Basic aspects of interaction between a high velocity Diesel jet and a highly porous medium (PM)

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There are four characteristic phases of the jet interaction with the cold porous medium that have been observed in the reported investigations. One phase concerns outlet from the nozzle and formation of a free jet in available space between nozzle and PM. The next phase relates to jet interaction with PM-interface resulting in partial propagation into PM-volume, and partial reflection from this interface. In the following phase, liquid distribution throughout the PM-volume is considered giving rise to self-homogenisation effect in this volume. As the last phase, liquid leaving PM after travelling throughout the PM-volume may be observed if the injection pressure, pore size and geometry of the porous medium permit so long penetration path of the liquid. The observed phenomena may be utilized in new concepts for mixture formation and homogeneous combustion in I.C. engine having potential for operation with a near-zero emissions level. These new concepts are also presented in this paper.

1. Introduction

The most promising trend in development of future engine combustion system is realization of a homogeneous combustion process having potential for a near-zero emissions level. Besides conventional concepts, such as HCCI (homogeneous charge compression ignition) there are also new concepts which significantly change conditions for mixture formation and combustion in engine. In new concepts considered in this paper, the engine processes are supported by application of porous medium (PM) technology [1-3]. In all of them, one of most important processes is a high-pressure fuel injection in PM-volume. This process is followed by spatial fuel homogenization, vaporization and mixing with air. In this paper 3D-porous structures of a high porosity (porosity higher than 80%) are considered, as shown in Figure 1.

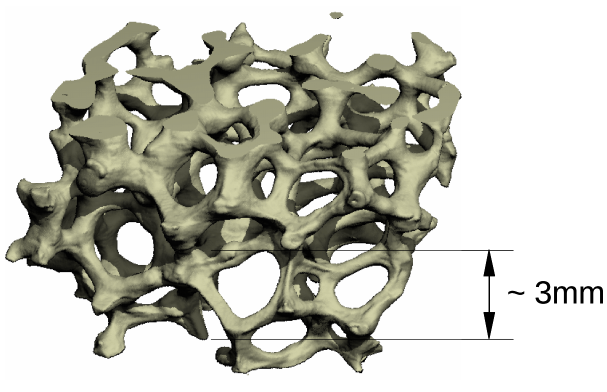

Fig. 1 CT view of highly porous 3D-structure (SiC foam)

The porous medium structure is characterized by a large specific surface area, large heat capacity and transparency for gas and liquid (spray) flow . A high pressure fuel injection into or onto such 3D-porous structures shows quite different features from those observed during fuel injection in a free volume of the combustion chamber. The present paper indicates these differences and shows most important features of a high pressure injection in PM-volume. The authors make first attempt in analysing of these phenomena.

2. A simple model for analysis of interaction between CR Diesel jet and a highly porous structure

In the present paper, the attention is focussed on interaction between jet produced by a common-rail Diesel nozzle and a highly porous medium. Especially, the effect of spatial distribution of the liquid jet throughout the porous medium volume is considered in the present analysis. There are four characteristic phases of the jet interaction with the cold porous medium that are selected in this paper (see Fig.2):

- phase A represents outlet from the nozzle and free jet formation,
- phase B represents jet interaction with PM-interface,
- phase C represents liquid distribution throughout the PM-volume,
- phase D represents liquid leaving the PM-volume.

