Strategy for intelligent Internal Combustion engine with homogeneous combustion in cylinder

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Abstract

In this report the author proposes strategy for development of intelligent combustion systems with a goal to approach a near-zero emission internal combustion engine operating in a wide range of speeds and loads. Main requirement for future I.C. engine is to develop a system permitting homogeneous combustion process (minimum of engine emissions) under all operational conditions. The author suggests, that none existing individual combustion system may satisfy these conditions. However, combination of different individual combustion modes in a one system may permit homogeneous combustion in a wider range of loads. Such combination of individual systems having potential for a homogeneous combustion and operating in different ranges of engine loads is here defined as an intelligent engine. In order to make this strategy practicable a new concept for mixture formation (MDI-Mixture Direct Injection) and homogeneous combustion based on the Porous Medium (PM)- technology is proposed in this paper.
This is probably first publication indicating possibility of developing of intelligent combustion systems in engines. This paper concentrates on MDI system that may adopt an actual combustion mode realizing in engine (i.e. ignition and combustion conditions) to actual engine operational conditions

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1. Introduction

Two characteristic parameters will be required for future internal combustion (I.C) engine: near-zero emissions level and as low as possible fuel consumption. These parameters strongly depend on the mixture formation and combustion process which are difficult to be controlled (under different engine operational conditions) in a conventional engine combustion system. Especially important are air flow structure, fuel injection conditions, turbulence as well as ignition conditions. The art of mixture formation, art of ignition and combustion realized in conventional direct injection (DI) engines indicate a lack of mechanisms for homogenization of the combustion process, as shown in Figure 1. The homogenization of combustion process, however, is necessary for radical reduction of engine emissions directly in a primary combustion process keeping very low specific fuel consumption. The question remaining still unresolved is the method for realization of homogeneous combustion in IC engine, especially if variable engine operational conditions (load and speed) are considered.

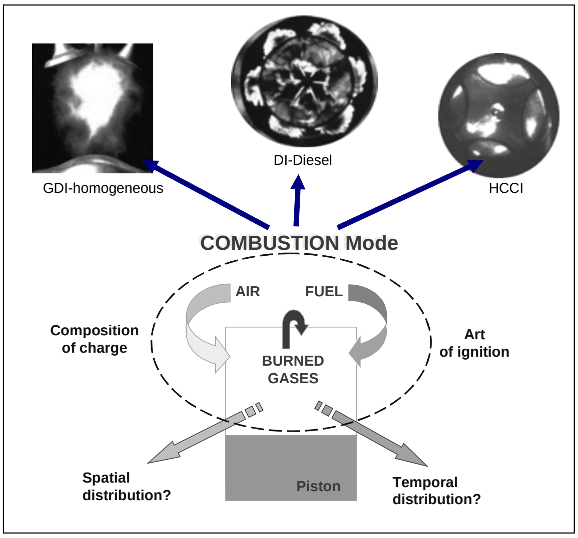

Figure 1: Basic processes of engine cycle

The author would like to indicate in this paper which physical processes limit the existing combustion concepts and how could existing problems be resolved by applying of new technologies. The goal of the paper is also to indicate that new concepts for mixture formation and combustion processes realized in IC engines are necessary for achieving a homogeneous combustion leading to significant reduction of engine emissions in a wide range of engine operational conditions. In this paper the author proposes new concepts for homogeneous combustion systems based on the porous medium (PM) technology.

In section 2, required conditions for future engine are discussed. Main requirements are near zero-combustion emission level in a wide range of engine operational conditions and possible high engine cycle efficiency. Necessary conditions for a homogeneous combustion process are defined in section 3 and particular role of the art of ignition on the combustion mode is also indicated. Different modes of homogeneous charge combustion according to the ignition method are discussed in this section. Characterization of conventional concepts for homogeneous combustion in engines is given in section 4 indicating three main practical limitations of existing systems: control of ignition timing, control of heat release rate and extension to higher engine loads.

Section 5 describes a new concept for mixture formation using a porous medium technology with possible application to conventional systems (GDI[1], HCCI and to radical combustion RC). It is also shown in this section, that a combination of different combustion modes in the same engine (i.e. multi-mode combustion system), could permit homogenous combustion conditions under variable engine load and speed, This combination of different combustion modes in one engine is called as an intelligent engine concept.

2. Main requirements for future engine

Basic requirements for future clean internal combustion (I.C.) engine concern very low (near-zero) exhaust emissions level for both gaseous and particulate matter components under as low as possible fuel consumption. Internal combustion engine (especially for road vehicle applications) has to operate in a wide range of speeds and loads and should satisfy selected requirements under all operational conditions. For vehicle application, the following conditions are required for future engine:

Operation with a homogeneous (nearly) stoichiometric charge for high power density (full load operational conditions).

Operation with a homogeneous-lean charge for low specific fuel consumption (part load operational conditions).

[1] GDI-Gasoline Direct Injection; HCCI-Homogeneous Charge Compression Ignition; RC-Radical Combustion.

Realization of homogeneous combustion[2], for all mixture compositions for the lowest combustion emissions.

For significant reduction of specific fuel consumption and for a near-zero combustion emissions especially attractive would be realization of engine operating with a lean-homogeneous charge at part loads, assuming that the combustion process is homogeneous (see section 3). For vehicle application, additional factors such as a high power density, good dynamic properties, low combustion noise and a high durability of the engine have to be considered.
In the author opinion, further development of after-treatment systems may help but will not probably be able to resolve the problem of engine emissions, especially for emissions regulations beyond 2008 including CO_2 reduction to the level of 120/140g/km. Here, significant reduction of raw emissions from the primary combustion process will be necessary. EUCAR (European Council for Automotive R&D) suggests, that in the future the exhaust emissions will be reduced so far, that there will be no need for further emission legislation [5]. For the actual legislation, for gasoline engines, NO_x and HC have been reduced by 40% for Euro 3 and by 70% for Euro 4. CO has been reduced by 30% and 70%, respectively. For small Diesel engines, particles has been reduced by 40% for Euro 3 and by 70% for Euro 4. NO_x and HC have been reduced by 12% for Euro 3 and by 56% for Euro 4. CO has been reduced by 40% and 50%, respectively. For large Diesels, particles has been reduced by 30% for Euro 3 and by 80% for Euro 4/5. NO_x has been reduced by 30% for Euro 3, by 50% for Euro 4 and by 70% for Euro 5.
In the case of fuel consumption, also vehicle contributes to the overall level of emissions (Fig.2).

