The effect of synthetic jets on heat fluxes in a transitional channel with flow separation

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Abstract. The results of a numerical study of the effect of synthetic jets on the flow in a transition channel using RANS and URANS methods are presented. The total pressure losses in the channel and the heat flux to the wall are estimated.

1. Introduction
The problem of flow separation from a streamlined surface is observed in various modern devices with the motion of a liquid or gas. Occurrence of the separated flow region results in a sharp change in the main performance of devices: increase of total pressure losses and flow non-uniformity, increase in heat flux to surface elements, decrease in lifting force and increase in aerodynamic drag, etc. In connection with this, the actual solution to these problems is the separation control.

To solve the problems of flow separation, various passive and active flow control tools are used, with the help of which it is possible to significantly reduce the area of separated flow or completely eliminate it. The principal difference between passive and active control tools is that passive tools are devoid of regulation in time. Passive flow controls include various kinds of swirlers [1], which are installed just before the separation zone. With their help it is possible to achieve significant reduction of separated flow for definite operation regime. Lack of regulation, low life cycle resource and the danger of destruction greatly complicate their application. These disadvantages are deprived of active flow control tools, by which may be implemented by time control, i.e., turn on or off. This allows not only to control the flow depending on the operating mode, but also to save the working medium. However, the blowing and suction gas [2, 3] which relates to the active agents, require additional air flow rate. In addition, gas manifolds are required for their operation. Therefore, synthetic jets have been recently studied as an active flow control tools [4]. The device for creating synthetic jets is called the synthetic jet generator (SJG), which is a closed cavity with an aperture through which the phases of injection and exhaustion of gas are successively alternated due to oscillation of the actuator (figure 1). The advantage of SJG usage is that it is an independent control system with zero gas flow over time. For its operation, it is only necessary to supply energy to excite oscillations, which are responsible for changing the volume of a closed cavity. In addition, with the help of the SJG, it is possible to implement a pulse-continuous mode of operation that reduces the power consumption.

In this paper an investigated as active flow control tools were selected blocks of existing SJG with 450 fluid jet injection angle to the flow, that have been developed and experimentally studied in [5]. To study the control of a separated flow, a plane model transition channel was chosen [6], in which the
conditions of a real inter-turbine transition channel of a prospective power plant were simulated. The purpose of this paper is to investigate the effect of the SJG on the flow in a flat model transition channel with a detached flow, to estimate the total pressure losses in the channel and the heat flux to the wall in the region of the effect of the SJG.

2. Statement of work

The calculation was carried out using the program complex ESI-ACE+ under a three-dimensional description of the gas-dynamic processes in the cavity of the SJG units. In the calculation, the adjoint problem was solved: calculation of the flow field using RANS and URANS methods in combination with the SST model of turbulence and calculation of the thermal state of a solid body with heat transfer of heat from the flow to the body wall. At the boundary of the solid body and gas, the solution was cross-linked with respect to temperature and heat fluxes. Under calculation the real air model of variable heat capacity was used.

A flat channel with an 15° opening angle consisted of an entrance section of \( H_1 = 75 \) mm height and an output section of \( H_2 = 150 \) mm height with a constant channel width \( L = 100 \) mm. The length of the input and output sections was increased by a length of three calibers from the height of the channels in order to reduce the effect of simplified boundary conditions. Numerical simulation was carried out for the inner part of the SJG unit. Dimensions inside of vibration unit constituted 15x65x58 mm and dimensions 0.5x35x10 mm slot (\( s_l/l_1/h_1 \)). A computational grid was constructed for a flat channel with three SJG blocks (figure 2), the number of cells in the entire region was \( 4.2 \times 10^6 \). Numbers of grid lines in all areas of channel are increased near the walls for better description of flow details. The applied “wall law” on the walls made possible to reduce the number of cells in the entire grid. At the input channel boundary total flow parameters were set (total pressure \( P_0 = 1 \) atm, the total temperature \( T_0 = 1000 \) K). At the channel outlet boundary, the static pressure difference \( P = 2000, 3000, 4000 \) Pa was set. The longitudinal velocity at the inlet varied from 190 to 280 m/s (Mach number \( M_{inlet} = 0.3–0.5 \)). These flow parameters correspond to the parameters at the inlet to the transition channel between the high and low pressure turbine cascades. Temperature of external side of low channel wall was set equal to 500 K. For calculation of heat transfer and effect of synthetic jets on separated flow downstream the place of SJG blocks installation the thickness of steel wall was accepted of 3 mm. The flow control system consisted of three SJG units with injection of synthetic jets at an angle of 45° of 1 kHz frequency. The SJG units were arranged in series one after another in the middle of the inclined section of the transitional channel. The condition for the grid oscillation at the boundary of the membrane was set, which completely reflects the work of the SJG in reality. The grid oscillation was varied according to the harmonic law:

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X = X_A \cos(2\pi ft),
\]

where \( X \) is deflection of the membrane, m; \( X_A \) is amplitude of deflection of the membrane, m; \( f \) is the frequency of oscillation, Hz.

