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

This work is devoted to the development of the mathematical and numerical model of gas-dynamic 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.

The pulse process in such an engine is initiated due to the excitation of high-frequency oscillations in a gas-dynamic 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].

The mathematical and numerical modeling is a basic method for a detailed investigation of fast gas-dynamic processes and calculation of their integral characteristics in different modes. 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 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 calculations for pulsating nozzle flow without taking viscosity into account were carried out in work [3].

Laminar approach to description of pulsating flow proposed in [4] reveals overall model instability that can be compensated by introducing of “artificial viscosity” or via very small time step (two orders of magnitude lower than used in present work). The onset of instability in calculations with Euler equations is connected with the appearance of shockwaves in the solution. It is known [5] 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.

Proposed in this work 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 multicriteria 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, T (total pressure and total temperature) characterizing air at the annular nozzle inlet 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. Nozzle geometry can be changed by variation of nozzle throat axial width. Relative and absolute thrust values 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 gas-dynamic 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. The flow is considered axisymmetrical.

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.

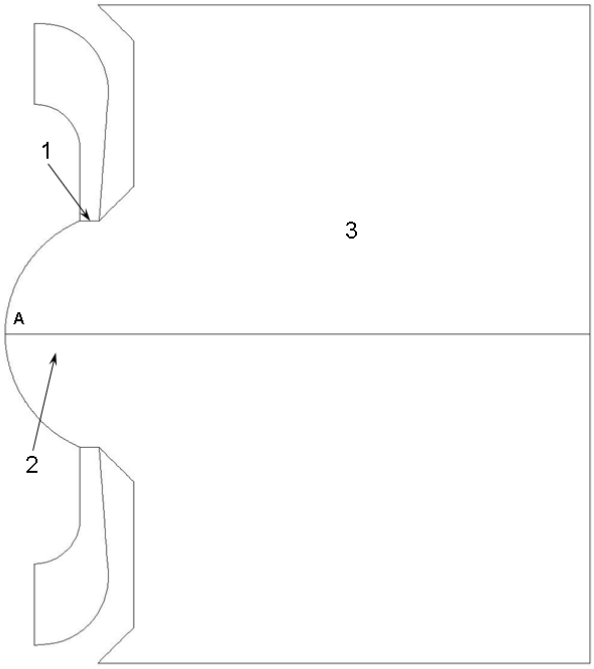

Fig. 1. Resonator scheme (A – resonator central point)

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.

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.

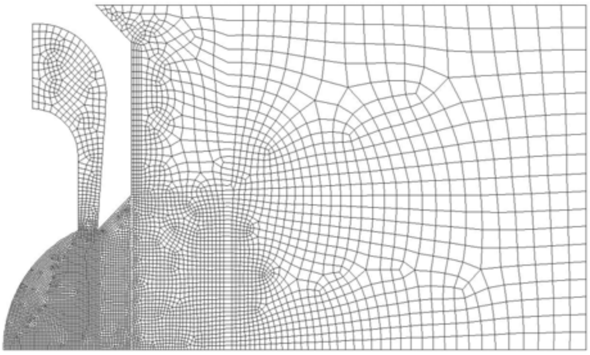

Fig. 2.Calculation domain including nozzle, resonator cavity and portion of ambient where the jet issues (mesh size – 21,000 calculation cells)

Mesh resolution is high in near-wall region ($Y^{+}\approx 3$) and in resonator cavity. Mesh in adjacent open space region is much coarser (see Fig.2). Analysis of mesh resolution influence on flow behavior has shown that mesh refinement in near wall region and outside resonator cavity does not affect noticeably on flow behavior. The matter is that pulsation regime is governed by jet collision not surface interaction.

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 calculations were performed for the following values of the governing parameters:

- Total pressure and temperature in ambient: $P = 10^5$ Pa, T = 300 K;
- Duct entry flow total pressure and temperature: $P = 4{\cdot}10^5$ Pa, T = 300K;
- resonator outlet section diameter – 90 mm.