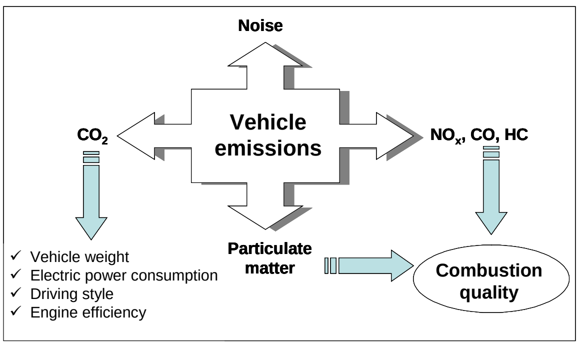

Figure 2: Vehicle emissions structure

Most important are here vehicle weight, electric power consumption on board, aerodynamics and driving style. For example, reduction of vehicle weight in a 100kg gives reduction of fuel consumption on order of 0,5l/100km. 1kW electric power consumption on the board requires approximately 1,5l/100km additional fuel consumption.

3. Definition and characterization of homogeneous combustion process

Let`s start this analysis from the definition of the conditions for the homogeneous combustion process in IC engine. The homogeneous combustion is here defined as a process in which a 3D-ignition (volumetric) of the homogeneous (premixed) charge is followed by simultaneous (no flame front) heat release in the whole combustion chamber volume characterized by a homogenous temperature field (see Fig. 3).

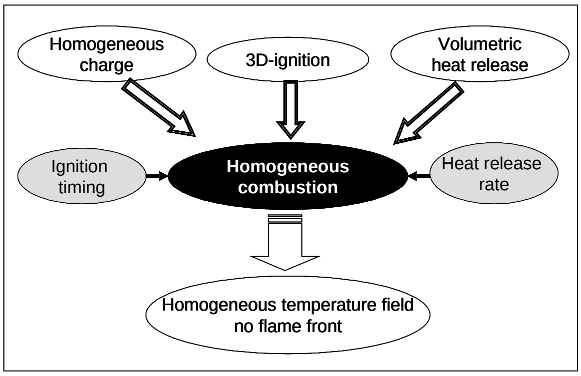

Figure 3: Definition of homogeneous combustion process

According to this definition a 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:
1 -degree of charge homogenisation (with a goal to get a homogeneous, premixed, gaseous charge);
2 -art of ignition (goal is to realize a volumetric ignition);
3 -homogeneity of combustion process and its temperature field (represented by simultaneous heat release in combustion chamber volume).

There are several additional aspects that have to be considered for analysis of particular homogeneous combustion system. First of all, considered is the question related to the combustion temperature, especially for close to stoichiometric charge compositions. It would be necessary to lower the combustion temperature from the adiabatic level in order to permit nearly zero NO_x emissions for these mixture compositions. Another aspect concerns range of available engine loads; especially higher engine loads are critical for this kind of combustion. Addi-

[2] For definition see section 3.

tional requirement concerns correct mixture formation and combustion processes in a wide range of engine speed (time scale).

There are two principal requirements given to the combustion system that are necessary for satisfying the homogeneous combustion conditions:
Controlling of the ignition timing under variable engine operational conditions,
Controlling of the heat release rate for different mixture compositions.

Additionally, for low combustion emissions it is necessary that the liquid fuel is completely vaporized prior the ignition occurs. The author wants to underline, that the homogeneity of the charge is not sufficient for realization of homogeneous combustion in engine; the volumetric ignition play here a critical role.
There are four basic arts of ignition that may be realized in I.C. engine (Fig.4):
Local ignition (e.g. spark plug)
Compression ignition
Controlled-auto-ignition (chemical ignition)
3D-thermal-PM-ignition (thermal ignition in a porous medium volume) [1-2]

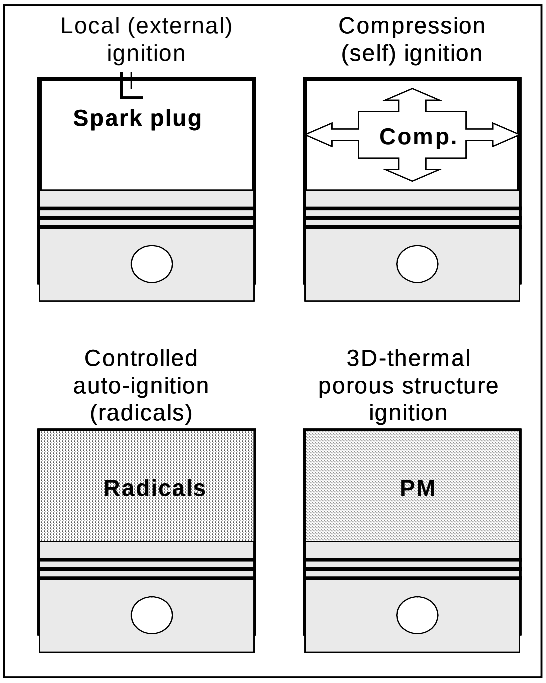

Figure 4: Characteristic arts of ignition in I.C. engines

The last three selected systems have potential for realization of volumetric ignition in engine. Thus, the art of resulting combustion depends on the mixture homogeneity and ignition mode.

In the case of local ignition, even if homogeneous and premixed charge is applied, we cannot satisfy the requirements of the ignition defined for a homogenous combustion. In this case a flame kernel will be followed by the flame front propagating throughout the combustion chamber. The resulting combustion process is not homogeneous.

