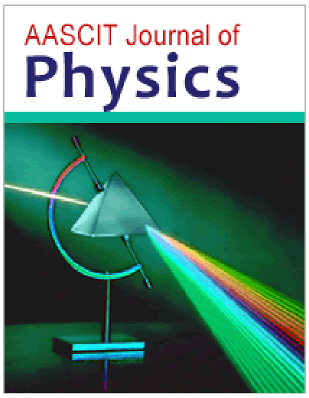
AASCIT Journal of Physics
2015; 1(4): 328-333
Published online July 30, 2015 (http://www.aascit.org/journal/physics)

American Association for Science and Technology



Keywords
Resonator,
Pulsejet Engine,
Added Mass,
High-Nonstationary Gas Dynamics

Received: April 1, 2015
Revised: May 26, 2015
Accepted: May 27, 2015

Numerical Simulation Features of the Spherical Gas-Dynamic Thrust Amplifier

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Citation
Vasily Ivanovich Bogdanov, Dmitry Sergeevich Khantalin. Numerical Simulation Features of the Spherical Gas-Dynamic Thrust Amplifier. *AASCIT Journal of Physics.*
Vol. 1, No. 4, 2015, pp. 328-333.

Abstract
The results of numerical simulation of high-nonstationary pulsating flow in a spherical gas-dynamic resonator for purposes of its thrust pulse determination are presented. The flow analysis showed that in an oscillatory working flow unstable in time mass addition occurs that increases thrust pulse of the resonator. It was found that the exact description of gas mass addition processes requires a sufficient long calculation time with small physical timescale and application of a vortex-resolving turbulence model (models of large or separated vortices). Fulfillment of these conditions and taking into account dynamic component of thrust in an annular nozzle enabled to obtain conformation of the calculation data with the experimental data. Based on the analysis results of the present study directions of the follow-up studies are determined; necessity to conduct similar computational experiments using high-capacity computer systems is shown.

1. Introduction

In recent years interest in application of the periodical workflow in the propulsive devices (pulse-jet and detonation engines) increased. The pulse-jet engines compared with the traditional stationary flow engines, have not only a high thermodynamic efficiency, but a tendency to increase the thrust pulse through the effects of joining the gas masses in the oscillatory workflow.

In a well-known design-theoretical study of the one-dimensional scatter of detonation products [1] the possibility of the 3 times thrust increase in the atmosphere compared to the vacuum is shown due to the wave joining of additional air mass. At the definite moments of the oscillating process, the worked-out gas goes back to the source and then can become an additional mass for the next cycle. Basically, these gas-dynamic phenomena define the possibility of the pulse-jet engine propulsion efficiency increase.

The experimental studies prove this possibility of the pulse-jet engine significant thrust performance improvement due to the high-efficiency wave joining of additional gas mass in the oscillating process (Discovery No. 314 [2], NPO Saturn JSC [3,4,5], A. Lyulka Scientific-and-Technical Center [6], Institute of Mechanics of the Moscow State University [7], NASA Glenn Research Center [8]).

2. Model for Numerical Studies

The pulsing spherical gas-dynamic resonator (Fig. 1) can serve as the jet engine thrust augmenter. In this type of the resonator the gas is delivered to the hemispherical cavity through the annular slot where high-frequency oscillations with complex shock-waves structures are created.

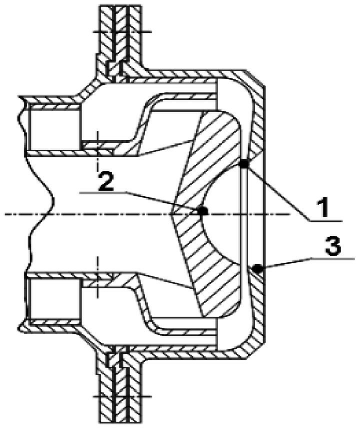

Figure 1. *Spherical resonator geometry: 1 – annular nozzle throat; 2 – spherical resonator; 3 – discharge nozzle.*

From the experimental data (A. Lyulka Scientific-and-Technical Center) under a certain combination of mechanical-geometrical relationships in the flow the thrust growth in the resonator compared to the ideal Laval nozzle can amount to 100% [6].

3. Physico-Mathematical Model

Numerical investigations (ANSYS CFX) of the pulsating flow in the spherical gas-dynamic resonator (thrust augmenter) were conducted isothermal tests at NPO Saturn (Rybinsk) [9]. Calculations have been done for the resonator geometry and the boundary conditions at which up to 12 % specific thrust increase versus the ideal Laval nozzle was obtained by experiments.

