A Study of Starting a Jet-Engine Ring Nozzle

Vladimir A. Levin[1], Nataliya E. Afonina[1], Valeriy G. Gromov[1], Ivan S. Manuylovich[1], Gennadiy D. Smekhov[1], Aleksander N. Khmelevsky[1], Vladimir V. Markov[2]
[1]Institute of mechanics of the Moscow State University, 119192, Moscow, Russia
[2]V.A. Steklov Mathematical Institute, RAS, 119991, Moscow, Russia

1 Introduction

As compared to Laval nozzles, ring nozzles with a deflector having the shape of a spherical segment [1] are shorter, possess the property of self-adjustment, and are regarded as promising nozzles for the realization of a pulsed fuel combustion regime [2]. When operating in a steady-state regime, they belong to a class of nozzles with a central body, which are used in the design of advanced samples of aircraft and rocket engineering [3]. In these nozzles, the recirculation flow region plays the role of a gaseous central body; this zone is formed in the process of starting a nozzle [4]. Pulsed wind tunnels are a convenient tool for the experimental study of the ring nozzles considered. In the experiments in a pulsed wind tunnel, the flow regimes in such nozzles and the time of transition to a quasi-stationary flow stage are depend significantly on the start-up conditions, including the shape and dimensions of the supply channels. In the present study, on the basis of Euler equations, a numerical simulation of the flow in a jet engine model with a ring nozzle is performed for different configurations of supply channels. The working media are air at room temperature and high-temperature products of combustion of an acetylene-air mixture. The calculated and experimental data for the pressure at different points in the flow channel and the output nozzle thrust are compared.

2 Mathematical model and problem formulation

For the description of an axisymmetric gas flow, we use the 2D Euler system of differential equations [5]. The numerical investigation of a gas mixture flow is carried out using an original software package, which implements the modified Godunov method [6] on multi-block computational grids. The developed code allows us to define and modify the boundaries of the computational domain, to conduct a partition of the domain onto curved tetragonal calculation blocks, to specify the composition of multi-component mixtures and the initial and boundary conditions. The calculations can be carried out on a PC, as well as on a supercomputer due to code parallelization based on MPI. In this work MSU "Lomonosov" supercomputer was exploited. All calculations here for different geometries of the models were performed on 490-500 cores of the supercomputer processor.
The shape and size of the calculation domain completely corresponds to a pulsed wind tunnel, in which the investigated models were tested. A detailed description of the set-up was given in [4]. The geometry of the through-flow channels with the pressure gages (bold dots) is shown in Figure 1.
The purpose of the research is experiment-calculated investigation of regimes features of the starting of the ring nozzle, blowed in pulsed wind tunnel, in dependence on the form variation of the entrance

Correspondence to: khmelevsky@imec.msu.ru

supply channels. The problem of research is also the receiving non-stationary fields of gas dynamic flow parameters in through-flow channel of the set-up and time dependences of signals from pressure and thrust force sensors, shown in Figure 1.