The oscillation frequency and the deflection amplitude of the membranes are 1 kHz and 1 mm, respectively. In this case, a high-frequency synthetic jet acts on the flow along the channel wall. The time step was \( 10^{-5} \) s, while the period of oscillation of the membranes was \( 10^{-3} \) s at a frequency of 1
kHz. Consequently, in the phases of gas injection and exhaustion for one SJG operation period there were 100 calculated points in time.

3. Results
As a result of calculations arrays of flow parameters were obtained for which local and averaged flow characteristics in various channel sections have been identified. Averaging of local parameters over the time and over the area was conducted both for the stationary (RANS) and non-stationary (URANS) task approaches at the input and output channel cross sections.

Figure 3 shows the dependence of the heat flux on the wall $q$ along the channel length and the longitudinal velocity distribution in the symmetry plane at inlet Mach number equal to 0.316 (longitudinal input velocity 193.4 m/s). The calculation was performed in a stationary (RANS) formulation with no operating SJG blocks. It is found that as the Mach number increases at the entrance to the channel, the separation region increases. It leads to an increase in the heat flux to the wall. The maximum heat flux to the wall is observed at the point of flow attachment.

Further computational studies in the model transient channel in the nonstationary (URANS) approach with a flow control system were performed for the Mach number at the channel entrance equal to 0.316 ($U_{\text{inlet}}=193.4$ m/c). Blocks SJG operate in synchronism with an oscillation frequency of 1 kHz at the amplitude of the velocity equal to 220 m/s.

Figure 4 shows the relationship of the Stanton number (St) in the nonstationary (URANS) and stationary settings (RANS) along the length of the channel and the distribution of the longitudinal velocity in the central section and the outlet section at the time moment of 30.3 ms ($U_{\text{RANS}}$).

Figure 4 shows the relationship of the Stanton number (St) in the nonstationary (URANS) and stationary settings (RANS) along the channel length and the distribution of the longitudinal velocity in the central section at the time of 30.3 ms. At the expiration of 20 ms after the beginning of SJG blocks operation there is a complete elimination of the separation region, and time setting of the main flow characteristics. During the operation of the SJG, the average value of the heat flux to the wall is less for a period than without the operation of the SJG. Thus, the SJG operation helps not only to reduce the flow separation, but also to reduce the thermal load on individual structural elements.
To estimate the effect of the SJG blocks operation on the flow in a flat transition channel the exit cross section was selected. Figure 5 shows the longitudinal velocity profiles along the channel height near the curvilinear wall. It should be noted that at various inlet Mach numbers there is a zone of reverse flow near the wall. When inlet Mach number is increased zone of reverse velocities also increases.

In figure 5 there is a change velocity gradient at the wall under the SJG action on the flow in the channel. SJG action increases the flow total impulse and eliminating separation due to increase of near wall velocity.

For comparison an estimation of the total pressure losses in the channel without the work of the SJG (RANS) for various Mach numbers at the input and with the operation of the SJG (URANS) was made. It was found that the level of total pressure loss in the channel outlet transition section increases from 2.2% to 4.5% at increasing the inlet Mach number from 0.3 to 0.5. At SJG operation for 30 ms value of total pressure loss in the outlet section is reduced by 13% at the Mach number at the channel inlet 0.316.

4. Conclusions
Computational studies of the synthetic jets effect on the flow in the model transition channel have been performed. The joint task was solved under the calculations: 1) calculation of the flow field using RANS and URANS methods in combination with the SST-model of turbulence; 2) calculation of the thermal state of a solid wall with heat transfer from the flow into the wall.

Main results are the following:
• In the channel a detachment flow is formed, which is physically caused by a positive pressure gradient on the wall due to the large diffuser expansion angle;
• There is an increment of heat flux into the wall in zone of separated flow;
• When inlet Mach number increases, the dimensions of separated zone is grown and, thus, the heat flux to the wall increases also;
• The maximum heat flux is observed at the point of attachment of the separation flow;
• The SJG increases the total impulse of the near-wall flow, which leads to an increase in the stability of the flow to separation;
• Reduction in the size of the separation region leads to a decrease in the total pressure loss;
• The average value of the heat flux to the wall during the operation of the SJG is less than without the SJG, which is due to the fullness of the velocity profile near the wall. The maximum value of reducing the heat flux to the wall reaches 50%;
• The value of the total pressure losses in the output channel section is reduced under SJG operation by 13% with the 0.316 input Mach number.

Consequently, it can be concluded that the use of SJG in the transition channels allows not only to reduce gas-dynamic losses in the channel, but also to weaken the thermal load on individual structural elements.

Acknowledgments
The authors are grateful to our colleagues from the CIAM, D V Komratov and V A Vinoradov for assistance in the formulation of the problem and in analyzing the results.

The work was supported by the Russian Science Foundation under the grant 18-08-00271.
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