Numerical Simulation Of Turbulent Flow Behind The Diaphragm With Periodic Consumption Pulsations

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Abstract-The motion of liquids and gases in technical devices rarely occurs without external disturbances that lead to the change of environment flow regimes and flow characteristics. Besides, a joint effect of disturbances on the flow is possible. The article describes the results of a three-dimensional numerical simulation of a separated turbulent flow of viscous compressible fluid in a channel behind the diaphragm. The periodic pulsations of flow in a stream at the frequency of 230 Hz are initiated by a periodic function of mass flow changes in time. The calculations use the Reynolds-averaged Navier-Stokes equations of continuity and energy in a three-dimensional statement (RANS), the ideal gas equation, the equations of quadratic high Reynolds standard k-ε of turbulence model with standard wall functions. The implementation of numerical experiment was carried out in the software package STAR-CCM + using a computational grid, consisting of 1.6 million cubic cells. The values of friction coefficient on the channel wall and the coordinates of separated flow attachment points are determined. The vortex flow structure is analyzed. It was noted that during the oscillation period the tear zone is expanded and then divided into two swirls, one of which is detached and carried away by the flow and the other one begins to stretch. Therefore, at certain periods of time a sharp reduction of separation zone length takes place. The results are qualitatively consistent with the experimental data and confirm the presence of a complex three-dimensional non-stationary vortex structure of a separated pulsating flow. A satisfactory quantitative agreement of calculation results is reached along the integral and separate local flow parameters.

Keywords: separated flow, friction coefficient, turbulence, periodic pulsations of flow, vortex structure.

1. INTRODUCTION

The movement of liquids and gases through the devices, including pipelines, rarely occurs without external disturbances. This fact and the turning on of valves, and the adjustment of modes by regulatory equipment, and the changes of consumption volume, etc. take place. These effects lead to changes of environment flow modes, first of all, they become non-stationary, the hydraulic resistance varies, the additional effects with the possibility of resonance phenomena appear [1, 2].For example, it is the imposition of external disturbances on the own acoustic oscillations of environment [3]. Thus, the combined influence of disturbances which differ from the initial exposure is possible.

In this regard, it is necessary to carry out a detailed study of specific external disturbance influence on the flow parameters and eliminate the dependence on other factors if possible.

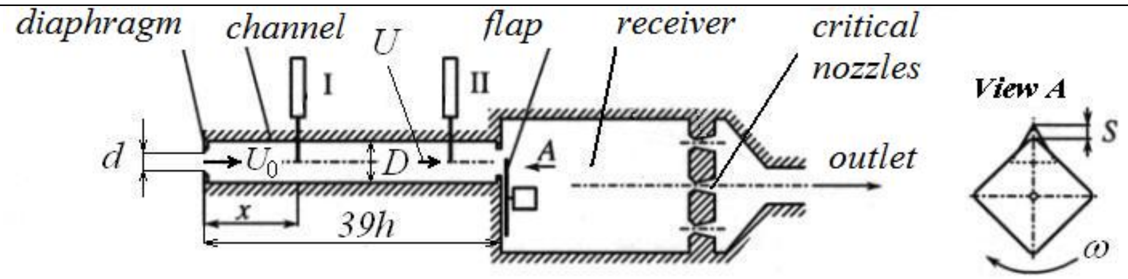

Fig.1. The experimental device scheme [5]

2. RESEARCH METHODOLOGY

The present study is based on the data of [4, 5], which studied the local characteristics of air flow in a cylindrical tube with an aperture at the entrance and a triangular hole in the output. Superimposed pulsations of flow were created by the rotation of a rhomboid flap, occasionally overlapping an outlet. In order to eliminate the influence of resonance phenomena associated with the proximity of superimposed pulsation frequencies and the acoustic vibrations of gas an experimental device is used (Figure 1) with a reduced length channel 39h (h = 12 mm - the distance from the aperture edge, d = 40 mm to the channel wall D = 64 mm). The studies were carried out at three different values of air average flow through the critical nozzles (0.0148, 0.027, 0.0533 m^3/s) in a wide frequency range f = 0-380 Hz.

