A METHODOLOGY FOR INVESTIGATION INTO THE AERODYNAMIC EFFECTS ASSOCIATED WITH THRUST REVERSAL

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ABSTRACT: Discussed in the present paper are possible aerodynamic and gas-dynamic problems associated with the aircraft thrust reverser's operation on landing. A methodology is proposed for computer analysis and experimental investigations using a special test facility for studying the ingestion of reversed engine jets into engine inlets and the effects of this phenomenon on the characteristics of a wind-tunnel model being tested.

INTODUCTION: Reversal of aircraft engines' thrust is one of the effective methods for aircraft deceleration during landing run. However, with deploying the thrust reverser some problems can arise due to influence of the reversed flows on the aircraft. The ingestion of reversed jets by engines distorts the velocity and temperature fields at the engine inlets, which can cause compressor surge and engine shutdown. Interaction of the reversed jets with the fuselage, wing and runway surface can affect an aircraft's aerodynamic characteristics at landing and during its rolling over the runway and distort the readings of sensors located on the fuselage surface.

To effectively resolve these problems proper methodologies have been developed at TSAGI and a specialized test facility has been constructed for TsAGI's T-104 wind tunnel to experimentally study the aerodynamic effects caused by trust reversers' operation. Advanced computational methods have been developed and a nonlinear mathematical model created to represent numerically the wind tunnel and setup in combination. One of passenger aircraft configurations was used to demonstrate the results of experimental and computational investigations into the effects of thrust reversers' operation under various test conditions as well as to evaluate the possible experimental errors due to wind-tunnel structural peculiarities and the methods for simulating reversed jets and runway surface. For the first time in TsAGI's history, measurements of a test model's aerodynamic characteristics have been performed with a strain-gage balance simultaneously with thrust reversal simulation.

LEADING PARTICULARS OF THE WIND TUNNEL AND EXPERIMENTAL SETUP. The T-104 wind tunnel is a closed type facility with a single return circuit and open test section. The circular exit section of its nozzle has a diameter of 7 m. The nozzle provides a 7:1 flow contraction ratio. The test section length is 13m. The maximum tunnel speed is 120 m/s. A special setup was created for the T-104 wind tunnel to carry out experimental studies on influence of reversed jets on aircraft's aerodynamics and gas-dynamic stability of airplane engines in the presence of a ground board to simulate the runway surface (Fig.1).

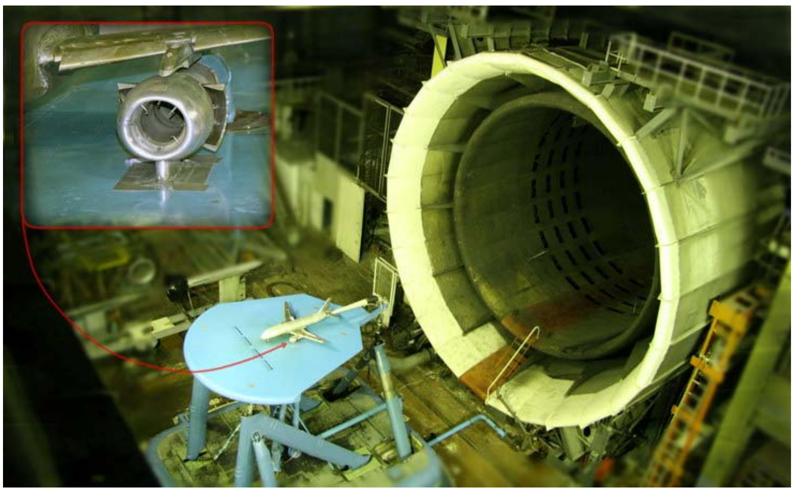

Fig. 1 Experimental setup in the T-104 wind tunnel

The experimental setup (Fig.2) includes: a ground board, kerosene fueled air heater, a sting with an aircraft model being studied, a six-component internal strain-gage balance, the model's instrumented engine nacelles with simulated thrust reverses, air tubes to bleed cold air from the nacelles, air tubes to supply hot air to simulated thrust reversers, pipelines to feed the heater with cold air, a pipe to discharge hot air into the wind-tunnel diffuser.

