EXPERIMENTAL AND NUMERICAL RESEARCH OF UNSTEADY FLOW IN CURVILINEAR CHANNEL WITH ACTIVE FLOW MANAGEMENT USING "SYNTHETIC" JETS.

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Abstract

In this paper we presented the results of experimental and computational research on the curvilinear channels with "synthetic" jet generator. The purpose of the experiments was to study effects of "synthetic" jets on flow characteristics in the channel. Collected data show decrease of the level of total pressure losses, depending on various "synthetic" jets generator parameters. In the calculation we used the high resolution large-eddy simulation method (LES) and found that calculated results match with experimental data. Besides, during calculation, we received additional turbulence properties of the flow, which are hard to measure experimentally. Also we investigated geometric and gas-dynamic properties in a wide range.

1 Introduction

The task of creating long-term, cost-effective, environmentally friendly aircraft can't be performed without use of new technologies of flow management based on influence to the flow boundary layer passing through the engine or the ambient airfoil. The flow separation zones degrade the characteristics of transition channels and airfoil, for this reason the flow control is directed primarily at their elimination or reduction. The appearance of flow separation zones is a deterrent to reduce the longitudinal dimension of the transition channels. For this reason, the struggle with the flow separation give much attention. The passive methods of flow control as vortex generators can be used to deal with flow separation in the transition channel. Their simplicity are advantage, but they are not regulated, and always have an impact on the flow, regardless of whether there is the need.

Active flow control is more promising, because the level of influence on flow can be adjusted as needed. The basic active methods of flow separation control are blowing into the boundary layer high energy gas, boundary layer suction and combinations of these methods. The feedback systems are possible to be created: activation and changes in the intensity of the devices will vary depending on the intensity of flow separation. These devices have an organic defect. They require a working body, which requires supply line into the zone of flow separation, and energy. Systems with a suction device require creating a low-pressure line and the exhaust air system. This increases the weight and dimensions of the mentioned systems. The systems with total zero net mass flux (ZNMF) of the working body is the more promising in use. The system of active flow control reduced to alternating clocks blowing gas from a closed cavity, followed by suction low energy flow from the channel. The cavity shall be disclosed only with the channel, so the total time the gas flux rate is zero. Formed by the operation of such devices jets are usually called "synthetic" and devices to create them are called generators of “synthetic” jets (GSJ). GSJ can be compact and can be installed directly at the place of blowing synthetic jet. You do not need a special working body, the system becomes simpler, lighter and more compact, and it can still create a closed-loop system with feedback.

On active control of turbulent flows separation a lot of attend because it have great practical significance of the problem to reduce and prevent flow separation. In [1] studied the effect of "synthetic" slits, its size and shape at the level of losses in the channel. Parameters of the synthetic jet in which the level of losses in the channel decreases were obtained. In work [2] examines the impact of "synthetic" jets on the flow around the airfoil. Numerically and experimentally shown that size of the separation zone on the back of the blade can be significantly reduced. In work [3] author was calculated "synthetic" jets using the LES method. Effectiveness of GSJ in transition channels at high speeds are shown, but there was no comparison with experiment. The authors of [4] was carried out an experimental study of the effect of "synthetic" jets at lower flow rates.

Study of flow in a shorter diffuser channels with the use of "synthetic" jets is the goal of this work is. The combined computational-experimental approach to the problem is a distinctive feature of this work. The experiment was performed which allowed a fairly limited information about the flow, parallel performed calculations using RANS / ILES method [5] made under the same parameters of the flow and channel geometry. During the comparison of calculation and the experiment conducted, which allowed verification of the numerical method. The parameters obtained in the course of the calculation to obtain experimentally difficult. For example it is the field of flow parameters in the channel, the level of fluctuations of flow parameters. A parametric study of the effect of GSJ in dependence of jets geometric and jets outflow mode was performed. The cases that could not be obtained in the experiment because of the model limiters are calculated. Further optimization of parameters such as location and frequency of the GSJ, the shape of the slit was made through the calculations. The data about GSJ with a phase difference between adjacent slits was obtained, which experimental model could generate.

