A New Concept of I.C. Engine with Homogeneous Combustion in a Porous Medium

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Abstract-The advantages of homogeneous combustion in internal combustion (I.C.) engines are well known and many research groups all over the world are working on its practical realization. Recently, the present authors have proposed a new combustion concept that fulfils all requirements to perform homogeneous combustion in I.C engines using the Porous Medium Combustion Engine, called "PM -engine". This is an I.C. engine with the following processes realized in a porous medium: internal heat recuperation, fuel injection and vaporization, mixing with air, homogenization, and 3Dthermal self-ignition followed by a homogeneous combustion. In the PM-engine the PM-combustion chamber is mounted in engine head. During the intake stroke it is weak influence of the PM-heat capacitor on the in-cylinder air thermodynamic conditions. Heat exchange process (non adiabatic compression) increases with continuing compression, and at the TDC the whole combustion air is closed in the PM volume. Near the TDC of compression the fuel is injected in to PM volume and very fast fuel vaporization and mixing with air occur in 3D-structure of PM-engine. The self-ignition process and homogeneous combustion occur in PM volume close to the TDC.

Keywords- PM-engine with open chamber, PM-engine with closed chamber.

I. INTRODUCTION

The nature of the mixture formation and the followed combustion processes realized in a direct injection engines, indicate a lack of mechanisms for controlling the mixture formation and homogenization of the sequence of process and, hence, do not allow homogeneous combustion. The entire homogenization, however, is necessary for significant reductions of engine emissions in primary combustion [1,2]. There is also no doubt today, that the future trend of development means *homogenization* of the combustion process with a goal to develop such combustion systems that could operate under part to full loads with homogeneous combustion. Such a new concept has been recently proposed by Durst & Weclas [3,4] and is discussed in this paper. It has not only been studied theoretically but has been technically realized.

Combustion or **burning**[is a high-temperature exothermic redox reaction between a fuel and an oxidant, usually atmospheric oxygen, that produces oxidized, often gaseous products, in a mixture termed as smoke. Combustion in a fire produces a flame, and the heat produced can make combustion self-sustaining. Combustion is often a complicated sequence of elementary radical reactions. Solid fuels, such as wood, first undergo endothermic pyrolysis to produce gaseous fuels whose combustion then supplies the heat required to produce more of them. Combustion is often hot enough that light in the form of either glowing or a flame is produced. A simple example can be seen in the combustion of hydrogen and oxygen into water vapor, a reaction commonly used to fuel rocket engines. This reaction releases 242 kJ/mol of heat and reduces the enthalpy accordingly (at constant temperature and pressure):

$$2H+O_2 \rightarrow 2H_2O$$

Combustion of an organic fuel in air is always exothermic because the double bond in O_2 is much weaker than other double bonds or pairs of single bonds, and therefore the formation of the stronger bonds in the combustion products CO_2 and H_2O results in the release of energy.[2]The bond energies in the fuel play only a minor role, since they are similar to those in the combustion products; e.g., the sum of the bond energies of CH_4 is nearly the same as that of CO_2. The heat of combustion is approximately -418 kJ per mole of O_2 used up in the combustion reaction, and can be estimated from the elemental composition of the fuel. Uncatalyzed combustion in air requires fairly high temperatures. Complete combustion is stoichiometric with respect to the fuel, where there is no remaining fuel, and ideally, no remaining oxidant. Thermodynamically, the chemical equilibrium of combustion in air is overwhelmingly on the side of the products. However, complete combustion is almost impossible to achieve, since the chemical equilibrium is not necessarily reached, or may contain unbent products such as carbon monoxide, hydrogen and even carbon (soot or ash). Thus, the produced smoke is usually toxic and contains unburned or partially oxidized products. Any combustion at high temperatures in atmospheric air, which is 78 percent nitrogen, will also create small amounts of several nitrogen oxides, commonly referred to as NO *x*, since the combustion of nitrogen is thermodynamically favored at high, but not low temperatures. Since combustion is rarely clean, flue gas cleaning or catalytic converters may be required by law.