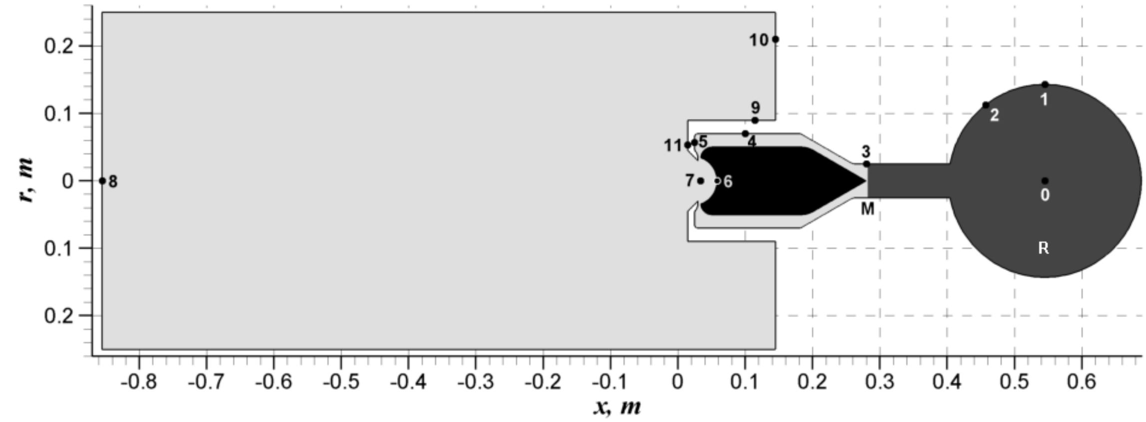

Figure 1. Set-up scheme. Numbers 0-11 indicate pressure gages, M-diaphragm, R-reactor.

It is assumed that a spherical reactor and an attached cylindrical pipe is filled with a quiescent gas, which is either air at room temperature or equilibrium high-temperature products of combustion of an acetylene-air stoichiometric mixture with the given gas composition, pressure, density, and temperature [4]. The rest part of the set-up, consisting of a ring adapter, a ring nozzle, a resonator, and a vessel for exhaust, is filled with quiescent air at room temperature and at given low pressure of 0.001 atm. At the initial instant of time, the separating diaphragm is instantly removed. As a result, a gas motion develops. At the points (1, 2, 3, 4, 5, and 6 in Figure 1) on the inner surface of the through-flow duct, piezoelectric sensors for measuring the pressure are installed. In addition, the force acting on a spherical thrust wall is measured using a strain sensor. In the numerical simulation of the flows, in the points denoted in Figure 1 as 0-11 the time dependences of all gas dynamic parameters and the parameters distributions inside the calculation domain were recorded. The experimental set-up may have the ring nozzle with different widths of the critical section and supply channels of different shapes. In the calculations, the shape and size of the computational domain were completely similar to the set-up layout. In Figure 2 the configurations of the computational domain part with calculated streamlines are presented.

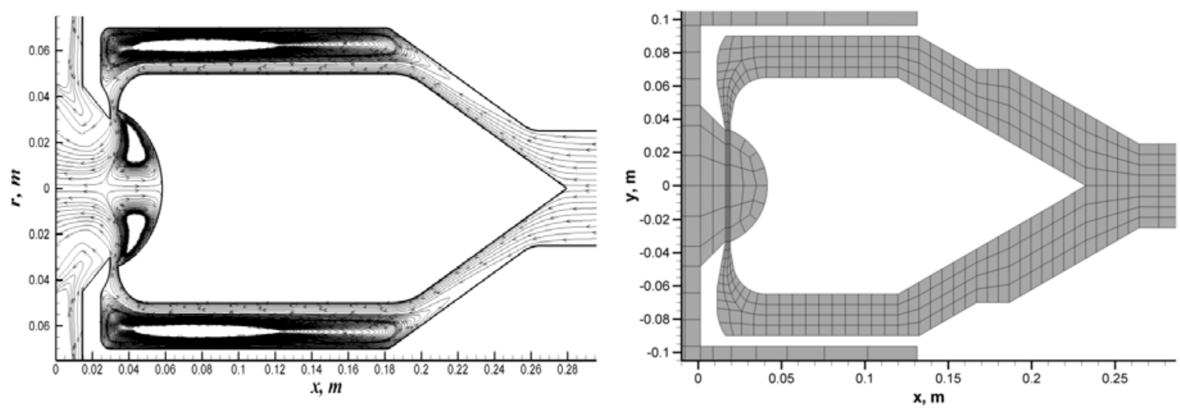

Figure 2. Sample configurations of channels. (left - the ***T*** configuration and streamlines at P_* = 14.73 atm, right-the ***B*** configuration).

The left figure corresponds to the ***T***-configuration with the critical section of the ring nozzle being equal h* = 4.4 mm, the conical ring adapter without a step and the external part of the inlet section of the channel throat smoothed by a circle. The right figure shows the ***B***-configuration with h* =3 mm, conical adapter with a step, and a rectilinear part of the external region of the throat.

