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A Concept of Internal Combustion 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. 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" has been proposed. 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, 3D thermal self-ignition followed by a homogeneous combustion.**

I. INTRODUCTION

The nature of the mixture formation and the followed combustion processes realized in direct injection engines, indicate 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 reduction of engine emissions in primary combustion. 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.

Fig.1 View of PM-engine head and SiC reactor

II. 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:

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

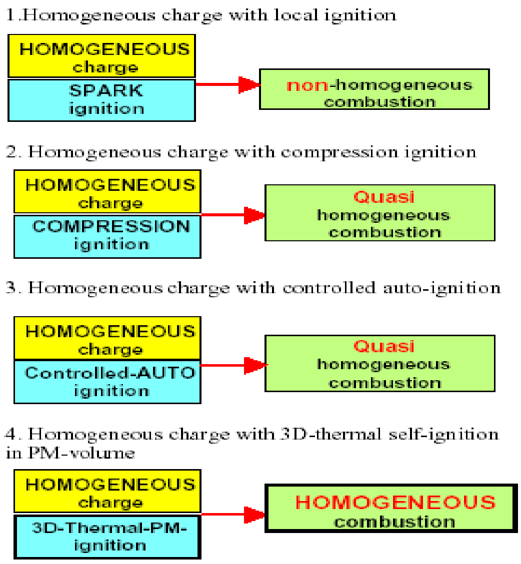
Four different ignition techniques may be selected:

- Local ignition (e.g. spark plug).
- Thermal self-ignition (e.g. compression ignition).
- Controlled auto-ignition (e.g. low temperature chemical ignition).
- 3D thermal PM self-ignition (e.g. 3D-grid-structure of a high temperature).

The last considered ignition system, uses a 3D structured porous medium (PM) for the volumetric ignition of homogeneous charge. The PM has homogeneous surface temperature over 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.

Let us consider four possible combustion modes of a homogeneous charge:



III. 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 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. A close view of a magnified 3D-structure of SiC ceramic foam is given in figure 2.

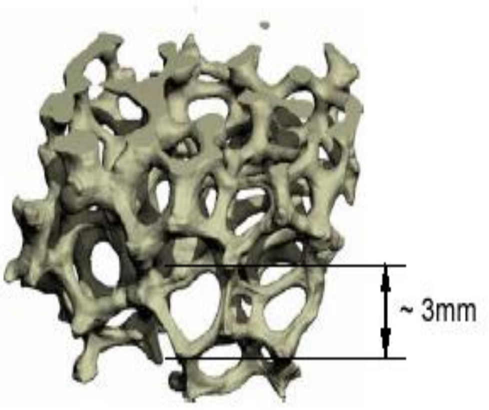


Fig.2 View of magnified SiC foam structure

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 (radiation, conductivity), transparency for fluid flow, spray and flame propagation, pore sizes, pore density, pore structure, 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. A view of the thermal test of SiC-reactors for engine application is shown in fig 3.

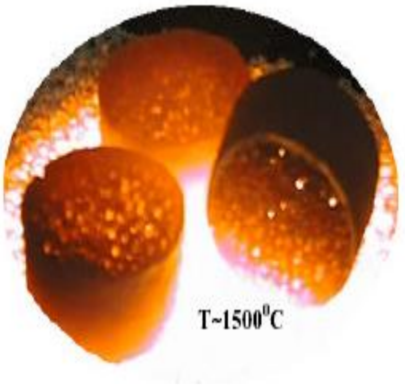


Fig.3 View of the SiC reactors under thermal test for engine application

3.1 Properties of Porous Medium

Typically used PM has pore density between 10 and 30ppi (pores per inch)

The mean pore size ranges from 3mm to 1mm

Porous medium plates have thickness of approximately 3 to 4 pores

Cylindrical porous medium discs have diameter in the order of several tens of pores

3.2 Principle of the Pm-Engine

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

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

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

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

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

One of the most interesting features of PM-engine is its multi-fuel performance. Independent 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-stroke and four-stroke cycles. Owing to the differences in thermodynamic conditions, the PM-engine cycle has to be separately analyzed for closed and open chambers, as described below.