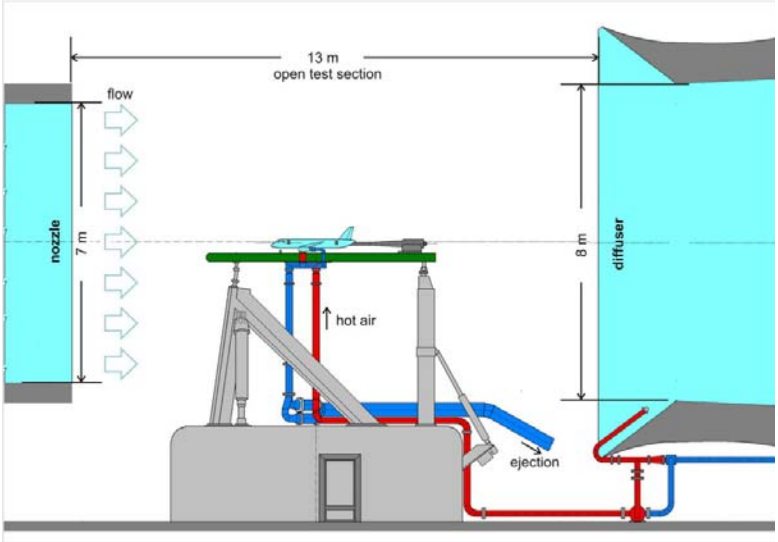

Fig. 2 Schematic of the thrust reversal setup

The ground board – a runway surface simulator – is an oval-shaped metal construction, which is 5530 mm long and 4006 mm wide. It has a rounded leading edge. The engine nacelles, structurally separated from the model, are attached to ground board. In the wind tunnel, the ground board is installed on struts located at the top of the control room. Installed over the ground board on a special sting is the aircraft model under study, whose pylons are separated from its nacelles with a narrow gap. Each aircraft nacelle is fed with heated compressed air through a separate strut, the air is ejected against incoming air flow. The amount of air being supplied is controlled. Simultaneously, forced suction and regulation of air mass passing through the engine are provided with the help of the wind-tunnel ejector system. Together with the control room, the ground board and aircraft model can turn around a vertical axis within the yawing range of 0°-15°.

Heating the reversed jets allows registration of their ingestion into the engine air inlets thanks to an abrupt rise of flow temperature in the inlets with decreasing the speed of the aircraft rolling along the runway. The temperature is sensed by thermocouple units at the air inlets, which allows one to determine the aircraft speed corresponding to the onset of reversed jets' ingestion into the engine. Air heating provides a possibility to effectively visualize the boundaries of reversed jets' propagation over the ground board, fuselage and wing of the model under study. To detect the changes in the thermal patterns on the ground board caused by the thrust reverser's operation a infrared imager [1] is used. The infrared imagers observe the ground board and model surface under two aspects - from the side and from the top. The record of the thermograms is in synchronism with the measurement of the model's aerodynamic characteristics by the balance. In such experiments, one can use aircraft wind-tunnel models with balance and stings, whose dimensions are suitable for testing in the transonic T-128 wind tunnel. The setup's equipment provides a way of performing combined investigations to determine the aircraft rolling speed corresponding to the onset of ingesting hot reversed jets by inlets, to evaluate the influence of thrust reversal on the aerodynamic forces and moments acting on the aircraft, and to study flow patterns around the airframe.

It should be emphasized that in real life the aircraft moves along the runway through still air. On the contrary, in wind-tunnel experiments the air mass moves past the stationary aircraft model. In this case, the boundary layer builds up on the ground board, which is able to distort test results. For partially bleeding the boundary layer, the ground board is fitted with slots located before the model. This boundary-layer bleed is provided due to a suction zone arising behind a special flaps installed in the slots beneath the ground board. For boundary-layer control there is used total pressure rake. Positioning it in front of the bleed slot and behind it, one can control the boundary-layer bleed by changing the flap's deflection angle. Such measurements were performed at a tunnel airflow speed of V= 86 m/s. The boundary-layer thickness on the ground board upstream of the slot was in this case 21.5 mm, while the displacement thickness was 2.9 mm. These parameters at the air inlet were reduced to 10 mm and 1.4 mm, respectively, with the help of an automated boundary-layer suction system used in the experiment. Pressure distribution in the area of the nacelles' location was also measured and found to be sufficiently uniform.