In particular, the author [4] observed the evolution of a separation zone in the experiment, caused by superimposed pulsation of flow during time. Based on the analysis of conditionally averaged characteristics they were proposed with the following flow pattern in the separation region at imposed flow pulsations (Figure 2).

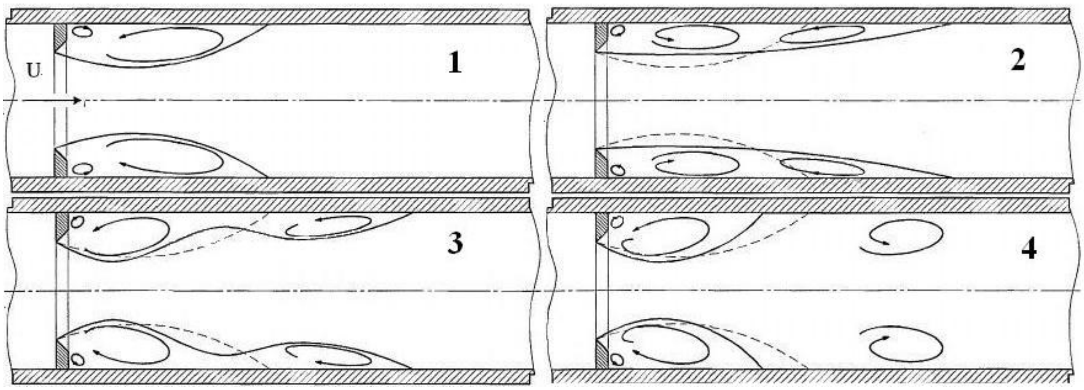

Fig.2. The flow pattern in the separation region behind the diaphragm at the imposed flow pulsations [4]

By lowering the pressure the resulting area of dilution is filled with air from neighboring areas downstream. At that the axial velocity drops - the tear zone is "elongated" in the longitudinal direction and reduced in a transverse direction. Moreover, a large part of the period is characterized by a maximum axial velocity at the distance of 55 mm from the diaphragm section (the main flow compression is the maximum one).

The process of separation zone lengthening ends by its abrupt reduction during the emissions and the demolition of the vortex downstream from the recirculation zone. Then the process begins again.

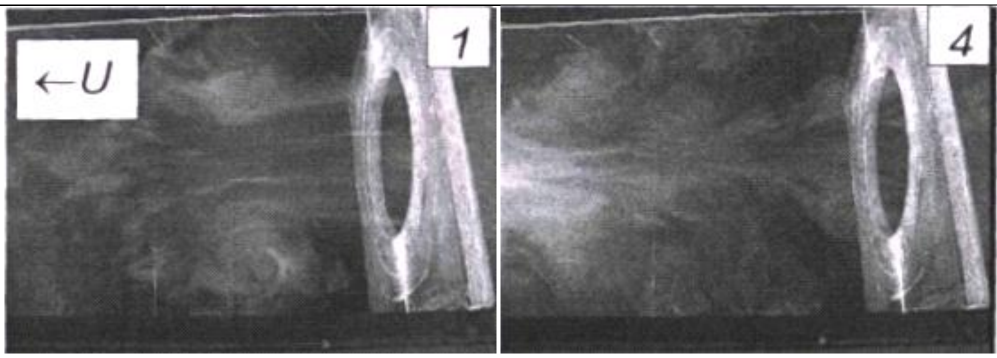

Fig. 3. The results of pulsating separated flow smoke visualization behind the diaphragm [4]

The smoke visualization [4] of a pulsating separated flow behind the diaphragm (Fig. 3) showed that the toroidal vortices with the frequency equal to the imposed pulsation are developed behind the diaphragm edge.

After the toroidal vortex separation from the edge of the diaphragm a central plume follows after it for some time, thereby forming a mushroom structure. Thenthecycleisrepeated.

