NUMERICAL MODELING OF FLOW IN GASDYNAMIC RESONATOR AND MODEL VALIDATION BY RESULTS OF PULSE ENGINE TESTS

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Abstract

Pulse engines attract growing interest due to possibility of aeroengine performance improvement based on change-over from the heat-supply-at-constant-pressure cycle to the periodic heat-supply-at-constant-volume cycle. One of the possible realizations of this concept is an excitation of high-frequency oscillations in a gasdynamic resonator that is periodically filled with a specially prepared air-fuel mixture.

This work is devoted to the development of the mathematical and numerical model of fluid dynamics in such resonator. Comparison of obtained numerical simulation results with the results of experiments involving the pulse demonstrator engine is presented.

1 Introduction

One of the possible ways to improve the aeroengine performance consists in change-over from the heat-supply-at-constant-pressure cycle to the periodic heat-supply-at-constant-volume cycle. The pulse engine concept and scheme considered in this work does not include mechanical valves and a special ignition system. The pulse process in such an engine is initiated due to the excitation of high-frequency oscillations in a gasdynamic resonator that is periodically filled with a specially prepared air-fuel mixture. The heat release enhancing the oscillation amplitude occurs as a result of supersonic (detonation) combustion of mixture in shock-wave structures formed in the resonator. Available at present are test facilities and models of individual resonators, the characteristics of which confirm the previous assessments of the proposed scheme effectiveness [1-2].

This work is devoted to the development of the mathematical and numerical model of gasdynamic processes in the resonator offered in [1-2] as well as to the comparison of the obtained theoretical results with the results of experiments involving the pulse demonstrator engine.

It should be also noted that the ejector nozzle connected to the resonator permits to increase its thrust characteristics considerably.

The mathematical and numerical modeling is a basic method for a detailed investigation of fast gasdynamic processes and calculation of their integral characteristics in different modes.

The multiparametric optimization which can be carried out on the base of the mathematical model allow choose the optimal (from one or another point of view) object parameters. Such an investigation permits to substantially reduce both a number of experiments and quite expensive model and full-scale tests as well as to write the effective program of their conduction.

This work includes numerical experiments in the specified range of thermodynamic and geometric governing parameters. The developed software system allows optimize the configuration of the gasdynamic resonator and its dimensions as well as the thermodynamic parameters of the working medium.

The proposed mathematical model describes the flow that develops at gas issue from the annular nozzle and its interaction with the resonator. As a result of this interaction, a pulse jet propagates into the ambient. The model is constructed on 3D with respect to spatial coordinates unsteady equations of gas dynamics taking account of friction and heat exchange (Reynolds-averaged Navier-Stokes equations involving a two-parameter turbulence model). Numeric modeling enables to follow the process from its beginning – the nozzle opening – to the moment of reaching the periodic mode by jet flow. The initial-boundary value problem corresponding to different operating conditions of the resonator has been formulated for the partial differential equations.

The analysis of parameters governing the process involving a pulse gas jet has been carried out. The number of parameters governing the pulse flow is more than in the case of steady flow that provides more possibilities to optimize the process. But it is necessary to note that multiparametric optimization of a pulse engine (PE) represents an independent complex scientific-technical problem.

The possibility of realizing the change in the governing parameters technically is determined by way of developing the pulse process. Parameters P_1^0, T_1^0 characterizing air at the annular nozzle entry and the nozzle geometry are considered the most available for varying (from the technical point of view) as applied for the PE studied in this work. Any values can vary from the point of view of calculations. The values of relative and absolute thrust have been selected as an integral characteristic for assessing the effectiveness of a PE with a resonator. The comparison with the results of two PE models tests regarding the integral characteristics has shown a good agreement of experimental and calculation investigations.

2 Problem statement

The scheme of the gasdynamic resonator under study is given in Fig.1. Here 1 is for the annular nozzle from which a prepared gas mixture issues, 2 – for the resonator cavity that represents a spherical segment, 3 – for the zone to which the jet issues. Axisymmetric flow conditions are considered.