2 Experimental research.

The experimental model is a curved channel with a height of 32 mm input, height of 72 mm output, a width of 150 mm, length 200 mm curved area. The jets were generated by 10 slits 20x0.5 mm, located along the flow, the distance between the slits was 10 mm. The slits located on the upper wall of the channel at a distance 160 mm from the entrance. Power of the GSJ speaker was 80 watts. In the two slit lengths from the GSJ, in section A, has two full pressure combs - in opposite to the GSJ slits, and the second between the two slits. Combs showed a direct impact on the GSJ to profiles of total pressure and total pressure fluctuations near the wall. At the exit of the channel (350 mm from the entrance to the channel - section B), to get the overall level of losses were placed uniformly set of 6x7 combs Pito. Schematic of the experimental model is shown in Fig. 1.

The experiment studied the effect of GSJ on the flow at Mach number 0.1-0.7 at the entrance to the channel. The measurements were performed for three different capacities of the GSJ. Measurements showed that the velocity at the exit slit was approximately 35, 55 and 70 m/s on the resonance frequency 150 Hz. Carried out measurements of the amplitude of the total pressure at the exit of “synthetic” jets with a fixed capacity and different frequencies of the generator. Emission band of the generator was 50 - 700 Hz and a resonance in the band 100 - 200 Hz (Fig. 2.).

The relationships between various parameters GSJ were determined. The loss of total pressure was 0.65% at Mach number M = 0.2, 3.2% for M = 0.4, 7.7% for M = 0.6. The loss begins to increase sharply with M>0.3, which is associated with an increase in separation flow at the upper wall of the channel. Profiles of total pressure and its fluctuations, as well as losses decrease in the channel dependence of the frequency of GSJ obtained with different flow rates and frequency of "synthetic" jet.

Complete elimination of flow separation is observed for the GSJ for M=0.2 with GSJ. Profiles of total pressure at the outlet of the channel are filling up. Static pressure increases and velocity at the outlet of the channel decreases. The optimal frequency of GSJ is 125 Hz. The total pressure lossless at the outlet of the channel is reduced by 40%.

Flow separation zone is significantly reduced at Mach 0.4 with GSJ (Fig. 3.). The position of the flow changes, due to the deep penetration of jets into the stream. In the absence of GSJ, core flow is shifted to one of the side walls of the channel. In the presence of GSJ the general level of the total pressure raised and the flow becomes more symmetric (Fig. 4.). The optimal frequency of GSJ was 275 Hz, it reduced the total pressure loss by 25%.

Flow separation zone does not disappear completely at Mach 0.6 with GSJ. The static pressure increases slightly and flow velocity of channel output is reduced. The flow at the outlet of the channel when using the GSJ becomes more symmetric but not completely. The optimal frequency of GSJ was 225 Hz, which reduced the loss by 18%.

The relative effectiveness of GSJ decreases with increasing Mach number (Fig. 5.). The jets which at a flow rate M = 0.2 reduces the 40% of pressure losses, for M = 0.6 removes only 18% of the pressure losses. Excessive power increase at low speeds reduces the effectiveness of the GSJ, and at certain frequencies may increase the losses. This indicates that there is exists a maximum of efficiency at a given power GSJ. The absolute values of reduction total pressure loss increases with increasing Mach number (Fig. 6.). At the M=0.1-0.2 jets with speed 35 m/s are the most effective. At the M=0.3-0.5 jets with speed 55 and 70 m/s are the most effective. The highest efficiency is observed when the number of Mach 0.6. The pressure losses decrease with increasing power GSJ, which indicates that the limit has not yet been reached. At M=0.7 GSJ fully enters into the flow separation zone, which can not be eliminated, and its efficiency drops.