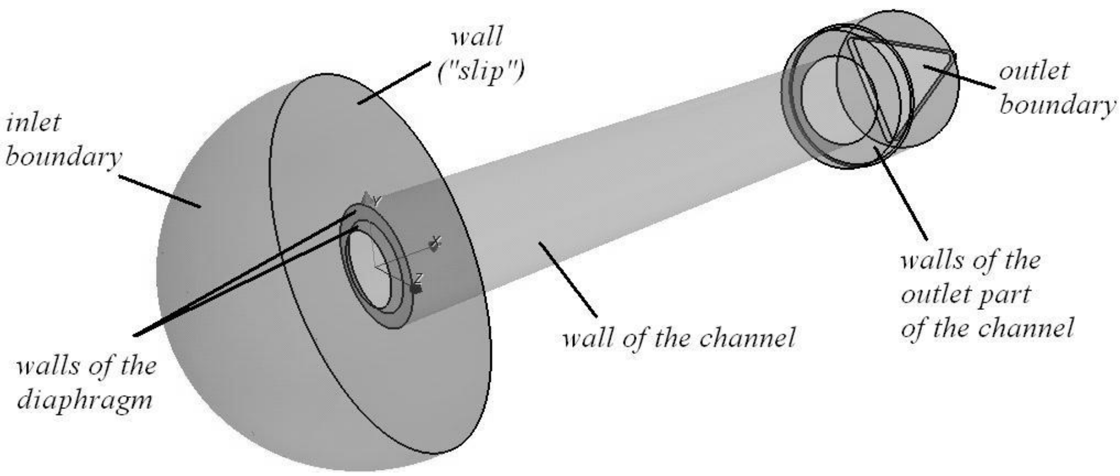

Fig.4. Calculation domain scheme.Boundary conditions

In order to obtain such data by numerical method [6] it is necessary to provide full terms of the physical experiment in the mathematical model. However, computing resources and time factor require the use of simplifications. The rotation of a damper with a fourfold outlet channel overlap with respect to the number of rotations is replaced by a harmonic function of mass flow change. The air intake from an unlimited area is modeled by the ingression of the environment through a special inlet added hemispherical region (Figure 4), the radius of which is selected on the recommendations of [7].

A mathematical model of unsteady turbulent flow of viscous compressible gas (air) included the following equations: 1) Reynolds-averaged Navier-Stokes and continuity (RANS) equations in a three-dimensional formulation [8]; 2) the differential equation of total enthalpy transfer (energy equation) [9]; 3) ideal gas equation; 4) the equations of standard highly Reynolds quadratic k-ε turbulence model with standard wall functions [9, 10].

Estimated area and its boundaries are shown on Figure 4.

At the entrance boundary the condition of "braking at the entrance» (stagnation inlet) is applied. The following parameters are given: the brake pressure (total pressure) of 101325 Pa, the total temperature of 20 °C, the turbulence parameters - turbulence intensity 0.001, relative turbulent viscosity 10.

The outlet boundary uses the condition of "mass flow inlet". In the steady flow The mean mass flow rate according to the average volume is determined $Q_{mCP} = -191{,}89$ m^3/h. The unsteady flow is represented by harmonic function of mass flow change (f - superimposed pulsation frequency, t - time):

$$Q_m(t) = Q_{mCP} \cdot \left(1 + 0{,}3 \cdot \sin\left[2\pi \cdot f \cdot t\right]\right).$$

The channel walls have the conditions of "tightness" and "no-slip", and a flat wall of an additional input field has the condition of "tightness". Theadiabaticflowisacceptedforallcalculationdomain.