Fires occur naturally, ignited by lightning strikes or by volcanic products. Combustion (fire) was the first controlled chemical reaction discovered by humans, in the form of campfires and bonfires, and continues to be the main method to produce energy for humanity. Usually, the fuel is carbon, hydrocarbons or more complicated mixtures such as wood that contains partially oxidized hydrocarbons. The thermal energy produced from combustion of either fossil fuels such as coal or oil, or from renewable fuels such as firewood, is harvested for diverse uses such as cooking, production of electricity or industrial or domestic heating. Combustion is also currently the only reaction used to power rockets. Combustion is also used to destroy (incinerate) waste, both nonhazardous and hazardous. Oxidants for combustion have high oxidation potential and include atmospheric or pure oxygen, chlorine, fluorine, chlorine trifluoride, nitrous oxide and nitric acid. For instance, hydrogen burns in chlorine to form hydrogen chloride with the liberation of heat and light characteristic of combustion. Although usually not catalyzed, combustion can be catalyzed by platinum or vanadium, as in the contact process.

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 and combustion may be selected that define the ability of a given combustion system to operate as a homogeneous combustion system:

A. Homogenization of charge.
B. Ignition conditions.

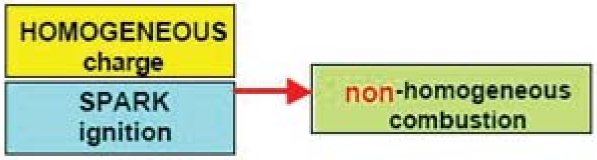
Four different ignition techniques may be selected:

A. Local ignition (e.g. spark plug).
B. Thermal self-ignition (e.g. compression ignition).

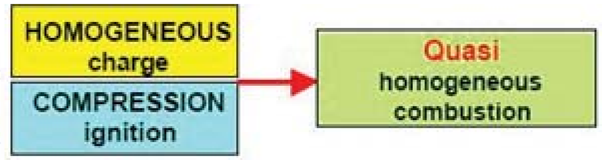
C. Controlled auto-ignition (e.g. low temperature chemical ignition).
D. 3D-thermal PM -self-ignition (3D-grid-structutre of a high temperature).

The last considered ignition system, has been recently proposed by Durst & Weclas [3,5,6] and uses a 3Dstructured 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 NOx level control almost independently of the engine load or of the (A/F) ratio. Let us consider four possible combustion modes of a homogeneous charge:

1. Homogeneous charge with local ignition

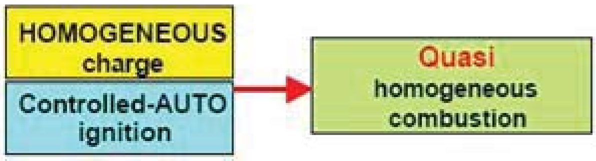


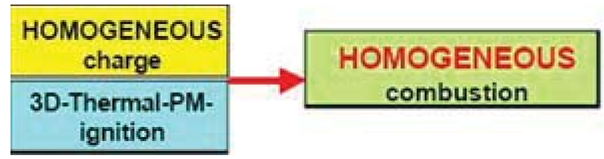
2. Homogeneous charge with compression ignition



3. Homogeneous charge with controlled auto-ignition

4. Homogeneous charge with 3D-thermal self-ignition in PM-volume





Porous medium (PM) technology: The porous medium technology for IC engines means here the utilization of specific features of a highly porous media for supporting and controlling the mixture formation and combustion processes in I.C.engines. The employed specific features of PM are directly related to a very effective heat transfer and very fast flame propagation within the PM. Generally, the most important parameters of PM for application to engine combustion technology can be summarized as follows: heat capacity, specific surface area, heat transport properties, thermal resistance of the material, mechanical resistance and mechanical properties under heating and cooling conditions, PM material surface properties. For IC engine application, the thermal resistance of the porous medium is one of the most important parameter defining its applicability of a given material to combustion in engine.

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 PMcombustion chamber in engine can be used to design different engines:

A. Cylinder head (PM is stationary).
B. Cylinder (PM is stationary).
C. 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. Owing to the differences in thermodynamic conditions, the PM-engine cycle has to be separately analysed for closed and open chambers, as described below.

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. 2). 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. 2) Near the TDC of compression the valve in PM chamber 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. The resulting heat release process performs simultaneously in the whole PM volume. The three essential conditions for a 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.

