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COMBUSTION, EXPLOSION, AND SHOCK WAVES

3D versus 2D Calculation of Thrust Characteristics of the Air-Breathing Pulse Detonation Engine under Supersonic Flight Conditions

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Abstract—3D calculations are used to confirm the conclusion that the specific thrust of the air-breathing pulse detonation engine is 20–30% higher than that of the ideal ramjet in which normal combustion takes place.

Keywords: deflagration-to-detonation transition, pulse detonation engine, specific impulse

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In an earlier work [1], we calculated thrust characteristics, namely, specific impulse, specific fuel consumption, specific thrust, and thrust coefficient for an air-breathing pulse detonation engine (PDE) with an air intake and a nozzle in supersonic flight at a Mach number of 3 and various altitudes (8–28 km above sea level), taking into account the external flow past the engine, the physicochemical features of the oxidation and combustion of the hydrocarbon fuel (propane), the finite time of turbulent flame acceleration, and the deflagration-to-detonation transition (DDT) in the combustion chamber. The working process in the PDE was numerically simulated in the 2D axisymmetric approximation. It was concluded [1] that the specific thrust of the PDE is >20% higher than that of the ideal ramjet in which normal combustion takes place. This important conclusion was to be verified by solving the corresponding 3D problem in the same formulation at the same values of the determining parameters. The purpose of this report is to compare the PDE thrust characteristics obtained by 3D and 2D calculations.

In this study, we considered a PDE with a total length of 2.12 m and an outer diameter of 83 mm, including an air intake, a receiver, an annular bypass channel, and a combustion chamber. The latter included a mechanical valve, nine annular turbulizing obstacles, and a converging/diverging nozzle. (This engine design received the name of a base design [1].) As in our previous work [1], the flow model underlying the calculations was the Reynolds-averaged mass, momentum, and energy conservation equations for unsteady-state, compressible, turbulent, reacting flow, but in full 3D rather than axisymmetric 2D formulation. The turbulent flows of matter, momentum, and energy were simulated in terms of the standard k–ε model of turbulence. The contributions from frontal combustion and bulk preflame reactions to the chemical sources in the turbulent combustion of propane were taken into account by using the explicit flame front capturing algorithm and the particle tracking method [2]. The particle tracking method was modified to allow for preflame self-ignition reactions occurring in stagnant zones on the upstream and downstream sides of the obstacles [3]. The system of equations of the model was closed using initial and boundary conditions and the caloric and thermal equations of state for an ideal gas with a variable heat capacity. All thermophysical parameters of the gas were considered to be variable.

The numerical solution was obtained by a method based on the finite-volume discretization of differential equations with first-order approximation with respect to space and time. In order to avoid excessive grid densification at solid surfaces with flow sticking, we used the standard wall function method. The calculation was carried out for a PDE under supersonic flight conditions for a Mach number of 3 and an altitude of 16 km (atmospheric pressure of 0.01 MPa, air temperature of 216.7 K).

As in our previous work [1], the PDE operating cycle consisted of four stages: blowout, filling, combustion, and outflow. The calculation was started with a short-time blowout of internal duct of the engine with incident air (blowout stage). Next, gaseous propane was injected into the air stream entering the combustion chamber, and the combustion chamber was thus filled with a stoichiometric propane–air mixture nearly up to the nozzle inlet (fill factor of 0.9 [1]).

The filling stage was followed by the combustion stage: the mechanical valve was instantaneously closed, and the fresh mixture was ignited by 12 weak point ignition sources (one source per 30° sector), which were placed in one cross section of the combustion chamber in the stagnant zone downstream of the first turbulizing obstacle. The ignition source energy was adjusted so that, 0.2 ms after ignition, the flame front had traveled the same distance along the chamber axis as in the 2D axisymmetric calculation [1], in which the mixture was ignited using an annular source. After ignition, the flame front moved downstream with an acceleration mainly caused by the high intensity of turbulence in the fresh mixture, and a shock wave formed and propagated before the flame front, with its amplitude increasing with time. At a certain distance from the ignition system, which is called the predetonation distance, a local spatial explosion occurred in the region between the flame and the shock wave ("explosion in the explosion," which is among the determining stages of PDE operation [4]), with the explosion center located in the stagnant zone on the downstream side of one of the annular turbulizing obstacles. This local explosion generated a overdrived detonation wave, which then transformed into self-sustaining detonation propagating in the fresh mixture toward the PDE nozzle. At the nozzle inlet, the detonation degenerated into a shock wave. After the shock wave left the nozzle, the outflow of the detonation and combustion products into the atmosphere (outflow stage) began.

