The parametric studies of the effect of synthetic jets on the distribution of heat fluxes in a flat model channel

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Abstract. The results of the calculation of the flow on the plate under the influence of synthetic jets using the RANS and URANS methods are presented. The dependence of the parameters of synthetic jets on the distribution of heat flux into the wall on the plate is shown.

1. Introduction

In the field of internal and external aerodynamics, it is often necessary to control the flow parameters since there is a possibility of a flow separation when the operating mode of the power plant changes. Flow separation on a streamlined surface may increase total pressure losses and aerodynamic drag, and heat fluxes to surface elements, and decrease the lift, etc.

To solve the problems of flow separation, various passive and active flow control tools are used. Passive flow control tools are various kinds of swirlers that are installed directly in the channel [1, 2]. The positive effect of their impact can be obtained only in one mode, since there is no regulation in time. In addition, there is a danger of destruction of the swirl. These shortcomings are not specific for active tools that can adapt to the mode of operation of the power plant. Gas injection and suction gas [3, 4] as active means of controlling the flow are used in many areas. However, their use implies consumption of the working fluid and the necessary lines for the supply and removal of gas. This complicates their application in the channels of the power plant. Therefore, in recent years, active flow control tools with various ways of supplying energy to the flow without the consumption of the working fluid are being investigated: dielectric barrier discharge [5], microwave arresters [6], spark gaps and synthetic jets [7]. A device for creating synthetic jets is called a generator of synthetic jets (SJG) [8], which is a closed cavity with an opening through which the phases of injection and suction of gas alternate sequentially due to the oscillation of the actuator (figure 1). The advantage of using the SJG is that it is an independent control system with zero gas flow over time. For his work it is only necessary to supply energy for the excitation of oscillations, which are responsible for the change in the volume of a closed cavity. In [9, 10], it was shown that the SJG blocks have a positive effect on gas-dynamic and thermal-physical [11] flow parameters in a flat diffuser channel with a separated flow.
The purpose of this work is to investigate the effect of the SJG on the flow in a flat model channel and to estimate the change in heat flux into the wall on the plate as the parameters of synthetic jets change.

2. Statement of work

The calculation was carried out using the ESI ACE + software package by modeling the spatial viscous turbulent flow of a compressible gas based on the Navier-Stokes equations, the integration of which was carried out using a finite-volume numerical scheme of the second order of approximation in spatial coordinates based on the Roe scheme. A distinctive feature of this scheme is to use the exact solution of the one-dimensional self-similar problem of decay of a discontinuity for the determination of the average flow parameters on the faces of the cell. In the calculation, the coupled problem was solved: the calculation of the flow field using the RANS and URANS methods in combination with the SST model of standard-type turbulence and the calculation of the thermal state of a solid with the transfer of heat from the flow into the wall. At the boundary between solid and gas, the solution was joined by temperature and heat fluxes. When calculating, a model of real air with variable heat capacity was used.

A flat model channel with the dimensions of the passage section of 100x100 mm was considered. The length of the pre block SJG was 1.5 calibers from the height of the channel and the length behind the block SJG of 5.5 caliber. In this paper blocks of existing SJG with 90° fluid jet injection angle to the flow were selected as investigated active flow control tools. Numerical simulation was carried out for the inner part of the SJG unit. Dimensions inside the vibration unit were 15x65x58 mm and dimensions of the slot were 0.5x35x2.5 mm (width / length / height). Parametric studies of the SJG block in the model channel were carried out with a change in its location. The first option is one block across the channel (figure 2a) and the second option is two blocks placed along the channel at a distance of 10 mm from each other (figure 2b). A computational grid for a flat channel was constructed for two variants of the SJG block arrangement. Figure 3 shows the grid for a channel with a transversely located SJG block; and the number of cells in the entire region was 3·10⁶. Numbers of grid lines in all areas of channel are increased near the walls for better description of flow details.

Figure 1. SJG operation scheme
At the input channel boundary total flow parameters were set (total pressure $P_0 = 1$ atm, the total temperature $T_0 = 1000$ K). The turbulence parameters $\kappa$ and $\omega$ were set based on the values of the turbulence intensity and the hydraulic diameter of the channel, which were 0.1 and 0.1 m, respectively. At the channel outlet boundary, the static pressure difference $P = 2000$ Pa was set. Behind the SJG blocks, there was a 3 mm thick and 495 mm long steel wall. Temperature of external side of low channel wall was set equal to 500 K.

The condition for the grid oscillation at the boundary of the membrane was set to completely reflect the real work of the SJG. Also, to simplify the numerical simulation, the calculation was carried out for the oscillation of a rectangular wall, rather than a circular membrane. The grid oscillation was varied according to the harmonic law

$$X = X_a \cos\left(\frac{2\pi t}{T_0}\right),$$

where $X$ is the deflection of the membrane, m; $X_a$ is the amplitude of deflection of the membrane, m; and $f$ is the frequency of oscillation, Hz.