Insufficient computing resources available for the non-stationary full-scale model calculation (10 Intel Xeon 5355 quad-core processors, with a frequency of 2.6 GHz and integral main memory of 40 GB) forced simplification of the simulation model up to 6 degree periodicity segment.

The resonator model was divided into the hexahedral elements. The mathematical model describing the flow in the resonator was based on the Navier-Stokes unsteady equation algorithms. Implicit finite-difference scheme of the second-order accuracy in space and time was used during the numerical simulation. 4 internal Newtonian iterations have been solved at each simulation time step to increase stability and to decrease the linearity error. The physical time step was 10^{-7} s.

Different turbulence modeling and description approaches: k-ε and SST models of turbulence, DES and LES models (detached and large eddy simulation) have been applied.

Air was used as the working medium. Calculations have been done within the resonator inlet pressure range of 0.2÷0.3 MPa with the inlet active gas temperature of 690 K and the annular nozzle throat height of 0.0045 m.

4. Analysis of Initial Results

When analyzing the computation results it has been defined that due to the Hartmann-Sprenger effect, an unsteady pulsating supersonic flow followed by the multiple shock wave structures formation and multiple interaction appears in the resonator (Fig. 2). It was defined that addition of mass featuring the wave nature (active mass from the annular nozzle and the external one from the atmosphere) takes place in the high-frequency oscillating process. Reverse flow of the active and external gas mass has been noted that can take part in the pulse generation over and over again (Fig. 2).

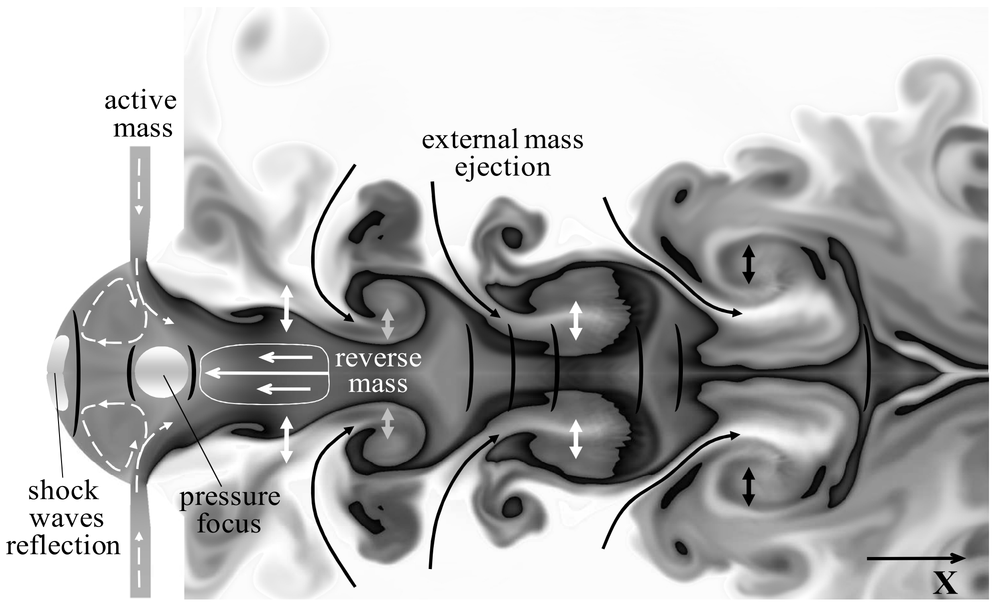

Figure 2. *Scheme of the oscillatory wave process in the resonator.*

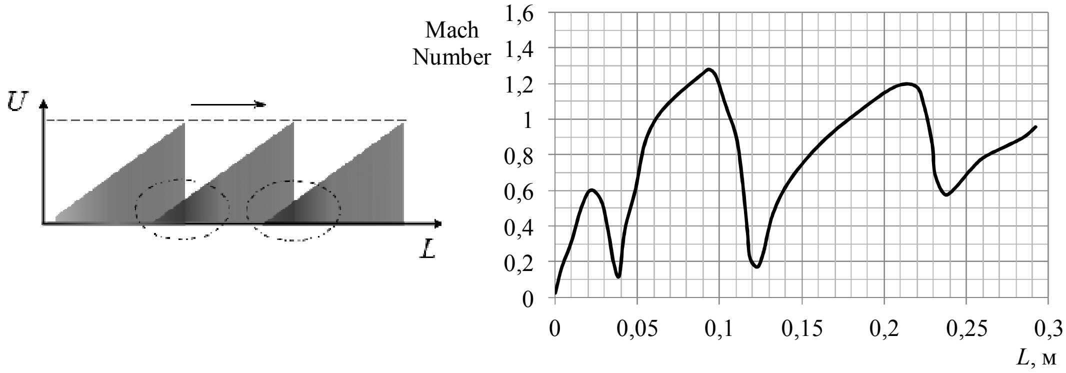

Figure 3. *Velocity distribution in the resonator main flow: on the left – theoretical model; on the right – typical distribution of velocity in the main flow obtained by numerical simulation.*