In the case of compression ignition applied to a strongly non-homogeneous and heterogeneous charge (see Diesel engine) a multi-point ignition can be achieved. The resulting combustion process is highly non-homogeneous and diffusion (mixing) controlled. If in the same system a homogeneous charge is applied, a nearly volumetric ignition would be possible (HCCI system). Such a process (if volumetric) would lead to very high pressure gradients in the cylinder depending on the mixture composition and thermodynamic parameters of the cylinder charge. Control of the ignition timing and following heat release rate are the most critical factors limiting practicability of the conventional concepts of HCCI systems.

4. Characterization of conventional concepts for homogeneous combustion in engines

Available technologies for supporting engine processes and for reducing of engine emissions in conventional DI Diesel are selected in Figure 5.
HCCI system, as compared to conventional DI Diesel engine, has substantially lower emissions of particulate matter (soot) and NO_x. In practical realizations known from the literature, these low emissions are result of highly diluted homogeneous mixture in addition to low combustion temperatures of lean charges. In practical realizations, the charge in HCCI engine is made diluted by being very lean, by stratification or by using exhaust gas recirculation. The lack of flame propagation in HCCI system allows higher dilution levels that can be applied to the engine. Very important benefit of HCCI system, besides potential for very low emissions and high cycle efficiency, is its fuel tolerance. However, there are number of challenges which presently limit applicability of conventional concepts for a homogeneous combustion in engines. High HC and CO emissions, high NO_x emissions for more close to stoichiometry charge compositions and cold start conditions remain still to be unresolved.
However, the following three problems are main limiting factors to make conventional HCCI concept practicable:

Control of ignition timing under variable engine load.
Control of heat release rate under variable engine load.
Availability of higher engine loads.

The control of above selected parameters in HCCI combustion system would be possible by controlling the following parameters:

- compression temperature history,
- cylinder pressure,
- mixture structure and its composition,
- charge heat capacity,
- charge chemical activity (ignitability).

The first required factor for properly operating HCCI engine is controlling of the ignition timing under variable engine operational conditions and for different mixture compositions. HCCI ignition process (in volume!) is determined by the charge composition (air-to-fuel ratio), charge homogeneity (or local non-homogeneity), charge ignitability, cylinder charge temperature and pressure, art of fuel and its properties. It would be necessary for future HCCI system to control the temperature history of the cylinder charge, charge ignitability and TDC compression temperature for different charge compositions, engine speeds and loads. This control becomes even more critical during rapid transients of the engine.

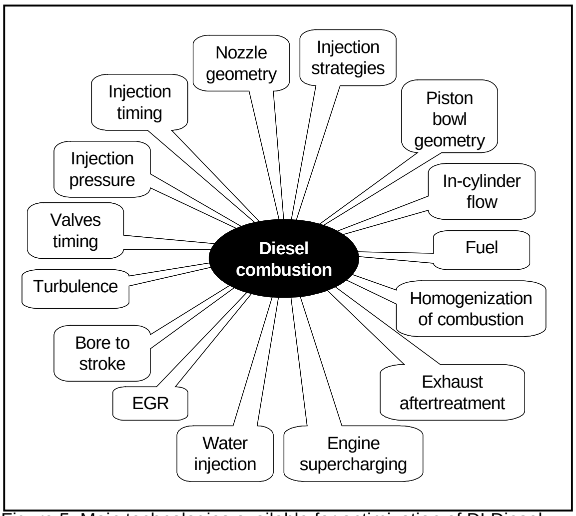

Figure 5: Main technologies available for optimization of DI Diesel combustion system

Presently, the researchers are trying to get control on the ignition timing by applying of hot EGR, by variable compression ratio, variable valve timing, by variable fuel injection timing and by heating of intake air. In the last case, three different ranges of the combustion process may be selected according to the inlet air temperature [6]:

Knocking at nearly-stoichiometric charge compositions and higher inlet air temperatures
Moderate and stable combustion for leaner charges and higher than 423K inlet air temperatures
Misfire or unstable combustion at lower inlet air temperatures and lean charges.

As suggested in [6], the hot EGR has a similar effect on the ignition timing to inlet air preheating.
Combustion in HCCI system depends on the chemical kinetics of low- and high-temperature oxidation processes. Actual cylinder temperature deals as an accelerator for switching from low-temperature oxidation to a high-temperature oxidation process. As shown in [10] the increasing cylinder pressure breaks this transition. According to [4] there are three characteristic combustion regimes in operation of HCCI system (see Fig.6):

Misfire at low compression ratios in the whole range of mixture compositions
Low temperature oxidation at moderate compression ratios for lean to very lean mixture compositions (without transition to a high temperature process)
High temperature oxidation (complete combustion) at proper thermodynamic conditions.

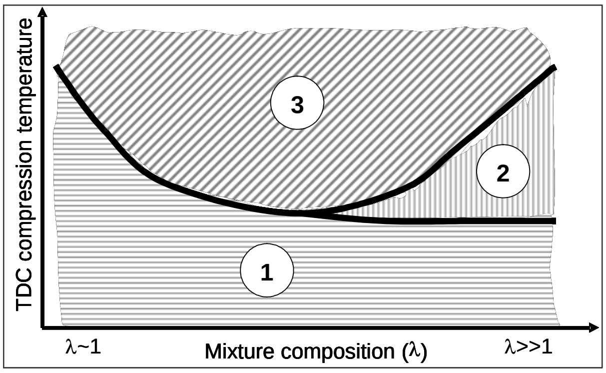

Figure 6: Characteristic combustion modes of HCCI engine (based on the data from [4]); 1-misfire, 2-low temperature oxidation, 3-stable combustion.

Heat release rate in HCCI system becomes critical at high loads and more stoichiometric charge compositions. One possible solution, which presently is considered, is a dual-mode (or hybrid) engine operation. This means, that the engine operates e.g. as HCCI system at light loads and as a conventional Diesel engine at higher loads.
This, however, limits the potential of HCCI system for reducing the engine emissions. Another possibility is to use a controlled stratification of the

charge composition or stratification of the temperature field to reduce the combustion rate. However, the local combustion quality may significantly be reduced (emissions).
For more practicability of HCCI concepts, it is necessary to extend the available engine operational conditions to higher engine loads. This factor is strictly related to both above discussed problems: controlling of ignition timing and controlling of heat release rate. At higher loads, the heat release rate may be very high (very rapid combustion process occurs) generating unacceptable high combustion noise and cylinder pressures. Additionally, possible high NO_x emissions depending on the actual mixture composition (A/F ratio) may be expected at high engine loads if the combustion temperature is high – see Fig.7.