The calculation with the transverse arrangement was carried out in three modes of operation of the SJG block. The oscillation frequency and the amplitude of the deviations of the membranes are 1 kHz and 0.2; 0.1; 0.05 mm, respectively. The calculation with a longitudinal arrangement was carried out on one mode of operation of the SJG unit. The oscillation frequency and the amplitude of the deviations of the membranes are 0.9 kHz and 0.05 mm, respectively.

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. Result

As a result of calculations, arrays of flow parameters were obtained, by which local and averaged flow characteristics were determined. When solving the stationary (RANS) and non-stationary (URANS) problems, time and area averaging were performed at the entrance to the channel and on the plate. Time averaging was performed over one period of operation of the SJG blocks after the flow in the channel was established. At the entrance to the channel a flow was formed with a longitudinal speed of 99 m/s, and this speed was constant for all calculations. The flow was formed at the cut of the slots of the SJG blocks, with a frequency corresponding to vibrations of the membranes and speeds of synthetic jets $V_1 = 143$ m/s, $V_2 = 116$ m/s and $V_3 = 79$ m/s.

The dependence of the ratio of the Stanton number $St$ in non-stationary (URANS) and stationary setting (RANS) on the plate from the side of the gas flow was obtained. Figure 4 shows the distribution of gain in reducing the heat flux into the wall when the SJG blocks operate and the longitudinal velocity field in the central section at the time instant is 30.5 ms. The time setting of the main parameters of the flow is observed after 20 ms. In all modes of operation of the SJG unit, the averaged value of the heat flux into the wall on the plate for a period is less than without SJG operation.
Figure 4 shows the nature of the distribution of heat flux into the wall on the plate with a change in the amplitude of the speed of synthetic jets and a constant oscillation frequency of 1 kHz. In the initial part of the plate, up to \( x = 0.07 \) m, with an increase in the amplitude of the velocity, a decrease in the impact from synthetic jets is observed. And in the section above \( x = 0.07 \) m, the opposite effect occurs. This is due to the fact that with an increase in the impulse of the speed of the synthetic jet and the constant speed of the incident flow, the synthetic jet is blown away faster and cools on the plate more intensively. The decrease in heat load in the averaged central section during the operation of the GSS blocks was 15; 18; 17.4%; synthetic jet speed was 143; 116; 79 m / s, respectively. The best mode of operation of the SJG unit is mode 3 \( (V_3 = 79 \text{ m/s at the frequency of 1 kHz}) \), since at a low speed of the synthetic jet there is a significant attenuation of the heat flux into the wall on the plate.

Figure 4. The distribution of gain in reducing the heat flux into the wall when exposed to synthetic jets along the length of the plate and the field of longitudinal velocity at time of 30.5 ms for the first mode of operation of the SJG

Figure 5 shows the dependence of Stanton numbers St in non-stationary (URANS) and stationary setting (RANS) along the channel width at a distance of 0.1 m from the beginning of the plate (figure 4). Figure 5a shows the distribution of the number St for the best SJG operating mode with a transverse arrangement, and in Figure 5b for the second version of the calculation with a longitudinal arrangement. The gain in reducing the heat load during the operation of the SJG blocks when averaged over the entire channel width for one period of operation of the SJG block is 5 and 0.5%, for the transverse and longitudinal location, respectively. It is shown that the distribution of parameters on the wall has a complex three-dimensional character under the influence of synthetic jets. With the transverse arrangement of the SJG block (Figure 5a), the maximum reduction in heat load is observed in the central section of the SJG block slot. In areas along the edges of the gap, the deterioration of parameters on the walls is observed. This may be due to the shape of the injection slot for synthetic jets. In the case of the longitudinal arrangement of the SJG blocks (Figure 5b), the deterioration of the parameters is observed both along the edges of the slots and between them.
Figure 5. The distribution of the Stanton number across the width of the plate at the distance $x = 0.1$ m: a – transverse arrangement (third mode), b – longitudinal arrangement

To reduce the heat load, it is necessary to adjust the number of slots and their shape in order to achieve the best result across the channel width. Thus the laws of formation and distribution of synthetic jets depends not only on the operating parameters of SJG blocks, but also on the location of the SJG blocks in the channel and form of slits for blowing synthetic jets.

Conclusion

Using parametric computational studies, laws were obtained for the formation and propagation of synthetic jets in a flat model channel, and the best mode of operation of the SJG unit was selected from the point of view of reducing the thermal load on the plate.

Calculation studies have shown that with an increase in the amplitude of the speed of a synthetic jet, the nature of the distribution of the heat flux into the wall on the plate changes. The best mode of operation of the SJG is achieved with the following parameters: the amplitude of the velocity $V_3 = 79$ m/s and the frequency of 1 kHz at the speed of the incident flow of 99 m/s. The gain in reducing the heat flux into the wall is 17.4% with the best mode of SJG operation.

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