3 The flows of air and combustion products

The calculations for air at room temperature and for combustion products were made for four values of the initial pressure in the reactor (stagnation pressure) P_* = 4.821, 9.769, 14.73, and 19.91 atm. It is established that in all cases after the rupture of the diaphragm a shock wave is formed, which propagates along the ring channel. The shock wave and the gaseous flow behind it interact with the walls, forming a sequence of oblique shock waves in the supply ring channel. The flow is strongly non-stationary up to a certain instant of time. Moreover, it turned out that the sonic line near the ring nozzle is movable, and at some moments it moves away from the nozzle, as a result of it the disturbances from the resonator can enter the ring nozzle and vice versa. Figure 3 (here and in what follows, in all the figures we reproduce the data for the ***T***-configuration and air) shows the time dependences of the pressure at four control points for P_* = 14.7 atm and the thrust, that illustrate strong fluctuations of the flow parameters in the nozzle start-up stage.

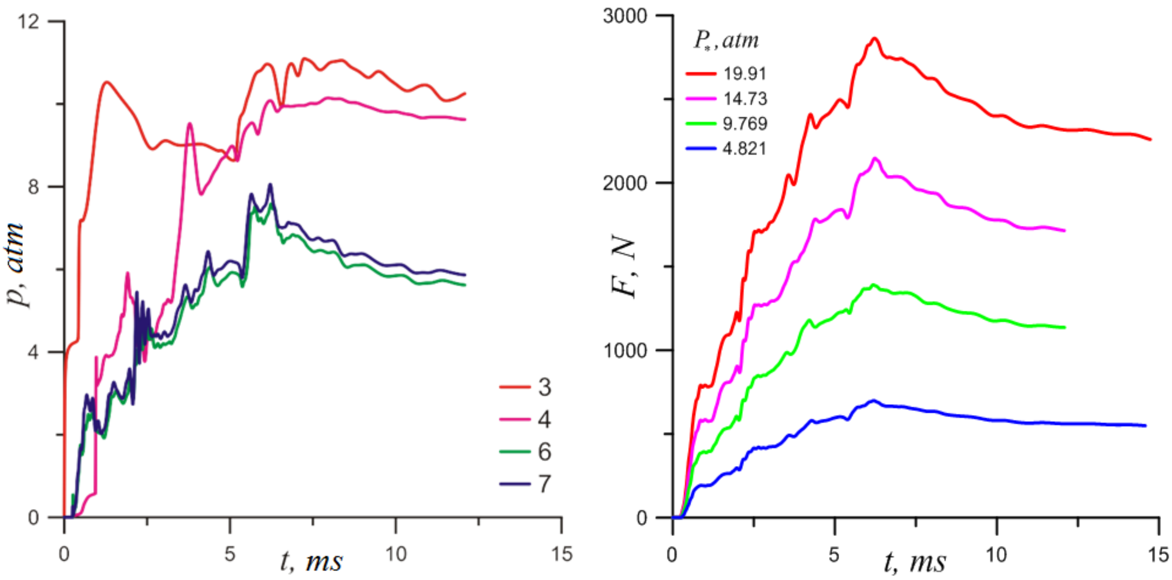

Figure 3. Pressure at points 3, 4, 6, 7 (left) and thrust (right) vs. time.

Meaningful for the stage of the nozzle starting are the results on the time dependences of the specific impulse ***I*** and the ratio p/ρ^{γ}, presented in Figure 4. It is clear that after about 6 ms, which corresponds approximately to the maxima of the pressure on the deflector wall and of the thrust (see Figure 3.), these quantities do not differ from the constants. This indicates that the nozzle starting process is finished and an adiabatic process of quasi-stationary outflow begins.

The time dependences of the calculated forces acting on the deflector thrust wall and pressure at six points are shown in Figure 5. Here F is the force exerted by the stream, F_e is the force due to the back pressure, and difference between them is the thrust F_{corr}. It is evident that the back pressure starts to affect the thrust after about 6-10 ms, and the values of F and F_{corr} at the points of their maxima are practically identical.