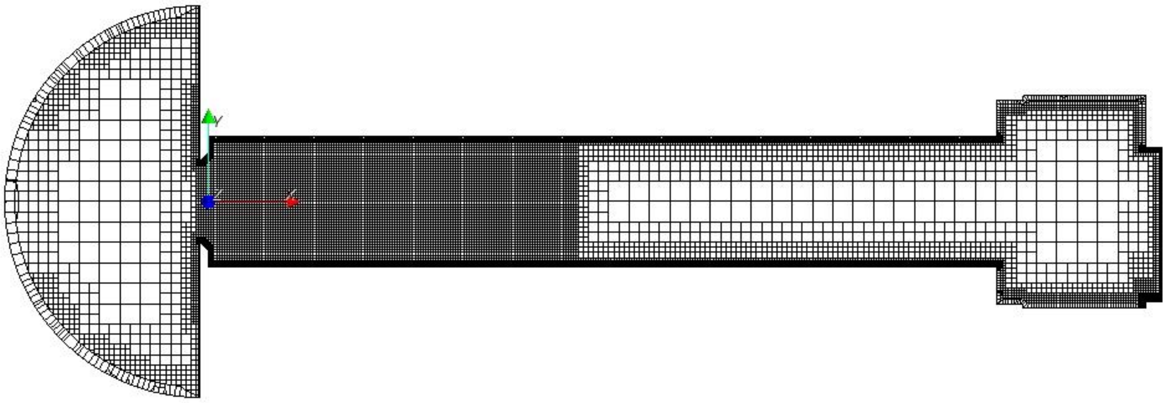

Figure 5. The calculated mesh in a longitudinal channel section

The implementation of numerical experiment was carried out in the software package STAR-CCM + [9].

The computational domain sampling was performed using computational the cells of the cubic form calculation grid (Figure 5), which are modified in the non-planar boundaries (Trimmer [9]). The grid thickening is used near the walls using the layers of prismatic cells.

The main parameters of the computational grid are as follows: the total number of cells makes about 1.6m., the size of the basic cells makes 5 mm., the cell growth rate from the surface makes 1.01, the size of the first wall cell along the normal to the wall makes 0.9 mm. The local dimensions of cells (Figure 6): 10-50 mm. within the inlet region, 2 mm. in the most critical area behind the diaphragm, 0.9 mm. at the edge of the diaphragm and the outlet wall, 1 mm. at the output border, 1 mm. along the channel wall, 2 mm. along the walls of the outlet channel part.

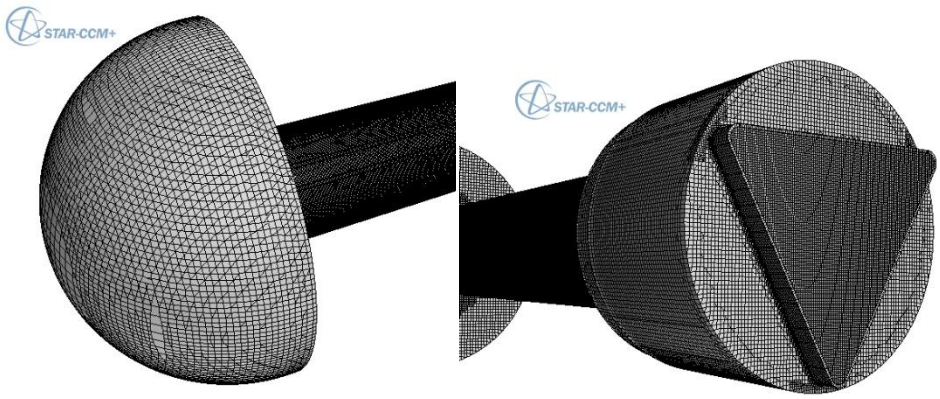

Figure 6. The fragments of the computational grid: borders - the inlet (on the left) and outlet (on the right)

At the initial stage it is necessary to solve a stationary problem. The convergence criteria were the pressure stabilization on inlet and the speeds on the output border and the level of of mean square residuals for all equations no more than 10^{-4}. The resulting solution was used as an initial approximation for each variant (according to imposed pulsation frequency f) of an unsteady flow.

During the simulation of unsteady flows the time step made 10^{-4} s. ("The survey frequency of sensors" made 10 kHz), the total simulation time made 0.03 seconds. ("The survey period"). The number of iterations within each step was chosen from the condition of discrepancy level reduction at least until 10^{-4}. The coefficient of surface friction C_f is related to dynamic pressure specified for the averaged flow rate by section and time in the channel below the point of attachment.