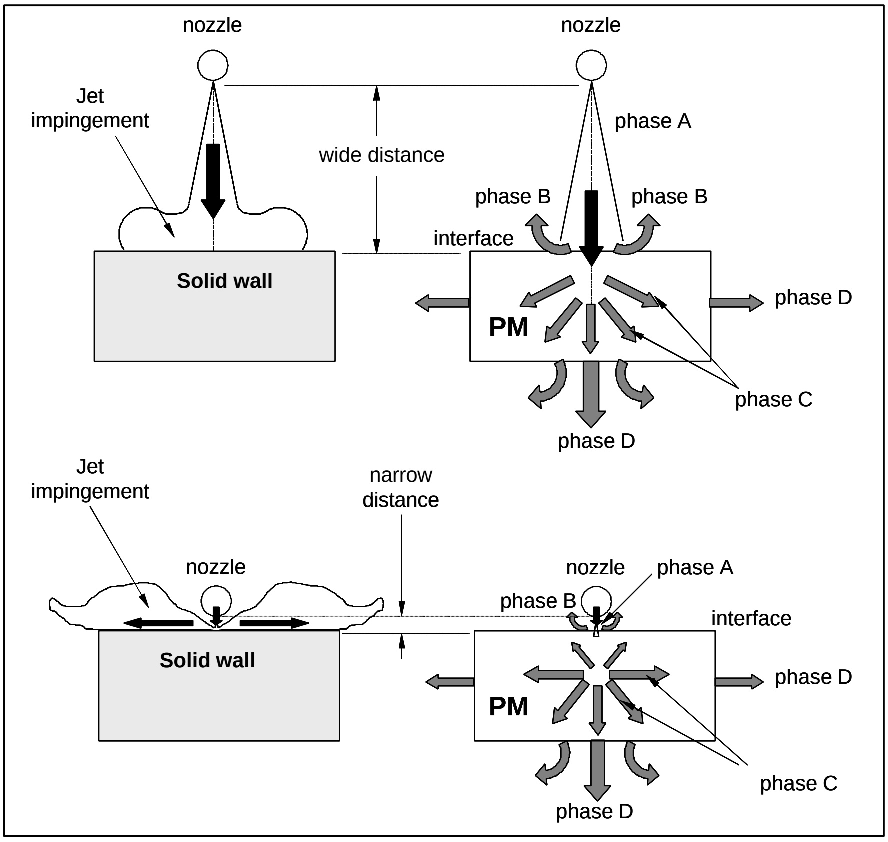

Fig. 2 Four characteristic phases of jet interaction with a porous medium

This figure shows phenomenological models of jet interaction with a solid wall (left hand side pictures) and an interaction with a highly porous structure (right hand side pictures). This figure indicates two characteristic geometrical configurations, selected according to

relative location between nozzle and impingement interface: a wide distance with available space for formation of a free jet (top pictures) and a narrow distance when the nozzle outlet is located in the proximity to the solid or PM surfaces (bottom pictures).
In a free space between nozzle outlet and porous medium surface (phase A), a free jet may penetrate throughout available space (defined by the distance between nozzle and PM) until impinging on to PM surface. A free jet in phase A is characterized by the jet angle, its velocity and propagation angle with respect to the PM surface. The jet impingement on to PM-surface may be divided in two parts: jet reflection from the interface (phase B) and jet entrance into PM followed by liquid propagation throughout the PM-volume (phase C). This impingement and division between phases B and C depend not only on the injection parameters (e.g. injection pressure) and nozzle geometry but also on the distance from the nozzle outlet, as well as on the pore size and its density. In Phase C the jet distributes throughout the PM-volume and this process is characterized by a wide jet spreading ("self-homogenization"). In the authors opinion, this effect is related to a multi jet splitting, as described below. The multi-jet splitting is a result of jet interaction with a large number of pore junctions (walls) present in the PM-volume. Depending on the jet impulse, PM geometry, pore size and density, part of the liquid may leave the PM-volume (phase D). This part of the jet is characterized by a very low outlet velocity from the PM-volume, even if the initial (nozzle outlet) velocity is very high (e.g. 300m/s).

3. Experimental investigation and test conditions

Different experimental investigations have been performed to describe the interaction between CR Diesel jet and a highly porous medium. All experiments have been realized in a low pressure chamber (see Fig.3) using two surrounding fluids of different densities: air and oil.

