observed permitting spatial distribution of the liquid fuel throughout the PM-volume. A strong heat transfer from hot PM-surface and gas to liquid fuel permits fast and complete fuel vaporization. No liquid or gaseous form of the fuel is present in a free volume of the cylinder. Injection timing, spray atomization or spray geometry are not critical in this system. In MDI system liquid fuel is directly injected in to PM-volume during the time when this volume has no connection with the cylinder space [20]. Complete fuel vaporization occurring under very low oxidant concentration atmosphere is permitted in PM-volume, and only gaseous form of the fuel may be supplied to the cylinder.

Mixture formation and charge homogenization conditions in DI system are very complex and difficult to control. Generally, two-phase charge is present in the cylinder and mixture formation significantly depends on the engine load. In this case, in-cylinder flow structure and spray atomization are very critical for mixture formation conditions.

Significantly different conditions for mixture formation occur in PM-engine. Here, 3-D PM structure controls the charge homogenization and the gaseous form of the fuel is present in the charge trapped in the PM-volume. In this case, the mixture formation conditions are almost independent of the engine operational conditions. The spray atomization and in-cylinder flow structure are not critical for the quality of the mixture formation. Again, the effect of self-homogenization in PM-volume permits pretty well homogenization of the charge to be exposed to high temperature conditions.

Also in MDI system no liquid fuel is present in the cylinder. Mixture formation of combustible mixture does not occur in PM-volume but in a free space of the cylinder. Mixture formation conditions are weakly dependent of the engine operational conditions, whereas the fuel is completely vaporized and the cylinder content is highly turbulent. Two-stage mixture formation is realized in MDI system. In the first stage, a non-combustible mixture is formed in the PM-volume containing burned gases and fuel vapors. In the second stage, a combustible mixture is formed in the cylinder as a result of mixing between air and gaseous content of the PM-chamber.

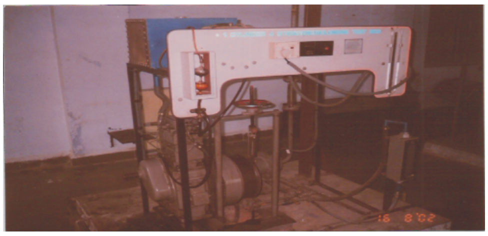
There are three possible modes of the ignition in conventional DI system: local ignition, compression ignition, and controlled (chemical) auto-ignition. Generally, the ignition following combustion process in DI engine is highly non-homogeneous process with uncontrolled temperature distribution in the combustion chamber [21, 22]. Ignition and combustion of homogeneous charges is limited to nearly stoichiometric mixture compositions, whereas the effective lean limit and ignition conditions select possible conditions under part load operation [23]. The art of ignition and resulting combustion process depends on the fuel used in the engine and on the fuel injection conditions.

Quite different situation is observed in the PM-engine system. Here, independently of the engine operational conditions a new art of ignition is realized: 3-D-thermal-PM self-ignition of the homogeneous charge is realized in the PM-volume. The combustion process is characterized by homogeneous and controlled temperature in the whole PM-chamber volume, and no combustion occurs in a free volume of the cylinder. The maximum temperature is reduced by heat accumulation in the porous medium giving rise to very low NO_x emissions [17-24] almost independently of the engine operational conditions. Owing to reduced temperature and pressure peaks, this combustion system is characterized by very low combustion noise. Generally, this is only one known system fulfilling all necessary conditions for a homogeneous combustion process with controlled temperature, offering a near-zero emission level. This system has been defined in this report as intelligent mono-mode combustion system.

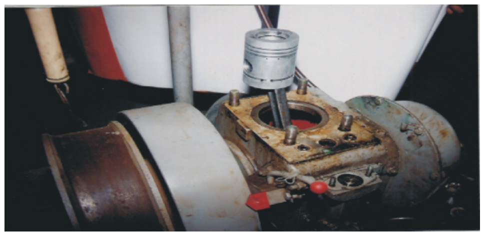
Also MDI system offers attractive advantageous in combustion process. This system may adaptively operate with different modes of ignition of homogeneous charge having potential for (quasi-) homogeneous combustion process in engine. MDI concept significantly increases ignitability and extends the lean effective limit for homogeneous charge. The combustion conditions are weakly depends on the fuel used in the engine. On the basis of MDI system, a concept of intelligent multi-mode combustion system has been defined in this report.

Experimental set-up and experimental results

Photograph 1 shows the complete experimental set-up on which the actual research work is carried out. The set-up consists of a Diesel engine having technical specifications as follows: single cylinder, four stroke, high speed direct injection diesel engine, water cooled, bore 80 mm, stroke 110 mm, 5 HP and compression ratio 16:1. Experimental reading on above engine is taken and performance of the engine is recorded by calculating various parameters like efficiency, fuel consumption, plotting *P-V*, *T-S* diagrams, and recording soot formation initially without PM, as shown in photograph 2, and the same readings with porous medium, as shown in photograph 3, without changing other specifications of the set-up.