Assume that the total pressure increase at the outlet of the channel is directly proportional to the total enthalpy change of the flow. Total enthalpy was calculated from the velocity at the channel inlet. Happened that at M>0.3, the enthalpy increase to greater than the power of the GSJ (Fig. 7.). This is because the effect of "synthetic" jet is not just about energy supply, but also in the aerodynamic effects on the stream. According to the electrical efficiency of GSJ is 15%, and thus the real power of "synthetic" jet does not exceed 10W.

The greatest effect of the synthetic jet with speed 75 m/s is achieved at M = 0.6. This can be explained by the fact that at higher flow velocity in the channel requires synthetic jet with higher energy. Also, it may be associated with a change in flow separation zone position in the channel. The dependence of the total pressure lossless at the exit of the channel from the amplitude and frequency of the synthetic jet is complex. The losses with increasing frequency of synthetic jets decrease. For some power of GSJ observed the maximum of performance. The deviation from the optimum power level increases the total pressure losses.

"Synthetic" jet positive impact on low-frequency pulsations of the total pressure. Changes is observed in the flow structure rate of several seconds, associated with the change of the flow core position, the formation and breakdown in the flow of large eddies. When GSJ turn on the general stability of flow increases, low-frequency pulsations disappear.

3 Computational research.

At the present paper to describe the flow we used a combined RANS/LES-method [5], which allows to describe separation zone with reasonable accuracy at moderate computational charges. With this approach, flow near the walls is calculated using the method of time-dependent RANS, and far from them - using LES. Using the combined RANS / LES method improved the accuracy of calculation of separated flows in the diffuser channels [6,3]. There are examples of the use of different variants of the direct numerical simulation to calculate the "synthetic jets" to control flow separation. In the papers [3,7,8,9,10,11,12] different variants of combined RANS/LES methods, including method for calculation of turbulent flows in curved diffusers with different separation flow were used in the calculation. The calculation results obtained using the RANS/ILES method [5], the effect of synthetic jets in a channel with area ratio 1.7 and Mach number at the input of about 0.6 is presented in [13]. Paper[14] include a comparison of these calculations with experiment for the same channel. A good agreement between calculation and experiment was obtained in terms of total pressure loss at the outlet of the channel and in terms of the influence of the synthetic jets parameters on flow in the diffuser.

To perform the calculation of turbulent flow separation in the diffuser channels was used a modified version of the research code JET3D, described in [5]. A distinctive feature of the code is the use of low-diffusive high fifth-order scheme to approximate the convective terms in the Navier-Stokes equations and turbulence model. In conjunction with the special form of writing the difference equations that makes it possible to perform calculations with high accuracy on relatively rough grids, even with a large non-orthogonality and non-uniformity of the grid. A typical mesh in the longitudinal section of the channel is shown in Fig. 8. Grid poins were unevenly distributed. The grid was condensed to the walls of the channel. In the longitudinal direction the similar to the uniform smallest grid was in the conical part of the channel. Non-uniform in the longitudinal direction grid was used in the straight sections of the channel. The maximum step was near the input and output sections. In the rough grid area and around the walls of the channel flow is described using the method of time-dependent RANS - URANS with turbulence model of Spalart-Allmaras and in the separated flow zone, where were used small mesh using the implicit LES with subgrid model ILES.

Modeling of experimental operating modes of GSJ which capacity depends on frequency (Fig. 2) was the purpose of calculations. The amplitude of "synthetic" jets selected close to observed in experiment. It should be noted that there were some differences between conditions of experiment and calculations. Mach number in experiment was fixed and not dependent on frequency of GSJ. At calculations pressure difference was fixed for all modes and is equal to 4200 Pa. The Mach number in the channel changed owing to change of level of losses of a total pressure depending on frequency of “synthetic” jets.

