THRUST PERFORMANCE OF AIR-BREATHING PULSE DETONATION ENGINE AT SUBSONIC FLIGHT AT DIFFERENT ALTITUDES

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One of the ways to increase the propulsive performance of ramjets is to replace a conventional combustor by a pulse detonation chamber [1, 2]. The operation cycle in such a chamber includes several stages: (*i*) filling the chamber with fuel-air mixture; (*ii*) ignition, flame acceleration, deflagration-to-detonation transition (DDT) in the mixture; (*iii*) fast mixture combustion in a propagating detonation wave; and (*iν*) exhaust of combustion products through a nozzle. Due to a very high propagation velocity of detonation waves ($\sim$ 1800 m/s), this operation cycle is close to the cycle with constant-volume combustion (Humphrey cycle). Ramjet engines with such combustors commonly referred to as pulse detonation engines (PDEs) have a potential to provide air-breathing propulsion over the wide range of flight Mach number from 0 to 5–6 and even above. Available theoretical studies indicate that the fuel-based specific impulse of PDEs can attain at least 5000 or 2000 s if hydrogen or hydrocarbon fuel is used, respectively. In most of these studies, direct detonation initiation in the PDE was presumed and turbulence–chemistry interaction was not taken into account.

The objective of the study outlined in this paper is to calculate main thrust characteristics such as thrust, fuel-based specific impulse, specific fuel consumption, and specific thrust of an air-breathing PDE comprising an air intake and a nozzle in conditions of subsonic flight at Mach number 0.8 at altitudes from 0 to 12 km above sea level with the account for aerodynamic drag, realistic physicochemical characteristics of oxidation and combustion of hydrocarbon fuel (propane), turbulence–chemistry interaction, and finite time of turbulent flame acceleration and DDT.

1 Formulation of the Problem

Figure 1 shows the schematic of an axisymmetric air-breathing PDE intended for subsonic flight which is used in this study. The engine consists of a standard subsonic air intake, annular bypass channel, mechanical valve, pulse detonation chamber, and supersonic converging-diverging Laval nozzle. The annular bypass channel is closed by the mechanical valve when air flows through the pulse detonation chamber and is open when the mechanical valve blocks air access to the pulse detonation chamber, thus providing continuous airflow through the engine. The mechanical valve is assumed to open/close instantaneously. The pulse detonation chamber includes fuel injectors, low-energy ignition source (ignition energy is 0.1 J), and distributed turbulizing obstacles for providing a fast DDT [3]. Fuel injection is modeled by local mass, momentum, and energy source terms in the corresponding conservation equations. Ignition is modeled by depositing a local hot spot in the flow in the recirculation zone behind a turbulizing obstacle. The obstacles are 2-millimeter wide orifice plates installed in the pulse detonation chamber with 82-millimeter pitch. The PDE operates on the stoichio-

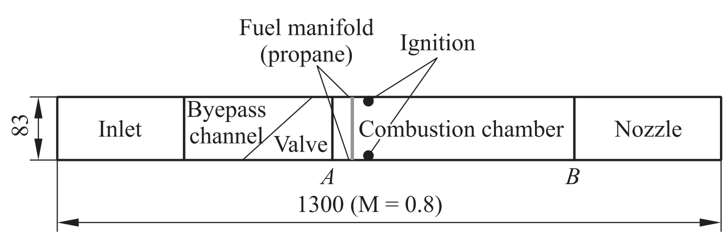

Figure 1 Schematic diagram of the axisymmetric air-breathing PDE. Dimensions are in millimeters

metric gaseous propane–air mixture. The main dimensions of the PDE are: full length is 1.3 m and the diameter of the pulse detonation chamber is 82 mm.

The operation process in the PDE is simulated numerically in the two-dimensional axisymmetric approximation. The mathematical model is based on Unsteady Reynolds-Averaged Navier–Stokes (URANS) equations. Turbulence is simulated with the k–ε model (k is the turbulent kinetic energy and ε is its dissipation rate). To determine the contributions of chemical reactions in a flame front and in a volume between flame front and the lead shock wave, the coupled Flame Tracking – Particle (FTP) combustion model is used [4]. The FTP combustion model has several important advantages over other known combustion models. The first advantage is that it takes simultaneously both frontal combustion and multistage (with "cool" and "blue" flames and "hot" explosion) volumetric oxidation and combustion into account, which is important for simulation of DDT of realistic fuels. The second advantage is that it intrinsically takes turbulence–chemistry interaction into account.

