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INVESTIGATION OF SYNTHETIC JETS EFFICIENCY ON SEPARATION FLOW IN DIFFUSERS OF DIFFERENT GEOMETRY WITH RANS/ILES-METHOD

D.A.Lyubimov*, I.V.Potekhina*
***Central Institute of Aviation Motors (CIAM)**

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Abstract

Synthetic jets are a perspective means of active flow control. They reduce or eliminate the separation zone, resulting in flow in curvilinear diffuser. This becomes important due to the size reduction tendency of inter-stage diffuser ducts. This paper presents the numerical investigation of the influence of synthetic jets on separation flow in different geometry S-shaped diffusers using high resolution RANS/ILES – method. Parametric investigation of the influence of the amplitude, frequency synthetic jets, as well as the geometric parameters on the flow and turbulent parameters was considered.

1. Introduction.

Modern aircraft turbojet engines tend to compactness of some of their elements. Weight reduction, size reduction and increasing the rate of gas-dynamic perfection result in significant fuel savings. One way of improvement is to reduce the length of the transient diffusers which located between elements of turbojet engine. This inevitably leads to increasing of flow separation and unevenness of flow parameters in the diffuser outlet. To reduce or eliminate the separation zones in the diffuser the most effective is gas-dynamic flow control, which is now being intensively developed. Promising is the use of synthetic jets. In this case, the work of the gas-dynamic flow control system is an alternating cycles of fluid expulsion from a closed cavity by changing its volume, followed then suction of the low-energy flow from diffuser. The cavity is joined only with inner part of the diffuser, so that the total by time mass-flux is zero.

Direct numerical simulation methods began to apply for investigation of turbulent separation flow and gad-dynamic flow control in recent years (DNS, LES, RANS/LES) [1-4]. This is due to the fact that the accuracy of the separation flows description is above using the methods of direct numerical simulation than using methods based on the solution of unsteady Reynolds-averaged Navier-Stokes equations (URANS) with turbulence models. The present study used high resolution RANS/ILES-method. This method has been successfully used for the calculation of separation flows in diffusers including using of synthetic jets [5-8]. In this paper the separation flows and control them using synthetic jets in the S-shaped diffusers of different geometry: annular standard and shortened (“aggressive”), rectangular were investigated in this paper. During the calculations as gas-dynamic parameters of synthetic jets varied (amplitude q/U_0 from 0.4 to 1.4, where U_0 – inlet diffuser speed and the frequency f from 125 to 200Hz) so as geometric: the shape and position of slots for blowing jets. Regime parameters of synthetic jets providing maximum improvement in diffuser performance were selected as a result of calculations.

2. Numerical method.

To perform calculations of separation turbulent flows in diffusers a modified version of a research code, described in [9] was used. A distinctive feature of the code is the use of fifth-order approximation scheme for the convective terms in the Navier-Stokes equations and in the turbulence model. Convective flows on the cell faces were calculated using the Roe scheme:

$$f_{i+1/2} = ½[f(q_L)+f(q_R)] - ½\alpha|A|(q_R - q_L) \quad (1)$$

Here, $f_{i+1/2}$, $f(q_L)$, $f(q_R)$ are vectors of convection terms of the equations on the left-hand and right-hand sides of the cell face, respectively; |A| is the Jacobi matrix determinant; and α is the coefficient regulating the level of scheme viscosity. The parameters q_R and q_L were calculated on the cell faces using the MP5 fifth-order monotonic upwind scheme [10]. An additional decrease in scheme viscosity is attained by reducing the contribution of the diffusion part in expression (1) using the parameter α. At $\alpha_{max} = 1$, expression (1) corresponds to the original Roe scheme. At $\alpha < 1$, a combination of the central-difference and upwind schemes with reduced scheme viscosity is obtained. The minimal value of $\alpha_{min} = 0.3$ was chosen for reasons of stability and preservation of monotonicity of the scheme. This method does not include the explicit SGS model of turbulence. Its function is served by the scheme viscosity (LES with implicit SGS model—ILES).

Diffusion fluxes were calculated on the cell faces using second-order approximations with central differences. The ILES method was used to describe the flow only away from the solid boundaries. Unsteady Navier–Stokes equations with the Spalart–Allmaras model of turbulence [11] were solved in the vicinity of the walls, similar to the case of the hybrid DES method.

Convection fluxes on the faces of computational cells in the difference analog of equation for the turbulence model were calculated using the scalar analog of Eq.(1) with α=1, and the requisite parameters q_R and q_L were calculated using the WENO-5 scheme [10]. Diffusion fluxes were calculated on the cell faces using second-order approximations with central differences.

