Starting flow in an impulse wind tunnel with a throttled prechamber

Yu P Gounko and I N Kavun
Khristianovich Institute of Theoretical and Applied Mechanics SB RAS, 4/1 Institutskaya st., Novosibirsk 630090, Russia
gounko@itam.nsc.ru

Abstract. The unsteady axisymmetric flow forming in the process of starting an impulse wind tunnel equipped with a throttled prechamber was numerically simulated. A regime with the operating flow Mach number $M = 8$ was under consideration. Numerical simulation on the basis of Reynolds-averaged Navier–Stokes code and the $k-\omega$ SST turbulence model was performed. The starting process was simulated as a sudden rupture of a diaphragm separating the prechamber volume with high pressure and temperature from low pressure part of the facility including a nozzle, an operating section and an exhaust vacuum tank. The diaphragm rupture initiates a gasdynamic process associated with the Riemann problem when the primary shock wave arises which moves through the nozzle to the operating section. Computed data show another “inverse” shock wave emerging in the nozzle. A starting “shock-wave package” forms between these shock waves, it includes a flow portion of high temperature and pressure. The specificity is discussed of identified the characteristics and flow patterns forming during the process of moving the shock-wave package.

1. Introduction
As noted in [1, 2], hot-shot wind tunnels have been developed and used from the years 1960th through 1970th for experimental investigations of gasdynamic problems of hypersonic flying vehicles propelled by air-breathing engines and designed to fly with Mach numbers $M > 4-5$. These are impulse high-enthalpy facilities of short duration which operating principle is a virtually “instantaneous” input of energy by an electric discharge to the working gas in a prechamber separated by a diaphragm from the other parts of the facility a nozzle, subsequent an operating section and an exhaust vacuum tank. Prior to the wind-tunnel start up, the working gas is feed into the prechamber volume under high pressure and the vacuum tank is pumped out to a very low pressure. As soon as the energy is input, the diaphragm ruptures and the working gas begins to outflow through the nozzle to the operating section where a tested model is installed. An operating pseudo-steady flow occurs in the wind tunnel after a certain starting process.

Simple hot-shot wind tunnels were used in earlier years. They were characterized by a virtually unchanged operating flow Mach number but gradually decreasing pressure and temperature. An aerodynamic facility IT-301 of such a kind was introduce into operation at ITAM in 1970 [1-3] and demounted at the present time. Improved hot-shot wind tunnels of different arrangement were developed over time. In particular, a hot-shot wind tunnel IT-302M was developed at ITAM in 1980 [2,3], and it is operated nowadays. It has two operating regimes, a one provides stabilizing the pressure in the prechamber by a moving two-stage piston, and another is a regime without pressure...
stabilization when the operating gas flows out from the capacity of a fixed volume. And besides, its prechamber is throttled for increasing the operational regime duration.

The initial phase of forming the flow at starting impulse wind tunnels is largely unexplored. At the same time, the starting process of impulse wind tunnels proper affects the starting process of inlets or ducted bodies tested in them as studied at a numerical simulation of these processes as applied to an impulse wind tunnel of a type IT-301 [4]. The unsteady process of the flow evolution in the IT-302M was numerically simulated in [5], where a porous insert was used to model a prechamber throttling. Flow patterns of this process are presented in [5] but their wave structure was not analyzed. The same unsteady process of the flow evolution in an impulse wind tunnel which had a simplified configuration equivalent to IT-302M was numerically simulated in the present work. Throttling of the prechamber was provided by a grate with round slots equivalent to holes of the actual throttling insert of IT-302M. The regime of flowing the operating gas from the capacity of a fixed volume was considered. The specificity of identified characteristics and patterns of the starting flow is discussed.

2. **Configuration of the considered impulse wind tunnel**

A schematized configuration of the impulse wind tunnel accepted for the numerical simulation is presented in Figure 1.

![Figure 1](image)

**Figure 1.** Scheme of an impulse wind tunnel accepted for numerical computations (sizes in mm).

The facility incorporates a prechamber of 0.22 m diameter, 0.26 m length and 0.00988 m$^3$ volume which in an initial time moment is filled with the heated and high pressured working gas (air). The facility includes following components: a short tube of 0.05 m diameter and 0.054 m length at entrance of which a rupturing diaphragm is assumed to be mounted; an insert of 0.134 m length with a throttling grate; a second settling chamber of 0.08 m maximal diameter and 0.16 m length. An actual throttling grate of IT-302M consists of 7 holes of 0.006 m diameter, one is central and other 6 are positioned along a circle. For the considered simplified configuration of the impulse wind tunnel, 6 holes were replaced by a round slot of the same total area. The nozzle consists of a converging section of 0.067 m length with a throat of 0.02 m diameter and also a diverging contoured section of 1.45 m length with an exit cross section of 0.3 m diameter. Geometrical parameters of the nozzle correspond to a design nominal operating flow Mach number $M = 8$ at the nozzle exit. The nozzle exit cross section was connected with an operating section of the facility of 0.5 m diameter.