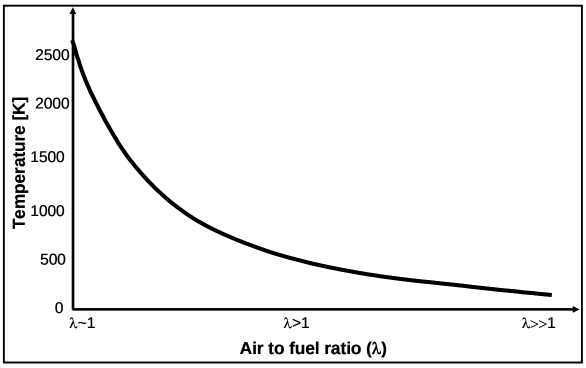

Figure 7: Qualitative distribution of combustion temperature vs mixture composition

The actual techniques used for extending the load range of the HCCI systems are: partial stratification (non-homogeneity) of the charge, temperature field stratification, and application of different fuels.

5. Definition of intelligent engine combustion system

A future engine operating with a homogeneous combustion process in a wide range of engine speeds and loads and having good transient response will require satisfaction of the following conditions (at least combination of them):
Variable temperature history during the compression stroke

- Variable TDC compression temperature
- Completely vaporized fuel prior the ignition process
- Variable mixture composition (A/F ratio)
- Variable reactivity (ignitability) of the charge
- Homogeneous and premixed charge prior ignition
- Variable charge heat capacity
- Fuel supply and fuel vaporization conditions independent of the engine load
- Volumetric ignition conditions

The engine combustion system which allows adoption of its in-cylinder thermodynamic conditions to actual operational conditions for permitting homogeneous combustion is defined as an *intelligent engine*. Especially important is adoption of these parameters to get controllable ignition (different modes are possible) and controllable heat release rate.
In the author opinion, in order to satisfy above selected conditions, it is necessary to develop new concepts for mixture preparation in engine with a goal to achieve a controllable homogenous combustion process. One approach, proposed by the author, is presented in the next section.

6. New concept of mixture preparation for homogeneous combustion in engines using porous medium technology

Different R&D activities of the author using porous materials (highly porous 3D-structures) (see LSTM at University of Erlangen-Nürnberg and Promeos GmbH in Erlangen) indicated unique features of this technology for mixture formation and combustion processes, also as applied to IC engines.

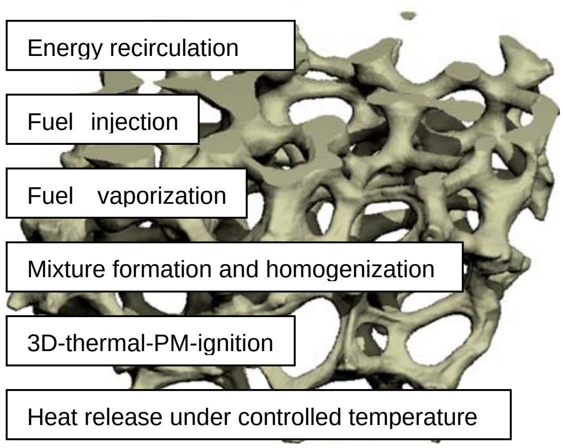

Figure 8: Most important engine processes that may be supported by the PM-technology

Porous medium (PM) technology is here defined as an utilization of specific and unique features of a highly porous medium as applied to individual processes of mixture formation, ignition and combustion realized in engine [7,8]. The most important features of a highly porous media are: large specific surface area, high porosity, high heat capacity, excellent heat transfer properties (especially heat radiation), variability of structure, pore density and pore geometry, high thermal and mechanical stability.

The following engine processes may be supported by the porous medium (see Fig.8):

Energy recirculation in engine cycle in the form of hot burned gases recirculation or combustion energy: this may significantly influence thermodynamic properties of the charge in the cylinder and may control its ignitability (activity). This energy recirculation may be performed under different pressures and temperatures during the engine cycle. Additionally, this heat recuperation may be used for controlling the combustion temperature level (Fig.9).

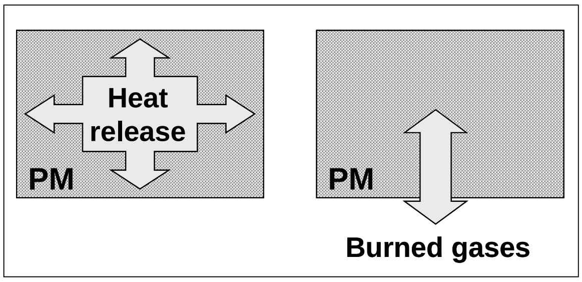

Figure 9: Heat accumulation and recirculation in porous medium

Fuel injection in PM-volume: especially unique features of liquid jet distribution and homogenization throughout the PM-volume (effect of self-homogenization) [9] is very attractive for fast mixture formation and its homogenization in the PM-volume (Fig.10 and 11).

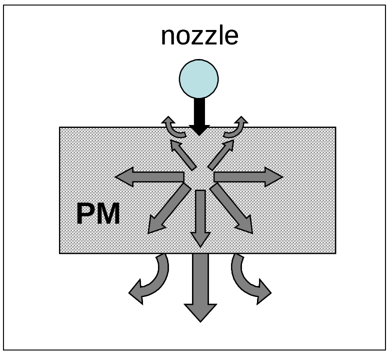

Figure 10: Diesel jet distribution in PM-volume

Fuel vaporization in PM-volume: combination of large heat capacity of the PM-material, large specific surface area with excellent heat transfer in PM-volume make the liquid fuel vaporization very fast and complete. Here two different conditions of the process have to be considered: vaporization with presence and without presence of combustion air (e.g. also “cool-flame” and “blue-flame” reactions).

