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APPLICATION OF MACRO-CELLULAR SiC REACTOR TO DIESEL ENGINE-LIKE INJECTION AND COMBUSTION CONDITIONS

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ABSTRACT

One of novel combustion technologies for low emissions and highly efficient internal combustion engines is combustion in porous reactors (PM). The heat release process inside combustion reactor is homogeneous and flameless resulting in a nearly zero emissions level. Such combustion process, however is non-stationary, is performed under high pressure with requirement of mixture formation directly inside the combustion reactor (high pressure fuel injection). Reactor heat capacity resulting in lowering of combustion temperature as well as internal heat recuperation during the engine cycle changes the thermodynamic conditions of the process as compared to conventional engine.

For the present investigations a macro-cellular lattice structure based on silicon carbide (non-foam structure) with 600 vertical cylindrical struts was fabricated and applied to engine-like combustion conditions (combustion chamber). The lattice design with a high porosity > 80 % was shaped by indirect three-dimensional printing of a SiC powder mixed with a dextrin binder which also serves as a carbon precursor.

In order to perform detailed investigations on low- and high-temperature oxidation processes in porous reactors under engine-like conditions, a special combustion chamber has been built and equipped with a Diesel common-rail injection system. This system simulates the thermodynamic conditions at the time instance of injection onset (corresponding to the nearly TDC of compression in a real engine).

Overall analysis of oxidation processes (for variable initial pressure, temperature and air excess ratio) for free Diesel spray combustion and for combustion in porous reactor allows selection of three regions representing different characteristics of the oxidation process represented by a single-step and multi-step reactions

Another characteristic feature of investigated processes is reaction delay time. There are five characteristic regions to be selected according to the delay time (t) duration. These analyses indicate qualitative similarity of heat release process as performed under Diesel-like and in porous reactor conditions, except significantly reduced combustion temperature in porous reactor due to its large heat capacity.

INTRODUCTION

Homogeneous combustion process in porous reactor as applied to internal combustion engine must be performed under complex mixture formation and combustion conditions: the process is non-stationary, is performed under high pressure and the fuel is injected directly inside the combustion reactor [1-2]. A special role in the thermodynamics of the engine cycle with heat release in porous reactor plays the reactor heat capacity resulting in lowering of combustion temperature as well as in internal heat recuperation during the engine cycle [3].

The hot reactor allows three-dimensional ignition and the heat release process is performed in the reactor volume, only. The reactor temperature together with fuel injection and mixture formation inside the porous reactor define the conditions for thermal ignition and following heat release (combustion) process. A novel kind of engine with a combustion process in highly porous three-dimensional reactors that could satisfy the above conditions has been proposed by Durst and Weclas [1-2]. This engine concept has great potential not only for high cycle efficiency but especially for a nearly-zero emission level allowing combustion temperature control below thermal NO_x-formation. The present paper concentrates on particular processes of mixture formation and combustion realized in a porous reactor volume under diesel engine-like conditions. There is a lack of information on the nature of these processes as

performed in porous reactors, especially in a macro-cellular structure, under engine-like conditions. The development of such a high-temperature open cell and highly porous macro-cellular structures is necessary for development of this kind of combustion systems [4]. These processes can be divided into two groups: direct fuel injection into a porous reactor and low- and high-temperature oxidation in the reactor. The former processes include Diesel-jet interaction with the highly porous structure described with reference to multi-jet splitting and fuel vaporization in a hot reactor [5-7]. Low-temperature oxidation processes include cool- and blue-flame reactions that occur just after injection begins during the ignition delay time period [8,9]. Thermal ignition and high-temperature oxidation (heat release) complete the investigated process. A heat release process in porous reactors having different structures and heat capacities is discussed in comparison with a Diesel-like process (free volume combustion). In both cases a direct fuel injection using a common-rail diesel injection system into the combustion chamber (free volume or porous reactor) is used.

NOMENCLATURE

m_{fuel}	=	mass of injected fuel [mg]
p_{IB}	=	initial chamber pressure at the time instance of fuel injection start [bar]
PM	=	porous medium
T_{IB}	=	initial chamber temperature at the time instance of fuel injection starts [°C]
t_{comb}	=	characteristic time of high-temperature reactions [ms]

1 Engine concept with combustion in porous reactor and engine simulator

Application of a combustion porous reactor to engine allows realization of homogeneous and flameless combustion process characterized by a near-zero emissions level [1,2,9]. Internal heat recuperation in porous reactor may allow increase of engine-cycle efficiency resulting in reduction of CO₂ emissions and results in significantly lowered combustion temperature permitting nearly-zero NO_x level. In the present investigation, a real engine with mixture formation and combustion in porous reactor (fig.1a) is considered. Diesel fuel is directly injected into porous reactor and is completely trapped in its volume. Investigation of mixture formation and heat release process out of engine but under engine-like conditions allows limitation of the system to the reactor volume and to the conditions at TDC of compression (fig.1b). For experimental investigation, these conditions have been simulated in a special well isolated constant volume high-temperature and high-pressure combustion chamber (fig.1c).