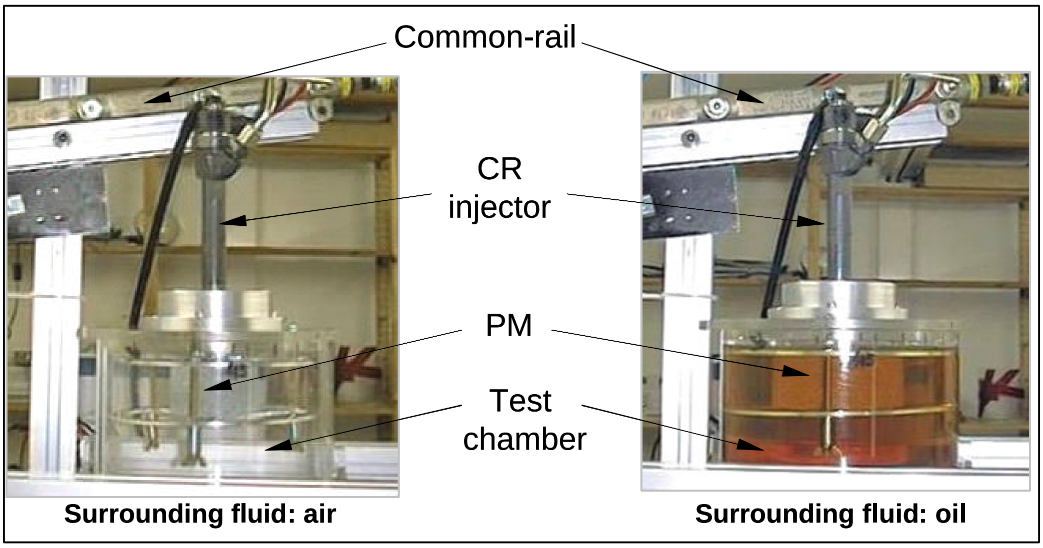

Fig. 3 View of the low pressure test chamber with two different surrounding fluids

In all experimental investigations a two-hole, horizontally orientated (180°) Diesel nozzle was used. The nozzle hole diameter was 164µm (see Fig.4). A conventional common-rail injection system with a Genotec control unit for realization of single injections was applied and the injection pressure (rail pressure) was available from 300bar to 1100bar. There are number of different PM structures that have been used in this investigation, e.g. cylindrical

PM disc geometry with injector nozzle located inside the PM (Fig.5a) and porous medium plates (plate thickness of order of a few pores) located in proximity or far away from the nozzle outlet (Fig.5b).

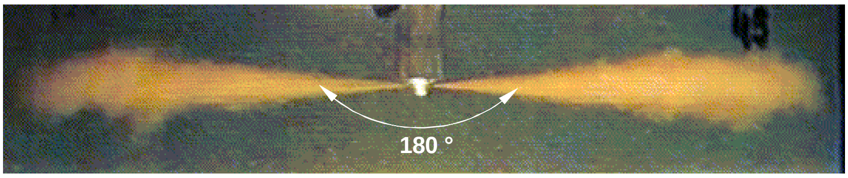

Fig. 4 A two-hole CR nozzle with injection in to oil

In the reported experiments typically used porous medium had a pore density between 10 and 30ppi (pores per inch) corresponding to a mean pore size from 3mm to 1mm, respectively. For PM plates, a typical thickness was approx. 3 to 4 pores, and for cylindrical discs, the diameter of PM was on order of several tens of pores (see Fig.5).

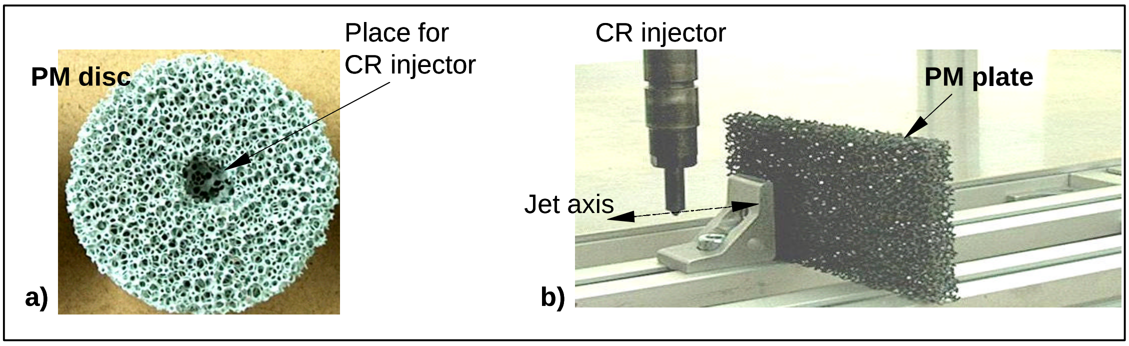

Fig.5 View of two different PM geometries used in experiments

In order to observe the jet interaction with a porous structure, under special attention paid to jet distribution throughout the PM-volume, two different measurement procedures have been applied: temporal and spatial localization of the liquid present outside the PM-volume as well as direct observation of spatial distribution inside the PM-structure. Injection parameters such as injection duration and pressure and corresponding mass of fuel supplied per single injection used in the reported investigation are given in Table 1.

4. Short description of most important features observed in phases A to D

As already indicated in section 2, the character of interaction between a high velocity jet and a highly porous medium significantly depends on the distance from the nozzle outlet. There are two characteristic configurations considered in the paper (see Fig. 2): a wide distance, where a free jet may fully develop before reaching PM surface, and a narrow distance, where a free jet may not fully develop before reaching the PM surface (see Fig.6).