In the calculations of air flows at different P_*, we observed the qualitatively and quantitatively (accurate to a constant factor) coinciding time dependences of the pressure at the same points. This indicates that in considered cases the dimensionless parameter related to the stagnation pressure has almost no effect on the process, and thus the pressure in the flow is proportional to the pressure in the reactor, all other conditions being equal. In addition, the force on the thrust wall and the mass flow rate through the ring nozzle are changed in proportion. The specific impulse, being the ratio of the thrust to the mass flow rate, depends only slightly on the pressure in the reservoir that is illustrated in Figure 4. According to the calculations, the moment of the beginning of a quasi-stationary regime and the time till full stop of flow are weakly dependent of the stagnation pressure. The total time of the expiration is 250 ms and the maxima of the thrust and the pressure at the center of the thrust wall are achieved approximately in 6-7 ms.

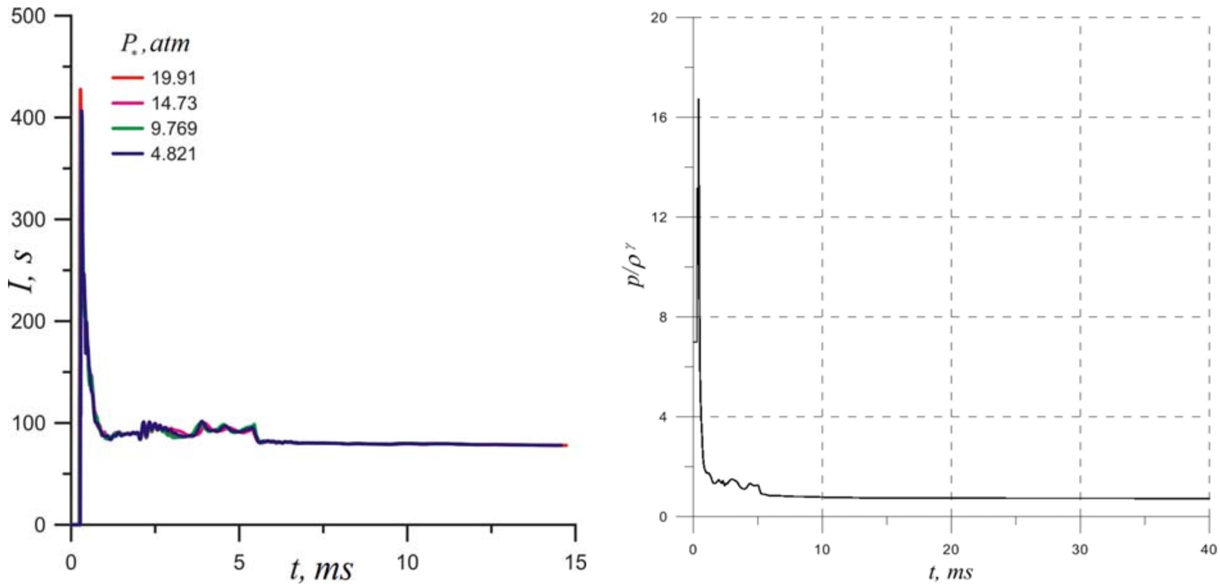

Figure 4. Time dependences of specific impulse ***I*** (left) and ratio $\mathbf{p}/\boldsymbol{\rho}^{\gamma}$ (right) at the center of the thrust wall for P_{*}=4.821 atm.