NUMERICAL SIMULATION OF THE AIR FLOW IN THE T-104 TEST SECTION WITH THE MODEL UNDER STUDY. The non-linear computation of the flow in the framework of the studies is based on a modern approach to numerically solving the Reynolds-averaged Navier-Stokes equations (RANS). The EWT-TsAGI computer program [2] was modified by the introduction of a multi-grid algorithm, while retaining the methodology of computing flow about passenger aircraft wind-tunnel models under industrial wind-tunnel conditions with regard to the effects of support devices [3].

The aforementioned mathematical model includes: an aircraft model with its support system and a strut to supply compressed air, a ground board, wind-tunnel nozzle and collector with an ejector and a control room. The computational grid was more dense in areas, where greater flow gradients were expected. The main goal of such a computation was the intention to get a deeper insight into the impact of the wind-tunnel structural components on the flow in the zone of the model's location on the ground board. This is associated with the fact that such large elements as the control room, nozzle and collector generate significant disturbances, which under some conditions can distort measurements. This computational method is described in detail in Ref. [3]. Presented below is an example of computed results for one of the characteristic flow regimes.

M	V, m/s	Po , Pa	To ,K
0,163	55,47	103222	289.681

The Mach number field and restored streamlines in the T-104 test section are presented in Fig.3 It can be seen that behind the control room a stable vortex arises, which is captured by the main flow. In the case the ejector does not allow the vortex to enter the zone of the model's location. The ejector is virtually pulled it out at the zone. Alongside the indicated vortex, there is an area of a weak reversed flow in the building accommodating the wind tunnel. The analysis performed allows one to conclude that the model and ground board are arranged in such a way that practically exclude the adverse influence of the wind – tunnel structural elements one the test results.

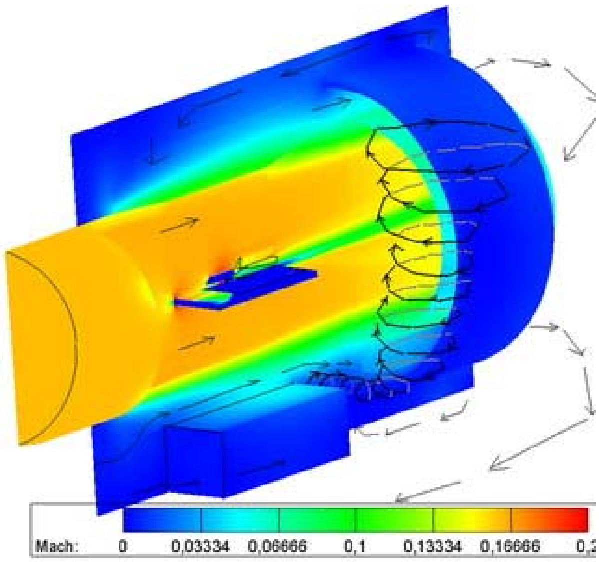

Fig. 3 Mach number field and restoration of streamlines in the test section of the T-104 wind tunnel.