Before comparison of results calculations with experimental data it is necessary to make some remarks. The sector of channel considered in calculation was in the width 20мм with a periodicity condition on walls while the tested channel was width 150 mm. The flow structure in the channel wasn't symmetric (Fig. 4.), that couldn't be found in calculation. The computational grid was constructed so that a step in the longitudinal direction in the output section of the channel was not enough to resolve small turbulent eddies. This led to what is on the bottom wall formed flow separated "laminar" zone, which is somewhat distorted the results and led to an increased level of total pressure losses in the section where made the experimental measurements of total pressure. In addition, the rate of synthetic jets depending of frequency is also evaluated approximately.

Fig. 9 contained the distribution of the relative level of decrease total pressure loss $(1.0\text{-}\sigma)/(1.0\text{-}\sigma_0)$,%, depending on the frequency of GSJ. The data obtained by calculations using RANS/ILES match with experimental data at a frequency $f<200$ Hz. Possible reasons for the differences already described above. We think that at high frequencies are set too low velocity amplitude of “synthetic” jets.

The data provided in Fig. 11 were obtained at a GSJ frequency of 150 Hz and the jets velocity of 70 m/s. Velocity at the channel inlet in the experiment was fixed at M=0.3. Velocity in the calculations was different, without GSJ M=0.33, with GSJ M=0.37. There is good agreement with the level of total pressure pulsations. Flow separation in the calculation stronger because of the higher speeds. To compensate for the strengthening of the separation flow caused by the increase in flow rate, the section was moved 15 mm closer to the entrance. Graphs better match for a location and level (Fig. 12).

Detailed comparison calculations with experimental data for the channel on the same modes showed good adequacy of the calculation method used for such flows. This made possible to take the next step and significantly extend the range of investigated parameters GSJ. Modes that can’t get in experiment were calculated. Jets with high velocities, large frequencies and amplitudes have been investigated. Parameters such as position and velocity angle of the slits of GSJ.

The optimal mode for flow with M = 0.6 was found. The losses in the channel decreased by 51% at a frequency 400 Hz and GSS jet velocity 80 m/s. With these parameters, the effectiveness of GSJ decreases with any change in the frequency and speed of GSS. This indicates that optimal control management on the flow existed. Similar conclusions were obtained from the experimental data for lower flow speeds. The positive effect on M=0.8 was found only at a speed of GSJ 150 m/s. This can be explained that at high speed and kinetic energy of the flow required for the effects "synthetic" jets with more energy.

We investigated the effect of phase difference of “synthetic” jets to flow parameters and efficiency of the impact the jets. The changed parameters of "synthetic" jets ranged within the following limits: amplitude - 50-200 m/s, the frequency - 100-200 Hz, the phase difference between neighboring jets - 0-180°. All other parameters remained unchanged.

Level of total pressure losses at the outlet of channel changed non-monotonically from the phase difference from 0 to 180 and the frequency of the jet. In most cases greater efficiency is observed when the phase difference is 45 ° (Fig. 12). The level of total pressure loss reduction is 21%. The maximum reduction of losses achieved when frequency is 150 Hz and the phase difference is 0°. The least efficiency of "synthetic" jets corresponds to the phase difference 90°. The increase of jets velocity amplitude from 50 m/s to 200 m/s decreased monotonically level of total pressure losses in the channel from 19% to 35%. Increasing "synthetic" jets frequency reduced the total pressure losses non-monotonic. It maximum was observed at a frequency of 150 Hz. The use of "synthetic" jets not only influence to a decrease total pressure losses, but also affects to distributions of averaged parameters and the level of turbulent fluctuations of these parameters at the channel. Unevenness of the time averaged static pressure decreases in the presence of "synthetic" jets.

