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Prospects for Practical Application Conditions of Abnormally High Amplitude Self-Oscillating Fluid Flow (Part 1)

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***Abstract:** The outflow of an incompressible fluid from a rectangular opening covered by a semicircular arched element is considered. The self-oscillatory expiration regime is numerically investigated. The computational algorithm implemented in the STAR-CCM+ software package includes a grid approximation in space, an implicit time integration method, and an algebraic multi-grid method for solving systems of algebraic equations. A variant of the hole geometry with an aspect ratio of $l/d = 2$ is considered. An explanation is given to the mechanism of the self-oscillatory process. The distribution of oscillation amplitude values in space at the exit from the hole is determined. Some possibilities of practical application of the described phenomenon are determined.*

***Keywords:** Navier-Stokes equations, incompressible fluid, turbulent flow, self-oscillation, numerical simulation.*

I.INTRODUCTION

Self-oscillating flows from holes covered by an arched element are of great practical and research interest in scientific and engineering problems of air distribution, liquid dispersion, mixing of poorly miscible liquids, and fuel combustion. However, there are very few works on the study of the flow mechanism and the characteristics of the self-oscillatory process.

Today it is already clear that the detected abnormally fast attenuation of the resulting ventilation air flow in the environment, noted in [1], has a powerful self-oscillatory process in its nature. This first mention was interpreted as the effect of the collision of opposing jets applied to ventilation technology.

The works [2, 3] are devoted to the interaction of two counter-coaxial flows. The work [2] presents the results of experimental studies of air flows from dimple holes. A rapid drop in the flow velocity downstream of the dimple hole was found. When explaining the mechanism of damping the flow velocity when outflowing from the hole, the presence of an oscillatory process was not noted. The work [3] presents the first attempts to study the process by methods of numerical simulation. The calculation results showed the presence of a periodic self-oscillating flow. The estimation of the influence of the geometric parameters of the hole on the characteristics of the self-oscillatory process is carried out. It has been established that the spectrum and amplitude of flow oscillations depend on the length of a rectangular hole relative to its width.

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The first attempt at an integrated approach to the study of the mechanism of the occurrence of self-oscillating flow from a hole covered by an arched element using numerical modeling methods is presented in [4]. Holes with different geometrical parameters and under different kinematic flow regimes are considered.

For a range of Reynolds numbers $Re = 2{,}1 \cdot 10^6 - 1{,}2 \cdot 10^7$ it found that the oscillatory nature of the flow is not dependent on the kinematic parameters of the flow, in particular $Sh \neq f(Re)$. However, a significant dependence of the amplitude of the oscillatory flow on the ratio has been established l/d. When $l/d = 1$, the self-oscillating nature of the flow is less pronounced and has a reduced amplitude of oscillations. At $l/d = 2$, a pronounced self-oscillatory flow is observed. At $l/d = 4$, a self-oscillating nature of the flow is also observed, but in contrast to the previous variants, this process proceeds less periodically, additional oscillation harmonics appear, and the oscillation amplitude decreases significantly.

Determining the relative amplitude of oscillations as the ratio of the amplitude of oscillations of the modulus of the flow velocity to the average flow rate, it was found that the relative amplitude of self-oscillations for other types of self-oscillating flows does not, as a rule, exceed 0.9. For example, in works [5-6], in which the outflow of a plane jet into a rectangular cavity is investigated, the relative amplitude of self-oscillations does not exceed 0.4. In works [7-9], in which the self-oscillatory process is investigated when flowing around bodies of various shapes, the relative amplitude of oscillations also does not exceed 0.9, and in papers [10-11], in which the self-oscillatory process of gushing a vertical flat jet of liquid is investigated, the relative vibration amplitude does not exceed 0.6. In works [12-13], in which the external flow around rectangular cavities is investigated at $Re = 10^3 - 10^5$, the amplitude of self-oscillations does not exceed 0.9.

In this work, we numerically investigate the self-oscillating mode of outflow from a hole covered by an arched element. The main goal of the study is to elucidate the mechanism of formation of a self-oscillating flow, as well as to determine its main characteristics. A variant of the geometry of the hole with the aspect ratio is considered $l/d = 2$, since at this ratio the self-oscillating outflow mode is most clearly observed [4]. Based on the simulation results, the distribution of the field of oscillation amplitudes in the plane of the jet flow is determined.

Statement and Method of Solving The Problem. The self-oscillatory flow of a viscous isothermal incompressible gas from a rectangular hole covered by an arched element is investigated (Fig. 1).