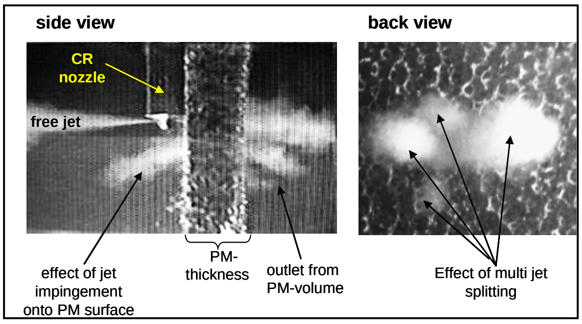

Figure 11: Diesel jet distribution in PM-volume (acc. to the author [9])

Mixing and homogenization in PM-volume: unique features of the flow properties inside 3D-structures allow very effective mixing and homogenization in PM-volume.

3D-thermal-PM-ignition (if PM temperature is at least equal to ignition temperature under certain thermodynamic properties and mixture composition): there is a new kind of ignition, especially effective if the PM-volume creates the combustion chamber volume [1].

Heat release in PM-volume under controlled combustion temperature (properties of homogeneous combustion): this is only one known to the author kind of combustion, that permits homogeneous combustion conditions almost independently of the engine load with possibility of controlling the combustion temperature level [1,2] – see Fig.12.

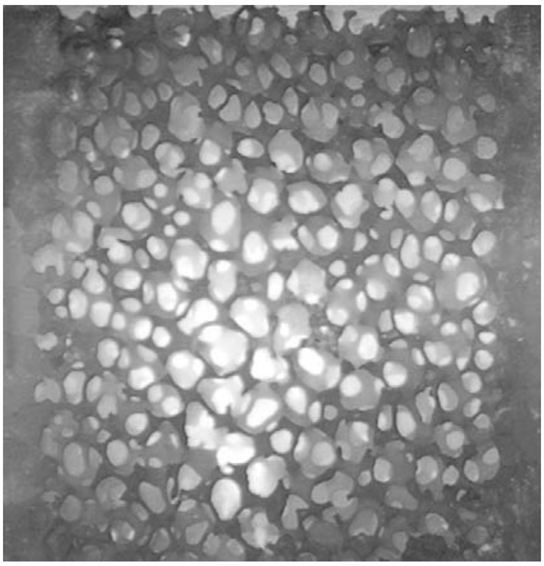

Figure 12: Glowing PM-reactor (T_{PM} ~ 1200^0C)

There are two new concepts that utilize a porous medium technology for permitting the homogenous combustion under variable engine operational conditions:

Mixture preparation system that may change its combustion mode according to actual engine operational conditions to keep homogenous combustion conditions, so-called *intelligent (multi-mode) combustion system* to be a matter of this paper (see Fig.13).

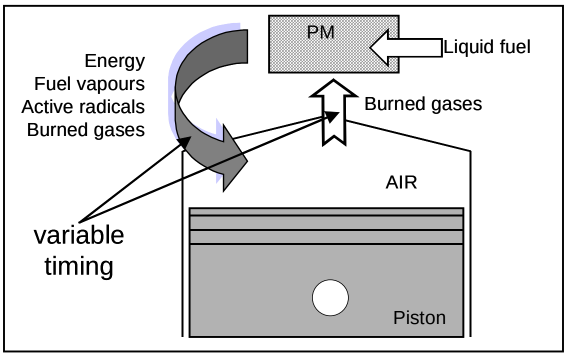

Figure 13: Principle of a multi-mode intelligent engine based on the MDI concept

System that may operate independently of the engine operational conditions permitting homogeneous combustion conditions from very light to full loads, so-called *mono-mode combustion system* – PM-engine concept proposed by Durst and Weclas [1,2] (Fig.14).

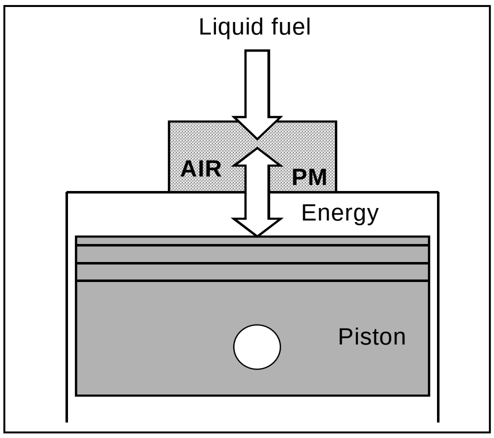

Figure 14: Principle of a PM-engine concept

6.1. Principle of Mixture Direct Injection concept and its ability for creating intelligent multi-mode combustion system

MDI - Mixture Direct Injection concept offers homogenization of the combustion process by performing of fuel vaporization, its chemical recombination and energy recirculation in a porous medium. The enthalpy of the burned gases is partly transferred to the porous medium and can later be supplied back to the cylinder. This energy is utilized for both vaporization of liquid fuel and for its chemical recombination in the PM-volume.
A practical realization of the MDI system requires a porous medium chamber to be mounted in proximity to the cylinder and equipped with a valve (in this paper a poppet valve is considered) permitting contact between PM-chamber and the cylinder volume. The engine cycle described below, models the real engine cycle, and other than presented timings for PM-chamber may be used. MDI concept may be combined with conventional combustion modes: GDI, HCCI and with radical combustion, and only control of the PM-chamber timing is necessary to select a combustion mode used in the engine. MDI concept offers combination of these individual systems by applying the variable timing of the PM-chamber, as described below.
Characteristic phases of the cycle with MDI mixture preparation are as follows (see Fig.15):

- **Phase I** - PM-chamber is charged with a burned gases containing energy,
- **Phase II** - liquid fuel is injected to PM chamber and fuel vaporization performs,
- **Phase III** - gas (evaporated fuel, energy, active radicals) discharges from PM-chamber to the cylinder (non-combustible mixture),
- **Phase IV** - mixing with cylinder air performs and ignition of combustible mixture is realized.

