Evaluation of temperature and concentrations of chemically active particles in the area activated by a high-frequency corona discharge in the HCCI engine

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Abstract: Formation of a combustion wave in a hybrid internal combustion engine is calculated, for conditions of combustion initiation by a high-frequency streamer corona discharge. An approach to account of the production of chemically active species and the gas heating by the discharge is described. It is shown that it is necessary to take into account the change in the mixture composition in the treated gas volume at passing through it of each of subsequent streamers.

Keywords: Plasma-assisted ignition, streamer propagation, chemical kinetics, HCCI engine.

1. Introduction

Currently, hybrid internal combustion engines are being created, that use for initiation of combustion not conventional sparks [1,2] but non-equilibrium electric discharges, for example, a pulsed corona discharge of megahertz repetition rate [3-5]. Such discharges are able to create stable conditions for operation of compression engines running with lean fuel-air mixtures or at low intake temperatures of the mixture. This type of discharge is considered also as an alternative to the spark plug in internal combustion engines. The possibility of controlling ignition by means of pulsed nanosecond corona discharges, affecting the low-temperature combustion stage in HCCI (homogenous charge compression ignition) engines, was demonstrated in [6].

When modelling the combustion chamber of a hybrid engine, it is necessary to take into account the impact of the discharge on the fuel-air mixture in addition to the usual combustion processes. To solve the problem of ignition and formation of a combustion wave, it is needed to develop approaches to creation of an activated discharge zone. The discharge has a filamentary structure, i.e. only a part of the area is filled with filaments. This zone initiates combustion in the combustion chamber of the engine due to presence of chemically active particles, resulting from dissociation of oxygen and fuel molecules by electron impact, and additional heating of this area.

Results of simulation of the propagation of a single streamer, determining its parameters (specific energy input, streamer radius, electric field, etc.) and the composition of chemically active species have been presented e.g. in [7,8]. Chemical kinetics of oxidation and combustion of the fuel-air mixture in the post-discharge stage was considered in our previous works [6,9]. However, description of the multi-pulse and multi-channel mode of the discharge operation, resulting in to the creation of activated area during a short time in a real device, is a complex and still unsolved problem. In this paper, an approach is proposed for evaluation of the composition and heating of the activated zone due to the action of a high-frequency corona discharge, for different values of the specific energy deposition. The calculations were performed for a lean (equivalence ratio ϕ=0.7) propane-air mixture N_2:O_2:C_3H_8=0.7671:0.2043:0.0286.

2. The model

A real HCCI engine is considered (its parameters are described in [6]), in which an activated zone is created using a high-frequency corona discharge with a typical pulse repetition rate of 5 MHz [4,5] during time t_d ~555 μs. This time corresponds to 5 degrees of rotation of the crankshaft when the crankshaft rotation speed is 1500 rpm. Activated region with a volume of V_{az} is close to the electrode at the cap of the engine cylinder (typically a few cm^3 [3]). The filaments of the discharge during the time t_d will be able to treat some volume $V_d < V_{az}$. The fraction of this volume V_d/V_{az} depends on pressure, temperature, specific energy, the size of the filament, etc. During the time t_d, the filaments, due to diffusion expansion of the channels, including the turbulent mixing associated with the movement of the piston and the fuel supply to the combustion chamber (estimates of the mixing time are given in [6]), create an activated region, the degree of homogeneity of which in the composition and temperature depends on different parameters.

The approach we use is based on consideration of a sequence of propagating plasma filaments – streamers. The fraction of volume occupied by streamers in one pulse is evaluated as in [10]. A spatial non-uniformity of gas parameters associated with the existence of a great number of plasma filaments in the discharge chamber and sequence of discharge pulses is taken into account. The following energetic parameters of a discharge are introduced: the total energy H injected into the volume V_{az}, average specific input energy Q_{az} injected into the mixture in activated zone, specific input energy into the streamer channels Q_d and total volume of all streamer channels V_{st} (all values are for the each pulse).

For evaluation of streamer characteristics, the dynamics of positive streamers in the mixture is simulated using two-dimensional axially symmetric fluid model [8]. As the result, the densities of produced of O and N atoms and radicals C_3H_7 (the latter being equal to the *G*-value for production of H atoms) are obtained and the gas heating in a streamer channel is evaluated.

Estimates show that to reach a required for ignition energy input, about 0.05 eV/molecule, it is necessary to pass 10 streamers with Q_d^0=0.005 eV/molecule through the same channel. To obtain the composition of the mixture in the streamer through 10 pulses going with a period of 200 ns, the calculations of the composition and temperature were carried out taking into account changes in the composition and temperature from pulse to pulse. In each pulse, in addition to that what was obtained at the end of the latter, the densities of O atoms, H, C_3H_7 radicals and heating due to streamer propagation were added. This composition and temperature were compared with the composition and temperature for one pulse with Q_d=0.05 eV/molecule through 2 μs, i.e. immediately combining 10 pulses, following through 200 ns, into one, but without taking into account the change in composition between pulses (the composition was obtained by a single calculation). The temperature in the streamer channel is almost independent of the calculation method. However, the densities of components differ significantly. Below it is considered how much this difference affects the ignition and the combustion wave velocity. The composition and temperature of the activated zone were averaged, taking into account the fraction of the volume processed by the discharge.

3. Formation of the combustion wave

Formation of a combustion wave for the conditions T_1=700 K, P_1=12.36 bar, Q_d=0.05 eV/molecule is considered.

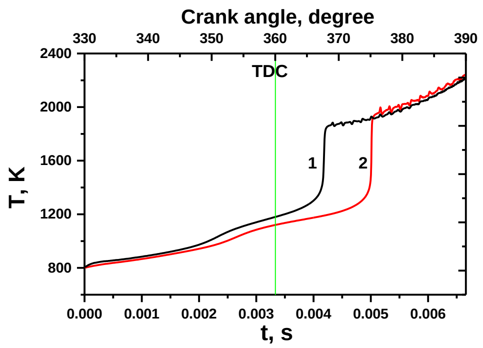

Fig. 1. Comparison of the ignition delay time in the activated region for two methods of calculating the composition of the mixture in the streamer channel: 1 - the change in the composition of the mixture after each pulse with Q_d^0=0.005eV/molecule was taken into account, 2 - the composition of the mixture was determined after the 10th pulse for Q_d=0.05 eV/molecule, without account of the change in the composition from pulse to pulse.

The results of 1D calculations given in Fig. 1 show that for the 10 pulse' mode taking into account the change in composition from pulse to pulse, the ignition time is 0.83 ms faster than in one pulse mode with the same total specific energy input, but without taking into account the change in composition. This is due to the higher concentration of hydroperoxides, which are produced from pulse to pulse, and are long-lived intermediate components in contrast to the O atom, which reacts quickly with propane molecules and disappears. However, the apparent velocity of the combustion wave after 6 ms is almost the same for the two calculation methods and is equal to 3.5 m/s.

4.Conclusion

The approach to evaluation of the temperature and composition in the region activated by corona high-frequency discharge is proposed. Multi-pulse and multi-channel nature of the discharge (non-uniformity in space) is considered. Calculations have shown that it is necessary to take into account the change in the composition of the mixture in the streamer channel at passing through it each subsequent streamer. This leads to a significant increase in the densities of intermediate components, such as hydroperoxides, formed by the interaction of O atoms, produced by the discharge, with propane. After some time, the combustion wave velocities become the same for both methods of calculation. The final temperature in the streamer channel is virtually independent of the calculation method: taking into account the composition change from pulse to pulse or without it.

5.Acknowledgement

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6.References

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