Investigation of Transition of Deflagration to Detonation in Moving Mixtures of Combustible Gases

D.I. Baklanov *, S.V. Golovastov *, L.G. Gvozdeva *, A. Kaltayev [+], N.B. Scherbak*, V.V. Volodin*

* Institute for High Energy Densities, Associated Institute for High Temperatures Russian Academy of Sciences 125412 Moscow, Izhorskaya 13/19, sherbak@ihed.ras.ru

[+] al-Farabi Kazak National University, Almaty, Kazakstan, kaltayev@kazsu.kz

In the report the new experimental data about essential reduction of predetonation distance are presented in the case of detonation initiation with an weak electric discharge in a detonable gas flow. Experiments were done at the device, which allows modeling one cycle of pulse detonation engine operation. The experimental data are compared to the results of numerical calculations. The good consent with experiments demonstrates feasibility of the offered methods of calculations and allows to give explanation to the observed experimental effects. The results seem to be of practical application to the control of detonation process in PDE.

Introduction

The problem of originating and development of detonation in a driving flow of a combustible mixture has risen in connection with some features of pulse detonation engines (PDE) operation. At the operation with a valveless fuel and oxidant injection system ignition, inflammation and transition from deflagration to detonation take place in a flow of combustion-mixture, moving with speed of tens of meters per second, i.e. in flows with developed turbulence. At PDE operaton with valves in the supply system, the DDT can occurs also in the moving flow of mixture in a detonation tube (depending on synchronization of the moment of initiation with valves operation).

The predetonation distance reduction in a turbulent flow was reported for the first time by Baklanov et al. (2003). The results were obtained on the PDE model, operating in a valveless mode with mixtures of methane with oxygen. The fact seems to be of practical interest to the PDE operation for the decrease of predetonation distance. In the paper of Baklanov et al. (2004) the numerical method of calculation of detonation initiation in a turbulent flow has been suggested and the calculations in the detonation tube of 1 m length in a stoichiometric mixture of oxygen and hydrogen have been conducted. The conditions with zero initial velocity and with velocities of initial flow of 35 and 50 m/s have been considered. It has been shown that predetonation distance notably decreases with initial velocity increase.

In the present paper the results of prolongation of previous researches are presented. The aim of the investigation is to create an installation of a single operating mode to carry out the experiments in the detonable mixture flow, modeling one cycle of PDE operation. It is possible to conduct more precise measurements with this set-up than those made with the working model of PDE. The set up being created, the results of the experiments and numerical simulation are presented.

The experimental installation

The experimental installation is a cylindrical tube of 3 m in length and of 83 mm in diameter. The tube is equipped with fast-response valves on hydrogen and oxygen gas lines. In the preliminary experiments the values of both components mass flows, and velocity of mixture propagation in the tube in dependence on time obtained. The mixture is ignited by an electric spark. It is possible to measure the time interval between the full opening of valves and the time of electric spark, therefore, to execute ignition in a mixture flow. It is possible also to control the mixture equivalence ratio.

The pressure transducers and photogauges are installed in the consequent cross-sections along the tube. The readings of pressure transducers and photogauges allowed to distinguish shock waves from flame fronts and from detonation fronts. The diagrams of all fronts propagation along the tube (x-t diagrams) has been obtained as a result of each experiment, on which the formation of detonation in the tube is tracked. Experiments are carried out in the mixtures of hydrogen with oxygen of different equivalence ratio at initial speed of flows varied from 0 to 60 m/s. These data are compared to the results of numerical simulation.

The numerical method

The method of calculation is used in this investigation presented in the paper of Kaltayev et al. (1999) and applied in the paper of Baklanov et al. (2004). Numerical simulation of deflagration to detonation transition in axsymmetric tube has been made in the same mixtures and velocities of flow as in the experiments.

At the simulation of deflagration to detonation transition it is considered that combustible mixture in a tube after the expiration of period of induction (determined by concentration of radicals) turns to the combustible products in step-by-step reaction. It is supposed that the process is one-dimensional, and heterogeneity on cross section, character of flow and influence of walls properties are taken into account at averaging the equations on tube cross section. The turbulence of flow is simulated with Bussinesk hypothesis after Favre-averaging of equations.

Set of one-dimensional, non-steady conservation equations for individual species, mass, and total energy is taken in the conservative form. The equations are obtained by integrating the Navier-Stokes equations over the cross section of tube in the cylindrical coordinate system, assuming the core flow is one-dimensional.

The turbulence model consists of two elements. The first is a simulation of diffusion processes by the wall and by flame generated turbulence using eddy viscosity formulation.

The turbulence generated by the wall is described through the turbulent production function by using the wall function and wall friction law.

The second element of turbulence model is the modeling of turbulent combustion. Kinetic of combustion is based on two-step-by-step parametric model, similar to Korobeinikov-Levin model, which reproduces the basic stages of combustion. On this kinetic scheme it is considered that chemical reaction in given place with allocation of heat in a flow goes after the expiration of the induction period during which discharge of energy does not occur. The time of reaction is generally determined by the period of induction.

The system of equations with the equation for kinetic energy of the turbulence is solved in two stages. Gasdynamic transfer of required quantities is calculated from the Euler equations at the first stage with the use of the open monotonous TVD - scheme of the second order of accuracy on space. At the second stage diffusion and kinetic terms are integrated implicitly with the use of Crank-Nicolson scheme.