The system considered in Figure 15 consists of the cylinder with a moving piston and of the PM-chamber equipped with a poppet valve. This valve allows control of the PM-chamber timing. Let us consider combination of MDI concept with individual combustion systems, while the PM-chamber timing depends on the ignition/combustion mode realized in engine.
Let us start this analysis from the middle expansion stroke (Fig. 15 top-left). A chamber contains the porous medium which is thermally isolated from the head walls. During this period of the engine cycle the valve in PM-chamber opens, and owing to the pressure difference between cylinder and PM-chamber, certain mass of a high temperature burned gases flows into the PM-volume (Fig.16).

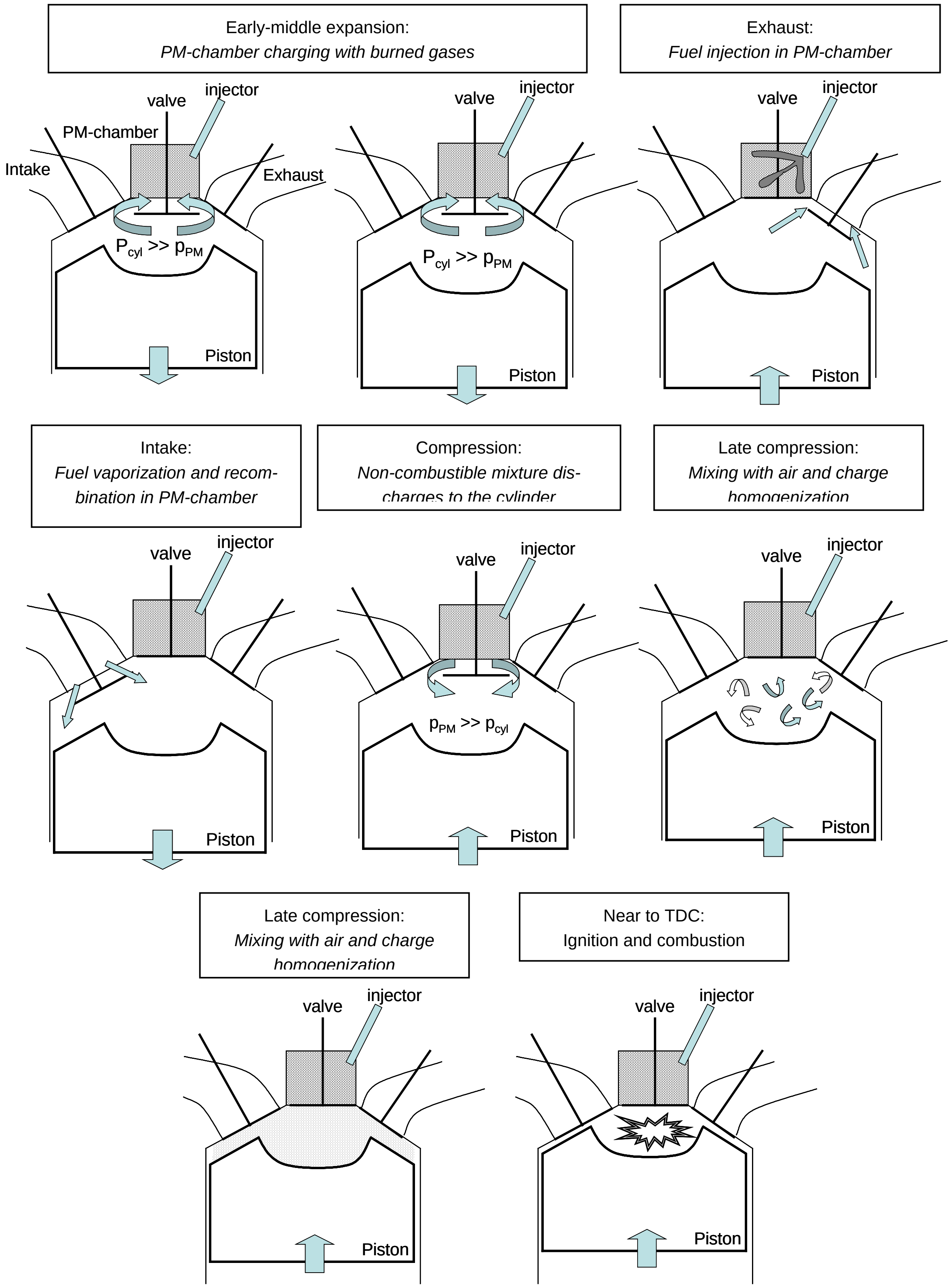

Figure 15: Main phases of MDI system operation

After closing the PM-chamber, the expansion andexhaust processes continue in the cylinder without any contact with the PM-chamber content. After closing the PM-chamber, liquid fuel is injected in to By closing the valve, this gas is trapped inside the PM-chamber. The control of the rate of the trapped in PM-chamber gases is permitted by controlling of the valve timing.
exhaust processes continue in the cylinder without any contact with the PM-chamber content. After closing the PM-chamber, liquid fuel is injected in to PM-volume, and time available for this process and for fuel vaporization is very long. Important is, that vaporization process is independent of the spray atomization, engine load or of the engine rotational speed.
Because the fuel is injected into the gas atmosphere with a very low oxidant concentration the resulting mixture in PM cannot ignite, even under high gas/PM temperature.

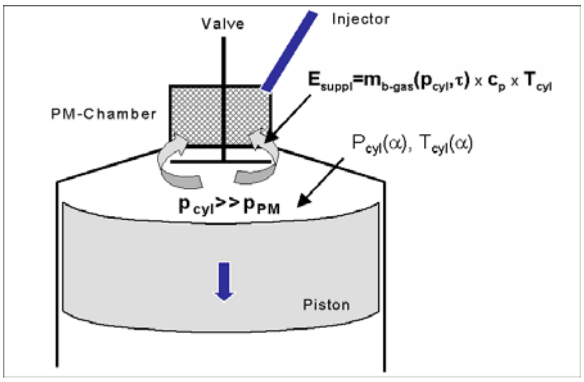

Figure 16: PM-charging with burned gases

This non-combustible gaseous charge formed in the PM-volume is „injected“ back to the cylinder when the PM-chamber valve opens, since the pressure in the PM chamber is much higher than the cylinder pressure (available timing is from intake to late compression period).
This high pressure gas discharge from the PM-chamber to the cylinder generates a highly turbulent flow conditions in the cylinder supporting mixing and homogenization of the cylinder charge.

