AERODYNAMIC DESIGN OF SINGLE-EXPANSION-RAMP NOZZLE FOR AIRCRAFT WITH SUPERSONIC CRUISE SPEED OF FLIGHT

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Abstract

The main goal of studies consisted in choice of nozzle configuration for advanced civil supersonic transport aircraft (SST) with low levels of the community noise and sonic boom. Advanced concept of SST assumes shielding of the power plant with airframe elements for solving ecological problems. Preliminary analysis showed that for such aerodynamic configuration two-dimensional single-expansion-ramp nozzle (SERN) could provide better thrust characteristics of engines than mixer-ejector and conventional convergent-divergent nozzles. Aerodynamic design, i.e. choice of the scheme and main geometry parameters of nozzle, was performed with both computational and experimental methods of studies. In result it is shown that SERN provides acceptable, just high level of engine thrust characteristics at the maximum continuous supersonic cruise flight regimes.

1 Introduction

Possibility of development of the new generation of the civil supersonic transport aircraft (SST) is closely connected with solving problems of impact of these vehicles on the environment. First of all ecological problems are connected with reduction of the community noise at take-off and sonic boom at supersonic cruise flight over populated territories. Up-to-date community noise requirements of ICAO are severe enough just for aircraft with supersonic cruise speed of flight, because its power plants should include turbofans with low bypass ratio (BPR≤1) for effective solving of transportation problem. Distinctive feature of such engines consists in high velocity of exhaust jet (V_j~500÷600 m/s or higher) that results in high level of jet noise at take-off regimes. Different estimations, summarized in reference [1] for the 1st generation of civil supersonic transport aircraft Tupolev-144 and Concorde, show that it is necessary to reduce jet noise approximately by 18÷20 EPNdB in order to meet Chapter 3 of ICAO regulations. For engines with higher bypass ratio (about 0.5÷1) required jet noise reduction level may be about 12÷14 EPNdB.

As a rule, mixer-ejector nozzle is considered as a typical variant of noise suppressor system for low bypass ratio turbofans. Photograph of a typical mixer-ejector nozzle model is shown in Fig. 1.

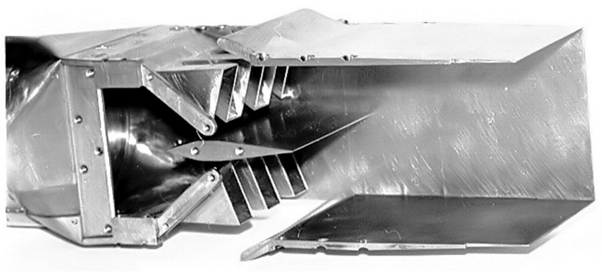


Fig. 1. Mixer-ejector nozzle model

At take-off regime mixer-ejector nozzle is a combination of the corrugated nozzle with the ejector. Corrugated nozzle increases area of the external surface of exhaust jet and thus intensifies its mixing with an ambient air. Primary mixing region is shielded with the ejector. For better absorbing of acoustic waves generated just in the primary mixing region ejector walls may be acoustically treated. In order to provide acceptable level of thrust losses at subsonic and supersonic flight regimes without noise suppression, mixer-ejector nozzle should be transformed into conventional convergent-divergent nozzle.

Investigations of axisymmetric and 2D mixer-ejector nozzles are being conducted in TsAGI and CIAM since 1988 [2]. Significant part of studies was carried out in cooperation with foreign partners, such as SNECMA [3] and International Science and Technology Center [4]. Experience of investigations of the aerodynamic and acoustic characteristics of mixer-ejector nozzle models in TsAGI and CIAM shows that such nozzles provide noise reduction at take-off by 10÷12 EPNdB with thrust losses level about 6÷8% of nozzle ideal isentropic thrust (see reference [1]). At supersonic cruise with Mach numbers M=1.6÷2.0 effective thrust losses (i.e. internal thrust losses plus nozzle external drag) in mixer-ejector type nozzles may be approximately equal to 3÷5% of nozzle ideal isentropic thrust. According to the authors opinion based upon analysis of results [1]-[5], the main features of mixer-ejector nozzles, side by side with high level of thrust losses, are complexity of nozzle transformation scheme from take-off to cruise configuration, long length and, consequently, heavy weight of structure.

At present, taking into account the reasons mentioned above and the trend of the ecology requirements toughening, serious attention is paid to the alternative approach to the community noise reduction, which consists in decrease of jet velocity by means of application of variable cycle turbofans with bypass ratio BPR~2÷3 (exhaust jet velocity $V_j \leq 400$ m/s) in combination with shielding of engines with airframe elements. Aerodynamic configurations of advanced SST and Supersonic Business Jets in which engines are mounted on the top surface of the airframe are considered within the frames of such approach in the USA, Europe, Japan and Russia.

Scheme of low-noise and low-boom SST proposed and studied in TsAGI is shown in Fig. 2. Engines are installed side-by-side on the top surface of the fuselage and are supplied with two-dimensional (2D) nozzles. Shielding of exhaust jets is realized by means of the wing and tail elements, which are washed with jet and form a part of the nozzle contour.

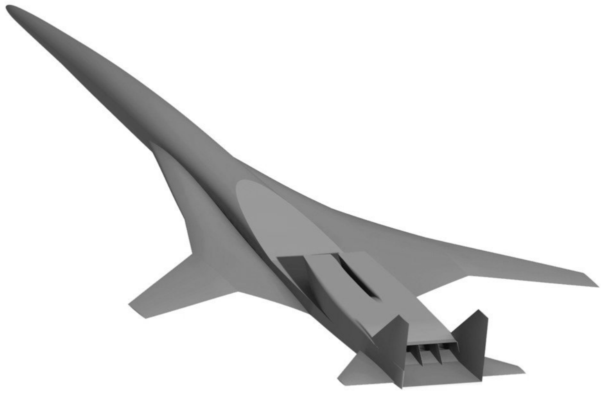


Fig. 2. Configuration with top-mounted engines

From the point of view of aerodynamics problem of exhaust system development for variable cycle engines with bypass ratio BPR~2÷3 may be some easier than for low-bypass-ratio turbofans. According to preliminary estimations, required jet noise suppression level at the lateral and flyover points, about 1.5÷2 EPNdB (formally up to Chapter 3 ICAO), may be realized by means of the shielding effect. Such approach gives possibility to refuse from complicated mixer-ejector nozzle and use conventional types of variable nozzles, which can provide optimum thrust characteristics in the wide range of flight regimes including supersonic cruise. The main goal of the present study consisted in choice of the scheme and basic geometrical parameters of exhaust system, which can provide minimum effective thrust losses at the supersonic cruise in the range of Mach numbers M=1.6÷2.0 in combination with maximum simplicity of nozzle design.

2 Methods of studies

Aerodynamic design of exhaust system for advanced SST, i.e. choice of the scheme and main geometry parameters of nozzle, has been done with both computational and experimental methods of studies.

2.1 Computational methods

Parametric computations were used for preliminary choice of the nozzle scheme and optimization of its configuration. Application of numerical methods also made possible to get detailed information about flow fields, reveal physical features of flows, and determine the main sources of thrust losses. Parametric computations were carried out in the 2D approach because of a large number of the geometry variants and wide range of Mach numbers M=0.25÷2.