3. **Conditions of numerical computations**

Numerical computations of the unsteady axisymmetric turbulent flow forming in the considered impulse wind tunnel were carried out on the basis a Reynolds-averaged Navier–Stokes equations and the $k$-$\omega$ SST turbulence model. The cylindrical coordinate system was accepted in computations. The origin of its reference $Oxy$-plane was positioned in the critical cross section of the nozzle throat and the $x$-axis was directed downstream along the wind tunnel axis. The computational grid was designed with uniform spacing in the radial directions. The number of radial cells in the pre-nozzle and nozzle
channels was equal to 100, the $4.2 \cdot 10^3$ cells were distributed along the axis of this domain. The time step was 0.1 $\mu$s with 200 iterations per step.

As for the impulse wind tunnel accepted for computations, initial parameters of the working gas (air) in the prechamber corresponding to a moment just before the diaphragm rupture were preset as $P_{ch} = 3.5 \cdot 10^7$ Pa, $T_{ch} = 890$ K; the initial pressure and temperature of the air in the vacuum tank and in the wind tunnel duct were equal to $P_v = 215$ Pa, $T_v = 290$ K. The heat capacity, viscosity, and thermal conductivity of the air were set depending on the temperature. The boundary layer was not resolved; near-wall functions for its determining were used. The walls of the wind tunnel were assumed to be adiabatic.

4. Initial flow corresponding to the Riemann problem
The well-known one-dimensional gasdynamic description of the process arising at the sudden rupture of a thin diaphragm is based on the solution of the Riemann problem for the perfect gas. The rupture of the diaphragm generates a high-speed flow which spreads into the low-pressure part of the tube initiating a primary shock wave propagating in the same direction. The high-pressure gas expands through an expansion wave which propagates into the high-pressure part of the tube. The expanded gas is separated from the compressed gas by a contact discontinuity, which can be regarded as a fictitious membrane traveling into the low-pressure part of the tube at a constant speed. The flow Mach number and temperature vary in a jump on this discontinuity but the velocity and pressure are the same across this surface. The initial data for the Riemann problem were at the rapturing diaphragm position $x = -0.366$ m.

The numerical solution of the Riemann problem occurs in the tube connecting the prechamber and the throttling insert. Note as for the considered axisymmetric flow, the shock waves or other gasdynamic discontinuities occurring in it have the shape of the surfaces of revolution; and in a longitudinal Oxy-plane, the flow picture is analogous to that for a 2D flow.

**Figure 2.** Flow pattern (Mach number contours) and axial distributions of flow parameters at $\tau = 23$ $\mu$s.

**Figure 3.** Flow pattern and axial distributions of flow parameters in the throttling insert and settling chamber at $\tau = 150$ $\mu$s.
A flow pattern obtained at $\tau = 23$ $\mu$s is shown in Figure 2. The flowfield is pictured as the Mach number contours, distributions of Mach number, static pressure and temperature along the flow axis are also depicted. The primary shock wave has reached a position $x \approx -0.319$ m, the flow Mach number after this shock wave is $M_1 \approx 2$. An interval $\Delta x = -0.323\ldots-0.327$ m with constant pressure corresponds to a “smeared” contact discontinuity. An interval $x < -0.33$ m corresponds to an expansion wave.

5. Flow in the throttling insert and settling chamber
At $\tau > 23$ $\mu$s, the primary shock wave comes out from the intermediate connecting tube into the duct section with the throttling insert. This shock wave, and other gasdynamic discontinuities following it, undergo here multiple reflections and interactions, so the flow pattern here becomes more complex and it is not interpreted in detail.

A flow pattern in the duct section between the prechamber and the nozzle is shown in Figure 3 for $\tau = 150$ $\mu$s. There is a shock wave located at $x \approx -0.28$ m in the duct section before the throttling grate which is reflected from the throttling grate and moves back in the direction of the prechamber. The primary shock wave has reached a cross section $x \approx -0.0134$ m somewhat before the nozzle throat, and its front has a flat shape. Distributions of flow parameters in an interval $\Delta x = -0.045\ldots-0.012$ m are presented in Figure 3. A “smeared” contact discontinuity approximately corresponds to a segment $\Delta x = -0.032\ldots-0.145$ m where there is a plateau pressure. Along a segment $\Delta x = -0.035\ldots-0.32$ m, there is a downstream decrease in the flow Mach number as well as increases in the pressure and temperature. This indicates of a presence of the “smeared” inverse shock wave moving downstream more slowly than the main flow. A peak level of the pressure and temperature takes place in the flow portion between the inverse and primary shock waves. That is why this local flow pattern can be named a “shock-wave package” or a “shock-wave cork” [4]. In the flow just upstream of the shock-wave package, there are considerable inhomogeneities near the duct wall. They evidently affect the evolution of the flow in the nozzle in the process of moving the shock-wave package through it.