Tab. 1 Injection parameters of CR system used in experimental investigations

Injection duration T[µs]	**Mass of fuel per injection [mg] at different injection pressures**				
	300 bar	**500 bar**	**700 bar**	**900 bar**	**1100 bar**
600	3,5	9,89	17,78	24,08	26,67
800	10,32	22,06	26,97	32,36	36
1000	19,25	29,86	35,39	42,03	47

1200	25,67	36,28	44,19	52,86	58,11
1400	32,11	44,39	53,33	62,67	71,86
1600	38,08	51,39	62,75	72,22	82,5
2000	52,58	67,08	79,53	91,61	104,11
2500	67,36	86,8	104,1	116,58	130,56

This figure shows jet interaction with a PM-plate for a narrow distance geometry. On the front of the PM-plate, a part of the reflected jet is observed (phase B) in this figure. This effect is a result of jet reflection from the PM interface (probably by a direct impingement of very narrow jet on to single pores junction) as well as reflection from the inner part of the PM plate. On the back side of the PM-plate, a multi-jet structure has been observed as indicated in Fig.6. This is a result of jet spatial distribution in PM-volume.

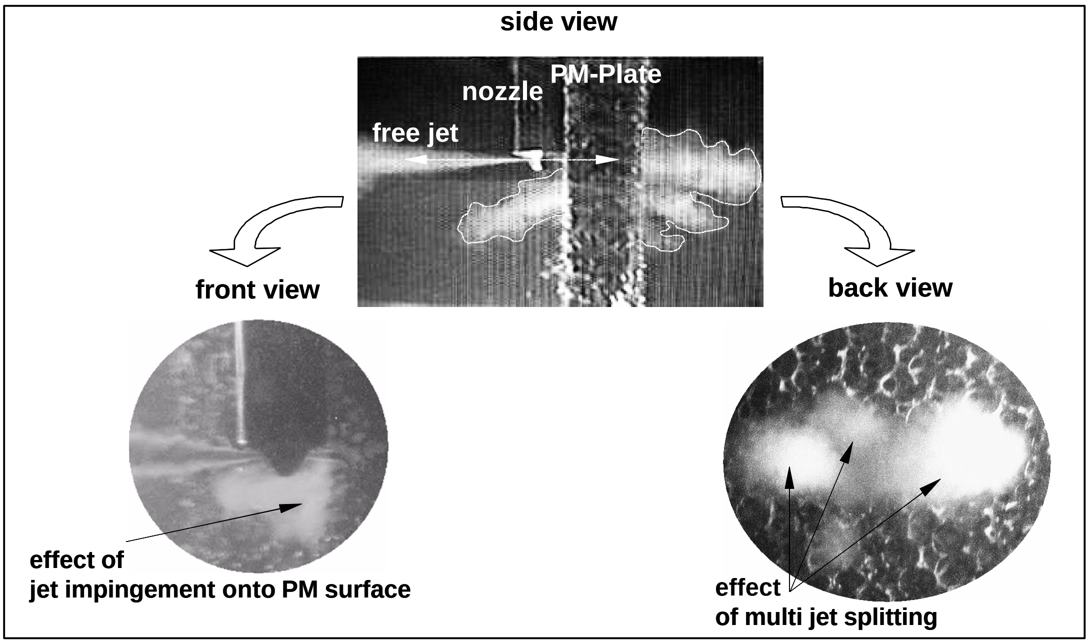

Fig. 6 View of the common-rail injector located in proximity to PM-plate: (left) front view of the jet interaction with PM, (right) back view of the PM-plate with visible multi-jets leaving the PM-volume

For a high velocity Diesel spray it is enough to pass through few pores only to get a strong spatial dispersion (spreading) in PM-volume. Additionally, it must be noted, that the jet impulse in outer (back) part of the PM-plate is significantly reduced (outlet velocity on the order of m/s) comparing to jet velocity leaving CR nozzle. In the case of a wide distance between nozzle outlet and PM-plate, a fully developed jet impinges on to PM surface having much larger impingement area comparing to a narrow spacing. However, still a large part of the jet enters the PM and propagates throughout the PM-volume (see Fig.7).