The gas-dynamic phenomena resulting in the repeated mass addition: velocity distribution in the main flow similar to the velocity distribution in the sequential scheme of mass addition (Fig. 3), reverse flow of the cyclic and external gas, counter-rotational vortices in the semispherical cavity and the vortex evolving formations in the main flow capable of pulse generation have been detected in the simulated pulsating working process in the resonator.

Analysis of the initial calculation results shows that in case of using the considered approaches in turbulence modeling the calculated specific thrust values $R_{specific}$ are equal to the thrust of ideal nozzle with complete expansion. During the experimental studies of the resonator in the formulation equivalent to the calculations, the specific thrust growth above the ideal one that can amount to 12 % with low π_c was obtained (Fig. 4).

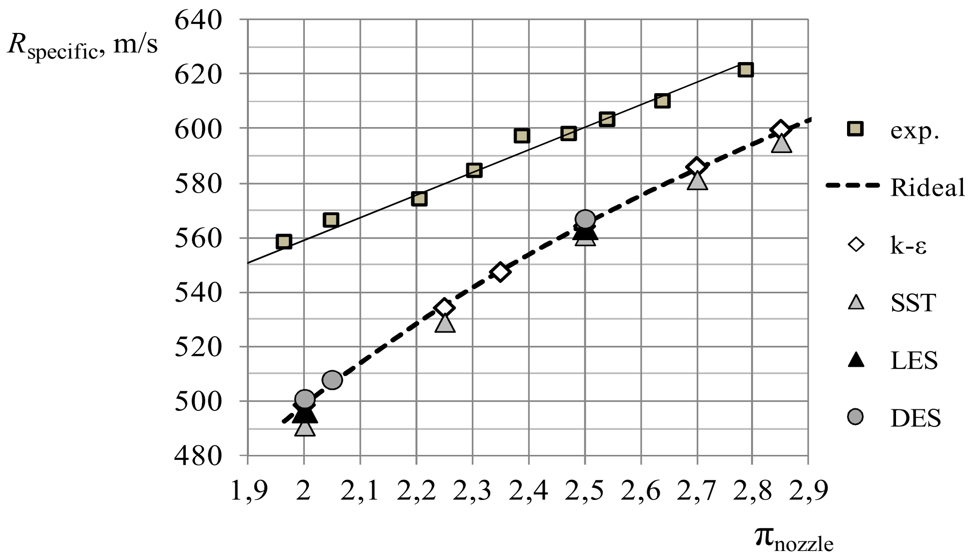

Figure 4. *Initial investigation results.*

It should be noted that with the application of various approaches in turbulence modeling (k–ε, SST, DES and LES) a more close values of the resonator specific thrust have been obtained, mainly dependent on the active gas flow rate at the annular nozzle inlet. With the use of various turbulence models, the resonator thrust remains unchanged.

Anisotropic models resolve the non-stationary flow in the resonator more precisely in contrast to the vortex viscosity models, in case of flow pulsation due to the wave and vortex interaction. With the use of the isotropic vortex viscosity models, the flow pulsation was practically absent – the quasi-stationary supersonic jet flow was generated.

The difference between the experimental and calculated data defines the problem in modeling the high-nonstationary pulsating working processes.

The initial flow analysis performed in the gas-dynamic resonator showed that the propulsion performance of the resonator at various input values of the thermodynamic parameters and taking into account the hydraulic and shock-and-wave losses (up to 10 % in thrust) are close to the similar performance of an ideal nozzle with complete, i.e. one can make a conclusion on the thrust increase by ~ 10% due to the mass addition. However, it should be mentioned once again that growth of the resonator thrust performance above the thrust of an ideal nozzle with complete expansion up to 100% [6, 7] (at optimum mechanical-geometrical relationships in the flow) has been also obtained during the experimental studies.

5. Verification of the Numerical Method

Variation of the calculated data from the experimental ones enables to assume that the real physics (mass addition processes) resulting in the thrust increase during the numerical modeling of the nonstationary pulsating flow in the resonator are not completely described. That is why the used numerical techniques have been verified using the known analytically solved high-nonstationary gas dynamics tasks where there appear the mass addition effects and the effects of the extreme initial condition of the thermodynamic system (high pressure gradients).