A time-marching numerical algorithm for solving of the Reynolds-averaged thin-layer Navier-Stokes equations (RANS) was developed on the basis of the implicit factored scheme proposed by Beam and Warming [6]. The algebraic turbulence model of Baldwin and Lomax [7] was used to compute the turbulent viscosity in the exhaust jet and external flow. The computer code developed in TsAGI was validated by means of comparison of computation results with available experimental data in reference [8].

Fragment of a typical computational mesh is shown in Fig. 3. 2D mesh included about 40,000 cells that made possible to perform parametric computations with personal computer. Maximum number of cells was located in the exhaust jet and near the upper external contour of nozzle.

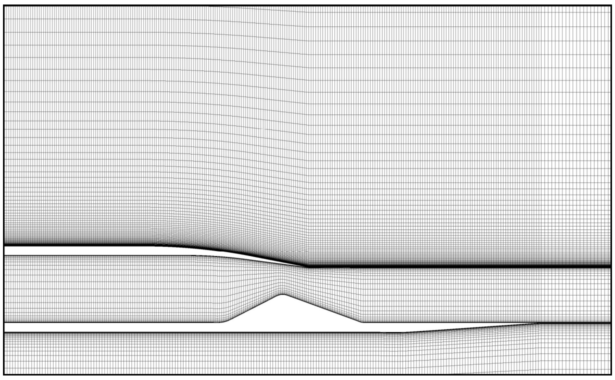


Fig. 3. Fragment of a typical 2D computational mesh

In order to get additional information about physics of flows, some numerical results were obtained by means of the 3D algorithm [9] with the two-parameter k-ε turbulence model developed by Chien [10]. In the 3D computations mesh included about 1,300,000 cells. Fragments of the 3D mesh are shown in Fig. 4. By analogy with 2D computation, maximum number of cells was located in the exhaust jet, near the upper external contour of nozzle and in the upper hemisphere, which are more important for reliable definition of nozzle thrust losses than the lower and side regions.

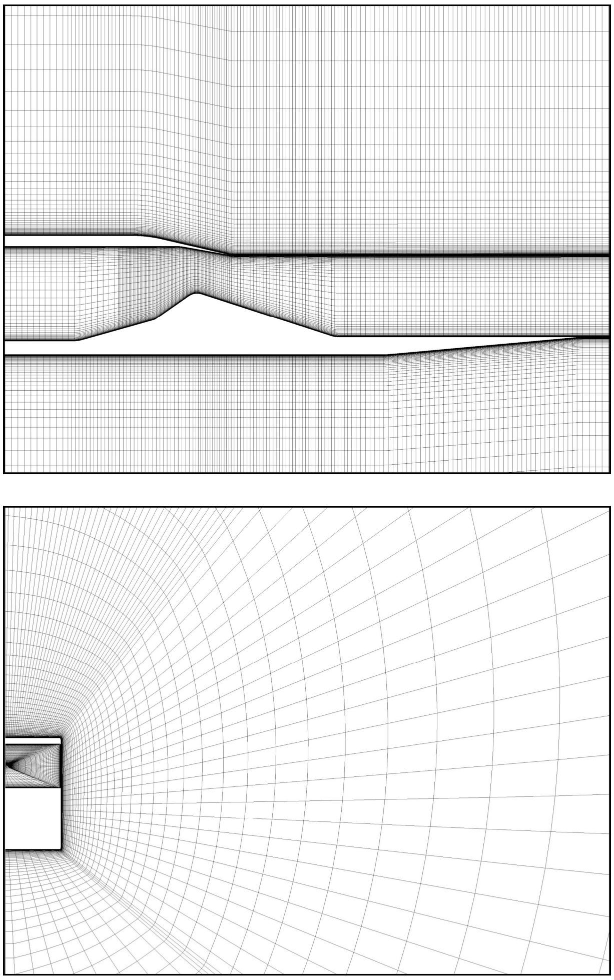


Fig. 4. Fragments of 3D computational mesh

2.2 Wind tunnels

In order to verify recommendations of the numerical studies, wind tunnel tests of the appropriate nozzle model were carried out. Cold jet tests were performed in the TPD-Tr and T-58 wind tunnels of TsAGI [2] in the range of Mach numbers M≅0÷2. In the subsonic and transonic range of Mach numbers M≅0÷1.1 tests are usually performed in the TPD-Tr test bench, which is designed for testing models of exhaust systems. Photograph of the TPD-Tr test bench is shown in Fig. 5.

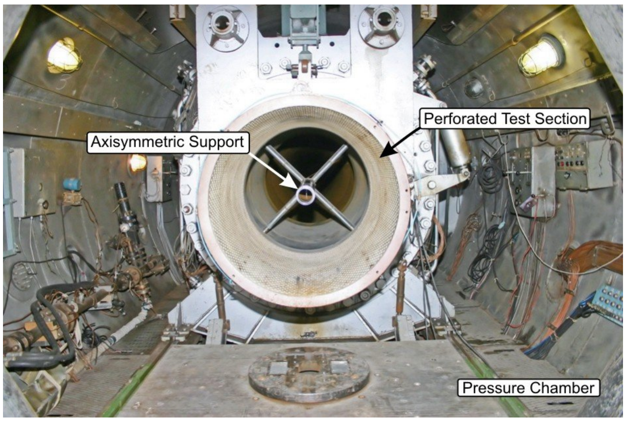


Fig. 5. TPD-Tr test bench

Testing is performed in an enclosed pressure chamber. Free stream is provided by means of axisymmetric convergent nozzle with a cylinder perforated test section. Diameter of the test section is equal to 800 mm. Reynolds number varies from 0.7×10^7 up to 1.7×10^7 in dependence of the free stream Mach number. The model is mounted on the axisymmetric support installed along the test section axis. Cold compressed air is supplied into the support duct and model through four struts mounted in the wind tunnel prechamber. Mass flow rate of the compressed air is measured by the flow meter located outside the test section. Standard axisymmetric support systems are equipped with internal multi-component strain-gage balances. In the present tests resultant aerodynamic loads were measured by six-component balance.

In the supersonic range of Mach numbers M≅1.5÷3 tests of nozzle models are usually performed in the T-58 wind tunnel, which photograph is shown in Fig. 6.

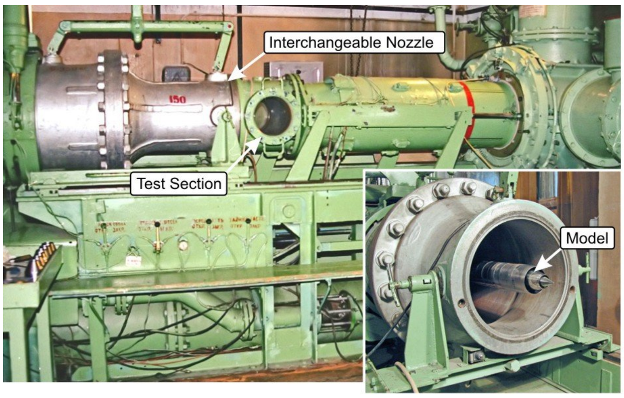


Fig. 6. T-58 wind tunnel

The T-58 has an enclosed solid-walls test section with the diameter equal to 400 mm. Free stream is provided by means of a set of axisymmetric interchangeable convergent-divergent nozzles. Tests are carried out with the same support systems and models as in the TPD-Tr wind tunnel.