The outflow stage lasted until the average pressure at the valve on the combustion chamber side decreased to a certain critical value P^* that still ensured a positive instantaneous total force (instantaneous effective thrust) acting on the engine in the flight. After the P^* value was reached, this force became close to zero, the valve opened, and all stages of the operating cycle repeated.

As in our previous study [1], the thrust characteristics of the PDE were determined by performing calculations for three or four operating cycles (until completely reproducible periodic operation was achieved) with the external flow past the engine taken into account. The instantaneous effective thrust was determined as the integral of the pressure and viscous friction forces over all solid surfaces of the PDE. It was considered to be positive if its direction coincided with the PDE flight direction. Along with the instantaneous effective thrust and valve opening pressure P^*, the operating cycle duration and, hence, the working process frequency f in the PDE and also the fuel mass flow rate were derived from the calculation.

For determining the instantaneous thrust of the PDE, it is necessary to know the aerodynamic drag force acting on the engine during the flight. This force was determined [1] by solving the above problem with two changes made to it, namely, one missing ignition (method 1) and two missing ignitions (method 2). In the former case, we initially solved the above problem until completely reproducible operation was attained (three or four cycles involving ignition) and, in the subsequent cycle, there was no ignition after the combustion chamber was filled with the combustible mixture. In the latter case, the problem was again solved until completely reproducible operation was attained (three or four cycles involving ignition) and the calculations for the next two cycles were performed without involving ignition. In both cases, the force acting on the PDE during the flight was determined in the last cycle, in which there was no ignition. The difference between the drag calculation methods was that, in the first case, the combustible mixture filling the PDE in the last cycle (without ignition) displaced, from the combustion chamber, the residual (hot) detonation products that were left after the preceding cycle, while in the second method it displaced the unreacted (cold) combustible mixture that was left after the preceding cycle. Knowing the instantaneous drag force, one can readily determine the average drag for, e.g., one operating cycle.

An analysis of our earlier data [1] demonstrated that drag determination method 2 leads to a somewhat larger aerodynamic drag value than drag determination by method 1 and, therefore, to an overestimated thrust value. We think that drag determination method 1 is more correct since it is more closely associated with the cyclic working process. For this reason, method 1 is more appropriate for calculating the aerodynamic drag acting on the PDE.

The aerodynamic drag force acting on the PDE can also be determined in another way. Since the aerodynamic drag for the incident air flow is created only by the walls past which the air flows, it is obvious that the internal walls of the combustion chamber make no contribution to this force when the valve is closed (at the combustion and outflow stages). However, when the valve is open (at the blowout and filling stages), the internal walls of the combustion chamber do make contribution to this force. If this circumstance is taken into consideration and the cycle-averaged aerodynamic drag acting on the engine is calculated, it will be easy to determine the thrust of the engine without performing additional calculations on cycles with missing ignitions.

Both methods of determining the aerodynamic drag must yield similar results. This is due to the fact that, when the valve is closed and an ignition event is missing, the contribution from the pressure and viscous friction forces on the inner surface of the combustion chamber of the PDE to the total aerodynamic drag of the engine is incommensurably small compared to the total contribution from the pressure and viscous friction forces on the other solid surfaces.