Figure 1: Different stages of simulation of engine with porous reactor: a-real engine; b-cycle limitation to constant volume at TDC; c-engine simulator (combustion chamber)

The chamber is equipped with common-rail Diesel injection system and electronically controlled piezo-actuated Diesel injector which injects fuel directly into porous reactor volume. Macro-cellular SiC reactor can be heated electrically. The combustion air is supplied to the chamber under selected pressure and the flow rate is controlled by a valve (for control of air excess ratio λ). The process is investigated using pressure histories measured by a pressure transducer mounted in the combustion chamber. This pressure history is used for reconstructing of heat release process (combustion) and corresponding temperatures.

2 Porous combustion reactors

SiC ceramics have been considered for application to combustion technology due to their superior properties at high temperatures, such as high thermal conductivity, excellent corrosion and oxidation resistance, and good thermal shock and thermal fatigue stability [10]. For the present investigations a macro-cellular lattice structure based on silicon carbide (non-foam structure) with 600 vertical cylindrical struts was fabricated and applied to engine-like combustion conditions (Fig.2).

Figure 2: View of the macro-cellular combustion reactor used in the present investigation

The lattice design with a high porosity $> 80\%$ was shaped by indirect three-dimensional printing of a SiC powder mixed with a dextrin binder which also serves as a carbon precursor. Pressureless infiltration of silicon melt at $1500\text{ }^{\circ}\text{C}$ driven by capillary suction finally resulted in dense struts of reaction bonded silicon carbide composed of approximately $50\text{ wt. \%}$ SiC and $50\text{ wt. \%}$ Si. Fig. 3 shows the macro-cellular structures at the various stages of processing. Total dimensional changes of $< 3\%$ during the whole processing stage were measured. An experimental procedure for manufacturing of the macro-cellular lattice structure has been described in detail in [4].

Figure 3: (a) Model lattice structure for three-dimensional printing; Macro-cellular structures manufactured by 3D printing: (b) as-printed and liquid silicone resin infiltrated, (c) pyrolysed and (d) Si infiltrated (SiSiC).

3 Experimental procedure and process analysis

Low- and high-temperature oxidation processes are analysed from time “zero” defined as a trigger signal for the Diesel injector (start of injection “IB”) - see fig.4. The procedure for setting of initial temperature $T_{IB}=T_{PM}$ and initial pressure p_{IB} in the combustion chamber filled with porous reactors is shown in fig. 4: step 1- a given mass of synthetic dry air at certain pressure p_1 is supplied to the chamber; step 2- the air trapped in the porous reactor which is electrically heated up to the required temperature T_{IB} corresponding to the porous reactor

temperature T_{PM} and results in increasing chamber pressure p_{IB} . Characteristic time t (delay time) of a particular phase of the process is analysed and measured, starting at zero-time point (point IB). For analysis of the reaction rate a slope of the reaction curve corresponding to the particular oxidation process is described by average pressure changes in time [bar/ms].

Figure 4: Procedure for setting initial conditions and investigated processes

4 Results and Analysis

Low- and high-temperature oxidation processes are analysed from time “zero” and are represented by a pressure and pressure gradient histories, as shown in fig.5.

Figure 5: Pressure histories measured during heat release in a macro-cellular SiC-combustion reactor for different initial reactor temperatures and pressures at constant air-to-fuel ratio

The heat release process in a macro-cellular reactor consists of steps similar to those defined for free volume combustion [8,9]. Just after starting of fuel injection process, the fuel partly vaporizes and the pressure changes to the negative range and is followed by low-temperature oxidation (exothermic) reactions resulting in a positive change of pressure. After this phase, a high-temperature oxidation occurs and is represented by a very quick pressure increase in the combustion chamber

is observed. A direct comparison of heat release process in a macro-cellular SiC-reactor and in a free volume combustion chamber (diesel) represented by a pressure and temperature histories measured after fuel injection starts is shown in figure 6.

Figure 6: Pressure (top) and temperature histories (bottom) measured during heat release in a macro-cellular SiC-combustion reactor and in a free volume combustion chamber at constant initial temperature 500°C and different initial pressures (mass of fuel is constant = 23.8mg)

The data are plotted at constant initial (gas and reactor) temperature 500°C for different initial gas pressures for a constant mass of supplied fuel. There are two main differences in the process observed in porous reactors and in the free volume. Firstly, a pressure peak of much greater value is recorded in free-volume combustion. This is due to heat transfer to the porous reactor according to its large heat capacity as compared to heat capacity of gas trapped in the reactor volume. This results in reduced combustion temperature allowing significant reduction of NO_x . Secondly, the delay time of the process is much shorter in the case of a porous reactor due to the very effective heat transfer inside the reactor volume and nearly constant reactor temperature conditions. This effect is more intense with increasing initial chamber pressure. Despite of these differences, the character of the process seems to be similar for both free volume combustion and porous-reactor combustion. Pressure distribution changes its character from negative to positive much faster in a porous reactor. Vaporization enthalpy cannot change the temperature in the reactor so much as it has much more accumulated energy as is the case with gas in a free-volume combustion chamber. The effect of initial reactor temperature on the temperature

history after fuel injection starts as a result of heat release process inside reactor volume is shown in figure 7.