3 Choice of the nozzle scheme

As it was noticed in the introduction, from the point of view of aerodynamics problem of exhaust system development for variable cycle engines with bypass ratio BPR~2÷3 seems to be some easier than for low-bypass-ratio turbofans, because it is possible to refuse from complicated nozzle of mixer-ejector type and use conventional variable nozzles. On the other hand, distinctive feature of such engines consists in relatively low nozzle pressure ratios (NPR) NPR~1.8÷5 in the subsonic and transonic range of Mach numbers M=0÷1.2, while at the supersonic cruise flight with Mach numbers M=1.8÷2 rather high values NPR~9÷11 are realized (for example, see reference [11]). So, in order to minimize thrust losses it is necessary to provide variation of the nozzle expansion ratio (ratio of the nozzle exit area A_e to the nozzle throat area A_t) in the range A_e/A_t≅1÷2.1. Besides that, variation of nozzle geometry should provide design flow structure in jet without overexpansion up to supersonic Mach numbers and formation of shock waves at take-off regimes.

Variable two-dimensional convergent-divergent nozzle (CDN) was considered as the preliminary scheme. Numerical computations showed that CDN provides design flow structure in jet (see Fig. 7a-7b) and acceptable level of nozzle effective thrust losses (internal nozzle thrust losses plus nozzle external drag) respectively equal about 1% and 3% of nozzle ideal isentropic thrust at take-off conditions and supersonic cruise flight, which are the most important regimes for SST. Nozzle external drag at M=1.8 was about 0.8% of nozzle ideal isentropic thrust.

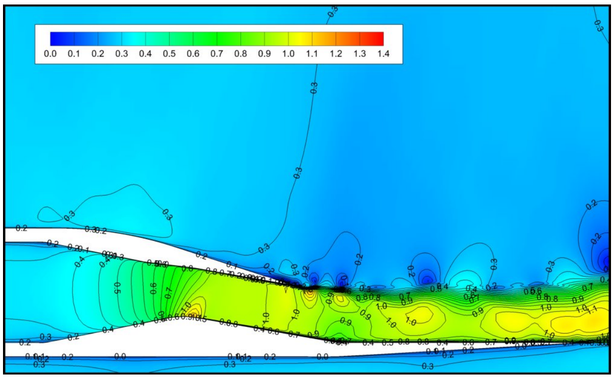


Fig. 7a. Field of Mach number: M=0.25; NPR≅1.8

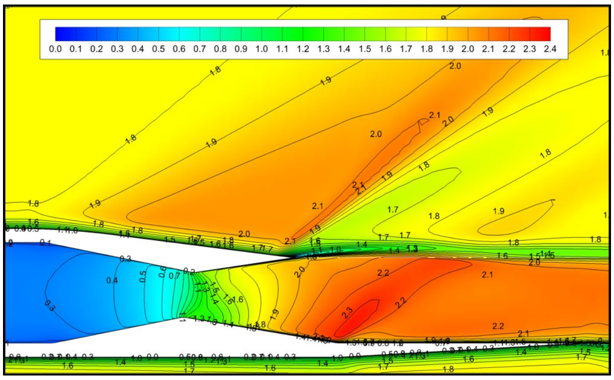


Fig. 7b. Field of Mach number: M=1.8; NPR≅9

The most problem regimes for CDN are subsonic and transonic Mach numbers M=0.9÷1.2, where design nozzle expansion ratio may be about $A_e/A_t \cong 1.1 \div 1.3$. Low expansion ratio results in high slope angle of the nozzle external contour (about 20°), increase of the external drag and high level of nozzle effective thrust losses approximately equal to 11÷16% of nozzle ideal isentropic thrust. Flow field at free stream Mach number M=0.9 is shown in Fig. 8.

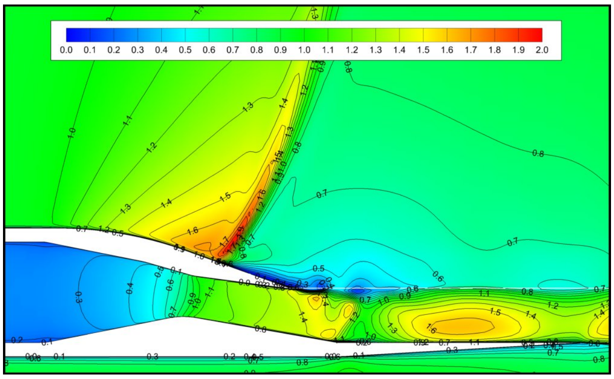


Fig. 8. Field of Mach number: M=0.9 NPR≅3.5

Numerical simulation showed that external flow may accelerate up to high supersonic Mach numbers on the upper nozzle external surface. In addition to high nozzle drag, the rarefaction zone results in appearance of significant normal force (about 35% of nozzle ideal isentropic thrust) and pitch moment that may additionally increase aircraft balance drag. 2D computations, as a rule, give overestimated values of aerodynamic forces, but such approach may be reasonable for configuration with four engines mounted side-be-side between two vertical tails.

Therefore it is reasonable to choose another scheme of nozzle for advanced SST configuration with top-mounted engines. It is necessary to note that the midsection of turbofans with BPR~2÷3 must be reduced to minimum in order to have acceptable supersonic characteristics of SST. This restriction means that it is necessary to simplify nozzle control system as much as possible, reduce number and dimensions of actuators and locate them in the internal volume of the airframe. Such scheme is the single expansion ramp nozzle, which may be considered as a self-adjustable nozzle in the wide range of free stream Mach numbers and nozzle pressure ratios. SERN can provide minimum effective thrust losses at the supersonic cruise in the range of Mach numbers M=1.6÷2.0 in combination with maximum simplicity of design. Nozzle scheme with minimum number of movable elements has been considered as the basic variant (see Fig. 9a).

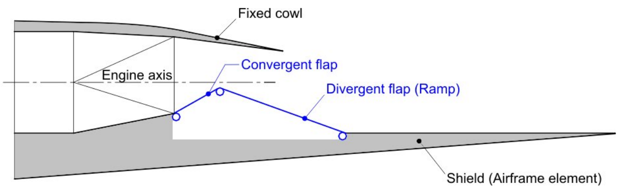


Fig 9a. Basic scheme of the SERN with fixed cowl

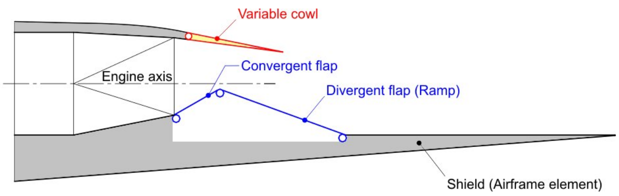


Fig 9b. Scheme of the SERN with variable cowl

Geometry of the nozzle cowl is fixed. Variation of the throat area and nozzle contour is realized by means of a pair of flat pivoted flaps. Experience shows that the main problem of such nozzle consists in possible overexpansion of exhaust jet at low nozzle pressure ratios. In order to solve this problem the scheme with variable cowl has been additionally considered (see Fig. 9b).

4 Results of parametric computations

In order to choose rational geometrical parameters of the single expansion ramp nozzle and its kinematic scheme parametric computational study has been conducted. Preliminary analysis showed that choice of the nozzle geometry for variable cycle turbofan with bypass ratio BPR~2÷3 must be carried out very carefully and just at the maximum continuous supersonic cruise flight where each percent of the nozzle thrust losses is approximately equal to three percent of the engine thrust losses. Due to this reason the main goal of nozzle optimization was to define combination of the geometrical parameters, which can provide minimum effective thrust losses at the supersonic cruise flight with Mach number M=1.8. Parametric calculations were also carried out at take-off conditions with Mach number M=0.25, and in the range of Mach numbers M=0.9÷1.2. Choice of the nozzle configuration was carried out with taking into account aerodynamic restrictions. For example, nozzle geometry should provide design flow structure in jet without overexpansion up to supersonic Mach numbers and formation of shock waves at take-off regimes. It is necessary to note that such restriction is the important factor of realization of required acoustic characteristics of nozzle.