Since the main interest of this work is focused on the investigation of the jet dynamics, the technical elements of the device responsible for the preparation of gas that enters the annular nozzle are not shown in Fig.1.

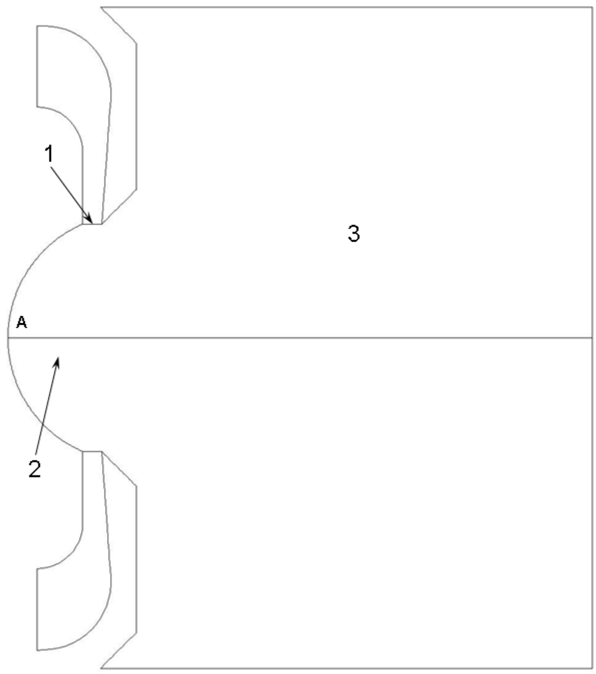

Fig. 1. Resonator scheme

The flow pattern in the resonator is unsteady (periodically varying) and has a strong radial anisotropy. The high gradients of flow parameters are observed in the resonator exit section. The formation of non-uniformly scaled vortex structures can be observed.

To give the mathematical description of the process in the resonator and in the jet issuing to the ambient we used unsteady Navier-Stokes equations (Reynolds-averaged) for the viscid heat-conducting compressible 3D gas flow. The k-ε turbulence model is used for the set of equations closure and adequate description of mixing processes in a turbulent flow.

The boundary conditions are set by deceleration parameters in the nozzle entry section, exit pressure (in the ambient where the jet issues) as well as by conditions of “attachment” on all hard walls of the device.

At the initial instant of time the thermodynamic values outside the nozzle are equal to the ambient parameters; the flow velocity is equal to zero. The parameters inside the nozzle are equal to deceleration parameters; the flow velocity is equal to zero. At instant of time t=0 the nozzle diaphragm opens, and the flow starts to issue to the ambient.

In all the calculations the parameters of active gas in the duct entry section were taken equal to the parameters of the corresponding experiment, the inflow velocity angle – equal to zero.

This work, according to the conducted experiments, studies flow without chemical reactions, so called “cold-air testing”. The equation of state for the perfect gas is used in the calculations. The experiments were carried out with the device at rest at constant parameters of ambient air. The calculation domain corresponds to the scheme presented in Fig.1 and includes a portion of the annular nozzle (from some section that is close to the entry downstream to the exit section), the resonator cavity and the attached zone of the ambient where the gas issues. The calculation domain with a calculation mesh is shown in Fig.2.

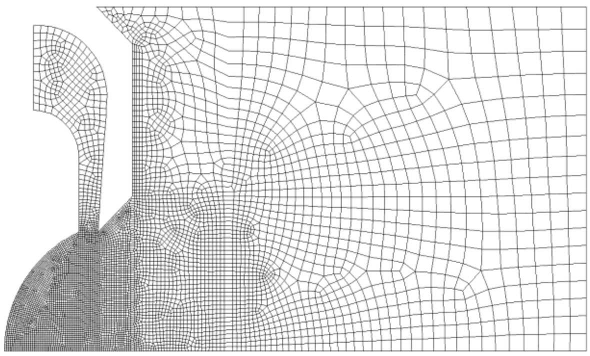

Fig. 2.Calculation domain including nozzle, resonator cavity and portion of ambient where the jet issues (mesh size – 21,000 calculation cells)

The mesh cells near the hard walls and near the nozzle exit are small for more exact calculation of the boundary layer, but the farther to the zone of the open space the larger the mesh cells become.