4 Summary.

Combined experimental and numerical research of "synthetic" jets influence on the flow in the channel was carried out. It was experimentally proved that the level of total pressure losses in the channel can be reduced by half. RANS/ILES method allows investigating the influence to flow characteristics position, frequency and amplitude of the synthetic jets, as well as the phase difference of the neighboring jets. Comparison of numerical simulation results and experimental data in a wide range of parameters "synthetic" jets showed good correspondence of this calculation method for such flows. We found that for all flow modes the synthetic jets improved the characteristics of the channel. It caused by that "synthetic" jets reduce or completely eliminate the flow separation zone on upper wall of the channel. Flow modes in the channel and the parameters of GSJ that could not be obtained experimentally have been investigated numerically. We found that the level of total pressure losses can be decreased by half for flows with Mach number < 0.6. Not-in-phase jets study showed that almost all the investigated modes are useful not-in-phase jets.

Figures

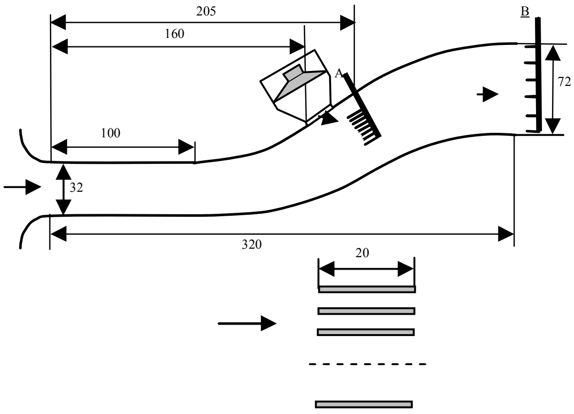

Fig. 1. Description of the experimental model.

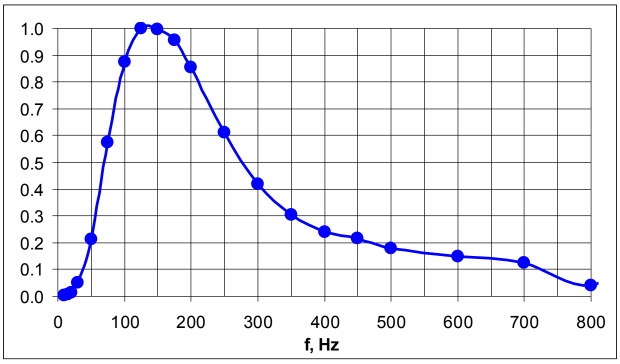

Fig. 2. The dependence of power density from frequency.

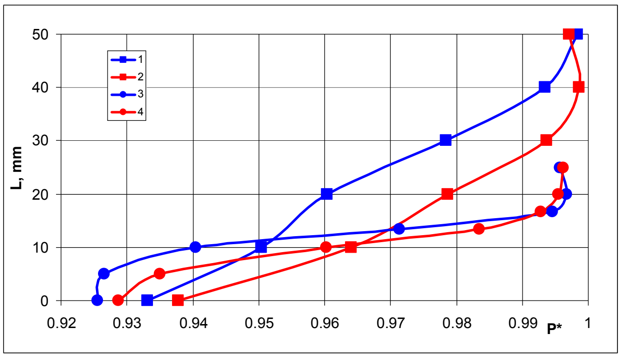

Fig. 3. Distribution of the total pressure values in the various sections of the channel at M=0.4. 1 – sections B, without the GSJ; 2 – sections B, with enabled GSJ; 3 – sections A, without the GSJ; 4 – sections A, with enabled GSJ.

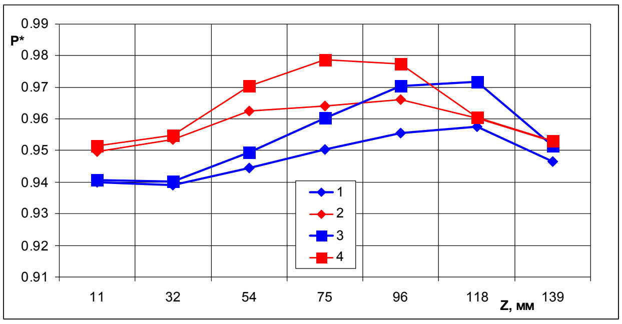

Fig. 4. Distribution of the total pressure values at 10 and 20 mm from the channel's upper wall at M=0.4. 1 - 10 mm from the channel's upper wall without the GSJ; 2 - 10 mm from the channel's upper wall with enabled GSJ; 3 - 20 mm from the channel's upper wall without the GSJ; 4 - 20 mm from the channel's upper wall with enabled GSJ.