The following test tasks have been selected:

- Comparison of pulse at the detonation products scatter in the air and vacuum in the infinite tube [1];
- Determination of the extreme air temperature value at the ultra-high diatomic gas compression [11].

Testing of applicable numerical method on the analytically solved tasks of high-nonstationary gas dynamics [10] showed that:

1. the pulse increase due to the mass addition during the detonation products scatter in the air over the computed impulse scatter in vacuum comprised 1.9, that makes 63 %, versus the analytical solution result;
2. when modeling the ultra-high air compression, the maximum temperature value attained behind the shock-wave front when it is reflected from the wall amounts to 2850 K, that makes 37% versus the analytical solution result.

This considerable disagreement of the results of two computing methods revealed the problem of getting the certainty results of high-nonstationary processes numerical investigation.

6. Analysis of New Investigation Results

To solve this problem of the possible improvement of the results, an in-depth analysis of the gas flow in the annular nozzle and at the resonator exit obtained by the initial calculation has been done.

The analysis demonstrated that:

- calculation time has a decisive impact on the result. With the calculation time increase the thrust R growth is observed (Fig. 5) followed by deceleration and relative stabilization (gas flow at the annular nozzle inlet remains unchanged and its average value is equal to the experimental one). Such thrust growth may be caused by the mass addition process intensification and its accumulation with the course of time. Absence of the result complete stabilization revealed the necessity of the calculation time increase.
- gas flow through the annular nozzle does not take place at the angle of 90° to the cavity axis, as it is provided by the flow path geometry, but with some deviation towards the exit (~ by 3°) that defines the appearance of the dynamic thrust component.

Based on the results of the analysis performed, in the new computation investigation the calculation time has been enlarged, the additional dynamic thrust component has been taken into account. The only difference of the initial calculation and new calculation consists in increase of time for simulation. To perform calculations, the DES model (requiring much lesser computing resources versus the LES approach) has been selected among the vortex-resolving turbulence models. Time spent for the new calculation comprised ~ 5 months (time spent for the initial calculation was 1 month).

