Nanosecond surface discharge at high pressures

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Abstract: The idea to use rapid compression machine (RCM) for experiments on initiation of combustion with the help of non-equilibrium plasma has been suggested. Initial parameters of ignition experiments (pressure and temperature) were discussed. Development of nanosecond barrier surface discharge in dry air at ambient initial temperature and 1-5 atm pressure was studied with the help of fast ICCD imaging.

Keywords: surface nanosecond dielectric barrier discharge, initiation of combustion, rapid compression machine

1. Introduction

Plasma assisted ignition/combustion (PAI/PAC) experiments are typically carried out at pressures close to 1 atm [1,2]. It is promising to extend the current knowledge in the field of PAC to higher pressures. Our recent experiments using a shock tube technique [3] proved that nanosecond pulsed discharge can be successfully used for kinetic measurements of plasma assisted ignition at high initial gas temperatures (close to autoignition threshold) and relatively low gas pressures (0.1-2 atm). Here, we discuss the idea of using rapid compression machine technique (RCM) for plasma-assisted ignition experiments. Low initial temperatures and high initial pressures are interesting for PAI/PAC experiments due to the following reasons: first, the effects connected with nonequilibrium processes in plasma can be the most evidently pronounced at relatively low initial gas temperatures. Second, high pressures are promising for engine industry. We propose to use surface nanosecond discharge [4] developed for aerodynamic applications in combination with rapid compression machine for quantitative study of PAC initiation at elevated pressures.

2. Rapid compression machines. Autoignition study

Detailed review of rapid compression machines, their application in combustion research and study of flow peculiarities under the conditions of fast compression can be found, for example, in [5,6]. Rapid compression machine simulates a single compression event under the experimental conditions close to those in internal combustion engines. Scheme of RCM [7] is given in Fig. 1. The main parts of RCM are the following: a combustion chamber with pumping and filling system, a piston, a system of piston driving. The chamber is evacuated and filled with the investigated mixture. The piston, driven pneumatically, compress the gas within a typical time of 10-50 ms. To stop the piston, the hydraulic oil-filled system is used. The work time of RCM is limited by a heat exchange with the walls and it comprises typically tens (up to hundreds) of ms. Size of combustion chamber depends upon the design of RCM but the typical distance between piston and the end plate at the point of maximum compression is less than 10 mm. Routine experiments using rapid compression machine techniques give the information about autoignition delay time for different gas mixtures at high initial pressures and low initial temperatures. The ignition delay time is determined as a time between the end of compression phase and sharp increase of pressure observed by the pressure gauges, mounted in the wall of combustion chamber.
data on ignition delay in millisecond time range are of significant importance for different combustion sub-fields, such as control of lean premixed mixtures combustion, development of homogeneous charge compression engines (HCCI), control of detonation in spark plug ignition engines etc.

A brief summary of existing RCMs [5] is reproduced in Table 1. Historically, the RCMs were used to measure oxidation and autoignition [8], effect of fuel structure and additives on combustion of hydrocarbons [9], and so on. It is worth noting that, during the last decade, a few other rapid compression machines [10-13] have been developed and adjusted (see Table 2). Development of kinetic experiments led to new design of the combustion chamber; for example, authors of [11] realized the optical access through the piston head. The only RCM application for artificial (laser stimulated) ignition is known [13].

Table 1. Experimental conditions and parameters of RCM reported in the literature (according to [5]).

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Pmax (bar), Tmax (K)</th>
<th>Compression ratio and time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Western Reserve University</td>
<td>&gt; 50 bar, &gt; 1100 K (post compression); 350 bar (post ignition)</td>
<td>21 (flat piston), 15.1 (creviced piston), 25-40 ms</td>
</tr>
<tr>
<td>University of Ireland, Galway</td>
<td>40 bar, 1060 K (post compression); 135 bar (post ignition)</td>
<td>13.4, &lt;22 ms</td>
</tr>
<tr>
<td>University of Leeds</td>
<td>20 bar, 1000 K (post compression)</td>
<td>14.6, &lt;22 ms</td>
</tr>
<tr>
<td>University of Science and Technology, Lille</td>
<td>17 bar, 900 K (post compression)</td>
<td>9.8, 20-80 ms</td>
</tr>
<tr>
<td>MIT (1990)</td>
<td>70 bar, 1200 K (post compression)</td>
<td>19 (flat piston), 10-30 ms</td>
</tr>
<tr>
<td>MIT (2004)</td>
<td>40 bar, 900 K (post compression)</td>
<td>12.5-16.5, 15 ms</td>
</tr>
<tr>
<td>University of Michigan</td>
<td>20 bar, 1000 K (N₂), 2000 K (Ar) (post compression)</td>
<td>16-37, 100 ms</td>
</tr>
</tbody>
</table>

The ignition has been obtained with the help of NdYAG pulsed laser. The authors demonstrated the extension of ignition limit to lower equivalence ratios (up to 0.5, CH₄-air mixtures), decrease of ignition delay, and increase of the rate of pressure rise.