The system of URANS equations, supplemented by the k–ε model of turbulence, and FTP combustion model with databases of flame properties and self-ignition kinetics was closed by the thermal and caloric equations of state for the mixture of ideal gases with temperature dependent specific heats and by initial and boundary conditions. The governing equations were solved numerically using the coupled algorithm "Semiimplicit method for pressure-linked equations (SIMPLE) – Monte Carlo method." The chemical sources were calculated by an implicit scheme with an internal time step of integration. The coupled algorithm was previously used to simulate flame acceleration and DDT in smooth tubes and in tubes with obstacles, as well as to solve the problems of shock-initiated autoignition and preflame ignition in confined spaces. In all cases, satisfactory agreement between the results of calculations and experiments was obtained.

2 Operation Process

Figure 2 shows the example of PDE operation in terms of the calculated time history of the effective thrust acting on the engine in five consecutive cycles (Fig. 2a) and in the last, 5th, cycle (Fig. 2b) treated as

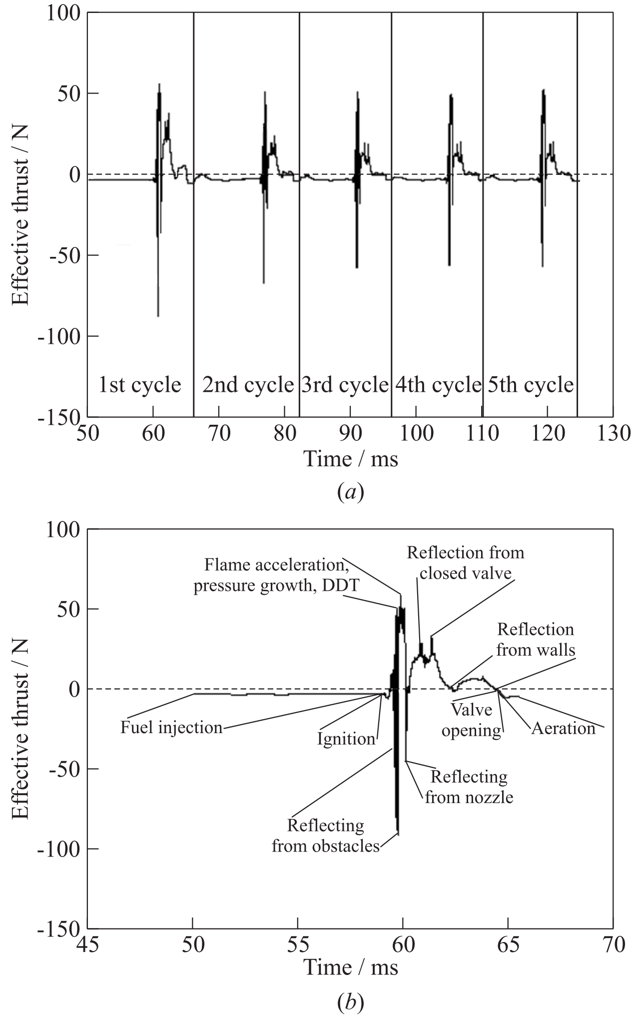

Figure 2 Predicted time history of the effective thrust of the PDE in the conditions of flight with M = 0.8 at altitude 1 km