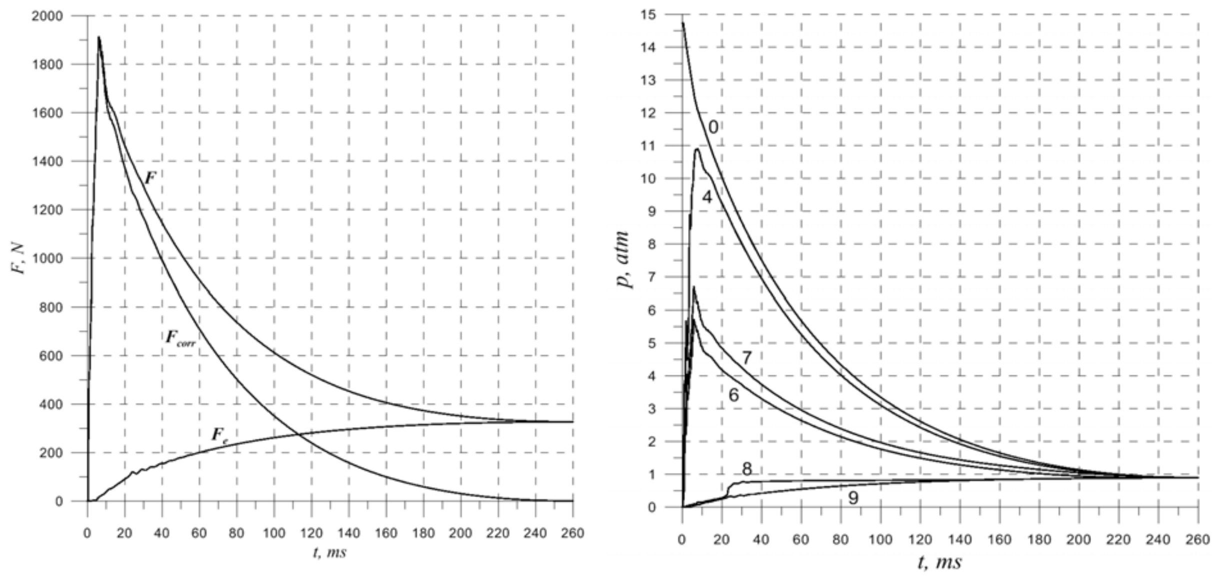

Figure 5. The forces acting on the thrust wall (left) and pressure recorded by sensors 0, 4, 6, 7, 8, 9 at P_{*}=14.73 atm (right).

The calculated maximum values of thrust F_{max} and pressure p_{A}, recorded by gage 6 at the center of the spherical segment (open circles and squares in Figure 6.) were compared with the experimental data (filled circles and squares). Specified quantities were plotted as points in the planes **(p_m, F_{max})** and **(p_m, p_A)**, where p_m is the pressure at gage 4. Due to the fact that in the calculated values F_{max} and p_A near the maximum with respect to time (about 6 ms in Figure 3) there is a pronounced jump, the calculated data were plotted with an error determined by the value the mentioned jump. The presented results show satisfactory quantitative agreement between the calculations and the real physical processes in the experimental set-up.

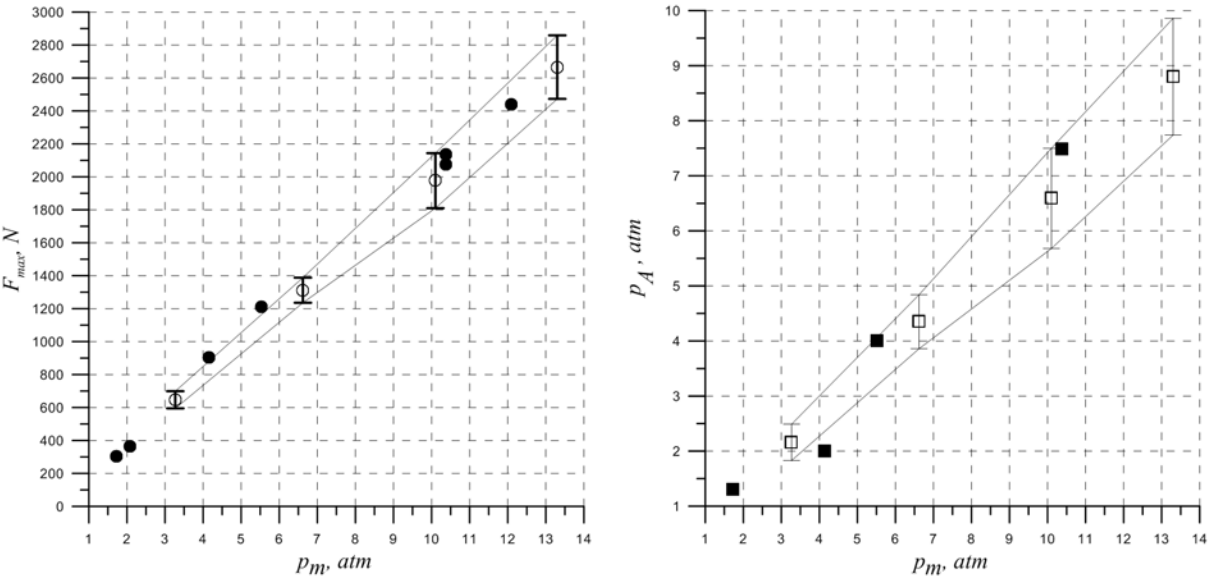

Figure 6. The calculated and measured values of the thrust (left) and pressure at gage 6 (right).