Main geometry parameters varied in the course of parametric studies are shown in Fig. 10.

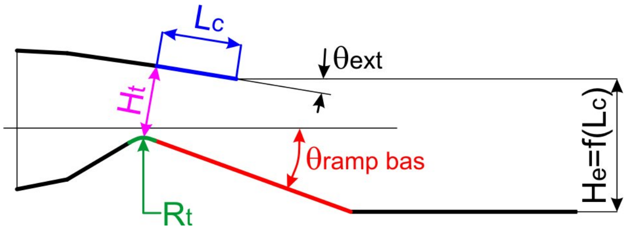


Fig. 10. Main geometry parameters of SERN

Nozzle throat area and consequently throat height (H_t) were set different for take-off, transonic and supersonic cruise regimes. Independent varied parameters were:

– curvature radius of the ramp in the nozzle throat (R_t),
– basic slope angle of the ramp in supersonic cruise flight ($\theta_{ramp\ bas}$),
– length of the cowl behind the nozzle throat (L_c),
– external slope angle of the cowl (θ_{ext}).

Height of the nozzle exit section is a dependent parameter, because it is a function of the cowl length and slope angle.

SERN with fixed cowl has been optimized first. In the frames of this nozzle scheme external slope angle of the cowl was the same at all flight regimes. Preliminary computations showed that an optimum external slope angle of the cowl strongly depends on Mach number. As it is shown in Fig. 11, for considered SST configuration optimum angle is about 6÷8° at the supersonic cruise flight, 9÷11° at Mach number M=0.9 and 16÷18° at take-off.

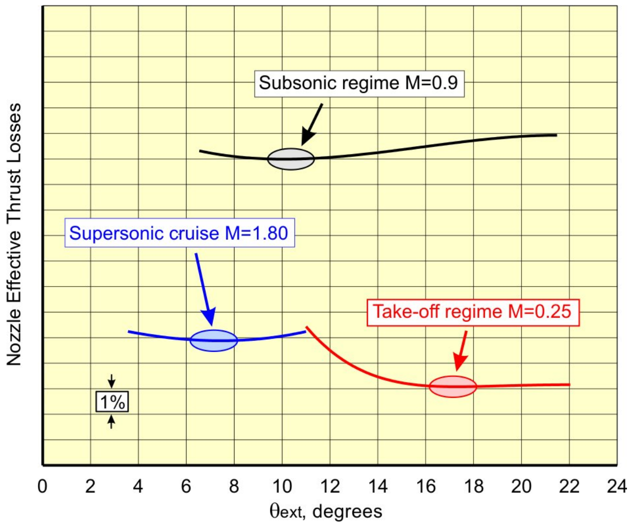


Fig. 11. Optimum values of the external slope angle of the cowl

High optimum slope angles at Mach number M=0.25 are result of trade-off between internal thrust losses and nozzle external drag. Because design nozzle expansion ratio for low values of NPR≅1.8÷2 is close to unity, it is necessary to decrease exit area as much as possible in order to avoid overexpansion of jet and significant increase of internal thrust losses. Increase of the external slope angle of the cowl isn't so important because values of external drag at M=0.25 are low itself. Analysis of results and preliminary estimations have shown that a compromise value of the external slope angle of the cowl may be about $\theta_{ext}\cong 10\div 11°$.

The next step consisted in choice of configuration of the nozzle cowl and throat curvature radius. The main results of parametric computations are shown in Fig. 12. Relative cowl length (L_c/H_t) and relative curvature radius of the nozzle throat (R_t/H_t) were varied in the ranges $L_c/H_t\cong 0\div 0.68$ and $R_t/H_t\cong 0.08\div 0.85$.

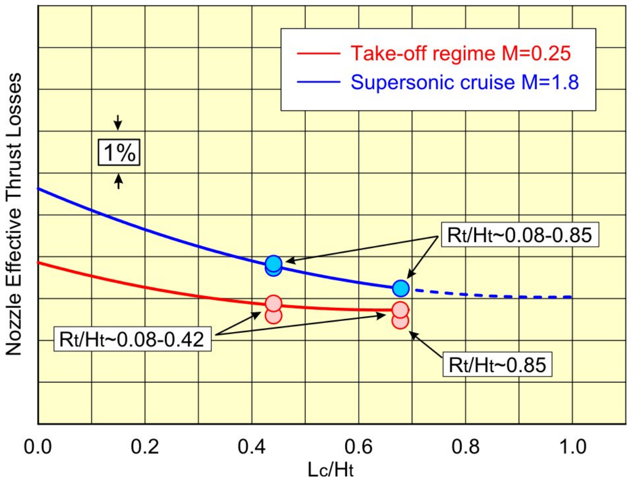


Fig. 12. Effect of the cowl length and throat curvature radius on nozzle effective thrust losses

Cowl length has a strong effect on nozzle thrust characteristics at the supersonic cruise flight. Increase of the relative cowl length from $L_c/H_t\cong 0$ to 0.68 decrease nozzle effective thrust losses approximately by 2.5% of nozzle ideal isentropic thrust. This result is illustrated with the fields of Mach number in Fig. 13a-13c. Location of the nozzle throat at the trailing edge of the cowl results in overexpansion of exhaust jet up to local Mach numbers about 2.8 (see Fig.13a), while the design Mach number in jet at NPR≅9 is about 2.1. Increase the relative cowl length up to $L_c/H_t\cong 0.42$ decrease thrust losses approximately by 2%. Extension of the cowl up to $L_c/H_t\cong 0.68$, which was the maximum value in parametric studies, provides additional decrease of thrust losses approximately by 0.5%. Both variants provide maximum Mach number in jet close to the design value (see Fig. 13b and 13c).

Besides that it is necessary to note that in the configuration with top-mounted engines interaction of exhaust jet with external flow results in appearance and propagation of intensive shock wave in the upper hemisphere that assists in sonic boom level decrease. Disturbances, which occur near the trailing edge of the shield on the lower bound of jet, are relatively weak.