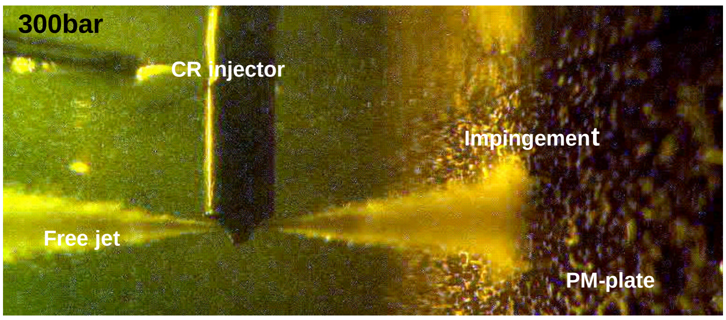

Fig. 7 View of the jet reacting with a PM-plate (injection pressure 300bar)

In order to get better overview on the spatial distribution of the Diesel jet inside the PM-volume, a special PM-structure has been constructed. This structure consisted of a number of PM-plates forming a homogeneous PM-volume. The fuel used in this experiment was a mixture of Diesel oil and fluorescent particles (below 1%). The injection process (constant injection parameters) has been repeated 3 to 6 times to get high contrast of fluorescent particles distributed inside the PM-volume. After experiments, the individual plates have been separated and the distribution of the fluorescent traces has been recorded. Examples of recorded traces for three different distances (l) between nozzle outlet and PM are shown in Figure 8. Additionally, spots representing free jet geometry at a given distance from the nozzle outlet are also marked in this figure.

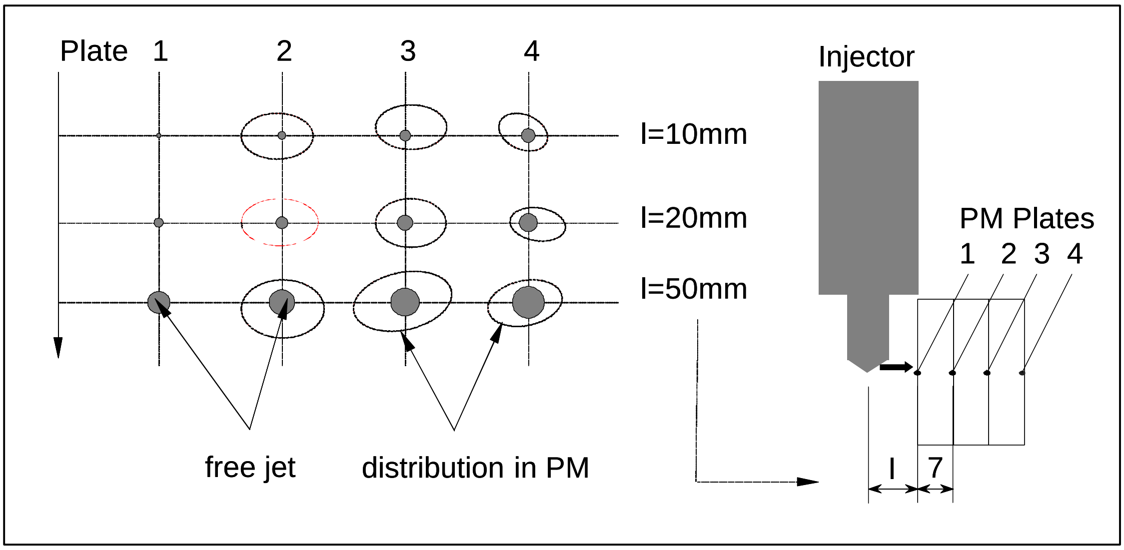

Fig. 8 Comparison of the CR jets spreading in a free space (filled circles) and in PM-volume (open circles) at different distances from the nozzle outlet

This figure indicates significant spreading of Diesel jet when propagating inside the porous medium. Since it is very difficult to record a real time fuel distribution inside of the porous structure, a 2D model of PM has been proposed. This model consists of parallel cylinders which are positioned perpendicularly to the spray axis. These cylinders simulate the pore junctions in a real PM. Such 2D representation of a real 3D-structure (despites of all limitations) allows a real time observation of jet propagation among the cylinders and jet interaction with individual walls.