We assume that in the case of ignition initiation by surface DBD nanosecond discharge, we will obtain the pressure trace similar to one indicated with a dashed line in Fig.2. There, a typical pressure trace taken from real RCM experiment [5] is given by a solid line Region I in the Fig.2 corresponds to the compression stage of rapid compression machine, and region II corresponds to the ignition stage, that is to the development of a chain reaction of ignition

Table 2. Experimental conditions and parameters of RCM reported in the literature (continued).

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Pmax (bar), Tmax (K)</th>
<th>Compression ratio and time</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groningen University Netherlands</td>
<td>70 bar, 1200 K</td>
<td>20, 10-20 ms</td>
<td>[10]</td>
</tr>
<tr>
<td>Technische Universitat Munchen</td>
<td>200 bar, 900 K</td>
<td>5-25</td>
<td>[11], [12]</td>
</tr>
<tr>
<td>ARGONNE national Lab, USA</td>
<td>362 bar, Ignition parameters: T=490 C, P=80 bar</td>
<td>10</td>
<td>[13]</td>
</tr>
</tbody>
</table>

We assume that in the initial pressure range 1-10 atm it will be possible to obtain stable picture of ignition with a high voltage not more than 25 kV on the high voltage electrode.

3. Surface nanosecond discharge. Preliminary experiments

The idea of RCM plasma-assisted experiments is the following: if to organize the nonequilibrium plasma between the end plate of the combustion chamber and the piston, or, at least, near the end plate, it will be possible to decrease the ignition delay time and to investigate quantitatively kinetics of plasma assisted ignition at high pressures. Surface discharges, particularly MW discharge, have been already used for ignition [15]. Preliminary experiments carried out at MIPT [16] demonstrate ability of pulsed nanosecond discharge to ignite premixed combustible ethane-oxygen mixtures at initial gas pressure about 1 atm. The parameters of plasma produced by nanosecond discharge are still under discussion. It was demonstrated with the help of emission spectroscopy [17] that high values of electric fields (800 Td at 1 atm) are realized in the discharge. The same paper reports significant gas heating in the near-surface layer (up to 400 K) and initiation of the shock wave.

The aim of present discharge experiments was to study the development of a surface barrier discharge at elevated pressures. Nanosecond discharge in a coaxial geometry of electrodes was used to produce a thin plasma layer in the vicinity of low-voltage electrode. High voltage pulses of 10-20 kV amplitude, 25 ns duration, 3 ns rise time, positive or negative polarity, repetitive frequency 40 Hz were used
to ignite the discharge in ambient air at P=1-5 atm. The diameter of high-voltage electrode was equal to 2 cm. The energy input in the discharge did not exceed approximately 10 mJ, or 10% of the energy stored in incident nanosecond pulse, in the first pair of pulses; there can be also up to 2-4 reflections with a similar energy input. Emission in the wavelength range 300-800 nm was registered by sub-nanosecond LaVision PicoStar ICCD camera (Figs. 2, 3, numbers at each frame designate time (in nanoseconds) starting from emission initiation). For the observed spectral range, the main contribution to the emission is due to the emission of second positive system of molecular nitrogen, $N_2(C^3Π_u) - N_2(B^3Π_g)$ transition. The excitation of $N_2(C^3Π_u)$ level takes place in relatively high electric fields (at least hundreds of Td) by direct electron impact. The life time of this level in air does not exceed 1.5 ns at atmospheric pressure. Thus, ICCD images with a short camera gates give us an idea about spatial quasi-uniformity of the discharge.

For all pressures we observed simultaneous (within 0.2-1 ns camera gate) propagation of streamers in radial direction, the width of plasma being about 1 mm. For each regime, two separate flashes were registered, as it is seen from Fig. 3. In our opinion, the second flash corresponds to the back front of the high-voltage pulse. For 1-3 atm, the character of emission in the first and the second flashes was the same, while for 5 atm the second flash was more intense and not so uniform. So, we demonstrated the ability of pulsed nanosecond discharge to produce thin quasi-uniform plasma layer at elevated pressures.

**5. Conclusions**

Quantitative experiments on plasma-assisted ignition of combustible mixtures with the use of rapid compression machine (RCM) technique have been suggested. Review of existing RCMs and on their parameters, such as pressure, temperature, compression time, was made. Nanosecond barrier surface discharge is proposed as an igniter for RCM-experiments. ICCD imaging of a nanosecond DBD
in dry 1-5 atm air has been performed. Peculiarities of discharge uniformity at different gas pressures were discussed.

References

[12]. Presentation of TESTEM Gesellschaft fur Mess- und Datentechnik mbH company, http://www.testem.de/

Fig. 5 ICCD images of the discharge at 5 atm dry air. Positive polarity of the high-voltage electrode, 22 kV, 25 ns duration. Camera gate is 1 ns.

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