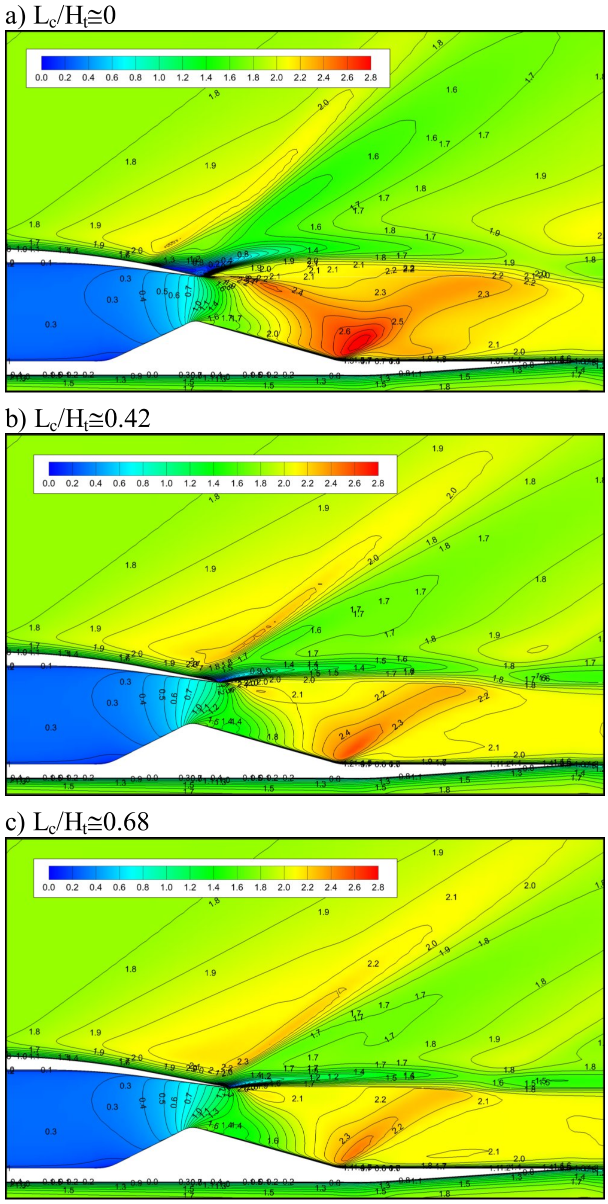


Fig. 13. Fields of Mach number: M=1.8; NPR≅9

Analogous computations carried out at take-off (M=0.25; NPR≅1.8) showed that the value $L_c/H_t\cong 0.68$ is close to an optimum for this regime. Extrapolation of numerical data at M=1.8 (dashed line in Fig. 12) showed that further extension of the cowl may decrease thrust losses only by 0.1÷0.2%. Thus, the compromise value of the relative cowl length may be about $L_c/H_t\cong 0.65\div 0.7$. Numerical studies showed that throat curvature radius isn't such important parameter as the cowl length. Curvature radius has just no effect upon nozzle thrust characteristics at supersonic cruise. At take-off regime increase of the curvature radius from $R_t/H_t \cong 0.08$ up to 0.85 decreases thrust losses only by 0.3%.

Another important parameter was the basic slope angle of the ramp, which was varied in the range $\theta_{ramp\ bas} \cong 12 \div 20°$ in the course of parametric computations (see Fig. 14).

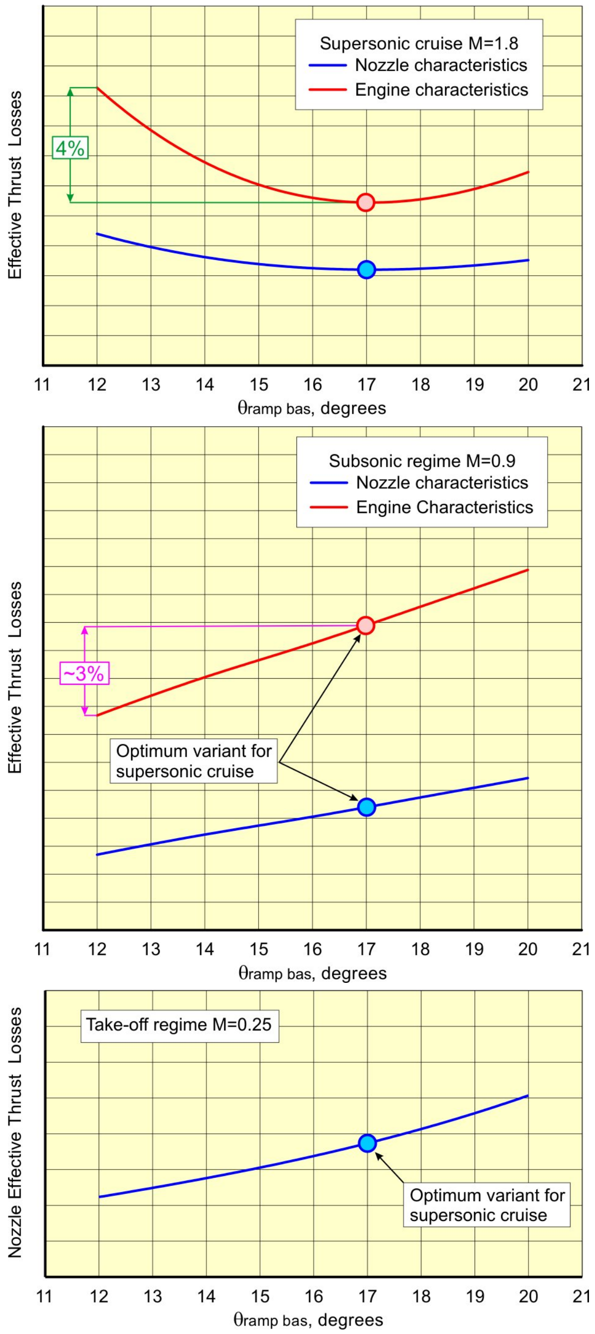
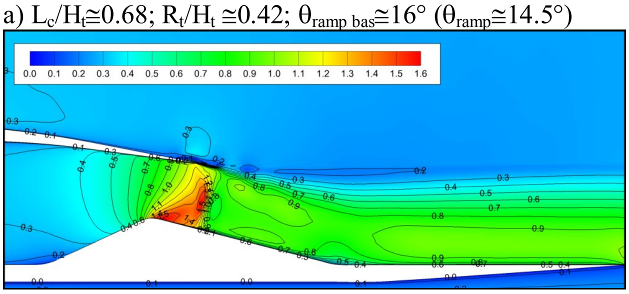


Fig. 14 Effect of the slope angle of the ramp on nozzle effective thrust losses

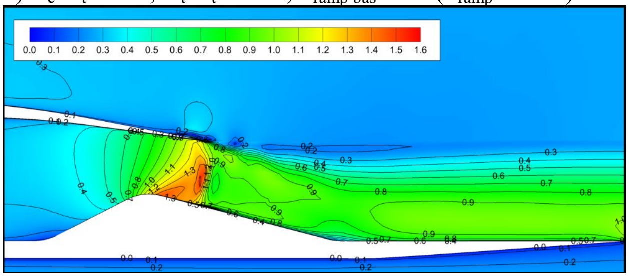
Within the frames of the nozzle scheme with fixed cowl optimization of the ramp slope angle allows to get sufficient decrease of engine effective thrust losses (about 4%) at the supersonic cruise flight. At Mach number M=1.8 an optimum value of the slope angle was about 17°. Optimum slope angle at subsonic Mach number M=0.9 and at take-off (M=0.25) was equal to the minimum value of the range of varied angles. At Mach numbers M=0.9 and 0.25 optimum supersonic configuration loosed to the optimum variants for subsonic Mach numbers respectively about 3% and 1.5% of nozzle ideal isentropic thrust. Nevertheless, taking into account long duration of the supersonic cruise and rather short regimes of take-off and subsonic climb, compromise value of the basic slope angle of the ramp has been chosen approximately equal to 16÷17°.