Fig.3 presents static pressure in-time distribution at resonator central point in the stable pulsations mode. Analysis of pressure oscillation spectrum at resonator central point has shown that obtained fundamental frequency of 1,250 Hz is in good agreement with the experimental results.

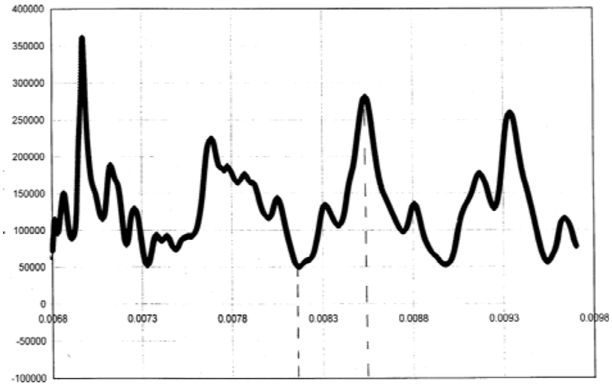

Fig. 3. Static pressure (Pa) in-time distribution at resonator central point in stable pulsations mode.

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 resonator outlet 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 gas-dynamic parameters in the calculation domain at some instant of time is presented in Figs. 5 and 6 for the following governing parameters: nozzle throat axial width = 5.17 mm, nozzle mass flow rate - 0.537 kg/s, inlet total pressure and total temperature P =2.45·10^{5}Pa, T=473K, the resonator outlet diameter -70 mm.

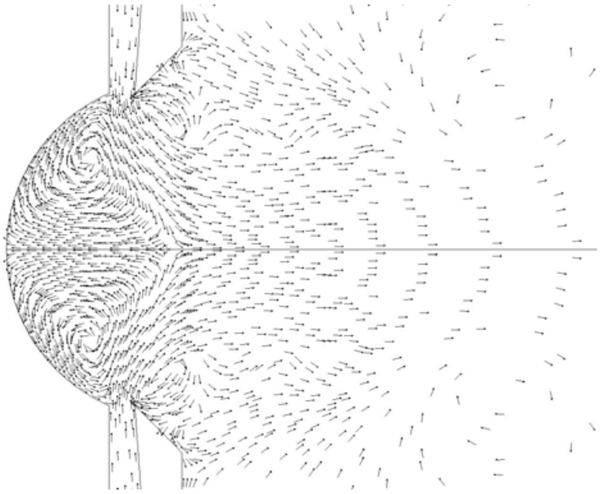

Fig. 4. Distribution of velocity vectors.

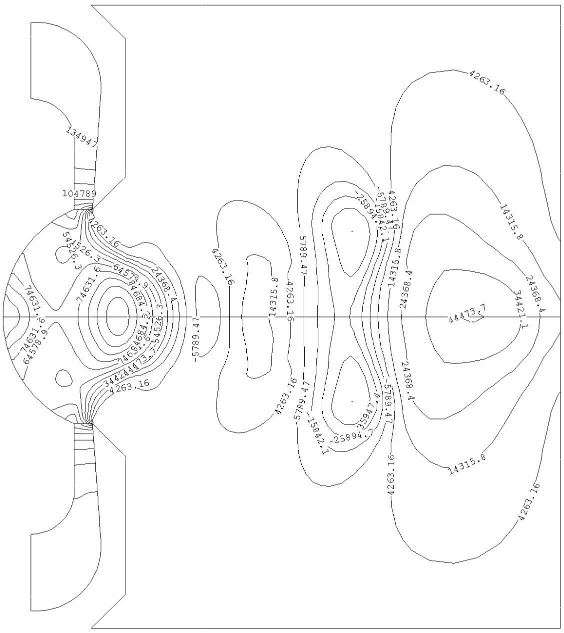

Fig.5. Distribution of relative static pressure (ambient pressure = 10^5 Pa).