In the ILES region, the Spalart–Allmaras model of turbulence varies so that the turbulent viscosity should be zero. This is attained by modifying the distance in the dissipation term in the equation for the turbulence model [11]. The new distance $\tilde{d}$ was calculated by the formulas [9]:

$$\tilde{d} = d, \quad d \le C_{DES}\Delta_{max}$$
$$\tilde{d} = d, \quad d > C_{DES}\Delta_{max} \quad (2)$$

In relations (2), d is the true distance from the wall the center of the cell under consideration, C_{DES}=0.65, and Δ_{max} is the maximal size of this grid cell. In the examples described below, the discontinuous pattern of did not affect the solution.

The equations were integrated with respect to time with the second order of accuracy by implicit scheme [9]. The use of implicit scheme enables one to select the time step in view of physical constraints. In this case, the relaxation with respect to the parameter occurs at each time step. In this case, the system of equations of continuity and motion was solved at each iteration using the Gauss–Seidel matrix method, and then the scalar equation was likewise solved using the Gauss–Seidel method.

The described method has been successfully used for the calculation of separation flows in diffusers [7] and in the study of synthetic jets [6], and the combined computational and experimental study of the effect of synthetic jets on the flow in a rectangular diffuser [8].

3. Geometric model and computational mesh.

In this paper two different s-shaped diffusers were considered. The first diffuser - rectangular with area ratio of input and output (aspect ratio - AR) AR = 2.16. The computational domain contains two slots for blowing synthetic jets located on the upper wall of the diffuser (Fig1). Total number of cells of the computational grid was 0.53×106. The second diffuser - annular with AR = 1.5. To save computational resources computational domain is a sector with an angle of 15°, which includes two slots for blowing synthetic jets (Fig.2), full annular channel contains 48 slots.

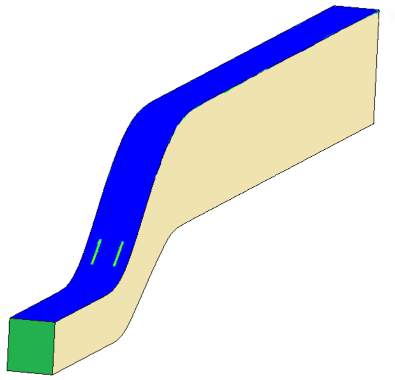

Fig.1. Diffuser geometry.

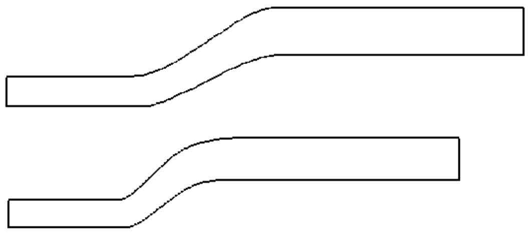

Fig.3. Longitudinal sections of the standard and "aggressive" diffusers.

This computational domain allows to use smaller mesh and more accurately describe the flow in the channel than when considering the entire channel. Total number of cells of the computational grid was 0.88×10^6.Annular diffuser was considered in two geometries: standard and "aggressive". Standard geometry is typical for inter-stage turbine channels. However, due to the trend of size and weight reduction of the engine was considered shorter diffuser. This "aggressive" diffuser 20% shorter than the standard, but has the same area ratio of inlet and outlet. Example of the computational grid is shown in Fig. 2. For all variants of diffuser geometry were applied the same boundary conditions. Periodicity condition is defined on the side faces of the grid. Parameters on the walls were determined depending on the value of Y^+ on the basis of the wall law or no-slip conditions. The total flow parameters and the angle of the velocity vector inclination were specified at the diffuser inlet. A constant static pressure and zero derivatives of all flow parameters along the normal to the boundary were specified at the diffuser outlet.

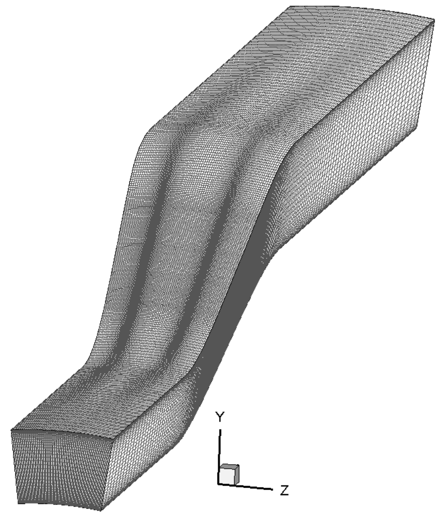

Fig.2. Computation mesh.