INFLUENCE OF THRUST REVERSAL ON THE AERODYNAMIC CHARACTERISTICS OF THE MODEL AND THE PHYSICAL PICTURE OF FLOW AROUND IT

The goal of this stage of the study is to determine the speed of an aircraft during its ground rolling, at which reversed jets ingestion starts to take place. At this speed the real engine flow rate and the rate of flow through the reverser are simulated. The procedure of the experiment was as follows. First, the heater was started and its operation stabilized to prepare the air with required parameters for the reverser in the wind tunnel. When the required temperature was established at the exit of the heater, the hot air was directed to the reverser's chamber. Simultaneously the tunnel start-up was performed to provide the flow around the model. All required information was presented in real time on the monitor screen. The rates of flow though the reverser and the air inlet together with other air parameters were controlled in interactive mode. As indicated above, the ingestion of the reversed jets by the engine was sensed by thermocouples located in the model's air inlets. For recording thermograms of the model's surfaces the NEC TS7302 infrared imager was alternately installed above the model and at its side. Fig.4 demonstrates the procedure of determining the rolling speed corresponding to the onset of reversed jets' injection by the air inlet for the model with high-lift devices deployed during landing run. Presented here are gas temperatures measured at the air intake and lift coefficient as functions of the speed V. Here $V=V_{rol}/V_{rev}$, where V_{rol} is rolling speed, V_{rev} is rolling speed at the moment of the reverser's deployment. The results are given for two reverser operation modes corresponding to the reverser air flow rates G equal to 30% and 80% of the total rate of air flow passing through the air inlet. As can be seen from the presented data, the rolling speed at which the hot-gas ingestion starts to take place depends on the normalized reverser air flow and decreases with decreasing this parameter.

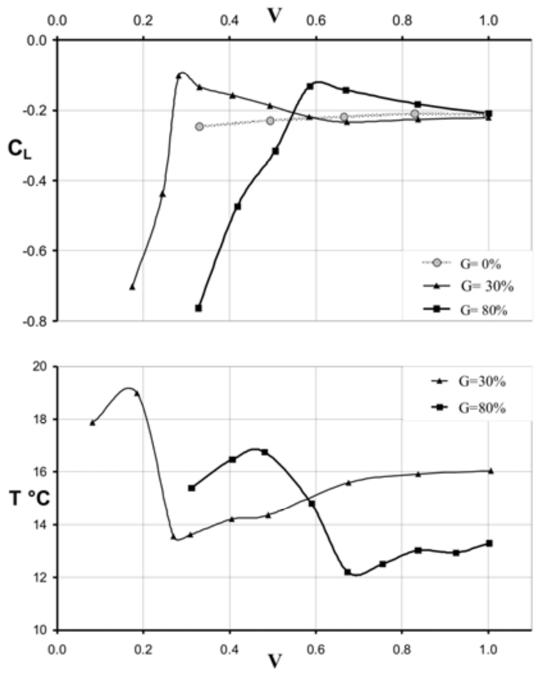

Fig. 4 The influence of rolling speed on the lift coefficient and the gas temperature at the air inlet

The aerodynamic characteristics of the model with nacelle pylons were measured with an internal strain-gage balance. The results of force and moment measurements at the reverser modes considered were somewhat unexpected. Against the background of the monotonically changing characteristics, a rather important aerodynamic effect was discovered: during deceleration of rolling speed, an abrupt growth in the lift coefficient absolute value occurs and the model exerts a greater downward force on the ground board. This change in the lift coefficient is rather significant: from C_L= -(0.1÷0.2) to C_L= -(0.7÷0.8), which can affect the process of aircraft ground rolling with reverser deployed. An accelerometer measuring pitch angle showed increased vibration of the model: the root-mean-square error of its pitch angle (for some reverser air flow rates) are presented in Fig.5. The cause of this effect was found through a flow analysis and computation. The drop in lift is associated with the turn of the reversed jet relative to the wing with decreasing rolling speed. We have a phenomenon as if there were a spanwise air bleed with an abrupt growth of the wing's fluid airfoil. This conclusion is supported by the thermograms of the temperature fields obtained simultaneously with the measurements of aerodynamic characteristics by the balance (Fig. 6). It can be seen that with decreasing the rolling speed the temperature of the ground board and model changes due to the deflection of the reversed jet. The effect of abrupt growth of negative lifting force is harmful. Trust reverse must be switched off at this moment.

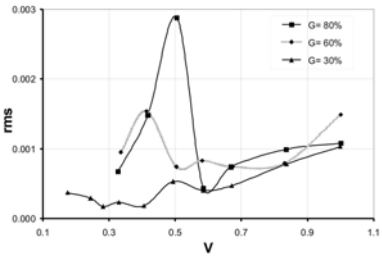

Fig.5 The effect of rolling speed on rms of the model's pitching angle.