3.3 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 (figure 4).

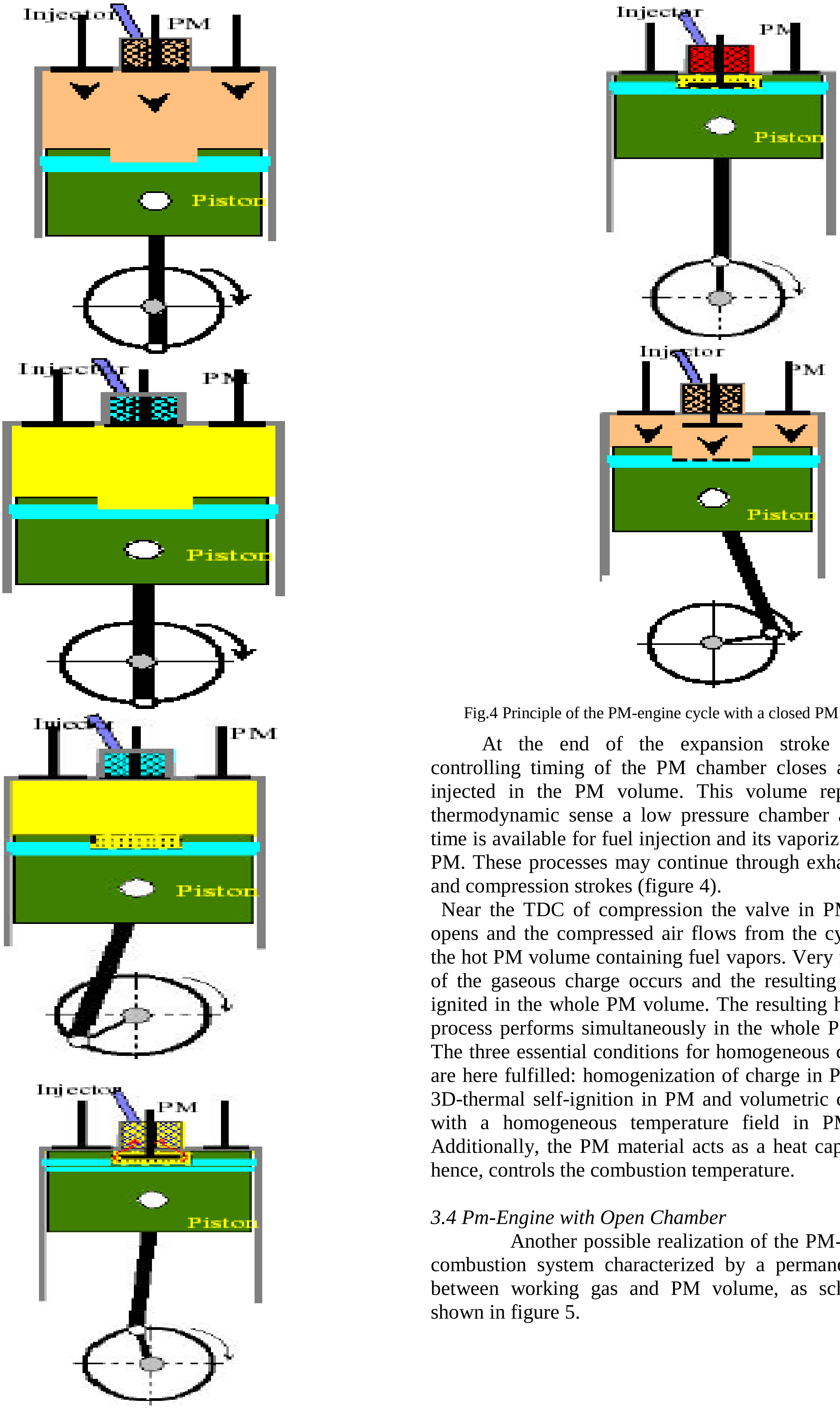


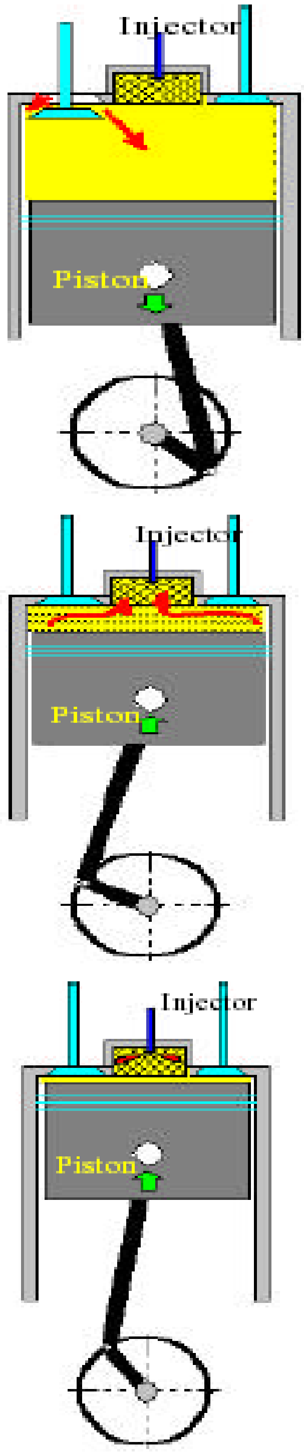
Fig.4 Principle of the PM-engine cycle with a closed PM chamber

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 (figure 4).

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 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 acts as a heat capacitor and, hence, controls the combustion temperature.