It is necessary to discuss results of numerical studies at take-off regime (M=0.25) in more details. Fields of Mach number in exhaust jet are shown in Fig. 15. In order to realize required acoustic characteristics of nozzle at take-off, nozzle should operate at low nozzle pressure ratio about 1.8 or lower in unchocked regime. Analysis of flow field in the variant with an optimum geometrical parameters for supersonic cruise (Fig. 15a) show that flow accelerates up to supersonic Mach numbers about M~1.6 on the ramp surface behind the nozzle throat and then decelerates in the shock wave up to design Mach numbers. According to reference [11] such flow structure may result in growth of jet noise level. Increase of the nozzle throat curvature radius up to $R_t/H_t \cong 0.85$ (Fig. 15b) or decrease of the real slope angle of the ramp from $\theta_{ramp} \cong 14.5°$ in the optimum variant up to $\theta_{ramp} \cong 10.9°$ (Fig. 15c) don't result in significant changes in flow field.

a) $L_c/H_t \cong 0.68$; $R_t/H_t \cong 0.42$; $\theta_{ramp\ bas} \cong 16°$ ($\theta_{ramp} \cong 14.5°$)



b) $L_c/H_t \cong 0.68$; $R_t/H_t \cong 0.85$; $\theta_{ramp\ bas} \cong 16°$ ($\theta_{ramp} \cong 14.5°$)



c) $L_c/H_t \cong 0.68$; $R_t/H_t \cong 0.42$; $\theta_{ramp\ bas} \cong 12°$ ($\theta_{ramp} \cong 10.9°$)

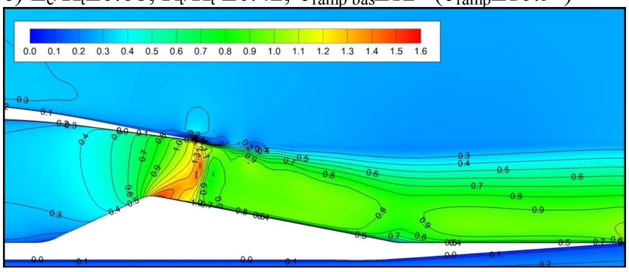
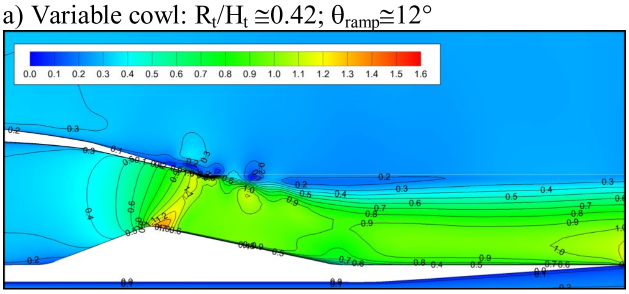


Fig. 15. Fields of Mach number: M=0.25; NPR≅1.8

Due to this reason single expansion ramp nozzle with variable cowl has been considered. Adjustable cowl gives possibility to keep constant throat area at different values of the ramp slope angle, which may be less in comparison with the variant with fixed cowl. Besides, it gives possibility to locate nozzle throat at the trailing edge of the cowl, thus transforming nozzle contour near the throat from the convergent-divergent to the convergent. Fields of Mach number in exhaust jet shown in Fig. 16 illustrate efficiency of such measures for decrease of velocity of exhaust jet.

a) Variable cowl: $R_t/H_t \cong 0.42$; $\theta_{ramp} \cong 12°$



b) Variable cowl: $R_t/H_t \cong 0.42$; $\theta_{ramp} \cong 10°$

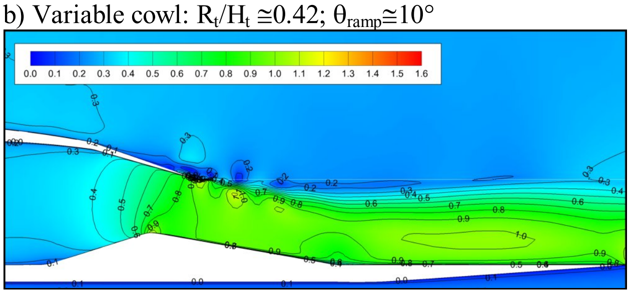


Fig. 16. Fields of Mach number: M=0.25; NPR≅1.8

The main results of parametric studies of thrust characteristics of SERN with variable cowl at take-off regime and over the flight envelope of SST are shown in Fig. 17. At take-off variable cowl provide design flow field in exhaust jet that may decrease thrust losses approximately by 2.4% of nozzle ideal isentropic thrust in comparison with SERN with fixed cowl. In the supersonic range of Mach numbers M=1.6÷2.0 choice of an optimum position of the cowl provides decrease nozzle effective thrust losses by 0.3÷0.5% in comparison with nozzle scheme with fixed cowl. In the range of Mach numbers M=0.8÷1.4 characteristics of both nozzle variants may be approximately the same.

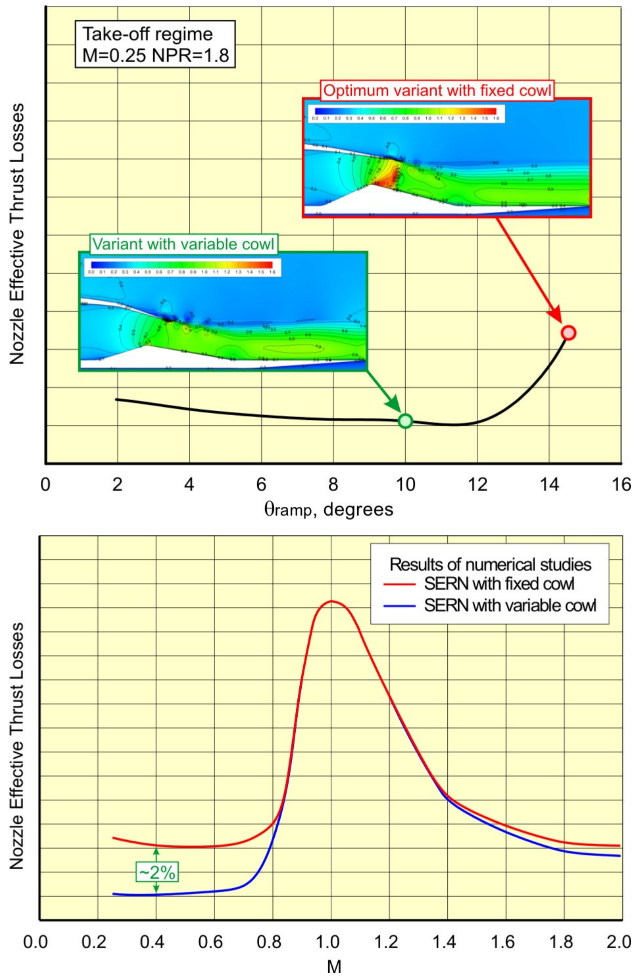


Fig. 17. Comparison of effective thrust losses of SERN with fixed and variable cowl

5 Results of wind tunnel tests

In order to validate recommendations of

numerical computations experimental studies of the appropriate model of the single expansion ramp nozzle were carried out. Tests were performed in the TPD-Tr and T-58 wind tunnels of TsAGI in the ranges of free stream Mach numbers M≅0÷1.1 and 1.7÷2.

Photographs of the SERN model kit and model installed in the test section of the TPD-Tr wind tunnel are shown in Fig. 18.