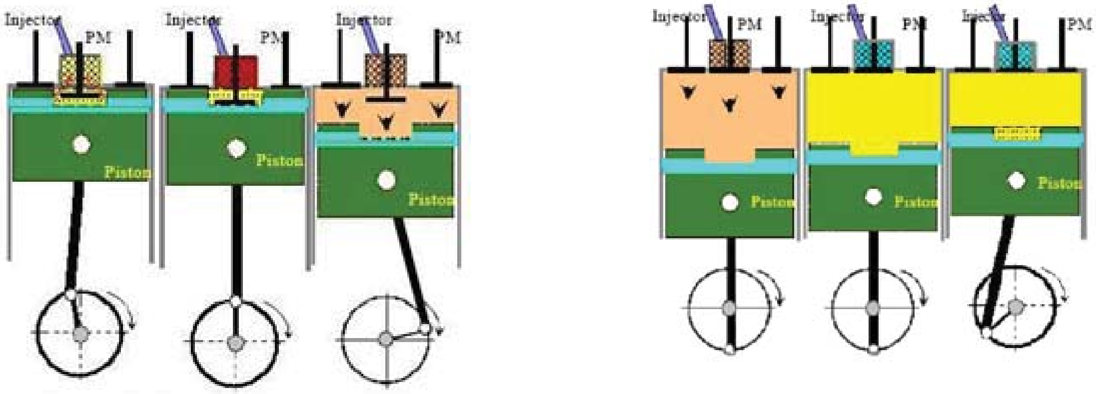


Fig-2 Principle of the PM-engine cycle with a closed PM chamber

PM-engine with open chamber: Another possible realization of the PM-engine is a combustion system characterized by a permanent contact between working gas and PM-volume, as schematically shown in Figure 3. 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 porous medium. The heat exchange. process (non-isentropic compression) increases with continuing compression, and at the TDC the whole combustion air is closed in the PM volume. Near the TDC of compression the fuel is injected in to PM volume and very fast fuel vaporization and mixing with air occur in 3D-structure of PM-volume. Again, the requested 3D-thermal self-ignition of the resulting mixture follows in PM-volume together with a volumetric combustion characterized by a homogeneous temperature distribution in PMcombustion volume. Again, all necessary conditions for homogeneous combustion are fulfilled in the PMcombustion chamber.

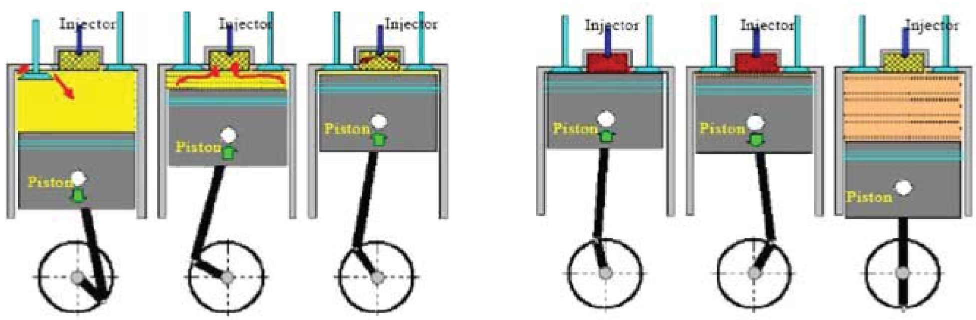


Fig-3 Principle of the PM engine cycle with a open PM chamber

Thermodynamics of PM-engine: thermodynamic model and theoretical considerations

The essential parts of the thermodynamic model to study the proposed engine cycle are presented in Figure 4. The model considerations are based on two parts: a cylinder with a working gas and a porous-medium heat capacitor as needed in the working cycle that can be thermally coupled with or decoupled from the cylinder content, e.g. see also [5,6]. It is assumed that no time elapses during the thermal coupling (i.e. heat exchange), and the heat capacitor has a very large heat capacitance in comparison with that of gas in the cylinder.

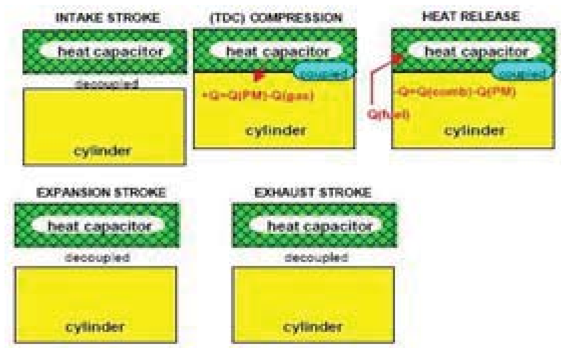


Fig.4 Thermodynamic model describing the PM engine cycle

This allows the modeling of the condition that the temperature remains constant during the heat exchange between the heat capacitor and the cylinder content. Figure 5 presents T-s diagram comparing the above PM-cycle with a Carnot cycle and with a conventional constant volume (CV) combustion cycle. For this analysis it is assumed, that all the cycles operate at the same maximum temperature.