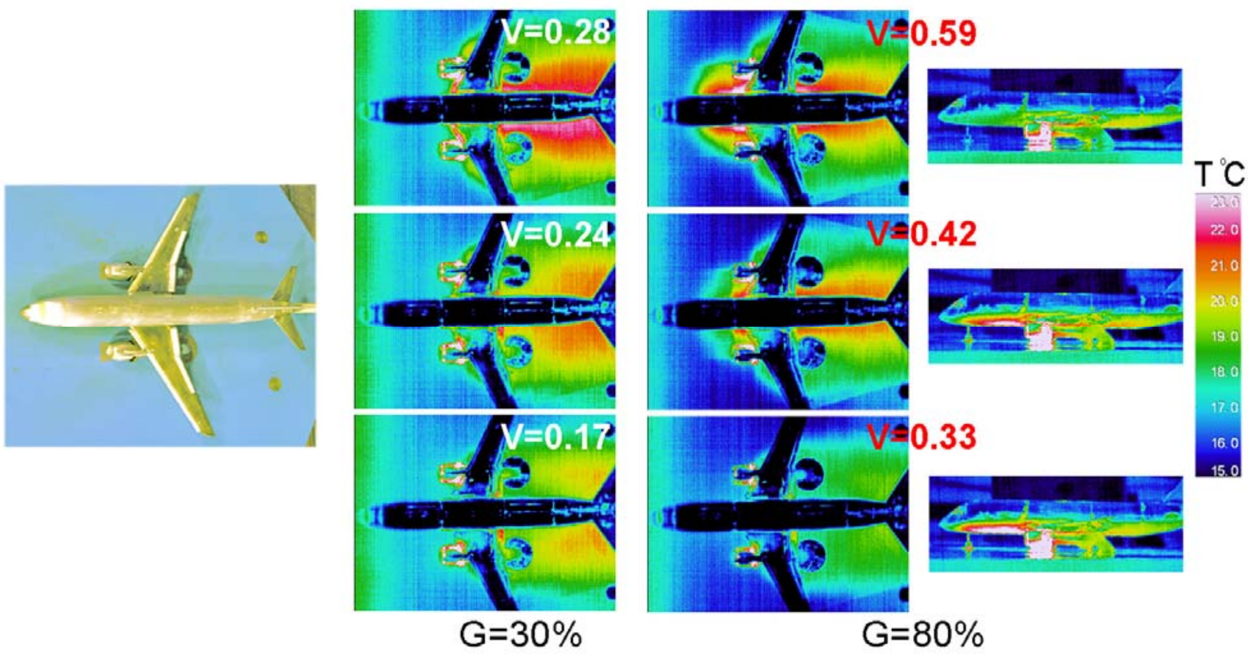

Fig.6 The effect of rolling speed on temperature field at G=30% & G=80% (visible model image and thermograms)

COMPUTATIONAL INVESTIGATIONS INTO THE PECULIARITIES OF THE FLOW PAST THE MODEL WITH THE REVERSER DEPLOYED.

An advanced methodology of numerical computations has allowed researches to perform studies into the peculiarities of flow about the test model on the T-104 tunnels setup with the reverser deployed. These numerical results correspond to one of the setup's operational modes:

M	Po, Pa	To, K	Po rev, Pa	To rev, K
0.163	103222	290	140629	320

Fig.7 demonstrates the flow fields (pressure coefficient C_p) and streamlines issuing from the reverser. An analysis shows that the reversed jets at this mode do not enter the air inlet. This is primarily associated with the fact that the vortex formed on the ground board between the engine nacelle and fuselage is positioned behind the air inlet, which results in the deflection of the streamlines away from the inlet. The absence of the vortex in front of the air inlet in the