To reduce the influence of these simplified boundary conditions straight sections length of 4-6 channel height were docked to the diffuser. Synthetic jets are modeled simply, using the modified boundary condition on the wall of the diffuser [7].With this approach uniform over the area flow parameters distribution varying by time harmonically was specified on part of the wall where jet is blowing. This can significantly reduce the computational cost compared with the calculation of the diffuser with docked generator synthetic jets. Slots for jet blowing were chosen of rectangular shape in all calculations, with a high ratio of length to width along the stream. Slots sizes were 20×0.5mm and 21.5×1mm.

4. Results.

Calculations of rectangular S-shaped diffuser with AR = 2.16 as the basic version without jets, and with jets were performed. The speed at the inlet of the diffuser was 115-150m/s, the total pressure $p_0 = 10^5$ Pa, the temperature T = 300K. Static pressure at outlet $p_{st} = 0.95\times10^5$ Pa. Reynolds number based on the diffuser inlet height the and the inlet speed in all calculations was 0.67×10^5. During the calculations parameters of synthetic jets varied: amplitude q/U_0 from 0.4 to 1.4, the frequency f from 125 to 200Hz, the geometry of the slots. Figure 4 shows the distribution of averaged velocity at the diffuser outlet without jets, and in the presence of synthetic jets. It is seen positive impact of jets: reduced separation zone in the upper part of the diffuser, the flow becomes more uniform at the diffuser outlet, the non-uniformity of the speed distribution is reduced by approximately 25%.

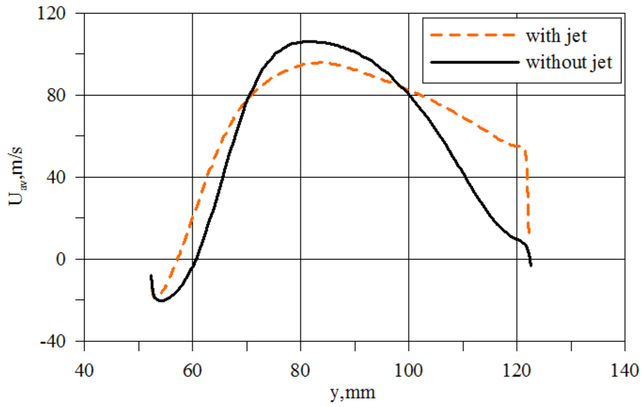

Fig. 4. Averaged longitudinal velocity distribution at the outlet of the diffuser with AR = 2.16.

Table 1 shows the results of calculations of the level of total pressure loss reduction in the diffuser outlet section x=350mm. The following notation is used in table: f - frequency of jets, q- amplitude of the synthetic jet velocity, q/U0 - the amplitude of the synthetic jet velocity divided by the inlet diffuser, Mi - Mach number at the inlet of the diffuser, cμ – momentum coefficient, equal to the ratio of the total synthetic jets momentum and the momentum of the main flow, σ - the total pressure loss coefficient at the outlet of the diffuser, last column shows the effectiveness of synthetic jet equals to the ratio of the difference between the values of σ for the current case and σ0 for base diffuser without synthetic jets to the value of losses in base diffuser (1.0-σ0).

It can be seen that the presence of the synthetic jet leads to a loss reduction in most of the considered variants. Most effective is the frequency f = 150Hz.

On the one hand with increasing of synthetic jets amplitude pressure loss reduces and efficiency of the jet increases. On the other hand it should be understood that the energetically costly to get a jet with a large amplitude, so it's need to evaluate the relationship of synthetic jets momentum and main flow momentum. It is also found that the using of synthetic jets is justified for M at the diffuser inlet is less than 0.5-0.6 [7].

Investigation of the influence of geometry of slot for synthetic jet output on their effectiveness was conducted. It was considered various forms of slots with fixed area from narrow elongated along the flow with ratio of length to width 21.5 to square. Fig. 5 shows the dependence of the total pressure loss reduction on the frequency and the geometry of the slot at fixed amplitude. It can be seen that the most effective is elongated slot with a large ratio of length to width; efficiency is practically independent of frequency. This result confirms the conclusions of [12, 13] about the effectiveness of elongated slots for output of synthetic jets. They also must be at the beginning of the separation zone [7]. Synthetic jet in this case generates a pair of high intensity differently directed vortices. They are carried by the main flow and interact with it and provide delivery of high-speed flow into the separation zone that lead to its reduction or extinction [12, 13].