The implicit finite-difference scheme of accuracy of second order with respect to time and space is used in numerical modeling. The advantage of the implicit scheme of integration consists in the possibility of increasing a time step as compared with the explicit scheme.

3 Calculation results

The results of calculations according to the program realizing turbulent flow are given in Figs. 3 and 4. The calculation is presented for the following values of the governing values

- pressure and temperature in ambient: $P^0 = 1 kg/cm^2$, $T^0 = 300$ K;
- active gas parameters in annular duct entry section: $P_1^0 = 4$ kg/cm^2, $T_1^0 = 300$K;
- inflow velocity angle – equal to zero;
- resonator exit section diameter – 90 mm.

Fig.3 shows pressure oscillations at point A of the resonator; Fig.4 demonstrates Fourier transform of pressure oscillations (Pa) at point A in the turbulent mode.

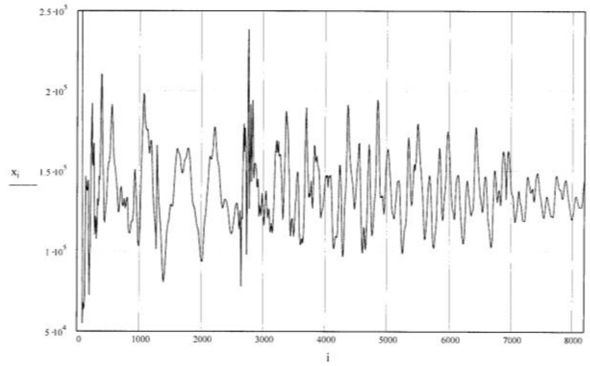

Fig. 3. Pressure oscillations (Pa) at point A in the turbulent mode over 8,000 time steps (f = 4,096 Hz).

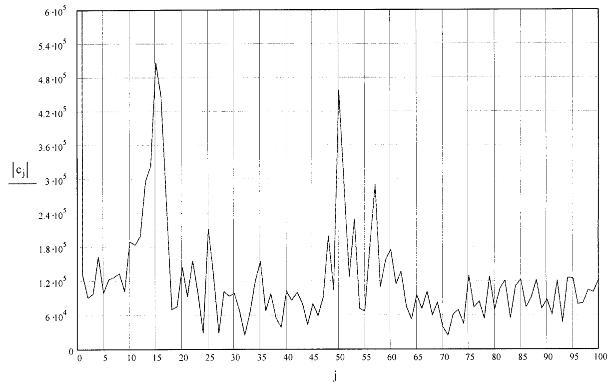

Fig.4. Fourier transform of pressure oscillations at point A

It should be noted that one of the pressure oscillation spectrum frequencies at point A is equal to f=4,096 10^3 Hz that is in good agreement with the experimental results.

By instant of time t ≅ 0.006 s the process stabilizes, the oscillations become more regular. M1 is set at the active nozzle exit but gas flow in the resonator cavity continues to keep unsteady-wave pattern.

Fig.5 presents pressure in-time distribution at point A of the resonator in the steady mode. Oscillation frequency is 1,250 Hz, average excess pressure at this point is ~125,000 H/m^2.

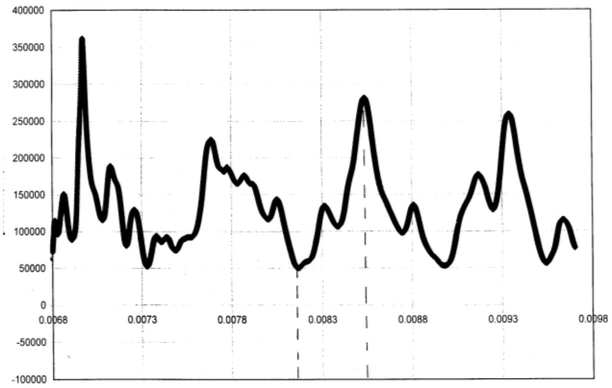

Fig. 5. Pressure (Pa) in-time distribution at point A of resonator in steady mode

The thrust oscillation frequency coincides with the pressure oscillation frequency at point A, and its average value is ~540 Hz.