Experimental set-up



Engine fitted with cup shape piston

Cup head piston of diesel engine fitted with porous material disc in cup shape and piston coated with SiC

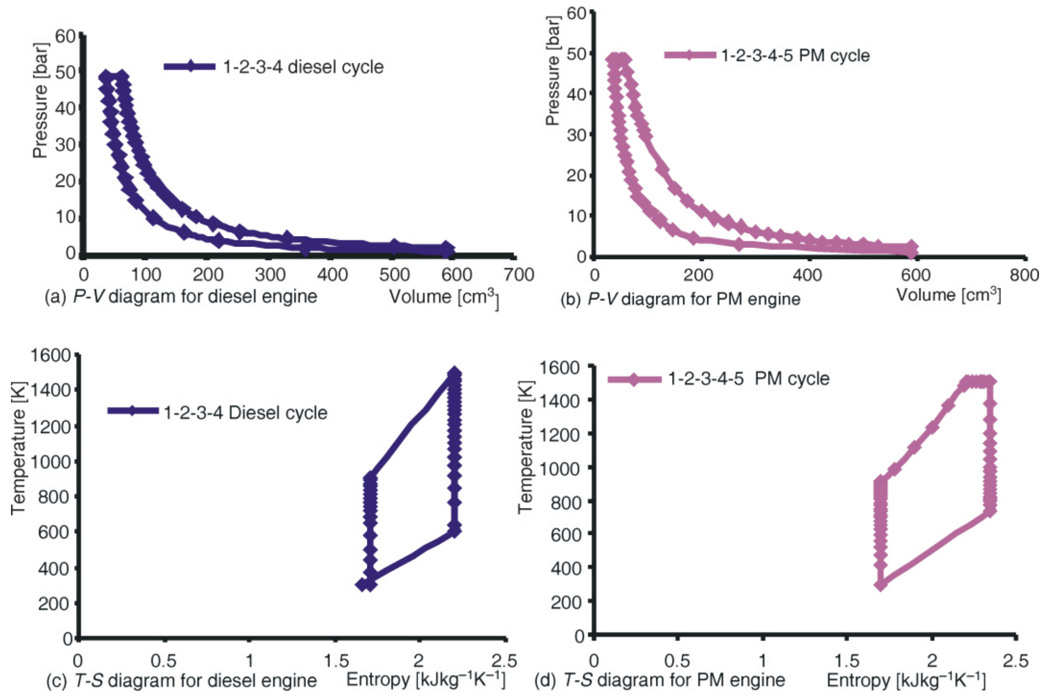
The results of the experiment carried out on the engine with the PM is compared with the normal engine and it is found that the efficiency of the engine has improved, exhaust emissions like NO_x, CO, and UHC are reduced drastically [25], and also it has been recorded that the soot formation is almost negligible, figs. 7(a)-(e) and fig. 8(a) and (b).

Conclusions

A porous medium technology has been defined as a utilization of large specific surface area, large heat capacity, high porosity, *etc*. of open cell structures for supporting different processes realized in engine. Especially important is the application of this material for homogenous mixture formation and complete combustion in engines.

In this paper novel concepts for combustion engines based on the application of PM technology is presented and discussed. The main attention is focused on the engine concepts having potential for homogeneous combustion process under variable engine operational conditions: intelligent engine and engine with combustion in a PM. It was shown that PM could be used for a great variety of improvements in the combustion process, especially for elimination of soot emissions and significant reduction of NO_x. Combustion process in porous reactor is homogeneous, and uses a new art of volumetric thermal ignition in the porous medium.

All these processes (*e. g*. gas flow, fuel injection and its spatial distribution, vaporization, homogenization, ignition, and combustion) can be controlled or positively influenced with the help of PM/ceramic foams or other structures [26].



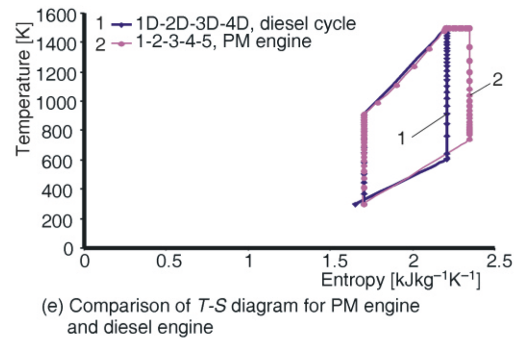


Figure 7(a)-(e). Comparison of engies cycles charateristics (color image see on our web site)

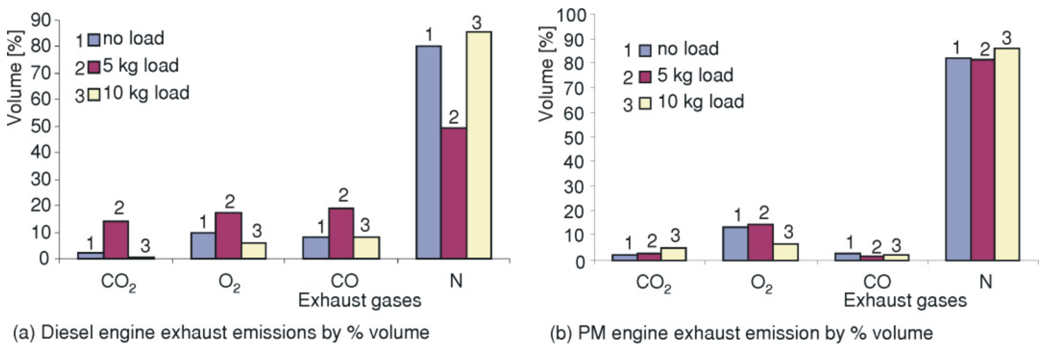


Figure 8(a) and (b). Comparison of exhaust emissions

All findings are claimed after conducting trials and observations during the experimentation; it is unique research work being conducted and a good approach towards the development of a near-zero emission engine.

Nomenclature

DI – direct injection
EGR – exhaust gas recirculation
GDI – gas direct injection
MDI – mixed direct injection
PM – porous medium
TDC – top dead centre
UHC – unburned hydrocarbons

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