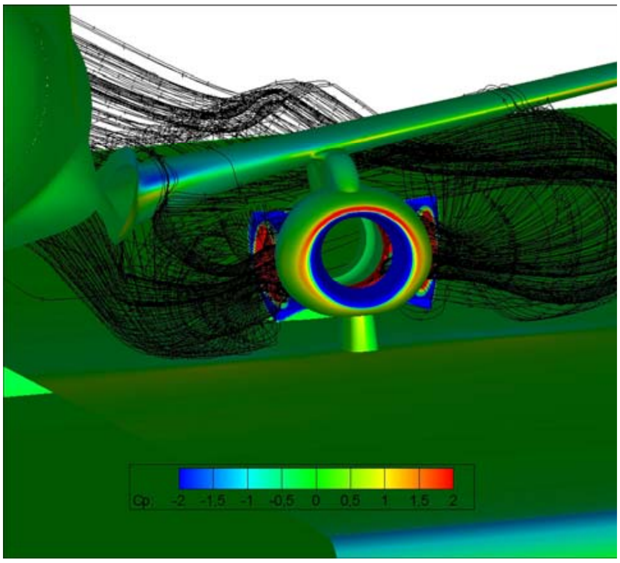

Fig.7 Calculated pressure coefficient field and streamlines in the engine' vicinity

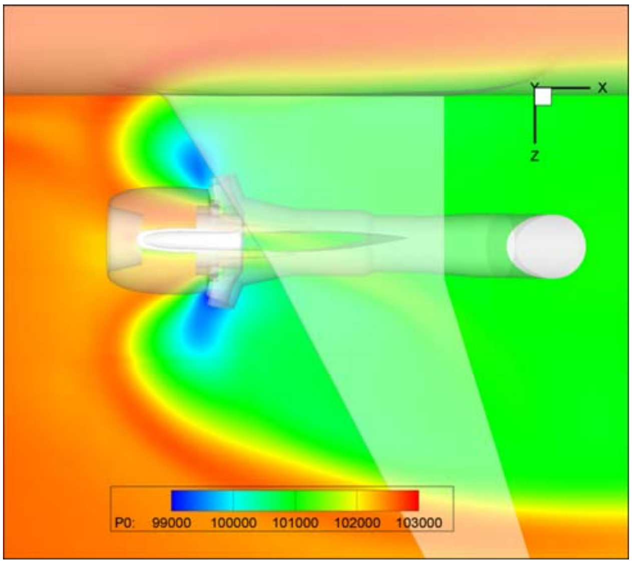

Fig. 8 Calculated total pressure distribution in the engine's vicinity

example presented is governed by an additional pressure generated by the strut delivering hot air to the engine nacelle, which prevents the flow swirling and inversed jets getting into the air inlet.

This effect is seen in Fig.8 where the total pressure distribution field is shown. It is well known that the total pressure pattern contains information on the jet shape. This is dictated by the fact that the total pressure remains constant along the streamline, but it may vary from line to line. As this takes place, the jet boundary distinctly stands out. This is supported by 3D visualization, as is shown in Fig.9. Jets' visualization in the experiments was provided with heaters, and their boundaries on the ground board were monitored with an infrared imager. The temperature field were computed at various Y=const stations, which made it possible to single out reversed jets and provided additional monitoring of their getting into the engine.

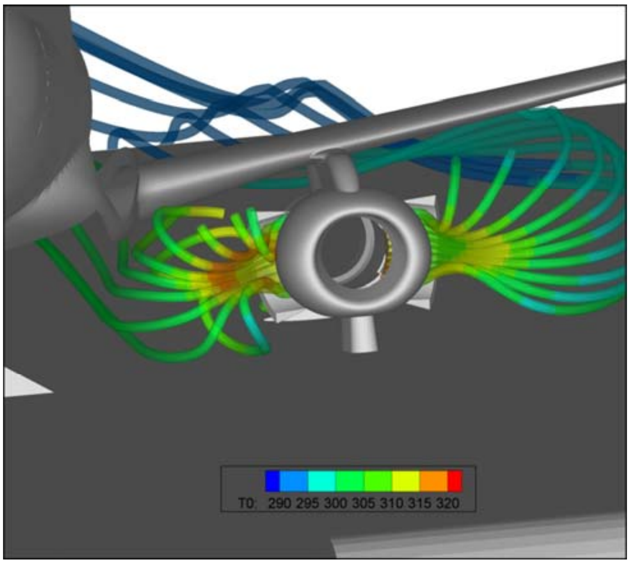

Fig. 9 Calculated stream filaments flowing out of the reverser

Fig.10 demonstrates a section of the computational area at the Y=-0.145 station. One can clearly see that reversed jets do not reach the engine inlet.