the limit cycle (no appreciable differences between the 5th and the 4th cycles exist). The effective thrust is calculated as the total pressure and viscous friction force acting on all internal and external rigid surfaces of the engine. The sign of effective thrust is taken positive if it is directed opposite to the approaching airflow. It follows from Fig. 2 that the time integral of the effective thrust is positive, i. e., the PDE produces a positive effective thrust and is capable of accelerating at given flight conditions. To understand how this positive effective thrust is obtained, Fig. 2*b* provides a detailed description of force origin at different stages of the operation cycle. At the filling stage, the effective thrust is negative. After ignition, the effective thrust is alternating in sign due to combustion-induced pressure rise at the closed mechanical valve (positive contribution) and due to reflections of flame-induced pressure waves from obstacles (negative contribution). The first long-duration positive peak of effective thrust is caused by the arrival of the retonation wave (formed due to DDT at a distance of 5–6 diameters of the pulse detonation chamber) to the closed mechanical valve. This peak is followed by the short-duration negative peak of effective thrust caused by the partial reflection of the propagating detonation wave from the nozzle converging part. The second and third long-duration positive peaks of effective thrust are caused by the arrivals of the reflected shocks (former detonation) to the closed mechanical valve. Finally, when the mechanical valve opens and the new filling stage starts, the effective thrust again becomes negative.

3 Results of Calculations

Table 1 summarizes the results of calculations of PDE thrust characteristics in the conditions of subsonic flight with Mach number $\mathrm{M} = 0.8$ at altitude Z ranging from 0 to 10 km. The following notations are used in Table 1: P_a and T_a are the pressure and temperature of the standard atmosphere; f is the PDE operation frequency; F is the effective thrust during one cycle; R is the thrust (the sum of force F and drag force); I_{sp} is the fuel-based specific impulse (the thrust divided by the mass flow rate of fuel); R_{sp} is the specific thrust (the thrust divided by the mass flow rate of air); C_{sp} is the specific fuel consumption (fuel consumption per 1-newton thrust per hour); and $\dot{m}_f$ is the mass flow rate of fuel.

Table 1 Results of calculations for flight Mach number 0.8

Z, km	P_a, MPa	T_a, K	f, Hz	F, N	R, N	$I_{\rm sp}$, s	$R_{\rm sp}$, kN/kg/s	$C_{\rm sp}$, kg/(N·h)	$\dot{m}_f$, g/s
0	0.101	288.2	75	33	263	1460	0.91	0.25	18
0.5	0.095	284.9	70	33	250	1470	0.93	0.25	17
1	0.090	281.7	70	30	230	1460	0.92	0.25	15
2	0.079	275.2	70	28	205	1450	0.91	0.25	14
3	0.070	268.7	70	27	185	1460	0.91	0.25	13
5	0.054	255.7	70	23	144	1460	0.91	0.25	10
8	0.036	236.2	70	23	104	1520	0.95	0.24	7
10	0.027	223.3	65	20	79	1520	0.95	0.24	5

To determine thrust R produced by the PDE, it is necessary to know the aerodynamic drag force acting on the PDE in flight. This force was determined by integrating pressure and viscous forces acting on all rigid surfaces except for internal surfaces downstream the closed mechanical valve (pulse detonation chamber and exit nozzle).

Table 1 shows that the operation frequency of 65–75 Hz can be attained in the PDE despite it operates in the cyclic DDT mode with relatively long flame acceleration after weak ignition. The fuel-based specific impulse of the PDE in subsonic flight conditions attains ~ 1500 s, which is twice higher than the characteristic fuel-based specific impulse of a pulse combustion ramjet of V-1 type. The effective thrust and trust of the PDE decrease with altitude remaining positive at the level of 30–20 and 260–80 N, respectively. The specific thrust and specific fuel consumption of a PDE operating on the stoichiometric propane–air mixture range from 0.91 to 0.95 kN/kg/s and from 0.24 to 0.25 kg/(N·h), respectively, at flight altitudes up to 10 km. At higher altitudes (12 km), the operation process in the engine becomes unstable due to low atmospheric pressure.

4 Concluding Remarks

Main thrust characteristics such as thrust, fuel-based specific impulse, specific fuel consumption, and specific thrust of a PDE comprising an air intake and a nozzle in conditions of subsonic flight at Mach number 0.8 at various altitudes (from 0 to 12 km above sea level) were calculated numerically in two-dimensional approximation with the account for aerodynamic drag, realistic physicochemical characteristics of oxidation and combustion of hydrocarbon fuel (propane), turbulence–chemistry interaction, and finite time of turbulent flame acceleration and DDT. It is shown that a PDE can operate effectively (with fuel-based specific impulse of ~ 1500 s) at subsonic flight conditions.

Acknowledgments

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