3. STUDY RESULTS AND THEIR DISCUSSION

Some results of numerical modeling concerning the considered separated turbulent flow with superimposed fluctuations at an average volume flow of 191.89 m3/h and superimposed pulsation frequency f = 230 Hz are shown on Figures 7-9.

After the distribution of surface friction calculation coefficient along the channel wall at different time points (Figure 7), the elongation of separation zone occurs first of all to decrease the shear stress at the wall. Then the recirculation zone is divided into two parts with different rotation directions. During the next moments of time a downstream vortex is separated and the remaining vortex begins to stretch.

Here, the length of the recirculation zone is determined according to the point position with a zero friction ratio value. According to the change of the friction coefficient sign one may judge on the direction of air motion in the near-wall layers, and, accordingly, on the direction of vortex rotation.

The experimental data [4] confirmed that at the frequency of imposed pulsations making 230 Hz at certain moments of time a sharp reduction of the recirculation zone X_R length takes place due to the vortex separation.

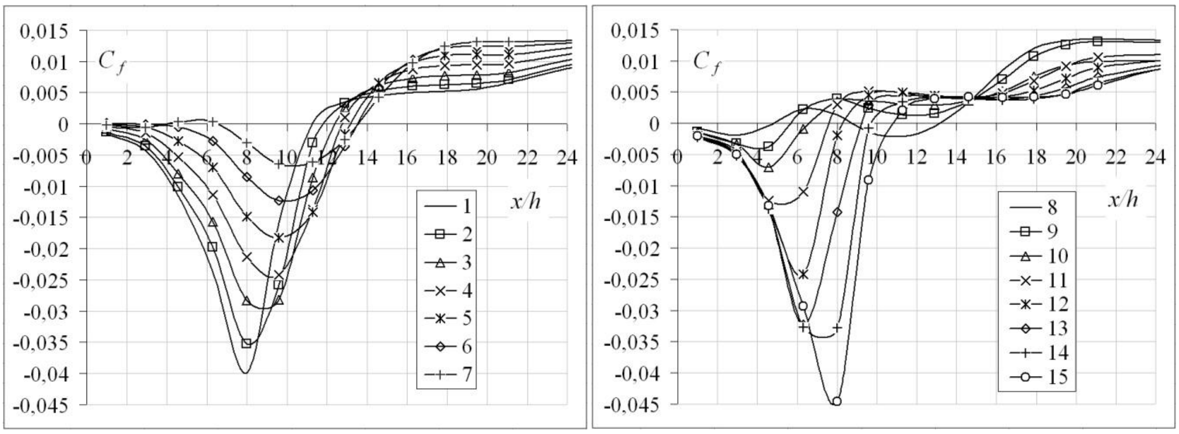

Fig.7. The distribution of surface friction ratio along the wall at different moments of time 1, 2, ... 15 (time step makes 0.0003 s) at the average volumetric flow rate of 191.89 m^3/h for the pulsing one with the frequency f = 230 Hz of a tear-off turbulent flow

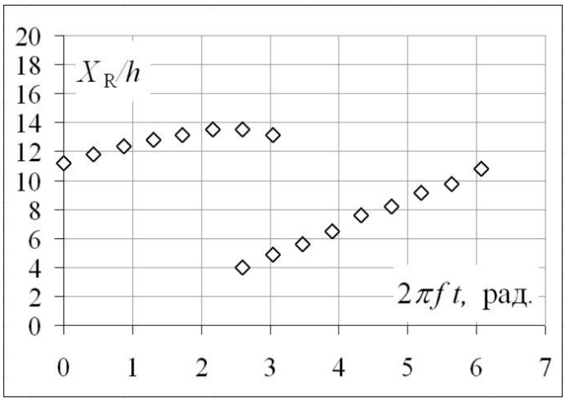

Fig.8. The distribution of a tear-off zone in different moments of time at an average volumetric flow rate of 191.89 m^3/h for the pulsing one with the frequency f = 230 Hz of a tear-off turbulent flow

Figure 8 shows that during the observation of vortex structure changes in the moments of time $2\pi \cdot f \cdot t$, equal to 2,6 radand 3 rad, there are two points of a separated flow attachment. Also, the graph shows that the formation of a new vortex on the diaphragm section begins after the separation of an original vortex with the frequency coinciding with the frequency of superimposed pulsations f.