3.4 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 5.



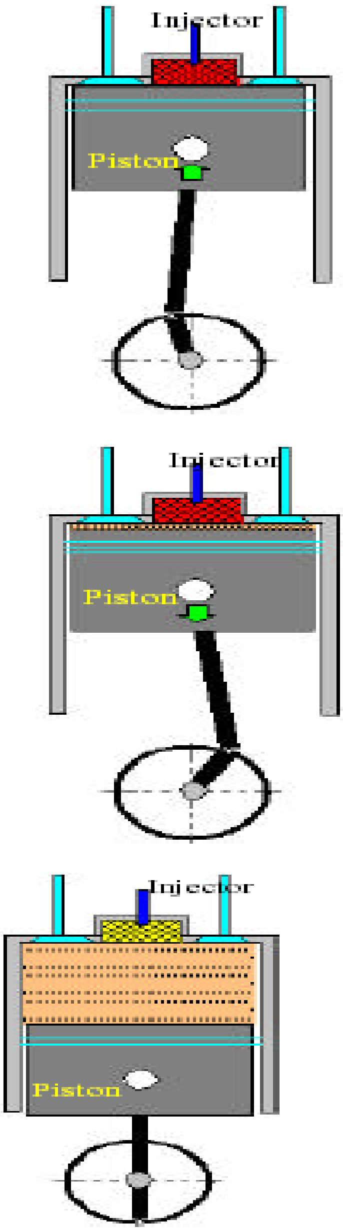


Fig.5 Principle of the PM-engine cycle with an open PM chamber

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

3.5 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 6. 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.

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.

