Realistic detonations in pulse detonation engine

Gvozdeva L.G., Baklanov D.I. and Scherbak N.B.

IHED IVTAN RAS E-mail: sherbak@ihed.ras.ru

The necessity of taking into account the nonideality of detonation is justified at the calculation of performance efficiency of pulse detonation engine (PDE). The estimation of thrust and duration of cycle for the lab-scale PDE model is carried out on the basis of experimental data of the authors.

Introduction The progress in understanding of detonation was achieved in 60-th years. It had become clear, that the representation of detonation as one-dimensional complex: shock wave – combustion front, is only a convenient idealization of the process. The real structure of detonation wave represents a composite three-dimensional wave complex, which can be described with the use of the size of detonation cell λ. Only for very large relations d/λ, where d is diameter of the tube, calculations of detonations under the one-dimensional theory are valid. In the other cases the losses from the reaction zone into the walls of the detonation tube should be taken into account. It has been shown that realistic detonation parameters differ strongly from the Chapman - Jouguet (CJ) parameters, especially pressure and relative speed of sound behind detonation wave, i.e. velocity of rarefaction wave in burned gases [1].

The last decade of the nineteenth century the idea of using a new effective thermodynamic cycle for thrust producing in the rocket engine was suggested by replacing a deflagration burning to detonation one. The investigations on PDE have been started [2]. At calculations of thrust and thermodynamic cycle of PDE, it is usually supposed, that detonation is ideal, that is, first, a predetonation distance is neglectably small in comparison with the length of the engine, and, secondly, that the parameters of detonation are close to the CJ parameters. However these two assumptions cannot be executed in practice especially for fluid hydrocarbons in mixtures with air, because of large cell size λ for such mixtures.

In the present work the authors have tried to estimate, how nonideality of detonations will influence the basic performance characteristics of PDE: thrust and maximum operation frequency.

Calculation of PDE thrust. Calculations were made for the lab-scale PDE model of valveless type described in [3].

Let's first consider a detonation cycle in the assumption, that the detonation wave arises instantly in the chamber of constant cross section near the closed end. Prior to the ignition the chamber is filled up to the pressure p_0 with combustion-mixture which flows with velocity w_0. Detonation forming near the closed end, propagates downstream to the open end with detonation velocity D_0 relative to the flow velocity w_0. If the length of the chamber is L, than the time, in which the detonation will pass the length of the chamber will be equal $t_1=L/D_0+w_0$. If the mixture was not moved, $t_1=L/D_0$. The pressure behind a wave sharply increases and becomes instantaneous higher than the feed pressure, therefore the supply of combustible gases is ceased and velocity w_0 becomes equal to zero.

The problem of distribution of parameters behind detonation wave at its motion to the open end of the chamber is solved in [4]. The flow of the burned gases behind the detonation wave is subsonic and the velocity w_1 of it decreases linearly, the value becomes equal zero at the point on a half of the distance, passed by the detonation wave. The speed of sound behind the detonation wave c_1 is equal to the difference $D_0 - w_1 = c_1$, where D_0 - detonation velocity. It behaves in the similar way, as velocity w_1 (Fig.1). The same distribution exists for pressure behind the detonation wave; the pressure drop behind the front takes place under the power law. The distribution of pressure at the closed end of a tube is given in [5]. It was obtained, that at the closed end, i.e. at the thrust wall pressure is constant and equals approximately $0.35p_{cj}$.

After detonation wave reaches the open end of a chamber, there is an exit of combustion products to the ambient space, and rarefaction wave propagates back in the combustion chamber with the velocity $(c_1 - w_1)$. When the rarefaction wave reaches the thrust wall, the pressure on it begins to decrease with an isentropic low. It happens in the moment $t_2'=0.5L/(c_1-w_1)+0.5L/c_1$.Then the rarefaction wave is reflected from the thrust wall as a rarefaction wave and goes back to the open end with the velocity of sound in the expanded and cooled gas. The propagation time is equal $t_2'' = L/(0.5c_1)$. At last, the chamber pressure becomes atmospheric. The full time of a exhausting is equal $t_2 = t_2' + t_2''$. At the moment, when the chamber pressure becomes less than the pressure in the feeding lines, the chamber begins to fill again with the fresh unburned gases during the time t_3. Thus the cycle is finished. The full cycle time consists of three parts: time t_1 of detonation propagation along the chamber, time t_2 of the expiration of detonation products from the chamber and time t_3 of filling the chamber by fresh combustible gases $T = t_1 + t_2 + t_3$. The maximum possible frequency is equal $f = 1/T$. Thrust can be determined as integral of pressure on the thrust wall.

The calculations of thrust and pulse repetition time for the detonation with CJ parameters for a stechiometric mixture of methane with oxygen were carried out for the detonation chamber of 660 mm length and diameter of 83 mm at initial parameters P_0=1 atm., T_0=15˚ C. For this diameter parameters are close to CJ ones. The results of calculation of pressure and thrust are given in figure 2.

Calculation of realistic detonation. To estimate the influence of nonideality the calculation for realistic detonation are made for the tubes of smaller diameter with the parameters obtained as a result of the analysis of experiments of the authors carried out earlier as in a single pulse mode [1], and in pulse mode [6] for mixtures of methane with oxygen. It has been found, that although the velocity of detonation depends little on nonideality of detonation wave, the considerable changes exist for the pressure behind detonation wave, and especially for the relative velocity of sound (c_1-w_1). And it affect strongly the estimation efficiency of the thermodynamic cycle and PDE thrust.

Quantitevly the results can be expressed as follows. The time of transition from deflagration to detonation which is not equal zero in realistic detonation increases a cycle time, that leads to the decrease of the mean thrust and specific impulse. The pressure decrease in the realistic detonation wave proceeds in decrease of the thrust of the device. The thrust decreases not only due to the pressure decrease, and also due to the decrease of time duration of constant pressure at the trust wall, the time t_2'' being less because (c_1-w_1) is much greater for realistic detonation than for CJ detonation. However, on the other hand the maximum operation frequency can be increased due to the increase of (c_1-w_1) in realistic detonation. So the total effect of influence of the realistic detonation parameters on the device efficiency can be obtained only as a result of calculation for particular model of the engine.

More large diversions than in methane-oxygen mixture turn to occur in mixtures of hydrocarbons with air. It is illustrated with the calculation of thrust and specific impulse for mixtures of gasoline and air.

References

1. Bazhenova T.V., Gvozdeva L.G. et al., 1989, Unsteady Interaction of Shock and Detonation Waves in Gases.- /Editor Urtiew P.A. Hemisphere Publishing

2. Roy G.D. 1999, Pulsed Detonation Phenomenon for Air Breathing Propulsion.- ISABE 99-71
3. Baklanov D.I., Gvozdeva L.G. Scherbak N.B., 2001, Pulsed detonation combustion chamber for PDE. in the book High-Speed Deflagration and Detonation: Fundamentals and Control/ Edited by G.D. Roy, S.M. Frolov et al./ Moscow: ELEX-KM Publishers, p.239-250
4. Stanukovich K.P., 1955, Unsteady flows of continuous medium.- State publishing house of technical theoretical literature, Moscow
5. Zeldovich J.B. and Kompaneec A.A., 1955, The detonation theory.- State publishing house of technical theoretical literature, Moscow 1955
6. Baklanov D.I., Gvozdeva L.G. and Scherbak N.B., 2003, Detonations of hydrocarbon – air mixtures in a pulse detonation combustion chamber/ Edited by G.D. Roy, S.M. Frolov et al./Moscow: ELEX-KM Publishers