Table 1

	f, Гц	**q, м/с**	**q/U_0**	**M_i**	**c_μ,%**	**σ**	**σ-σ_0/ (1.0-σ_0), %**
Without jets	-	-	-	0,333	-	0,9613	-
	100	70	0,544	0,373	0.96	0,9689	19.80
	125	70	0,533	0,376	0.94	0,9690	19.82
	150	70	0,507	0,377	0.94	0,9694	20.96
With jets	200	70	0,506	0,375	0.95	0,9693	20.60
	150	50	0,392	0,358	0.53	0,9667	13.82
	150	100	0,772	0,389	1.80	0,9710	25.13
	150	200	1,322	0,397	6.90	0,9747	34.66

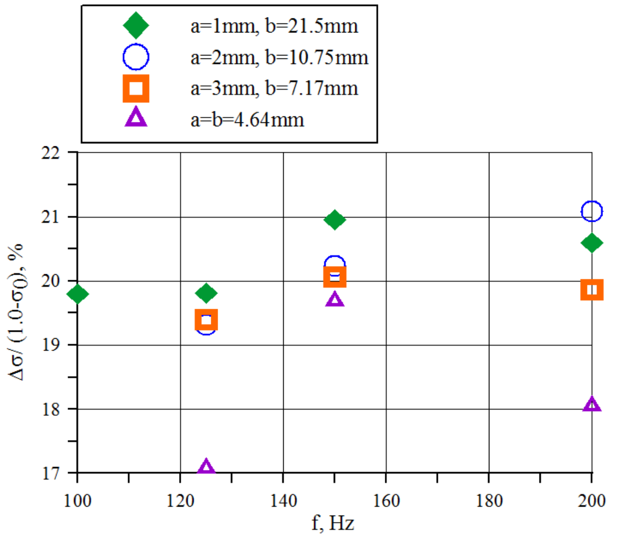

Fig. 5. Dependence of the total pressure loss reduction on the frequency and the geometry of the slot at fixed amplitude of 70m/s.

Also, it facilitates alignment of the parameters distribution in the diffuser outlet. When the slots locate across the flow synthetic jets vortices are rapidly destroyed due to their interaction with the shear flow in the boundary layer [13]. For this diffuser the effectiveness of synthetic jets, when the flow at the inlet has a temperature T=1200K was also investigated. In this case variants of the diffuser with cooled isothermal wall were considered. Cooling can reduce or eliminate the separation zone. These calculations considered the cooling of the upper wall of the diffuser, where occurs the separation zone, the wall temperature was T_W=900K. Calculations have shown that separation zone reduced, the non-uniformity of the averaged velocity distribution reduced (Fig. 6) and total pressure (Fig. 7) at the diffuser outlet when using the cooled wall. If cooled wall include synthetic jet, then there is a further reduction in the separation zone and the non-uniformity of the parameters (Fig. 6.7).

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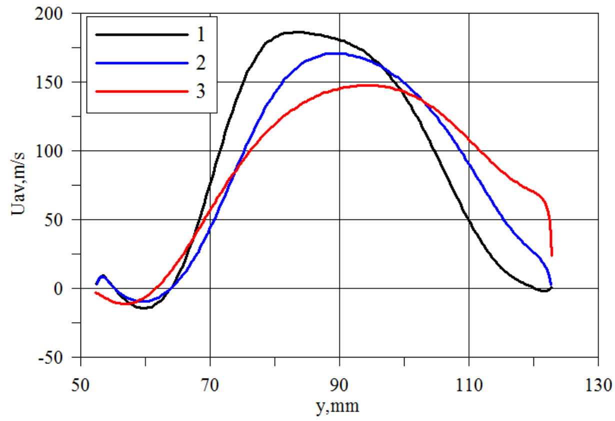

Fig. 6. Longitudinal velocity distribution at the outlet of the diffuser for the hot flow T=1200K. 1-base diffuser without jets; 2-cooled wall Tw=900K; 3 - cooled wall Tw=900K with synthetic jets q=70m/s, f=150Hz.