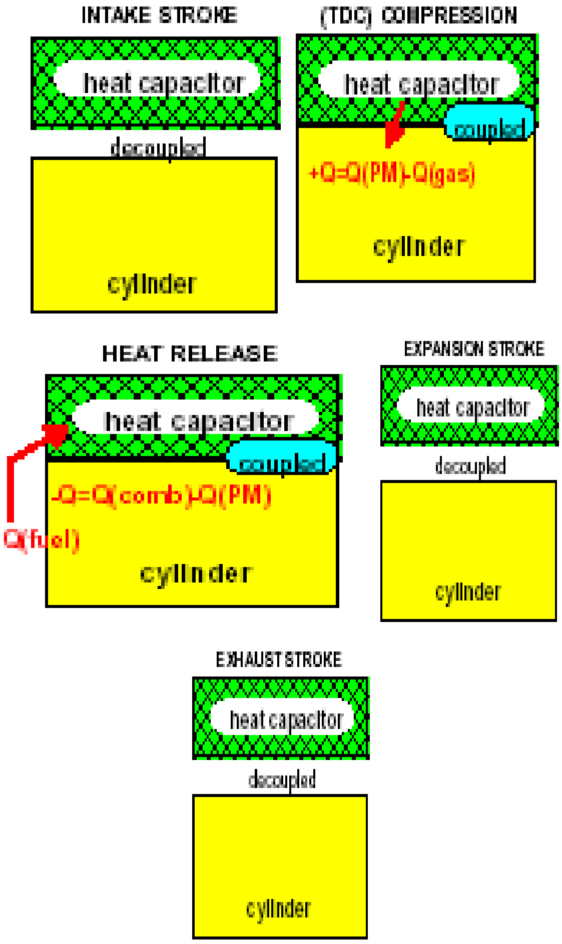


Fig.6 Thermodynamic model describing the PM-engine cycle

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 1.9 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.

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

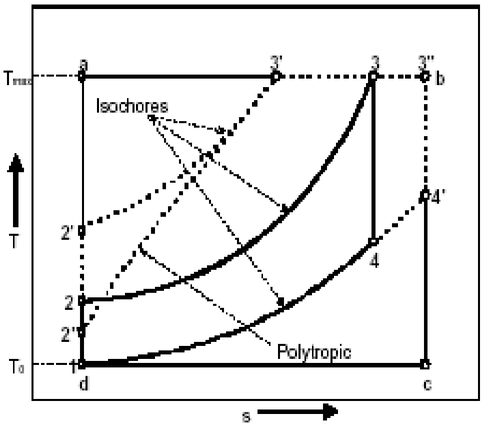
Two isentropes (d-a and b-c). Thus, the area a-b-c-d-a represents the Work done by this ideal cycle operating between temperatures T_0 and T_{max}. For the same temperature limits, the conventional (CV) engine Fig 1.9 T-s diagram for different cycles:
cycle cannot follow the Carnot cycle on the 1-2 line 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

$$\eta_{(constant\ volume)} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{C_V(T_4-T_1)}{C_V(T_3-T_2)} \quad \ldots \text{eqn}(1)$$

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

$$\eta_{(PM)(i)} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{C_V(T_4-T_1)}{RT_3 \ln (V_{3''}/V_a)} \quad \ldots \text{eqn}(2)$$

For a more realistic PM-engine cycle with periodic contact of gas with PM material 1-2'-3'-3''-4'-1, the efficiency is



$$\eta_{(PM)(Periodic)} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{C_V(T_{4'}-T_1)}{C_V(T_{3'}-T_{2'})+RT_3 \ln (V_{3''}/V_{3'})} \quad \ldots \text{eqn}(3)$$

For a more realistic PM-engine cycle with permanent contact of gas with PM material 1-2''-3'-3''-4'-1, the efficiency is

$$\eta_{(PM)(Permanent)} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{C_V(T_{4'}-T_1)}{C_V(T_{3'}-T_{2''})+RT_3 \ln (V_{3''}/V_{3'})} \quad \ldots \text{eqn}(4)$$

IV. STUDY RESULTS

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 offers 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.

Thus the new method of homogeneous combustion in porous medium reduces the emissions; hence a better and a safer environment are realized. Also a more economical mode of transport is obtained from the user's point of view due to higher efficiency.

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