Figure 1 compares the 2D- and 3D-calculated dependences of the apparent speed of the leading point of the flame front on the distance traveled along the PDE duct during one operating cycle after the establishment of the periodic operation mode of the engine with ignition in each cycle. Both curves terminate at an apparent flame speed of about 1000 m/s. Once this speed is reached, an “explosion in the explosion” takes place and the reaction propagation mechanism changes: the propagation of a turbulent flame front in the shock-compressed fresh mixture gives way to the propagation of a self-ignition front occurring immediately downstream of the front of the running shock wave. A comparison between the curves plotted in Fig. 1 shows that, in the 3D calculation, DDT occurs approximately at the same distance as in the 2D axisymmetric calculation. Note that, in the 3D calculation, the only cause of 3D effects is use of 12 point ignition sources in place of the one annular ignition source employed in the 2D calculation.

Note that the modifications made to the particle tracking method [3] led to the fact that, in the 2D calculation (Fig. 1), the predetonation distance is ~140 mm shorter than in the similar calculation that did not allow for preflame self-ignition in the stagnant zones near the turbulizing obstacles [1]. The unusually short predetonation distances for the stoichiometric propane–air mixture obtained in the 2D and 3D calculations (Fig. 1) are explained by the very high intensity of turbulence (~30%) and by the large values of temperature (450–500 K) in the fresh mixture flow core.

Figure 2 compares the 2D- and 3D-calculated time dependences of the instantaneous effective thrust during one operating cycle after the establishment of the

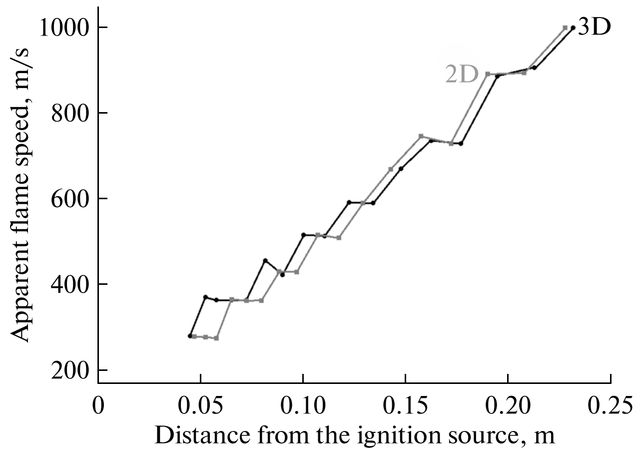

Fig. 1. Flame speed along the PDE duct according to the 2D and 3D calculations.

periodic operation mode of the engine with ignition in each cycle. From the curves plotted in Fig. 2, it is possible to determine the duration of one cycle and, hence, the working process frequency f in the PDE, and also the effective PDE thrust F averaged over one operating cycle. In the 3D calculation, f is slightly lower (54 Hz) than in the 2D calculation (56 Hz). This is mainly due to the increase in the blowout stage duration. As for the average effective thrust F (determined as the mean integral value of the instantaneous effective thrust in one cycle), it is positive in both cases; however, its value in the 3D calculation (13 N) is somewhat smaller than in the 2D calculation (19 N). This is due to the increase in the aerodynamic drag for the internal flow in the 3D calculation and to the corresponding lengthening of the blowout stage. The positiveness of the average effective thrust means that the PDE can move with acceleration.

By adding the instantaneous aerodynamic drag and the instantaneous effective thrust, it is possible to determine the instantaneous thrust of the PDE, from which one can readily calculate the DDE PDE thrust averaged over an operating cycle, R. Knowing the average thrust and fuel consumption per second ($\dot{m}_j$), one can determine the following thrust characteristics:

Results of the 2D and 3D calculations of the thrust characteristics of the PDE in supersonic flight at a Mach number of 3 and an altitude of 16 km

Calculation	f, Hz	P*, MPa	$\dot{m}_j$, g/s	F, N	R, N	I_{sp}, s	N_{sp}, $\frac{kN}{kg/s}$	C_{sp}, $\frac{kg}{N \cdot h}$
2D	56	0.138	15.4	19/17	252/250	1670/1650	1.06/1.06	0.22/0.23
3D	54	0.146	16.5	13	263	1630	1.02	0.23