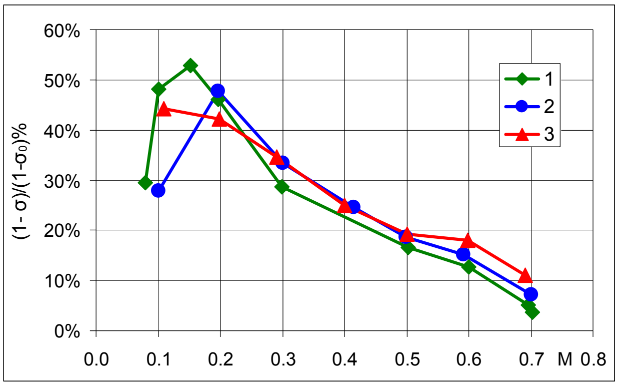

Fig. 5 The level of reduction of total pressure loss relatively base level, depending on the Mach number for three different GSJ velocities. 1 - 35 m/s, 2 - 55 m/s, 3 - 70 m/s. The frequency was chosen from the condition of maximum efficiency.

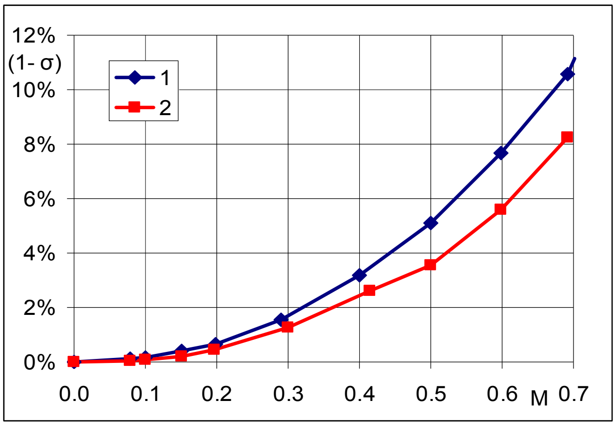

Fig. 6. The total pressure losses in the channel depending Mach number. 1 - without GSJ, 2 - with enabled GSJ.

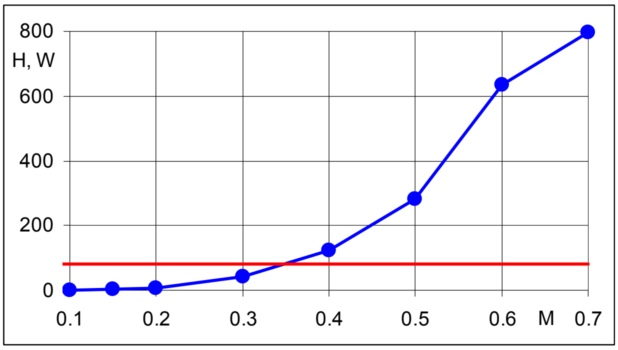

Fig. 7. The increase in total enthalpy flux with using generator "synthetic" jets depending Mach number.