These computations were made for one mode of the reverser operation at M=0.163. With decreasing the tunnel flow speed it should be expected without question a greater deflection of the reversed jet in the spanwise direction. Hence the computational results complement and support the experimental findings provided by the special setup. The developed methodology for numerical modeling has also made possible a number of important investigations for further improvement of the setup. For the reverser's mode investigated additional computations were performed to reveal possible distortions of the flow about the model due to the compressed air supplying strut located too close to the engine nacelle and due to the presence of the boundary layer developing behind the bleed slot. The boundary layer on the ground board was removed by passive suction only partially.

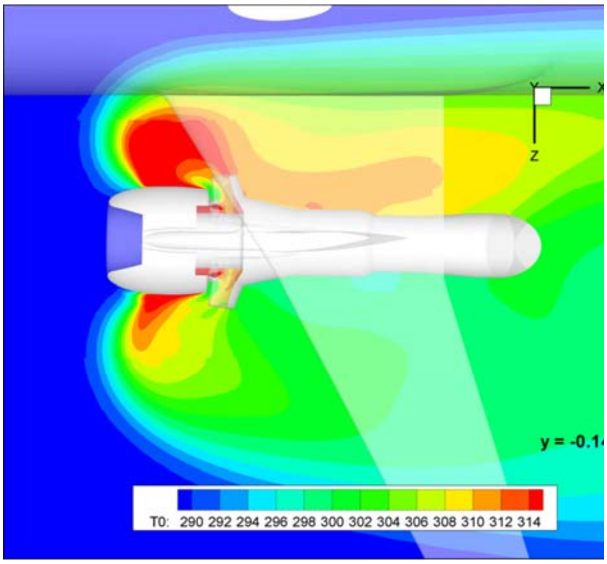

Fig. 10 Calculated temperature field at the Y=-0.145 station

The computations have shown that even a decreased boundary-layer thickness upstream of the engine nacelle influences the interactions of the reversed jets with the ground board and fuselage. The strut near the engine nacelle slightly decelerates the flow and moves the «main» vortex, which normally arises on the ground board, to the area behind the nacelle, and in this case the reversed jet bypasses the air inlet. If the strut is removed altogether or moved further behind the nacelle, the vortex will also be positioned behind the air intake, but stream filaments in this case will overcome opposite pressure and be ingested by the engine. The backpressure due to the strut was sufficient to radically change the flow pattern in front of the engine. If computations does not take into account the boundary layer (to provide moving-ground conditions), the vortex is slightly washed downstream and hot-gas ingestion does not take place.

Thus, the location of the air-supplying strut and the boundary layer on the ground board can provide opposite influence on the test results. The presence of the boundary layer on the board increases the rolling speed at which the reverser is stowed, while the presence of the strut decreases this speed. In the T-104 test conditions, both effects are on the some order of magnitude and cancel each others. Because of this, the results of the experiment to determine the rolling speed at which reversed jets start to enter the engine are sufficiently consistent.

For effective deceleration during landing roll, the latest generation aircraft use, as a rule, a combined aerodynamic braking system with air brakes on the wing and thrust reversers in engine nacelles with side cascade vanes for ejection of reversed hot stream efflux. This new reverse concept uses the capabilities of modern high-bypass-ratio turbofan engines, where the thrust reverser of the main duct can be abandoned. Only the bypass dust is fitted with a thrust reverser whose translating rear cowl forms the slot to eject reversed cold air. The retarding effect is provided not only by the reverse thrust, but also by a peculiar air cushion, formed in front of the aircraft and beneath the wing's lower surface. This significantly increases aircraft aerodynamic drag (as was shown be computations and direct measurements in the T-104 wind tunnel) and provides considerable negative lift, pressing the aircraft to the runway surface. With reversed jets ejected from the side doors on the engine nacelles, there is no lift jump at an intermediate rolling speed, while a negative lift, pressing the aircraft to the runway surface, is generated since the instant of the thrust reverser deployment.

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