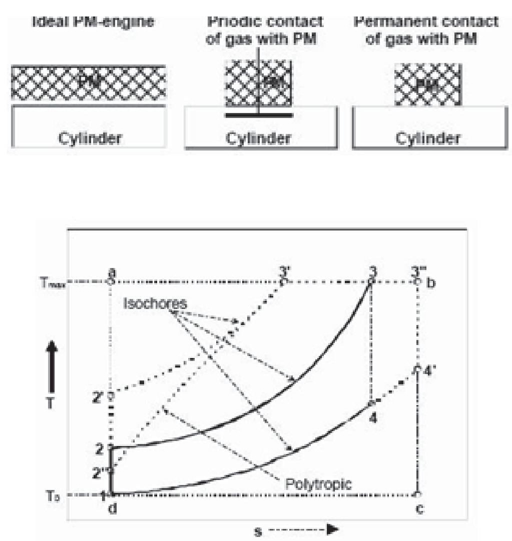


Fig. 5 T-S diagram for different cycles a-b-c-d-a carnot cycle, 1-2-3-4-1 ideal CV cycle, 1-a -3''-4'-1 Ideal PM engine cycle,1-2'-3'-3''-4'-1 Periodic contact of gas with PM, 1-2''-3'-3''-4'-1 Permanent contact of gas with PM

The Carnot cycle is realized along two isotherms (a-b and c-d) and two isentropes (d-a and b-c). Thus, the area a-b-c-d-a represents the work done by this ideal cycle operating between temperatures T0 and Tmax. For the same temperature limits, the conventional (CV) engine cycle cannot follow the Carnot cycle on the 1-2 line owing to the limitation set by the maximum temperature and corresponding maximum pressure. The cycle efficiency for the ideal CV cycle (Otto) 1-2-3-4-1 is

$$\eta = 1 - \left(\frac{Q_{out}}{Q_{in}}\right)$$

$$\eta = 1 - \left(\frac{c_v(T_4 - T_1)}{c_v(T_3 - T_2)}\right)$$

In the case of the ideal PM engine cycle, the engine can in the limit reach point a similarly to the Carnot cycle. However, as far as the expansion stroke is considered, it can only follow the line in the T-s diagram of the conventional CV engine cycle (4'-1). For the idealized PM-engine cycle 1-a- 3''-4'-1, the efficiency is

$$\eta_{(PM)(i)} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{C_v (T_{4'} - T_1)}{RT_3 \ln \frac{V_{3''}}{V_a}}$$

For a more realistic PM-engine cycle with periodic contact of gas with PM material 1-2’-3’-3’’-4’-1

$$\eta_{PM)(Periodic)} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{C_v (T_{4'} - T_1)}{C_v (T_{3'} - T_{2'}) \quad RT_3 \ln \frac{V_{3''}}{V_3}}$$

For a more realistic PM -engine cycle with permanent contact of gas with PM material 1-2’’-3’-3’’-4’-1:

$$\eta_{(PM)(Permanent)} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{C_v (T_{4'} - T_1)}{C_v (T_{3'} - T_{2''}) \quad RT_3 \ln \frac{V_{3''}}{V_3}}$$

More detailed thermodynamic analysis of the PMengine cycle may be found in [3, 7]

Fig. 6 View of the test engine with CR injection system

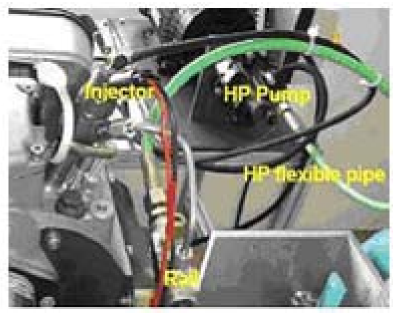


Fig. 7 View of the high pressure pump with E-driver and flexible high pressure pipe

Practical realization of PM engine: To demonstrate the practical realization of the PMengine concept with open chamber a single cylinder DI Diesel engine was adopted to operate as a PM-engine with a PM -combustion reactor mounted in the engine head. A view of the single- cylinder test engine with a common-rail injection system is shown in Figure 6. A high pressure pump of CR injection system is externally driven by E-motor. The high pressure pump was connected with the rail with a flexible high pressure (max. 180MPa) pipe (see Fig 7). SiC reactor was mounted in the engine head in a free space between intake and exhaust valves, as shown in Figure 8.