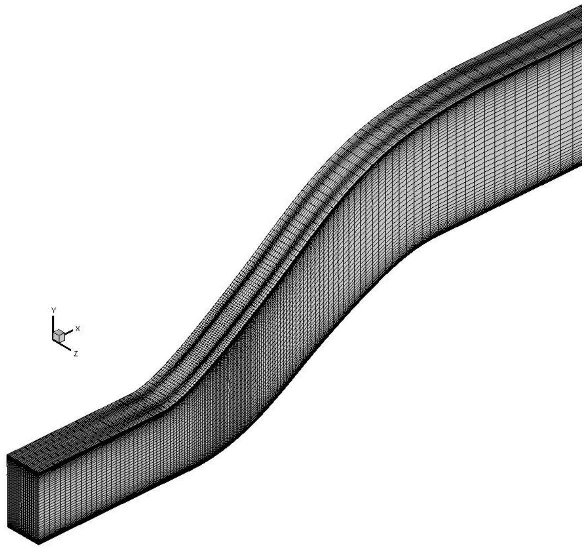

Fig. 8. The computational grid.

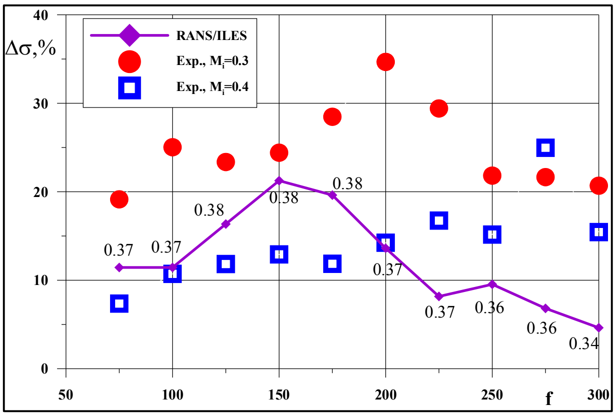

Fig. 9 Dependence of relative reduction of losses of a total pressure layer (1.0-σ)/(1.0-σ₀), %, in section B:X=350мм from frequency of GSJ. Calculations have Mach number tips.

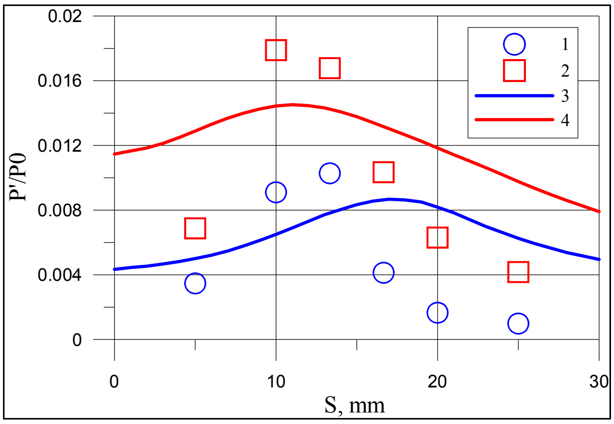

Fig. 10. The levels of pressure fluctuation in section A. 1 - experiment without GSJ, 2 - Experiment with GSJ, 3 - Calculation without GSJ, 4 - Calculation with GSJ. S is the distance from the upper wall of the channel.

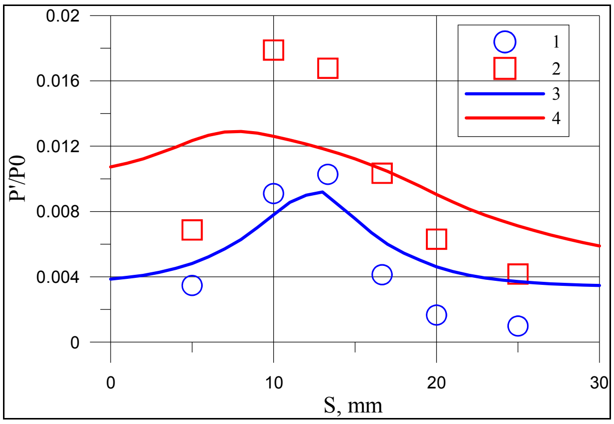

Fig. 11. The levels of pressure fluctuation in section A-15mm. 1 - experiment without GSJ, 2 - Experiment with GSJ, 3 - Calculation without GSJ, 4 - Calculation with GSJ. S is the distance from the upper wall of the channel.