The calculations showed the presence of the circulation zones in the supply channel (Figure 2, left), which in fact transform its shape. It is established, that these zones can be removed by a correction of the internal-channel surface, in particular, by reducing the outer radius of the ring supply channel (Figure 7, left).

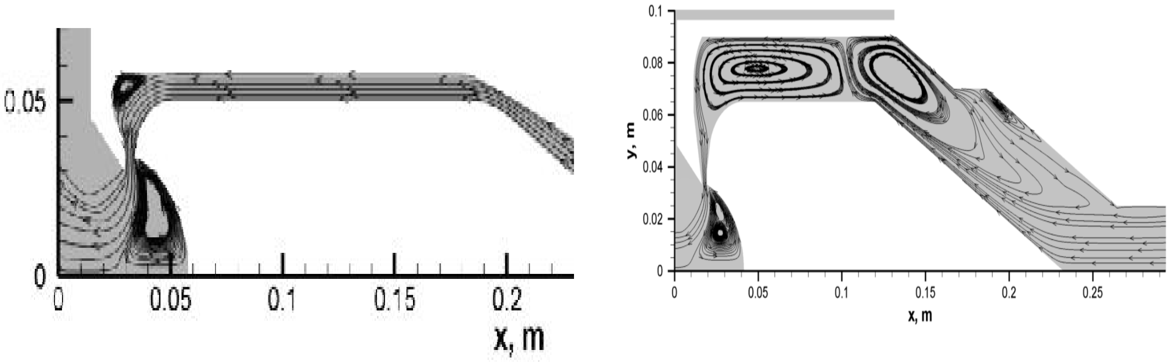

Figure 7. Streamlines in the ***T*** (left) and the ***B*** (right) configurations of the channels..

The flow calculations for the ***B***-configuration showed that the flow is significantly different from that in the ***T***-configuration. The main differences are observed in the vicinity of the ring nozzle inlet and near the step of conical adapter. In the quasi-stationary stage of the flow, two vortices are formed

behind the step (Figure 7, right). The main vortex near the entrance to the ring nozzle is swirled in the opposite direction, a compared to the ***T***-configuration. Because of this the streamlines entering the nozzle now pass near the ring supply channel wall with a larger radius.
The calculations of the flows of high-temperature combustion products revealed a flow structure similar to that for cold-air flow. In the quasi-stationary outflow regime of the combustion products, the streamlines are similar to those for the air flow, i.e. they are completely determined by the shape of the supply channel.

4 Conclusion

A numerical simulation of starting and the blowing through a jet-engine ring nozzle in a pulsed wind tunnel was performed. For different shapes of the nozzle supply channels the phase features of the start-up and steady-state flow were investigated. It is established that in some time a quasi-stationary subsonic flow toward the throat of the ring nozzle and supersonic flow behind it are formed. Unsteady fields of the flow parameters and time dependences of the thrust characteristics with account for a back pressure are obtained. A comparison of the calculated and experimental data showed a good agreement in the magnitude of the thrust and the pressure values at several points in the gas dynamic duct of the set-up. An analysis of the outflow dynamics revealed a non-stationary behavior of the sonic line near the ring nozzle during the start-up and the formation of vortex stagnation zones in the deflector cavity and in the supply channel in the neighborhood of the ring nozzle. It was demonstrated that it is possible to realize in the supply channel a flow without stagnation vortex zones by changing the shape of the channel. It was found that the quasi-stationary phase of outflow begins at the instant when the thrust and the pressure at the thrust wall center reach their maxima. Obtained that the variation of thermodynamic parameters at the quasi-stationary phase take place under the adiabatic law.
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