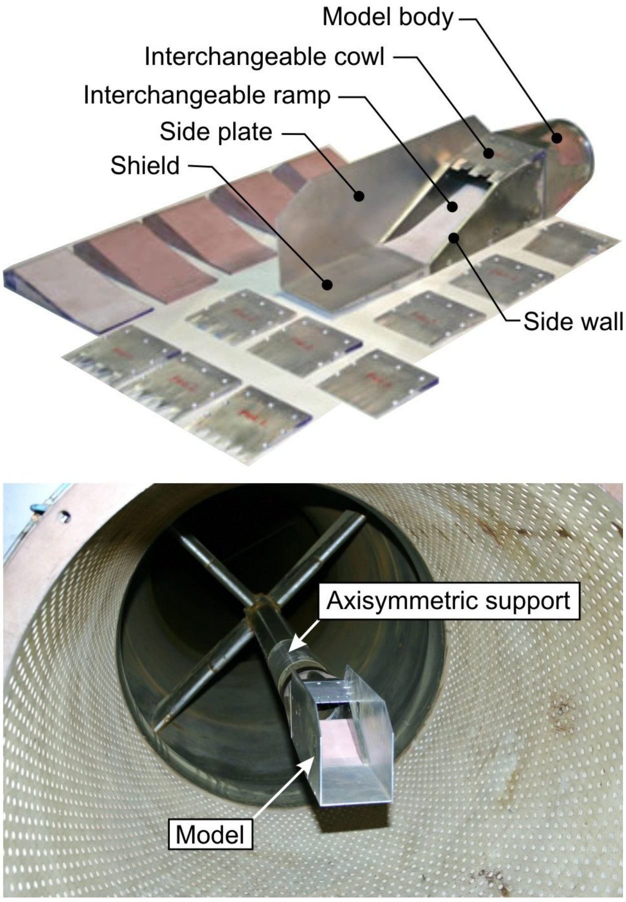


Fig. 18. Photographs of the SERN model

The main elements of the SERN model are model body, side walls, interchangeable cowl, interchangeable ramp, shield, side plates. Model body is attached to the standard axisymmetric support systems equipped with internal strain-gage balances. Nozzle duct is formed with interchangeable cowl, ramp and side walls. Side plates prevent cross flows in exhaust jet and free stream, thus provide analogous flow structure as in the SST configuration with four engines mounted side-by-side on the top surface of the fuselage between vertical tails.

SERN model has been developed with taking into account results of parametric numerical studies. For example, nozzle geometry variants with variable cowl were included in the model kit. At the same time, the geometry of the nozzle of model is not optimum due to objective reasons – process of model design and manufacturing is essentially more time-consuming than carrying out calculations.

Experiments in the wind tunnels were accompanied with 2D and 3D RANS computations of nozzle model thrust characteristics at the most important test regimes. Comparison of test results with numerical data is shown in Fig. 19.

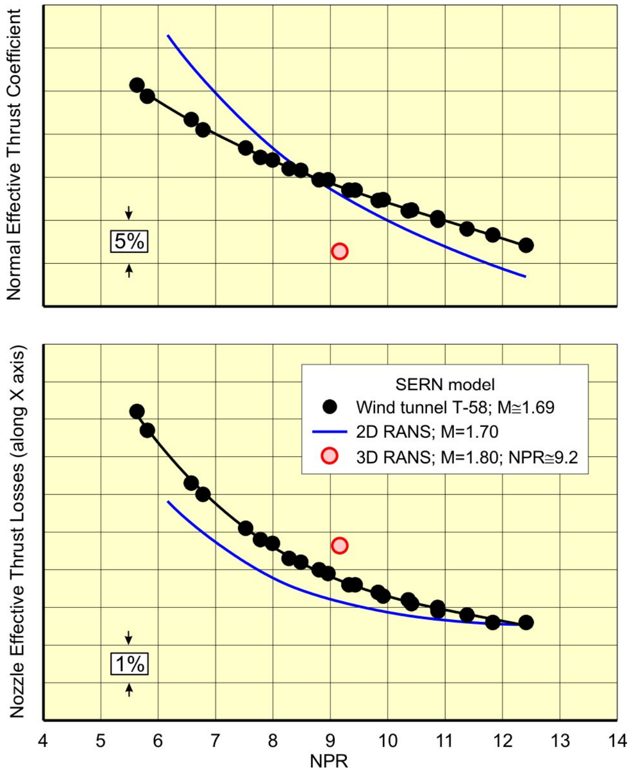


Fig. 19. Comparison of test results with numerical data

It is necessary to note concerning nozzle effective thrust losses along X-axis (i.e. internal thrust losses plus nozzle external drag) that maximum differences between experimental and numerical data don't exceed 1.2% of nozzle ideal isentropic thrust at free stream Mach number M≅1.69. At nozzle pressure ratios NPR≅8÷10 typical for supersonic cruise regimes this difference is about 0.5÷0.8%. Such result may be recognized as acceptable, because model geometry in computations was simplified. For example, base steps of the side walls and side plates were not simulated in 3D computations et all. Such simplification could result in less accuracy of calculation of normal effective thrust coefficient (internal normal effective thrust coefficient plus cowl lift force).

Interesting features of flows were obtained in 3D computation at M=1.8 (see Fig. 20).

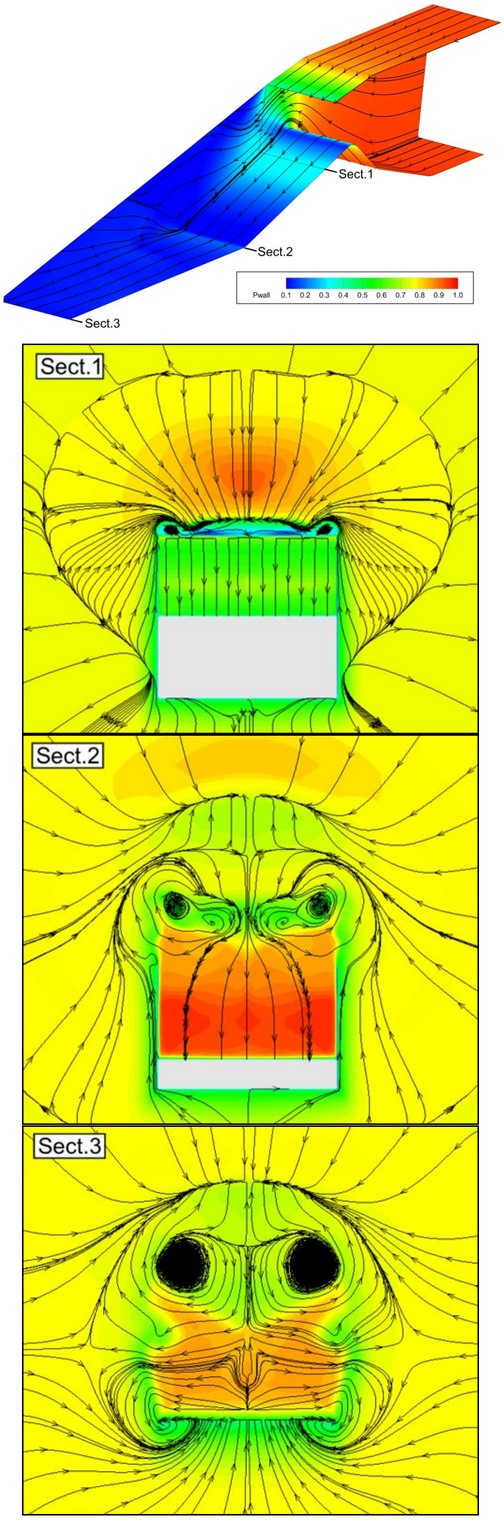


Fig. 20. Flow features in SERN nozzle

Analysis of streamlines showed that expansion of exhaust jet from the chute between side walls to the cocurrent flow is realized with generation of pair of vortexes behind the trailing edge of the cowl (Sect.1). Dimensions of the vortexes increase in the longitudinal direction (see Sect.2), and pair of additional vortexes appears near the bottom bound of jet at the trailing edge of the shield (see Sect.3). It is necessary to note that these results are related to the isolated nozzle. Physics of flows in the four-engine pack configuration may be different.