Let us note that the calculations carried out in this work cover the time interval that is 3-4 times as long as the time interval mentioned in the known works of other authors. The comparison with the experiment enables to choose the most accurate models.

Let us mark the main qualitative features of flow:

- velocity of active gas jet issuing from the nozzle is everywhere supersonic;
- vortex zone in the area between the jet and the resonator wall presents practically during all steady process;
- the area of high Mach numbers (M~1.3) (shock wave) detaches from the resonator wall at certain instants of time and moves in the positive direction of x-axis;
- at the moment of pressure minimum at point A the most intensive gas suction from the atmosphere takes place, the attached flow turns and moves along with the jet; Mach number in the jet increases;
- at the moment of pressure maximum at point A gas suction is not so intensive, the active gas jet changes its position and declines closer to the resonator axis;
- during the whole periodic steady process the active gas jet either expands or compressed along the axis at a certain frequency.

The distribution of different gasdynamic parameters in the calculation domain at some instant of time is presented in Figs. 6-9 for the following governing parameters: h_{thr}=5.17 mm, flow G=0.537 kg/s, P^0 =2.45·10^5 Pa at nozzle entry, T^0=473K, the resonator exit diameter -70 mm.

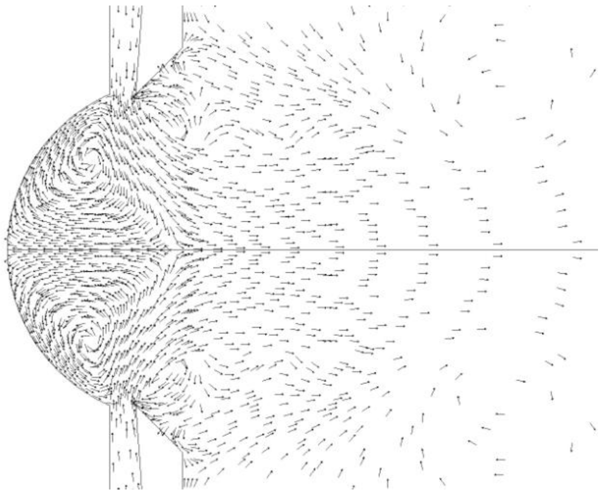

Fig. 6. Distribution of velocity vectors.

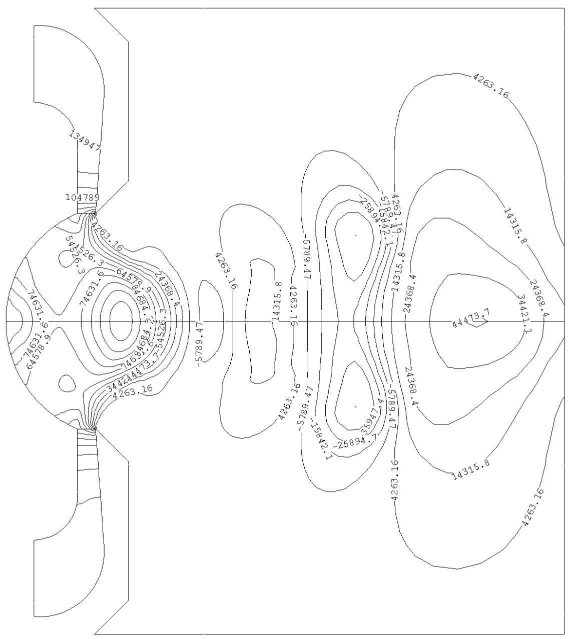

Fig.7. Distribution of relative static pressure (ambient pressure = 10^5 Pa).