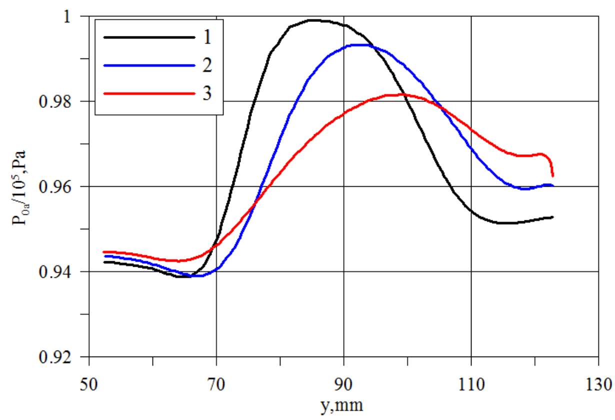

Fig. 7. Distribution of the total pressure at the outlet of the diffuser flow for hot flow T=1200K. 1-base diffuser without jets; 2-cooled wall Tw=900K; 3 - cooled wall Tw=900K with synthetic jets q=70m/s, f=150Hz.

Next were considered separated flows in the annular S-shaped diffusers: standard and "aggressive". During the calculations gas-dynamic parameters of synthetic jets varied (amplitude q/U_0 from 0.5 to 1, and frequency f from 150 to 200Hz). Table 2 shows the results of the calculations for the standard diffuser in Table 3 - for "aggressive"Notations in Table 2 and Table 3 are the same as in Table 1.

Table 2

	f, Гц	q, м/с	q/U$_0$	M$_i$	c$_\mu$,%	σ	σ-σ$_0$/ (1.0-σ$_0$), %
Without jets	-	-		0,356		0,9587	-
	150	70	0,568	0,362	1,23	0,9590	0,77
	150	100	0,773	0,379	2,29	0,9636	11,95
With jets	150	150	1,092	0,411	4,38	0,9719	32,02
	175	70	0,505	0,372	1,16	0,9633	11,32
	200	70	0,571	0,358	1,26	0,9597	2,43

Table 3

	f, Гц	q, м/с	q/U$_0$	M$_i$	c$_\mu$,%	σ	σ-σ$_0$/ (1.0-σ$_0$), %
Without jets	-	-		0,390		0,9626	-
	150	70	0,512	0,402	1,00	0,9649	5,96
	150	100	0,692	0,427	1,80	0,9708	21,99
With jets	150	150	0,988	0,450	3,65	0,9794	44,91
	175	70	0,515	0,400	1,01	0,9639	3,50
	200	70	0,515	0,400	1,01	0,9643	4,59

The synthetic jet reduces the total pressure loss in all of these variants. Position of the slots for blowing jets was chosen so that they are located at the beginning of the separation zone, so "aggressive" diffuser slots located closer to the inlet of the diffuser.

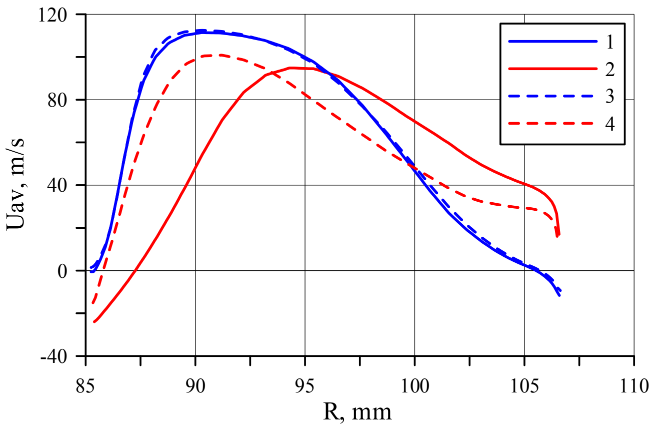

Fig.8. Radial distribution of averaged longitudinal velocity at the exit of the diffusers 1 – standard diffuser, 2 – "aggressive" diffuser, 3 – standard diffuser with synthetic jets q=70m/s and f=175Hz, 4 – "aggressive" diffuser with synthetic jets q=70m/s and f=175Hz.

The effect of synthetic jets on the radial distribution of the parameters in the outlet section of diffusers was studied for mode with amplitude of 70 m/s and frequency of 175Hz. Fig. 8 shows the velocity profile at the exit of "aggressive" diffuser becomes close to the velocity profile of the standard diffuser. This is due to the fact that the use of synthetic jets is significantly reduced separation zone. Fig. 9 shows the distribution of static pressure pulsation in the diffuser outlet for a standard diffuser and "aggressive" diffuser with jets and without them. It is seen that for a standard diffuser level of pulsations is reduced by 2 times, and for "aggressive" in 1.5 times.