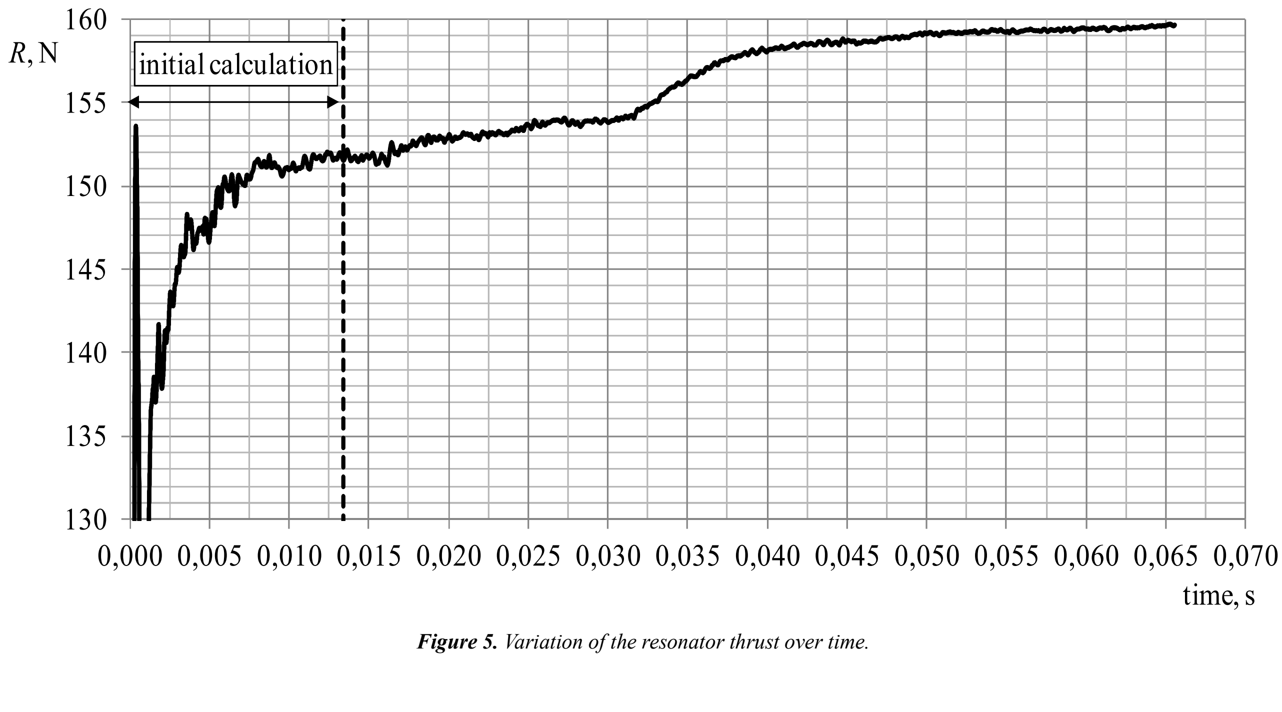

Figure 5. *Variation of the resonator thrust over time.*

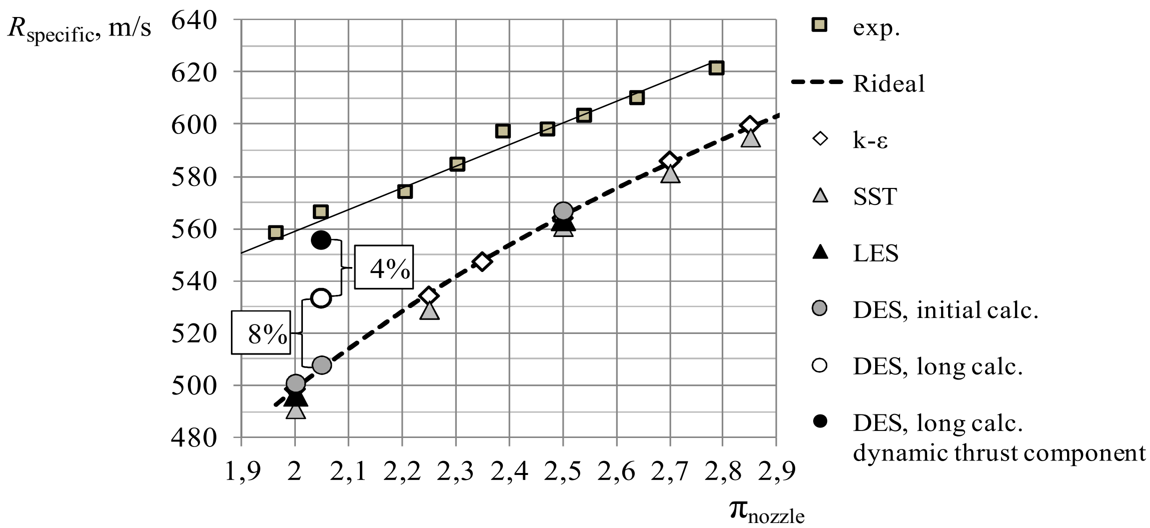

Figure 6. *New investigation results.*

Analysis of the new results showed that:

- the calculation time increase created the 8 % resonator specific thrust growth (Fig. 6), compared to the initial calculation, due to a more intense addition of mass, featuring an unstable accumulative character. It should be noted that the experimental thrust has been obtained in a time equal to ~ 1 minute. That is why much more computing time and, respectively, more powerful resources are required to perform calculations that will meet the experimental conditions;
- taking into account the dynamic thrust component has increased the specific thrust of the resonator by 4% (Fig. 6); to achieve the maximum thrust efficiency of the resonator it is worthwhile to consider optimization on the annular nozzle exit geometrical angle, for example, with the angles of 5°, 10°, 25° relative the vertical plane (to increase the dynamic thrust component); increase of this angle makes it possible to decrease the transverse dimensions of the resonator, being a critical parameter.
- increase of the calculation time and taking into account the dynamic thrust component in the annular nozzle produced the conformity of the calculation results with the experimental data. Total specific thrust augmentation comprised 12 %, non-convergence with the experiment comprised ~ 2 %.

7. Conclusions

1. Analysis of the calculations results showed that in an oscillatory working flow unstable in time mass addition occurs that increases thrust pulse of the resonator. It was found that the exact description of gas mass addition processes requires a sufficient long calculation time with small physical timescale and application of a vortex-resolving turbulent model (models of large or separated vortices).
2. During the calculation investigation of the resonator thrust-augmenting device (as well as the other pulsejet engine designs) it is necessary to perform the flow analysis in its components (for example, the dynamic thrust component appearance in the annular nozzle) based on the first preliminary calculation results. To use more powerful (with the short-term memory of ~ 3 TB) computation capacities (for example, for a long-term calculation in the full-scale scenario). When these conditions are met, adequate repeatability of calculation and experiment results can be provided.
3. To achieve the maximum thrust efficiency of the considered resonator, there is a good reason to consider its optimization to the annular nozzle exit geometrical angle, for example, with the angles of 5°, 10°, 25° relative the vertical plane (to increase the dynamic thrust component). Increase of this angle allows decreasing the transverse dimension of the resonator being a critical parameter.

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