This mixture discharge (“injection”) in to the cylinder permits additional energy and chemically active radicals (see result of pre-ignition chemical recombination) to be supplied together with a completely vaporized fuel (Fig.17).

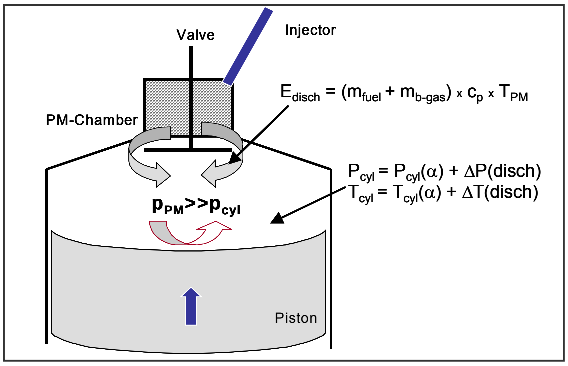

Figure 17: PM-chamber – discharging process; $\Delta p(disch)$ is the cylinder pressure increase due to discharge from the PM-chamber, $\Delta T(disch)$ is the cylinder temperature increase due to discharge from the PM-chamber,α is the cycle timing (carnkangle)

This gaseous charge supplied to the cylinder may be used for significant extension of the effective lean-limit of the homogeneous charges, for increasing of the charge ignitability and for controlling the thermodynamic conditions of the charge depending on the engine operational conditions.

The end compression temperature may also be controlled. The different fluid-dynamical coupling phases between PM-chamber and cylinder are shown in Figure 18.
MDI concept may be combined with different individual conventional combustion systems.
Combination of MDI with GDI combustion system offers the following features: extension of lean effective limit and improvement of charge ignitability of a homogeneous charge, reduction of temperature peaks under lean operation conditions
(homogeneous charge), no liquid fuel is present in the cylinder (no soot), excellent cold start conditions.

Combination of MDI with HCCI combustion system offers the following features: extension of lean effective limit and improvement of charge ignitability of a homogeneous charge, fuel supply and mixture preparation weakly dependent on the engine load, complete fuel vaporization, better and faster homogenization of the charge in the cylinder, no liquid fuel is present in the cylinder, mixture preparation process is almost independent of the art of fuel. MDI system offers control of the ignition conditions in the cylinder and may adopt these conditions to actual engine operational conditions.

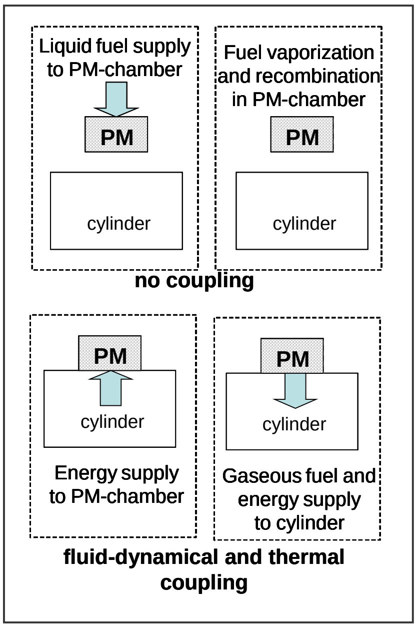

Figure 18: Fluid-dynamical and thermal coupling between PM-chamber and engine cylinder

Combination of MDI with RC combustion system offers the following features: elimination of hot EGR trapped in the cylinder, control of active radicals almost independent of the cylinder conditions, extension of lean effective limit and improvement of charge ignitability of a homogeneous charge, fuel supply and mixture preparation are weakly dependent on the engine load, better and faster homogenization of the charge, no liquid fuel is present in the cylinder, mixture formation conditions are independent of the art of fuel (Fig.19 and Table 1).

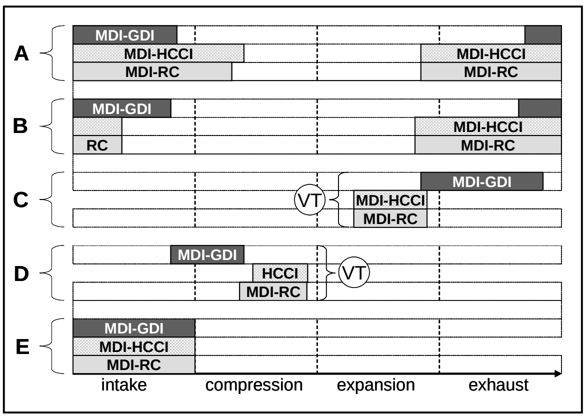

Figure 19: Timing of MDI system as combined with individual systems (GDI, HCCI and RC) for selected processes; VT – variable timing of the PM-chamber, A-liquid fuel vaporization, B-liquid fuel supply to PM-chamber, C-energy supply to PM-chamber (chamber charging), D-fuel vapours and energy supply to the cylinder (chamber discharging), E-air supply to the cylinder.

6.2. Potential of MDI system for creating intelligent engine combustion system

A choice of the combustion mode in MDI-adaptive system is related to the actual engine load, speed and mass of fuel supplied to the engine. This choice may be controlled by PM-chamber timing. Valve opening timing (beginning and duration) for PM-chamber charging with burned gases defines energy accumulated in PM, PM temperature, pressure in PM-chamber, amount of burned gases trapped in PM-volume, chemical activity of the fresh charge, possible timing for discharging to the cylinder. During this time the cylinder pressure is higher than the pressure in PM-chamber.