6. Flow in the nozzle
A flow pattern in the nozzle and distributions of the flow parameters are shown in Figure 4 for $\tau = 400$ $\mu$s. At this time, the shock-wave package has moved to an interval $\Delta x = -0.4\ldots0.53$ m. The primary shock wave has a convex shape. The flow between the primary and inverse shock waves along the axis is moderately supersonic with $M = 1.76\ldots1.83$, the flow just after the shock-wave package is of high Mach numbers up to $M = 7.6$.

A distinctive feature of the nozzle flow associated with moving the shock-wave package is the development of the unsteady boundary layer. After the primary shock wave, it begins to grow quickly. Its thickness is maximal near at the contact discontinuity position and then it decreases tending to reach a value corresponding to a steady supersonic flow forming in the nozzle [6]. This kind of swelling of the boundary layer in the considered flow pattern leads to a bifurcation of the inverse shock wave. As a result, an oblique shock wave arises which interacts with the inverse shock wave so the reflected shock wave emerges which falls on the boundary layer and the $\lambda$-shaped configuration of shock wave emerges.

A flow pattern in the nozzle at $\tau = 970$ $\mu$s is shown in Figure 5. At this time, the primary shock wave has reached a nozzle exit cross section ($x = 1.45$ m), and its front is almost flat. The shock-wave package extends along the nozzle axis in an interval $\Delta x = 1.27\ldots1.45$ m. The flow between the primary and inverse shock waves is moderately supersonic with $M = 1.73\ldots1.79$. The boundary layer swelling gets an interval $\Delta x = 0.8\ldots1.32$ m. In the given case, this swelling leads to emergence of focusing pseudo-conical compression waves. A resultant shock wave falls onto the nozzle axis and reflects irregularly with forming a triple-shock configuration including the Mach disc and the reflected shock wave.
In the given case, a size of the Mach disc is very small so “an illusory regular reflection” of shock waves from the axis is seen at $x \approx 1.07$ m.

The wave package comes out from the nozzle within $\sim 1130$ $\mu$s. The flow-field in a region at the nozzle exit for this time is shown in Figure 5. Before the exit cross section, the flow is highly non-uniform since there it contains intensive shock waves. These disturbances leave the nozzle exit at $\tau \approx 2250$ $\mu$s, then the velocity in the flow core here is enlarged up to $M = 8.5$. The process of steadying the nozzle flow begins when the swelling of the boundary layer shifts out of the nozzle exit (at $\tau \approx 2230$ $\mu$s).

7. Steadying the flow in the nozzle

Steadying the flow in the wind tunnel and in its nozzle was firstly estimated by monitoring the static pressures on the back face of the prechamber, on the side wall of the settling chamber, and at the point on the axis of the nozzle exit cross section (Figure 6). These parameters were monitored within 3.6 ms. The pressure in the prechamber decreases by $\sim 11\%$ within 3 ms. At the same time, the pressure in the settling chamber increases and practically stabilizes at $\tau > 2.8$ ms. The pressure in the nozzle exit cross section stabilizes on average at $\tau > 2.5$ ms, although there are its oscillations of an amplitude about 20%.

The flow parameters mass-averaged over a flow core of 0.2 m diameter were determined in various cross sections. During time period $\tau = 2.5 - 3.6$ ms, the Mach number increases by $\Delta M = 2.5\%$ to $M_{av} = 7.51$, the total pressure decreases by $\Delta p_0 = 13\%$, the total temperature decreases by $\Delta t_0 = 0.2\%$. Cross-sectional distributions of Mach number, static and total pressure and temperature are presented in Figure 7 for final monitored time $\tau \approx 3606$ $\mu$s.

8. Conclusion

The results of numerical simulations have shown the following.

The starting process of an impulse wind tunnel launches when, as it is predicted by the one-dimensional theory of the Riemann problem, the primary shock wave and contact discontinuity emerge at the diaphragm rupture. As for the considered impulse wind tunnel, these waves begin to move through the duct of variable cross-section, including the throttling insert and the settling chamber, to the nozzle. Multiple reflections and reciprocal interactions of these wave structures occur in this duct, so the flow structure is very complex and can hardly be interpreted.
Despite this, further the flow in the nozzle forms where the movement of the said gas-dynamic waves is complied with that known one treated in the one-dimensional approach. The inverse shock wave subsequent to the contact discontinuity emerges, it moves downstream with a velocity lower than the flow velocity. A flow portion with very high temperature and pressure occurs between the primary and inverse shock waves which can be named as a “shock-wave package”. Namely its moving through the nozzle determines the starting process of the impulse wind tunnel. Significantly, moving the shock-wave package is exposed to effects of development of the unsteady boundary layer on the nozzle wall. This is manifested in forming the current flow patterns.

In a time, when the shock-wave package comes out of the nozzle, the flow at the nozzle exit has an enlarged velocity, and then the process of steadying the flow in the wind tunnel takes place. There is no complete steadying the flow in an impulse wind tunnel in the covered time interval of the computations, only a pseudo-steadied condition was reached.

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