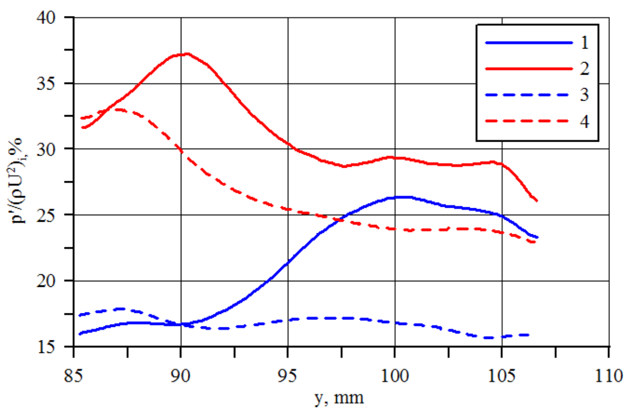

Fig. 9. Radial distribution of pressure pulsations at the exit of the diffusers 1 – standard diffuser, 2 – aggressive diffuser, 3 – standard diffuser with synthetic jets q=70m/s and f=175Hz, 4 – aggressive diffuser with synthetic jets q=70m/s and f=175Hz.

Fig. 10 shows the dependence of the total pressure loss reduction $\Delta\sigma=(1-\sigma)$ on the Mach number M_i for two variants of geometry. It is obvious that the "aggressive" diffuser total pressure loss level is higher than the standard, and with the increasing of velocity at the inlet of the diffuser, this difference increases. These results are caused by greater curvature of the channel walls, which leads to more intensive separation. When exposed synthetic jets with low amplitude q=70 m/s it was obtained that the level of the total pressure loss in the standard diffuser without synthetic jets and in "aggressive" diffuser with synthetic jets the same. Thus, it is possible to reduce the "aggressiveness" of the diffuser and improve its performance.

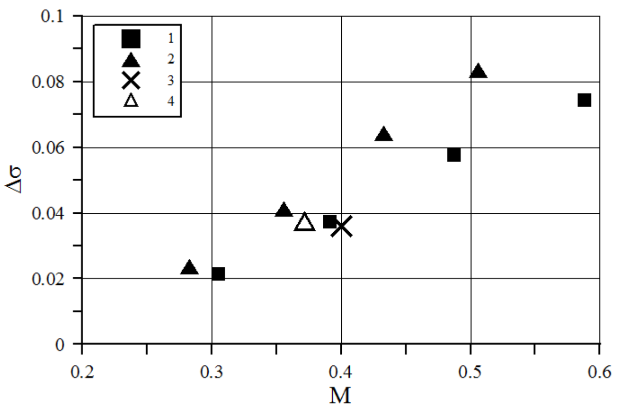

Fig.10. Total pressure losses at the exit of the diffusers. 1 – standard diffuser, 2 – “aggressive” diffuser, 3 – standard diffuser with synthetic jets q=70m/s and f=175Hz, 4 – “aggressive” diffuser with synthetic q=70m/s and f=175Hz.

5. Conclusions.

In this paper, using RANS/ILES-high-resolution method separation turbulent flow in S-shaped diffusers with different geometries: rectangular and annular was investigated. The distributions of flow and turbulence parameters at the diffuser outlet and the dependence of total pressure losses in diffusers from the inlet velocity were obtained.

The possibility of control of separated flow in diffusers using synthetic jets was investigated. During the calculations varied as the gas-dynamic parameters of synthetic jets so geometric parameters of slots for their output. It was found that the mechanism of influence of synthetic jets on separated flow was realized, as described in [12]: the most effective were the narrow elongated slots that generate paired vortices on providing the high-speed flow from the main flow core to separation zone. During calculations found that synthetic jets efficiency depends on the geometry of the diffuser and its AR.

Parametric investigation of influence of gas-dynamic parameters of synthetic jets shown that for the studied diffusers it was found that with the use of synthetic jets is possible to reduce the level of total pressure loss for diffusers with AR =1.5 by 45% and 32% for the standard and “aggressive”, respectively, and for the diffuser with AR=2.16 to 35%. Thus it is possible to reduce the non-uniformity of the velocity and the pressure distribution at the diffuser outlet and to reduce the size of the separation zone. Using of synthetic jets can significantly improve the performance of "aggressive" diffusers and to level up them to the standard diffuser. The momentum of synthetic jets is only 1% of the flow momentum at the inlet of the diffuser.

It was established that the synthetic jets, with the application of the cooling wall substantially reduced separation zone in the diffuser with a hot flow.

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