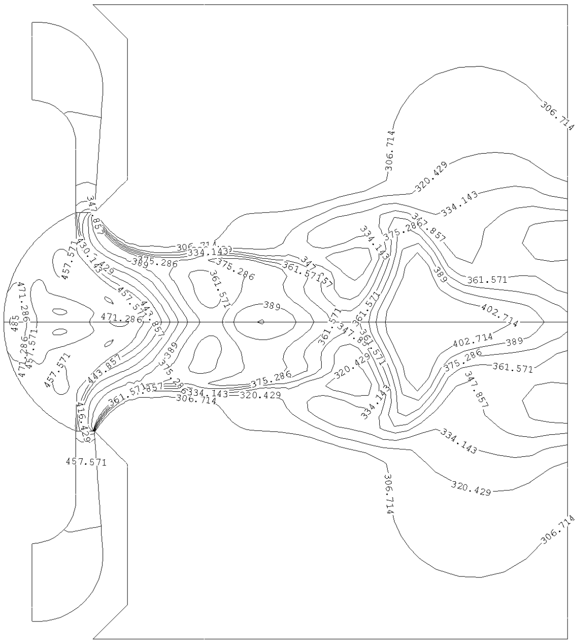

Fig. 8. Static temperature distribution

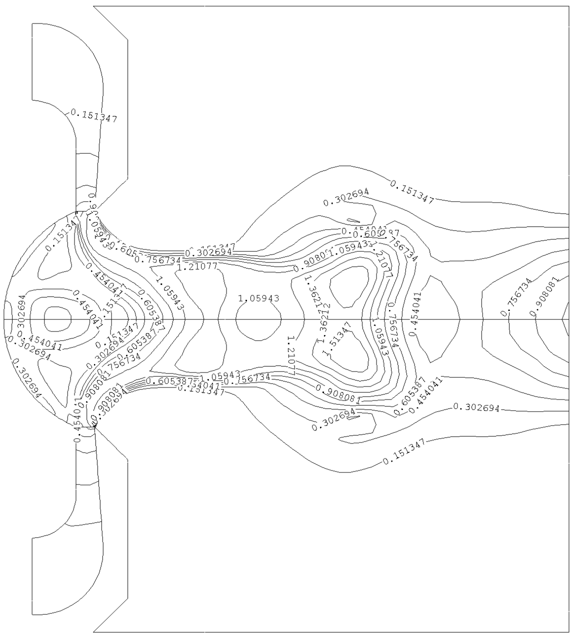

Fig. 9. Mach number distribution

4 Comparison of mathematical modeling results with experimental data

The calculations were carried out according to the experiment conditions: air with constant heat capacities was used as a working medium, the deceleration parameters (temperature and pressure) at the nozzle entry as well as the nozzle exit section dimensions varied. Thrust was chosen as an integral characteristic which was used to compare numerical and experimental results. Thrust in the numerical experiment was calculated by several periods (a time and solid surface double integral) and was time averaged.

This is the range of parameters variation in numerical modeling

- Nozzle gas flow – from 150 up to 550 g/s.
- Nozzle entry pressure – from 1.5 up to 5 kgf/cm^2
- Nozzle entry temperature – from 300 up to 900K.
- Annular nozzle throat height h_{thr} – from 2.86 up to 5.17 mm.
- Resonator exit section diameter – 70 mm.

The calculation and experimental data were compared for the different parameter interdependences:

- dependence of thrust and specific thrust on gas pressure at active nozzle entry
- dependence of thrust and specific thrust on nozzle flow
- dependence of thrust and specific thrust on nozzle entry temperature
- dependence of thrust and specific thrust on nozzle exit diameter
- dependence of nozzle flow on nozzle entry pressure
- dependence of nozzle flow on nozzle entry temperature, and other dependences.

Let us present some results of numerical and experimental data comparison. The experimental data in Figs. 10-11 are shown in dotted lines, and numerical – in solid lines. The figures denote different values of total temperature at the nozzle entry; their values are given in the under-figure rectangle.