Fig.9. The scalar field of Q-criterion at different moments of time in the longitudinal section of the channel behind the diaphragm (dark color marks the areas with Q<0, white color marks the areas with Q> 0)

Figure 9 presented a scalar field of Q-criterion in the longitudinal section of the channel at different moments of time. Q-criterion was calculated in the program STAR-CCM + according to the following formula:

$$Q = \frac{1}{2} \cdot \left(\|\Omega\|^2 - \|S\|^2 \right),$$

where Ω – vortex tensor, S – relative strain rate tensor.

According to the formulation of Q-criterion, the negative values correspond to the regions with the predominant deformational movement of a flow, and positive values correspond to the zones with dominant vortex motion.

On the left picture you can see the elongation of the recirculation zone with the release of a large toroidal vortex in it near the point of flow attachment. You may also note there an angular vortex behid the diaphragm near the channel wall. As in the experiments [4], the vortex flow is observed at the boundary between the tear-off zone and the main flow. The central picture demonstrates the disconnection of the toroidal vortex from the recirculation zone. The third picture demonstrates a significant reduction of the separation zone length. At the same time, the separated vortex taken away by the main flow is stretched slightly, and a central plume is developed behind it, which was specified in the work [4].

4.CONCLUSION

The obtained results of numerical modeling agree qualitatively with the experimental data and confirm the complex three-dimensional non-stationary vortex structure of a separated pulsating flow. Satisfactory quantitative results are achieved along integral and separate the local flow parameters.

5. SUMMARY

It is necessary to use a high-quality mesh, more complex models of turbulence, the real gas equations, etc. for a detailed study of the flow under consideration.

CONFLICT OF INTEREST

The author confirms that the presented data do not contain any conflict of interest.

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REFERENCES

[1] Galitseisky, B.M. The thermal and hydrodynamic processes in oscillating flows / B.M. Galitseisky, Y.A. Ryzhov, E.V. Yakush. - M.: Engineering, 1977. - 256 p.

[2] Kraev, V.M. The influence of hydrodynamic nonstationarity on the hydraulic resistance in a pipe // University news. Aviation equipment. - 2003. - №4.- pp. 73-75.

[3] Molochnikov V.M. Experimental study of the developed turbulent flow in a circular tube with periodic flow pulsations. Part 1. Pressure loss and resonance phenomena / V.M. Molochnikov, L.A. Feoktistova, G.V. Stinsky, N.S. Dushyn, O.A. Dushina // RAS news. Energy. - 2005. - №6.- pp. 25-31.

[4] Davletshin, I.A. The hydrodynamic and thermal processes in turbulent pulsating flows: Abstract from the thesis of techn. science Doctor / I.A. Davletshin. - Kazan, 2009. - 42 p.

[5] Davletshin, I.A. Pulsating flow separation / I.A. Davletshin, N.I. Mikheev, V.M. Molochnikov // Reports of the Academy of Sciences. Volume 417. - 2007. - №6.- pp. 760-763.

[6] Anderson, D. Computational fluid dynamics and heat exchange / D. Anderson, J. Tannehill, R. Pletcher. In 2 v. V. 1. - M.: Mir, 1990. - 384 p.

[7] Boldyrev A.V. The estimation of the inlet area border influence on the simulation results of separated turbulent flow / A.V. Boldyrev, S.V. Boldyrev, S.I. Kharchuk, S.S. Kharchuk // Scientific and Technical Gazette of Volga region. - 2011. - №5.- pp. 22-26.

[8] Loitsiansky, L.G. Fluid and gas mechanics. - 7-th ed., Rev. - M.: Drofa, 2003. - 846 p.

[9] User Guide STAR-CCM+ Version 7.04.006. - CD-adapco, 2012.

[10] Belov, I.A. Simulation of turbulent flows: Textbook / I.A. Belov, S.A. Isaev. - SPb.: Balt. StateTechn. University, 2001. - 108 p.