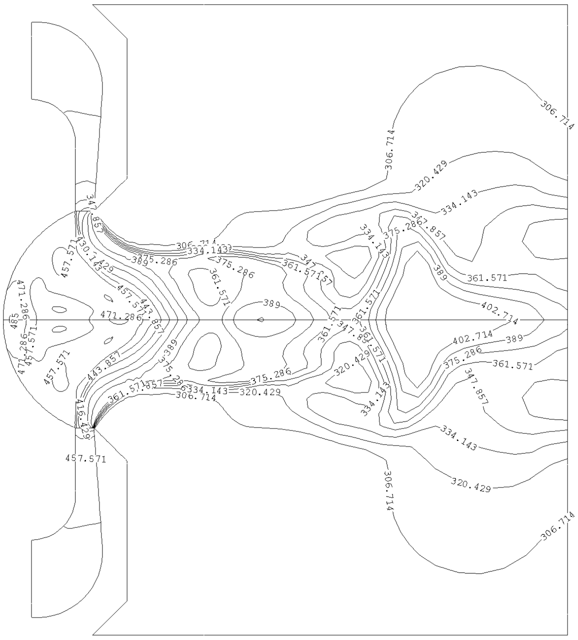

Fig. 6. Static temperature distribution

4 Comparison of mathematical modeling results with experimental data

The calculations were carried out according to the experiment conditions. 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

- inlet mass flow rate – from 0.15 up to 0.550 kg/s.
- Nozzle inlet total pressure – from $1.5\cdot10^5$ Pa up to $5\cdot10^5$ Pa
- Nozzle inlet total temperature – from 300 up to 900K.
- Nozzle throat axial width – 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 inlet pressure, mass flow rate and temperature
- dependence of thrust and specific thrust on resonator outlet diameter
- dependence of fluid flow on resonator inlet pressure, inlet temperature etc.

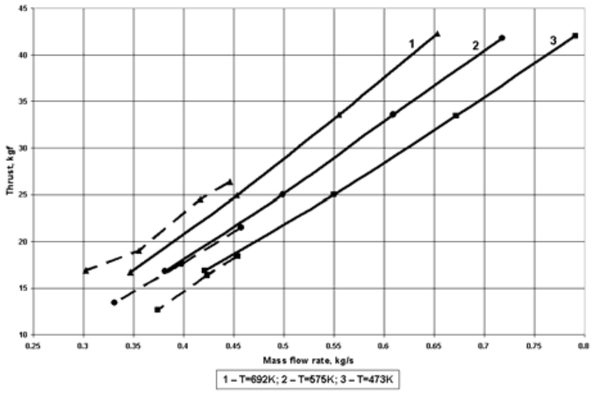

Fig. 7. Calculation and experimental results for thrust-flow relationship for various total temperatures and annular nozzle throat axial width = 5.17 mm.

Let us present some results of numerical and experimental data comparison. The experimental data in Figs. 7 and 8 are shown in dotted lines, and numerical – in solid lines. The figures denote different values of total temperature at the nozzle inlet; their values are given in the under-figure rectangle.

As it is 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 does not exceed 10%.

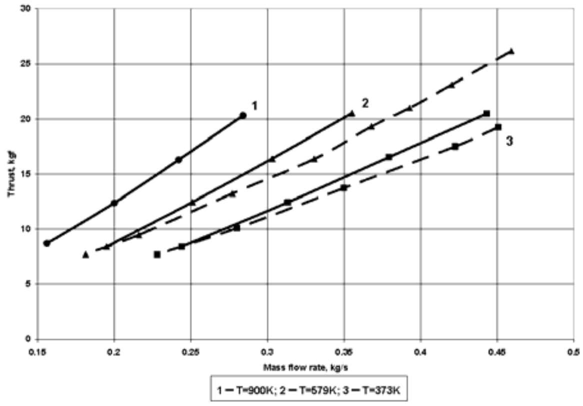

Fig. 8. Calculation and experimental results for thrust-flow relationship for various total temperatures and annular nozzle throat axial width = 2.86 mm.

Given in addition are the calculations for T=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 inlet 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

It is shown that correctly defined numerical model that takes into account viscosity and heat transfer allows to simulate transient fluid flow in pulse engine resonator with sufficient accuracy.

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