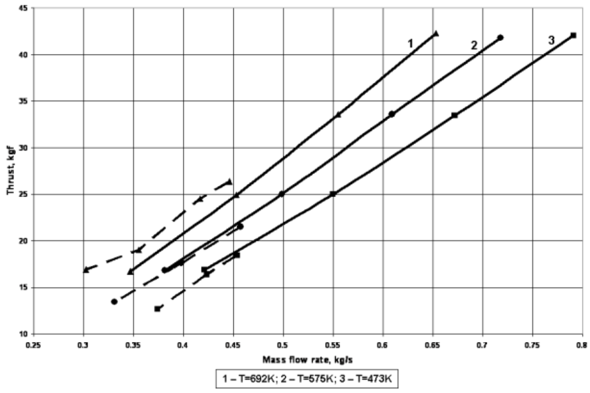

Fig. 10. Calculation and experimental results for thrust-flow relationship at three values of T^0 and annular nozzle throat h_{thr} =5.17 mm.

It follows from the presented data that thrust increases with rise in temperature at similar flows. The maximum difference between the numerical and the experimental results is ~ 8.5%.

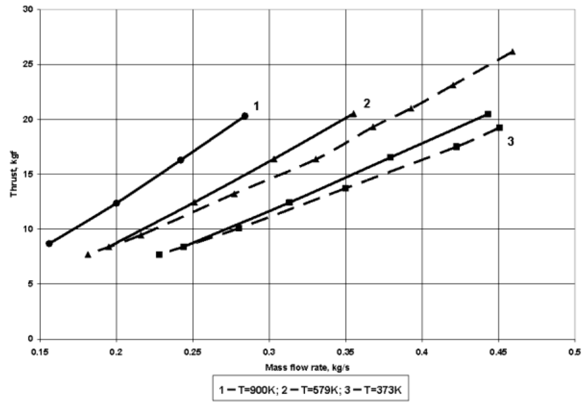

Fig. 11. Calculation and experimental results for thrust-flow relationship at two values of T^0 and annular nozzle throat h_{thr} =2.86 mm.

The results given in this figure qualitatively agree with the previous ones presented in Fig.10. The maximum divergence between the numerical and experimental results here is ~ 10% that is explained by a slight difference in temperature values in the experiment ($T1^0$~600K and $T2^0$=372K) from those accepted in calculation.

Given in addition are the calculations for T^0=900K. The experiments for this temperature were not carried out. The results of calculations confirm the main feature of the resonator – increase in thrust with rise in temperature under other identical conditions.

The construction of a thrust-versus-flow plot is the most total characteristic of the resonator process as the nozzle throat flow is considerably determined by the total parameters at the nozzle entry and its throat area.

The presented results demonstrate a good agreement of numerical and experimental data that is evidence that the mathematical model fits the physical processes in the resonator adequately both qualitatively and quantitatively.

5 Conclusion

Within this work on the investigation of the processes in the resonator [4] there were also used other mathematical models: Euler and Navier-Stokes equations for laminar flows. The calculations using the model that does not take account of viscosity, according to the program of the second order of accuracy, are unstable and demand introducing either “artificial viscosity” or a very small time step. That is why this kind of model was rejected for this work. The onset of instability in calculations with Euler equations is connected with the appearance of shockwaves in the solution. It is known [3] that the schemes of second order in the vicinity of shockwaves initiate the flow parameter variations induced by difference approximation of equations. The “calculation variations” can distort the pulse physical process pattern. As the oscillation process in the resonator and in jet is high-frequency, a time step should be very small that makes the calculation by Euler equations unreasonable. The calculations by Navier-Stokes equations as applied to laminar flows are close (by some results) to the calculations taking account of a turbulent flow pattern, but when compared with experiment they differ considerably.

The calculations without taking viscosity into account were carried out in work [5].

It is necessary to mention the fact that the preliminary investigations showed a high effectiveness of the connected ejector channel from the viewpoint of thrust increase of a PDE with a resonator.

The ejector channel with a pulse active jet can provide a 1.5-2 times increases in thrust [6] if the combinations of governing parameters are chosen optimally. At that, the frequencies are selected according to the natural frequency of the ejector channel and stabilized. The choice of the ejector dimensions, its position relative to the resonator demand the additional numerical and experimental investigation.

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