Results of calculations are represented as isolines of pressure, temperature, density and Mach numbers of gas flow in (x-t) plane. The different degrees of initial flow turbulence are modeled in calculations. The example of pressure isolines for DDT case in $2H_2 + O_2$ mixture is given in fig.1.

The results

In the report the results of experiments and numerical simulation are compared and analyzed. The main result is that the initial turbulence of flow influences essentially the transition of deflagration to detonation. Predetonation distance decreases with increase of initial flow velocity. It is concerned with the influence of turbulence on the flame acceleration. The speed of flame variation is not a simple superposition of a flow velocity and a speed of flame. Acceleration of flame varies sharply. Accordingly there are changes in formation of systems of shock waves before the flame front and formation of a flow gradient behind the leading shock wave. Different cases of detonation initiation can be obtained depending on the flame acceleration character.

Induction times, obtained by a numerical simulation of oxygen - hydrogen mixture at different temperatures and pressure are compared with experimental ones. The initial velocities and parameters of the arisen detonation are determined and compared to the CJ parameters.

The results obtained allow to make positive conclusions about the possibility of the using of dependence of predetonation distance on initial flow velocity for the control of detonation formation in PDE.

References

Baklanov D.I., Gvozdeva L.G. and Sherbak N.B. 2003 Detonation of Hydrocarbon-Air Mixtures in a Pulse Detonation Chamber.// Confined detonations and Pulsed Detonation Engines. (Ed. By G.D.Roy at al.) Moscow, Russia, Torus Press, , p.271-286.

Baklanov D.I., Gvozdeva L.G., Kaltajev A. and Sherbak N.B Transition of Deflagration to Detonation in Turbulent Flow in Pulse Detonation Engine.// Application of Detonation to Propulsion. (Ed. by G.D.Roy, S.Frolov, J.Shepherd) Moscow, Russia, Torus Press, 2004, p.86-90.

Kaltajev A, J. Leblanc and T. Fujiwara. Influence of Turbulence on the Deflagration to Detonation Transition in a Tube. 17th International Coll. on the Dynamics of Explosions and Reactive Systems. Heidelberg, Germany, July 25-30, 1999.

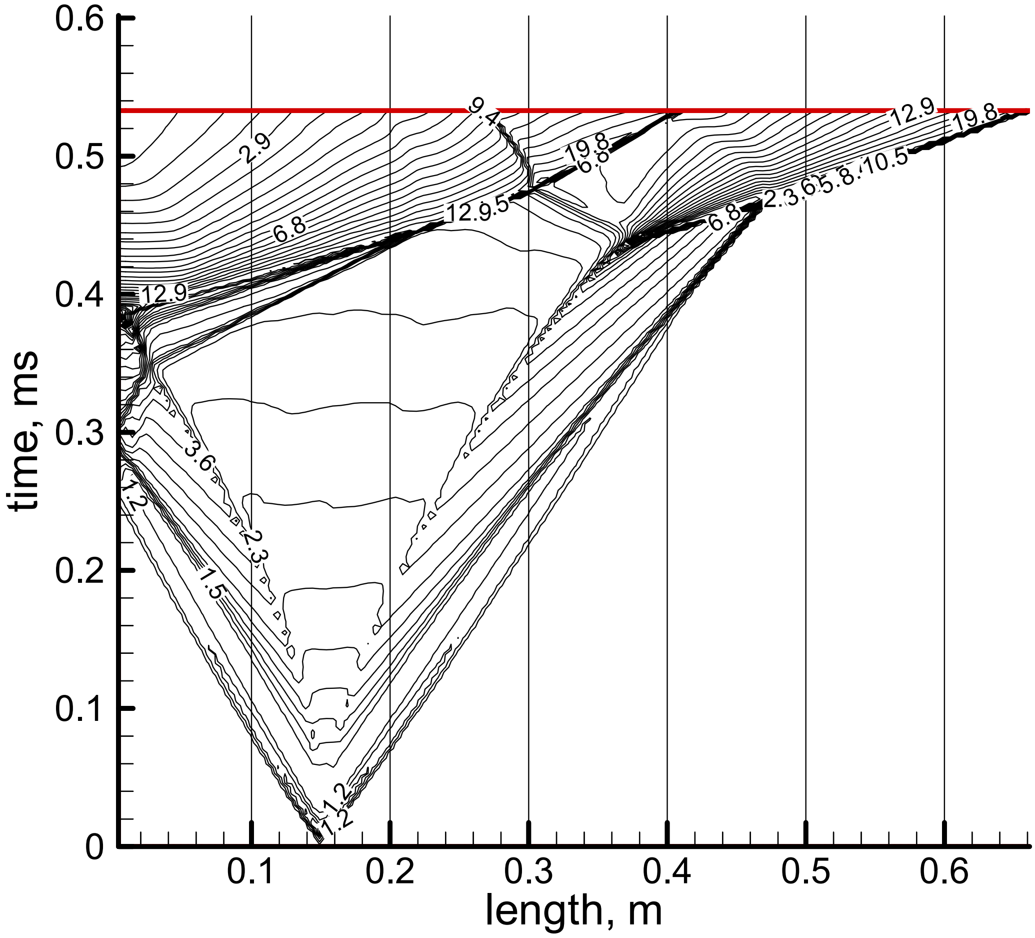

Fig.1. Plot of pressure in the (x-t) plane for the DDT in a tube of 83 mm in diameter in $2H_2+O_2$ with the initial velocity u=50 m/s. Initial temperature 300 K, initial pressure 100 kPa. Left closed end (x=0), right open end (x=L). Ignition by electric spark at the distance of 0.15 m from the closed end.