References

[1] Smid E., van Noort H., Hirschberg A., van Emden E., de Vries H., Stobbe H., Zwart G.G.M., Hoeijmakers H.W.M. Experimental Study on Fluidic Control of a Diffuser: influence of slit geometry. *AIAA paper*, № 742, 2009.

[2] Han Z. H., Song W. P., Qiao Z. D. On Limitations of Active Stall Control over a High-Lift Airfoil Using Synthetic Jet Technology. *AIAA paper*, № 534, 2009.

[3] Любимов Д.А. Применение комбинированного RANS/ILES-метода для исследования отрывных пространственных турбулентных течений в криволинейных диффузорах. *ТВТ*, Vol. 48, № 2, p. 261, 2010.

[4] Кашкин Ю.Ф., Макаров А.Ю., Степанов В.А. Экспериментальное и численное исследование нестационарного течения в криволинейном канале с активным управлением структурой течения с помощью «синтетических» струй. *Вестник Нижегородского университета им. Н.И. Лобачевского*, № 4(3), pp 837–839, 2011.

[5] Любимов Д.А. Разработка и применение эффективного RANS/ILES метода для расчета сложных турбулентных струй. *ТВТ*, Vol. 46, № 2, p 271, 2008.

[6] Кашкин Ю.Ф., Крашенинников С.Ю., Любимов Д.А., Панова О.И., Пудовиков Д.Е., Степанов В.А., Торохов С.А. О неоднозначности решения уравнений Рейнольдса при численном моделировании отрывных течений. *Всероссийская Конференция «Современные проблемы механики сплошной среды»,* p 79, 2007.

[7] Hiller S.J., Seitz P.A. The Interaction between a Fluidic Actuator and Main Flow using SAS Turbulence Modeling. *AIAA Paper* №3678, 2006.

[8] Qin N., Hia H., Detached Eddy Simulation of a Synthetic Jet for Flow Control. *Proc. IMechE*, Vol. 222 Part I. J. System and Control Engineering. Special Issue. Paper 373, 2008.

[9] Arunajatesan S., Oyarzun M., Palaviccini M., Catafesta L. Modeling Zero-Net Mass-Flux-Zctuators for Feedback Flow Control. *AIAA Paper* №743. 2009.

[10] Lopez O.D., Moser R.D. Delayed Detaced Eddy Simulation of Flow Over an Airfoil with Synthetic Jet Control. *Mecanica Computational*. Vol. 27, p 3225, 2008.

[11] Кашкин Ю.Ф., Коновалов А.Е., Крашенинников С.Ю., Любимов Д.А., Пудовиков Д.Е., Степанов В.А. Экспериментальное и расчётное исследование особенностей течения с отрывом потока в дозвуковых диффузорах. МЖГ, Vol. 4, p 90, 2009.

[12] Кашкин Ю.Ф., Коновалов Ф.Е., Крашенинников С.Ю., Любимов Д.А., Панова О.И, Пудовиков Д.Е., Степанов В.А., Торохов В.А. Исследование пространственных течений в диффузорных каналах. ТВФ, Vol. 83, № 1(694), p 65, 2009.

[13] Lyubimov D.A. Investigation of Impact of Jets with Zero Net Mass Flux on Flow in Curvilinear Diffusers. High Temperature, Vol. 49, No. 4, pp 540–550, 2011.

[14] Кашкин Ю.Ф., Любимов Д.А., Макаров А.Ю., Пудовиков Д.Е., Торохов С.А. Численное и экспериментальное исследование применения синтетических струй для управления течение в пространственных каналах. Труды ЦИАМ, № 1341. Теоретическая и прикладная газовая динамика. Т.1. Под. Ред. С.Ю. Крашенинникова. М., Торус пресс. 2010.

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