Figure 7: Temperature histories measured during heat release in a macro-cellular SiC-combustion reactor for constant mass of fuel injected (23.8mg) and $\lambda=1.35$ (initial temperatures and pressures varies)

The higher initial reactor temperature the shorter is delay time of the reaction and the faster heat release process. Both parameters can be investigated in figure 8.

Figure 8: Delay time (top) and reaction rate (bottom) vs initial reactor temperature measured in a macro-cellular SiC-combustion reactor for a constant initial gas pressure $p_{IB}=18\text{bar}$

Figure 8 presents distribution of reaction delay time (top figure) and slope represented reaction rate (bottom figure) in macro-cellular reactor at constant initial gas pressure (18bar). Summarizing their process analysis for free-volume and combustion reactors, the authors constructed fields representing characteristic combustion modes in porous reactors as compared to diesel conditions. These fields consider two kinds of parameters characterizing pre-ignition reactions (low-temperature

oxidation) and heat release (high-temperature oxidation): distribution of characteristic reaction behavior represented by a single- and multi-step oxidation (fig.9) and distribution of characteristic delay time (fig.10).

Figure 9: Fields representing characteristic combustion modes in porous reactors as compared to free Diesel injection conditions

All these data are plotted in a two-dimensional field of initial pressure and temperature. The data plotted have quantitative form, and only the shape of marked border lines among different combustion modes should be interpreted more qualitatively. The shape of the border lines depend on the reactor heat capacity, pore density and pore structure.

Figure 10: Fields representing characteristic combustion modes and delay times in porous reactors as compared to free Diesel injection conditions

There are three characteristic regions selected in fig.9 representing three different characteristic modes of the oxidation process: Region 1 is characterized by single-step reactions and is located at lower initial temperatures for all initial pressures; Region 2 is characterized by multi-step reactions with two slopes recognizable in the reaction curve and is located in the range of middle-high initial temperatures at middle-high initial pressures; Region 3 is characterized by multi-step reactions with three slopes recognizable in the reaction curve and is located in the range of higher initial temperatures at low-

to-middle initial pressures. In the case of reaction delay time the following regions have been selected in fig.10: Region A is characterized by very long delay times $t > 20\text{ms}$ and is located at lower initial temperatures at all initial pressures investigated; Region B is characterized by delay times $10\text{ms} < t \leq 20\text{ms}$ and is located at higher initial temperatures and lower initial pressures as well as in a small region of high initial pressures; Region C is characterized by delay times $5\text{ms} < t \leq 10\text{ms}$ and is located at higher initial temperatures and lower-to-middle initial pressures as well as in a small region of high initial pressures; Region D is characterized by delay times $2\text{ms} < t \leq 5\text{ms}$ and is located at higher initial temperatures and middle-to-high initial pressures; Region E is characterized by very short delay times $t \leq 2\text{ms}$ and is located at high initial temperatures and high initial pressures. Analysis of figures 9 and 10 indicates qualitative similarity of heat release processes as performed under Diesel-like and in porous-reactor conditions. A quantitative influence of porous-reactor features (reactor heat capacity, pore density, pore structure, specific surface area and fuel distribution in the reactor volume) is visible.

CONCLUSIONS

Heat release processes in macro-cellular highly porous reactors have been analyzed under diesel engine-like conditions. These data have been compared to the heat release in a free-volume combustion system as simulated in a special combustion chamber with a common-rail Diesel injection system. The heat release process has been investigated over a wide range of initial pressures and temperatures simulating thermodynamic conditions in an engine at the moment when fuel injection starts. At lower initial temperatures the process is accelerated in porous reactors. Combustion in porous reactors is characterized by additional heat accumulation in the reactor's solid phase as compared to a free-volume chamber. This results in significantly reduced pressure peaks and lowered combustion temperature level. Process delay time is significantly dependent on initial pressure and initial temperature, and, on the whole, decreases with pressure and with increasing temperature. This behavior has been observed in a free-volume chamber and in porous reactors. Heat release rate increases with initial pressure and initial temperature: in a porous reactor it significantly depends on the amount of heat accumulated in the reactor as a function of reactor heat capacity, pore density, specific surface area and pore structure. Characteristic modes of the heat release process in a two-dimensional field of initial chamber pressure and temperature have been selected and analyzed. Qualitative similarity of characteristic modes of the heat release process in a free volume and in porous reactors as performed under Diesel engine-like conditions indicates high probability of applicability of the combustion porous reactors to an internal clean combustion process.

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