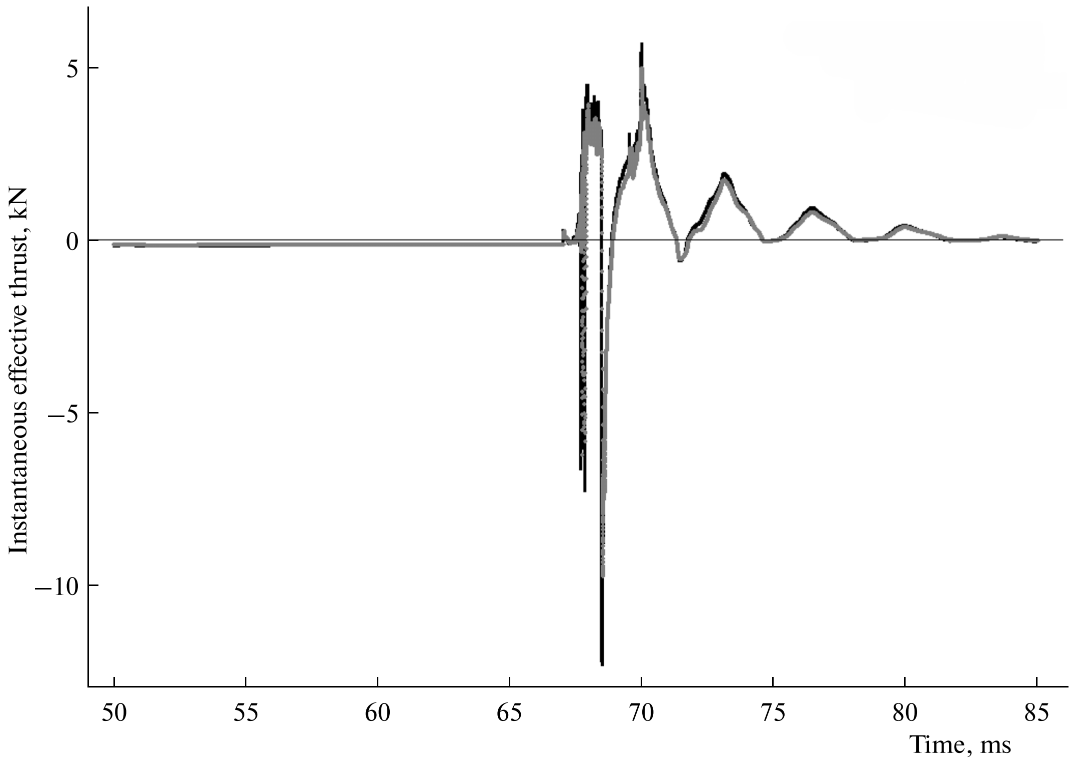

Fig. 2. Time dependence of the instantaneous effective thrust for the PDE with nine turbulizing obstacles under supersonic flight conditions at a Mach number of 3 and an altitude of 16 km according to the 2D (black curve) and 3D (gray curve) calculations.

specific impulse I_{sp} ($R/g\dot{m}_j$, g is the gravity acceleration), specific thrust N_{sp} (R divided by the weight of air consumed per second), and specific fuel consumption (hourly fuel consumption per newton of the average thrust of the engine).

The table presents a comparison of the specific thrust characteristics obtained by the 3D and 2D axisymmetric calculations. For I_{sp}, N_{sp}, and C_{sp}, two values separated by a slash are presented, one calculated via the determination of the average aerodynamic drag with one missing ignition (as in [1]) and th other determined without any ignition missing. It is clear from the data listed in the table that the specific thrust characteristics of the PDE obtained by the 3D and 2D axisymmetric calculations are approximately equal. Therefore, the conclusion [1] that the PDE is superior in specific thrust N_{sp} to the ideal ramjet in which normal combustion takes place has been confirmed by the 3D calculation. Quantitatively, this superiority is 20–30% over the ~0.85 kN/(kg/s) value for the ideal ramjet [5].

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