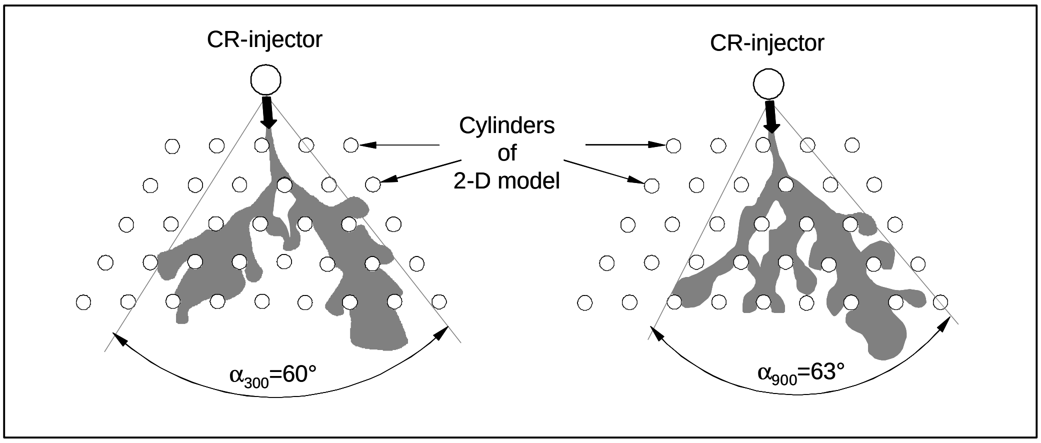

Fig. 9 Effect of a multi-jet splitting observed in a 2D-model of the porous medium for two injection pressures: left-300bar, right-900bar

Examples of reconstructed 2D-maps of fuel distribution inside this 2D-model are given in Figure 9. As shown in this figure, the Diesel jet propagating in a 2D-model interacts with individual cylinders and splits in to a number of smaller jets. This effect has been called “multi jet splitting”. This figure indicates also a weak dependence of the spatial distribution of the jet in PM-volume on the injection pressure. Results obtained in a 2D-model have been confirmed by experiments made in 3D-PM-structures (see Fig. 10).

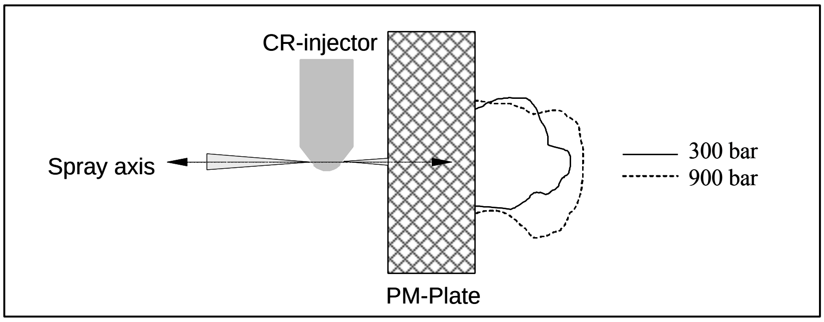

Fig. 10 Effect of jet interaction with a PM-plate for two injection pressures (PM thickness 10mm)

Additional parameters influencing the spatial distribution of a high velocity jet in PM-volume are: nozzle design, a PM pore size and its structure. Generally, the spatial spreading of Diesel jet in PM-volume increases with decreasing pore size and increasing pore density.

5. New concepts of mixture formation and homogeneous combustion in I.C. engines based on the PM-technology

There are recently proposed concepts of mixture formation and combustion in I.C. engines that utilize observed phenomena of interaction between high velocity jet and a highly porous medium. These concepts concern realization of a homogeneous combustion in I.C. engine, especially for significant reduction of combustion emissions. Principles of two new concepts are presented in this section (in a very short form owing to the limited space of this paper).
One concerns engine with mixture formation and homogeneous combustion in PM (“PM-engine” concept [1,2]). Another one realizes fuel vaporization, chemical recombination and internal heat recuperation in PM (“intelligent engine” concept [3]) with a homogeneous combustion in the cylinder volume.