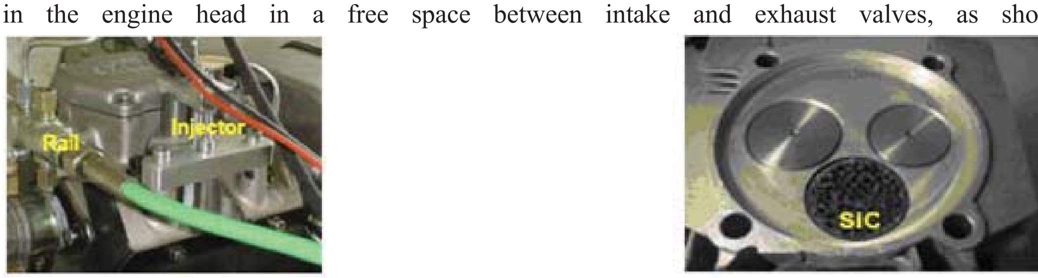


Fig. 8 Top and bottom view of the PM engine head with SIC reactor mounted in space between valves

First results and potential of PM engine: As already mentioned, the main features of the PM engine can be given as follows:

A. Very low emissions level due to homogeneous combustion and controlled temperature in the PM-combustion volume (for test engine without any optimization work): Measured NOx between 100 and 300 mg/kWh for the (A/F) ratio from 1 to 5 (the basic test engine NOx level was approx. 3000 to 5000 mg/kWh); Measured CO could be reduced by a factor of 5 comparing to the basic test engine; The experiments showed that it is possible to (almost) eliminate the soot formation.
B. Theoretically higher cycle efficiency due to similarity to the Carnot cycle.
C. Lowe compression ratio may be used.
D. Very low combustion noise due to significantly reduced pressure peaks.
E. Nearly constant and homogeneous combustion temperature field.
F. Very fast combustion yielding good engine performance.
G. Multi-fuel combustion system.

H. May operate with homogeneous charge: from stoichiometric to very lean mixture compositions.
I. Mixture formation and combustion processes are almost independent of in-cylinder flow structure, of turbulence or of spray atomization. The above points show that the PM-engine concept satisfies required conditions for homogeneous combustion with a controlled temperature field in the combustion zone. The-PM-concepts offers the realization of IC engines with emissions level of the primary combustion process being close to the long time requested zero-emission. Thus, PM-engine concept has the potential to realize a near-zero emission engines under both part and full load operational conditions. In a conventional DI engine the in-cylinder flow structure and turbulence play an important role for the mixture formation and combustion processes. In the case of the PM-engine the role of the intake system is to supply a required mass of air in to the cylinder. Instead of the fuel spray atomization very important in conventional DI engines, the PM-engine requires only a spatial distribution of the fuel throughout the PM volume. In the authors experiments a self homogenization of the fuel spray in the 3D-PM structure was observed and details are under investigation. The fuel spray (even if high injection pressure is used) is immediately destroyed and the spray impulse are spreads over the large specific surface area and over entire volume of the PM combustion chamber. First experiments have also indicated very effective secondary atomization to be present for the liquid jets injected onto the PM surface.

III. CONCLUSION

A new kind of an internal combustion engine is presented in the paper. The so-called PM-engine offers the realization of fully homogeneous combustion with a controlled temperature in the PM-combustion zone independently of the engine operational conditions. The temperature control is directly driven by the heat recuperation in the porous medium (heat capacitor). The significantly constant temperature distribution over the cycle and corresponding cylinder pressure distribution for the PM-engine is responsible for the higher cycle efficiency and very low combustion noise as compared to conventional DI engines. The multifuel properties of the PM -engine cycle permits a wide application range and offer new engine concepts to be realized. The PM-engine may use all components known in conventional engines, and only optimization of injection nozzle is required. New research aspects come out of the present work and are mainly related to the porous medium: from the optimisation of its thermal-mechanical properties, choice of its pores structure and density to the development of completely new materials and structures.

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