Summary relations of nozzle effective thrust losses upon free stream Mach number received in result of experimental studies in the TPD-Tr and T-58 wind tunnels of TsAGI are shown in Fig. 21. Thrust losses were determined at nozzle pressure ratios typical for variable cycle turbofan with BPR~2÷3.

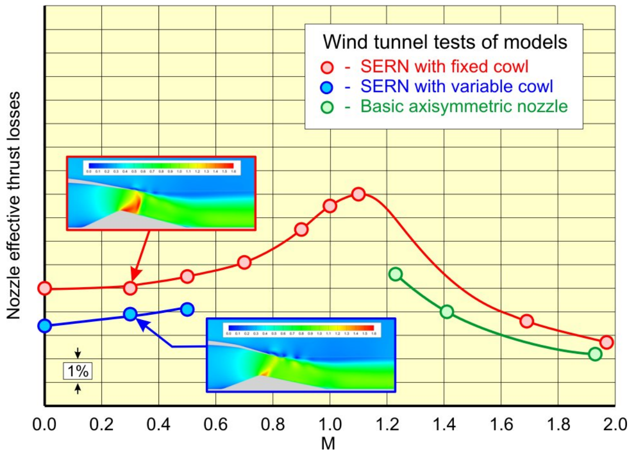


Fig 21. Nozzle effective thrust losses in the range of Mach numbers M≅0÷2

Experiment has shown that the most “simple” scheme of the SERN with fixed cowl provides effective thrust losses about 2.6÷3.5% of nozzle ideal isentropic thrust at the maximum continuous supersonic cruise flight in the range of Mach numbers M≅1.7÷2. Approximately the same level of nozzle thrust characteristics has been predicted in the course of parametric calculations (see Fig. 17). The most problem regimes for SERN are take-off, climb and acceleration in the range of Mach numbers M≅0÷1.1 where thrust losses grow from ~5% up to ~9% with an increase of Mach number. Scheme of the SERN with variable cowl has been also considered. According to test results adjustable cowl decreases nozzle effective thrust losses in the range of Mach numbers M≅0÷0.5

by 1.5÷1.8%. Approximately the same difference between the nozzle schemes has been received in the course of parametric numerical computations (see Fig. 17).

Comparison of thrust characteristics of the SERN in SST configuration (top-mounted engines) with conventional axisymmetric nozzle (isolated) shows that in the range of Mach numbers M≅1.4÷2 maximum difference doesn't exceed 1.5% of nozzle ideal isentropic thrust. Just at the supersonic cruise with Mach numbers M≅1.7÷2 effective thrust losses in the SERN are higher approximately by 0.5÷0.8% than in conventional axisymmetric nozzle. Taking into account complexity of aerodynamic configuration with top-mounted engines, additional losses in the internal transition duct from axisymmetric cross-section of the engine to rectangular one in the nozzle throat, and large surfaces of the shielding elements washed by exhaust jet, level of effective thrust losses in the SERN could be recognized as acceptable for SST.

The main goal of the experiment, side by side with measurement of nozzle effective thrust losses over the flight envelope of SST, consisted in choice of configuration of the devices for additional jet noise suppression. Deflectable mini-flaps (analog of chevrons and tabs) installed at the cowl behind nozzle throat were used as noise suppressor devices. Experience shows that differential deflection of the neighboring mini-flaps results in formation of corrugated jet and generation of longitudinal vortex structures, which may provide additional decrease of jet noise level at take-off regimes (see reference [12]).

Effect of the mini-flaps on nozzle effective thrust losses is shown in Fig. 22. Analysis of test results showed that noise suppressor devices increase thrust losses mainly at flight regimes, in which there is no need to reduce jet noise. For example, at Mach number M≅1.97 effective thrust losses in the model variant with triangular mini-flaps (without deflection) are higher than in the basic variant with fixed cowl approximately by 1.6÷1.8% of ideal isentropic thrust. Growth of thrust losses in this variant could be explained with generation of vortexes and overexpansion of jet in the area between neighboring flaps. Rectangular mini-flaps also increase thrust losses at Mach number M≅1.97, but only by 0.5÷0.7%. This variant of the cowl had gaps between neighboring flaps, which may be considered as imitation of a real structure. Growth of thrust losses in this variant could be result of leakages through these gaps.

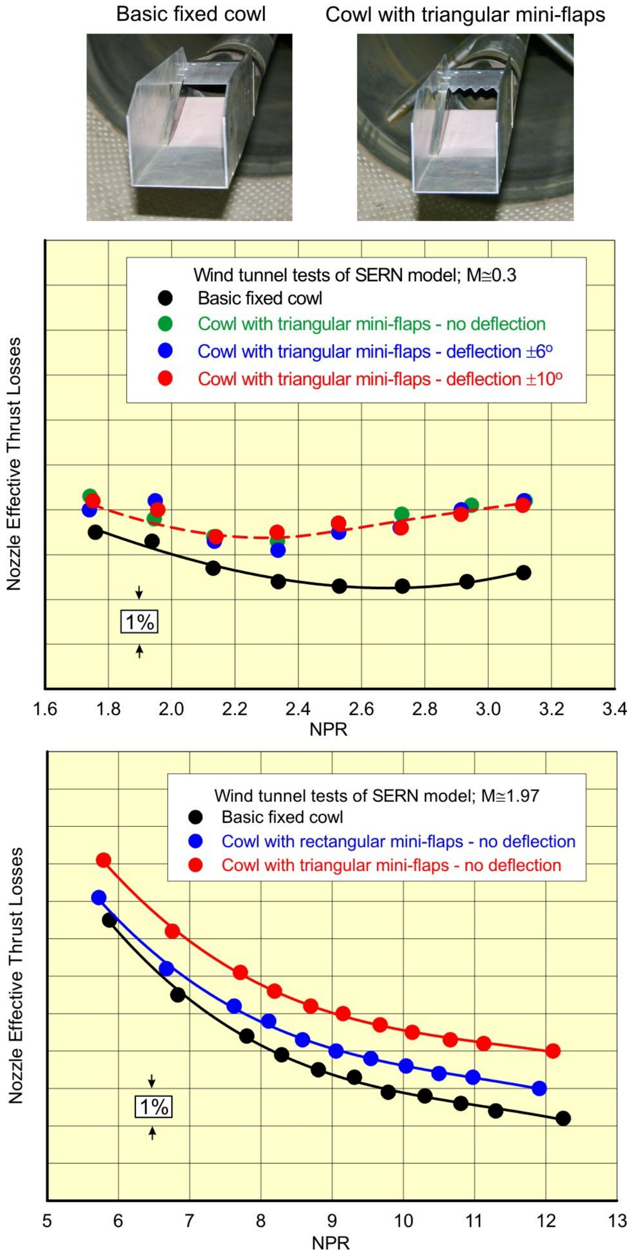


Fig. 22. Effect of noise suppressor devices on nozzle effective thrust losses

At take-off regimes with Mach number M≅0.3 in the range of nozzle pressure ratios NPR≅1.7÷2.2, typical for variable cycle turbofan with BPR~2÷3, triangular mini-flaps, which had the worst characteristics at the supersonic cruise, increase thrust losses in comparison with the basic variant with fixed cowl only by 0.5÷0.8%. Differential deflection of mini-flaps in the range of angles ±10° has just no effect on nozzle effective thrust losses. Approximately the same results at take-off regimes were obtained for rectangular mini-flaps.

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