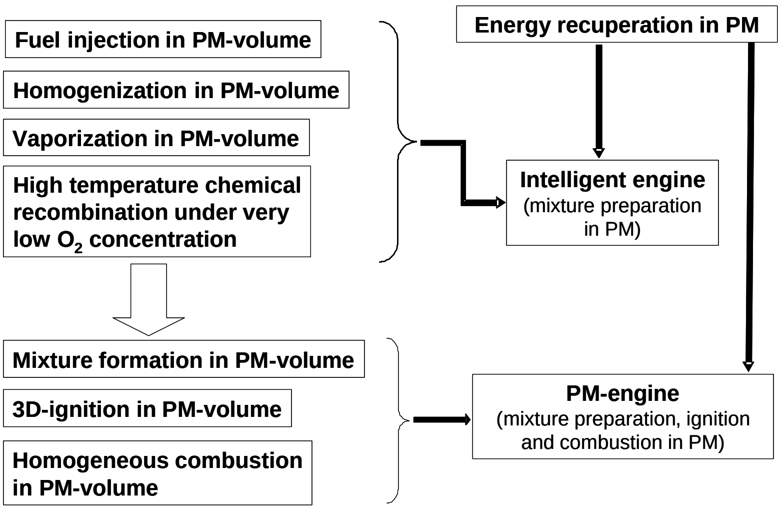

Fig. 11 Definition of new engine concepts according to individual processes realized in PM

Both systems are selected according to individual processes realized in PM-volume (Fig.11), and operation principles are presented in Figure 12. The intelligent engine concept 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, as described by Weclas [3]. This system allows realization of homogeneous combustion in a free cylinder volume and may operate in a wide range of engine loads.
On the other hand side, a new kind of internal combustion engine with a homogeneous combustion in a porous medium volume has been proposed by Durst and Weclas [1,2]. This system offers realization of homogeneous combustion process in PM-reactor almost independently of the engine operational conditions.

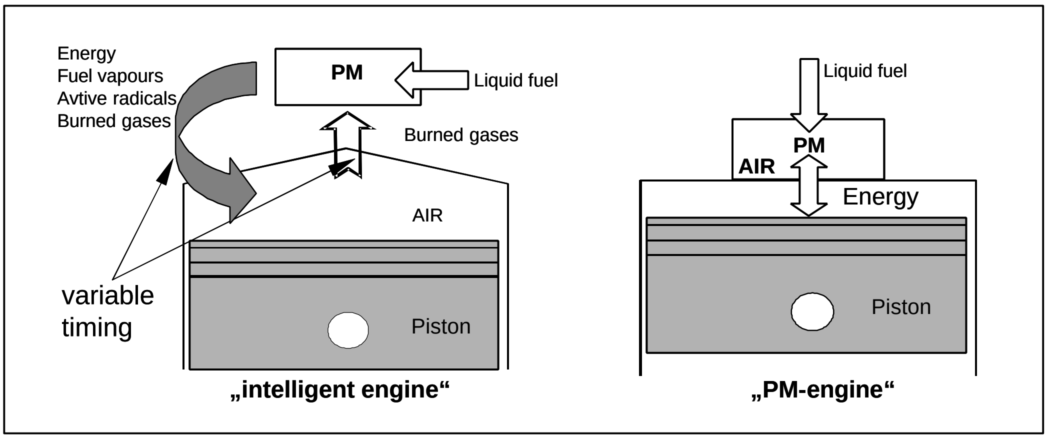

Fig. 12 Principle of the intelligent engine concept (left) and of he PM-engine concept (right)

6. Concluding remarks

On the basis of presented experiments, it is possible to select four characteristic phases of Diesel jet interaction with a cold porous medium. The first phase concerns outlet from the nozzle and formation of a free jet in space between nozzle and PM (depending on the relative distance between the nozzle and PM). The second phase represents the jet interaction with PM-interface resulting in partial propagation into PM-volume, and partial reflection from this surface. In the third phase, a liquid distribution throughout the PM-volume is characterized by multi-jet splitting effect. This is utilized for a self-homogenisation of the injected liquid in PM-volume. As the last phase, a liquid leaving PM after travelling throughout its volume may be observed (depending on the injection pressure, geometry of PM, pore size and pore structure). The observed phenomena have been utilized in new concepts for mixture formation and homogeneous combustion in engine having potential for operation with a near-zero emissions level by realization of homogeneous combustion process in engine.

7. References

[1] Durst, F., Weclas, M. 1999, Porous Medium (PM) Combustion Technology and its Application to Internal Combustion Engines: A new concept for a near-zero emission engine, [in:] Applied Optical Measurements, Ed. M. Lehner & D. Mewes, Springer, 1999.
[2] Durst, F., Weclas, M. 2001, A new type of internal combustion engine based on the porous-medium combustion technique, J. Automobile Engineering, IMechE, part D, Vol. 215, pp.63-81.
[3] Weclas, M., Strategy Strategy for intelligent engine combustion systems based on the MDI-concept, Report of INVENT GmbH, May, 2002.