MDI system offers the following abilities for variable engine load and speed:

- *Variable amount of energy supplied to the chamber* results in variable temperature of the cylinder charge, and variable end of compression cylinder temperature (using constant compression ratio) – Fig.15 to 19.
- *Variable hot EGR realized in PM-chamber* together with variable mass of fuel results in variable heat capacity of the cylinder content (Fig.20)

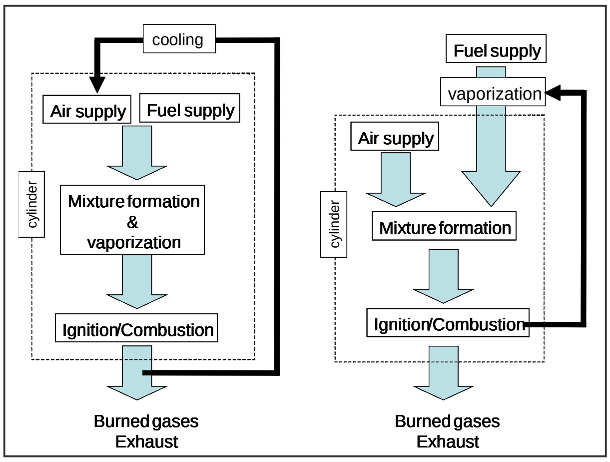

Figure 20: Energy (EGR) recirculation in conventional engine (left) and in MDI concept (right)

- *Variable timing of the PM-chamber* results in variable temperature history in the cylinder during intake and/or compression strokes – Fig.15 to 19.
- *Variable engine load* means variable mass of fuel supplied to the PM-chamber but still with long time available for fuel supply and complete vaporization

- *Variable temperature of the gas supplied to the chamber* and then to the cylinder results in variable chemical activity of the charge

- *Variable engine speed results* in variable timing of the cycle in the cylinder, but in PM-chamber the same period of crankangle is available for fuel supply and vaporization

- *Different timings are available for gas supply* from the PM-chamber to the cylinder, however only one requirement is given, $p_{PM} >> p_{cyl}$ (see Fig.21).

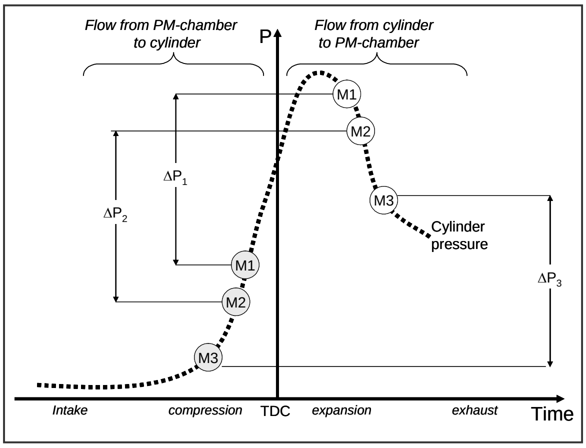

Figure 21: Examples of localization of characteristic timings for chamber charging and discharging with respect to the cycle timing and cylinder pressure; M- mode

Parameter	GDI	MDI-GDI	HCCI	MDI-HCCI	RC	MDI-RC
In-cylinder flow structure	Very critical	Not critical	Very critical	Not critical	Critical	Not critical
Timing of fuel injection (DI system)	Very critical	Not critical	Very critical	Not critical	Important	Not critical
Spray shape and atomization structure	Very critical	Not critical	Very critical	Not critical	May be critical	Not critical
Completeness of fuel vaporization by ignition and combustion timing	questionable	yes	questionable	yes	questionable	yes
Liquid phase present in cylinder, especially during combustion- soot	yes	not	possible	not	possible	not
Extension of lean limit for homogeneous charge	not	yes	not	yes	limited	yes
Nearly-Stoichiometric homogeneous charge compositions (high load)	yes	yes	not	yes	not	yes
Improved ignitibility	not	yes	not	yes	yes	yes
Internal energy recirculation	not	yes	not	yes	yes	yes
Active radicals	not	yes	not	yes	yes	yes
Turbulization of cylinder charge during late compression	not	yes	not	yes	not	yes
Operation under variable load-speed conditions	yes	yes	questionable	yes	limited	yes
Dependence on load	significant	weak	critical	weak	critical	weak
Trapping of hot burned gases in cylinder	not	not	not	not	yes	not

Table 1: Comparison of basic features of different DI-combustion systems with and without application of MDI concept

- *Despite of variable speed and load*, in the engine cylinder mix two gases under strongly turbulent conditions resulting in pretty well premixed gaseous charge prior ignition,

Variable load and speed require variable e. variable ignition conditions and variable charge reactivity according to the actual operational conditions, i.e. variable ignition and combustion mode (see intelligent system based on the MDI concept) as described in this paper.

The combination of these variable conditions allows not only realization of homogeneous combustion conditions (see definition) but also permits control of ignition timing and of heat release rate. These both aspects define practicability of the combustion system operating under homogeneous combustion conditions. Important is, that only one variable parameter (i.e. PM valve timing) is necessary in MDI concept to control the engine operational conditions.

This variable timing of MDI concept permit control of the following cylinder charge parameters:

TDC compression temperature.
- Temperature history during the compression stroke.
- Reactivity (chemical activity) of the charge.
- Homogeneity of the charge (with completely vaporized fuel).
- Heat capacity of the charge.

7. Concluding remarks

There is no doubt that the future of internal combustion engine is related to the homogeneous combustion process in a wide range of engine operational conditions.
This technique shows potential for a near-zero combustion emissions (especially NOx and soot) as well as high cycle efficiency (low fuel consumption). Moreover, this kind of combustion system is less fuel specific. However, the realization of homogeneous combustion in IC engine under variable loads and speeds will probably require new concepts for mixture formation and controlled ignition conditions under different engine loads. The future engine operating with a homogeneous combustion process in a wide range of load and speed will require variable temperature history during the compression stroke, variable TDC compression temperature, completely vaporized fuel prior the ignition process, variable mixture composition (A/F ratio), variable reactivity (ignitability) of the charge, homogeneity of the charge, volumetric ignition conditions, variable heat capacity of the cylinder content, and fuel supply and fuel vaporization conditions to be independent of the engine load. This means, that future engine must be able to change (itself) thermodynamic and chemical properties of the cylinder charge under variable operational conditions.

A chance to get such a control is offered by application of the MDI concept to intelligent engine combustion system as proposed in this paper.

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