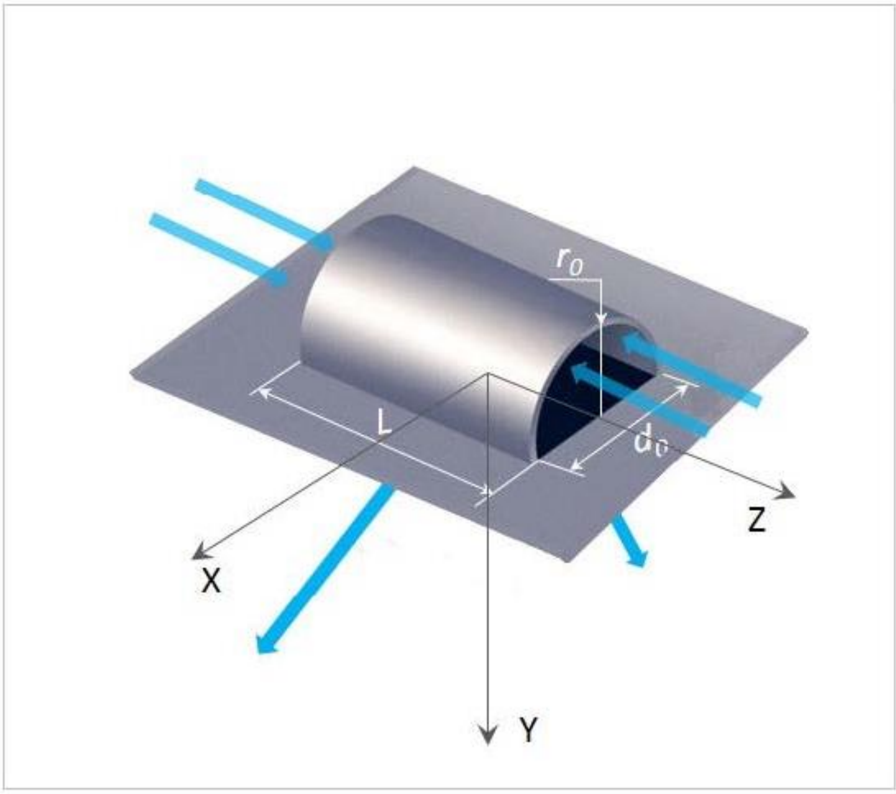

Figure: 1. General view of the investigated rectangular hole, covered with an arched element.

To describe the three-dimensional turbulent fluid flow, the large eddy-eddy method (LES) [14] was used, based on the solution of the space-filtered Navier-Stokes equations and the continuity equation (1.1-1.2):

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1.1)$$

$$\frac{\partial \bar{u}_i}{\partial x_i} + \frac{\partial \bar{u}_i}{\partial x_i} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_i}\left(v\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) + \tau_{ij}^{SGS}\right) \quad (1.2)$$

Here ν is the coefficient of kinematic viscosity, $\bar{u}_i$and $\bar{p}$are the components of the velocity and pressure filtered over space, respectively. Large-scale eddies are resolved directly from equations (1.1-1.2), and small-scale eddy structures are modeled in accordance with the Smagorinsky subgrid viscosity model (SGS). In accordance with the Smagorinsky model, two assumptions are made. First, a linear relationship is assumed between the subgrid stress tensor and the strain rate tensor:

$$\tau_{ij}^{SGS} - \frac{1}{3}\tau_{ij}\delta_{ij} = -2v_t\bar{S}_{ij}$$

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right)$$

Here $\bar{S}_{ij}$ is the tensor of strain rates, constructed from the averaged values v_t of the rate; - subgrid vortex viscosity. Second, by analogy with the mixing length model [14] for calculating the subgrid viscosity:

$$v_t = l_S^2|\bar{S}| = (C_S\Delta)^2|\bar{S}|$$

Here $|\bar{S}| = \sqrt{2S_{ij}S_{ji}}$; $l_S = C_S\Delta$, Δ - filter width; C_S – - Smagorinsky's constant.

In fig. 2 shows a diagram of the hole, the area of the inlet section of which is 0.15 m^2 , and the velocity in the inlet section into the design area is 0.039 m / s. The velocity in the inlet section is determined from the condition that the flow velocity from the holes of the arched element is $V_0 = 3$ m / s, and the area of the rectangular hole is 0.005 m^2 . At the outlet boundary of the computational domain, the pressure distribution $P = const$ and the Neumann condition on the tangential velocity components $\partial u_\tau / \partial \vec{n} = 0$.

All other boundaries of the computational domain are assumed to be solid walls and adhesion conditions are set on them.

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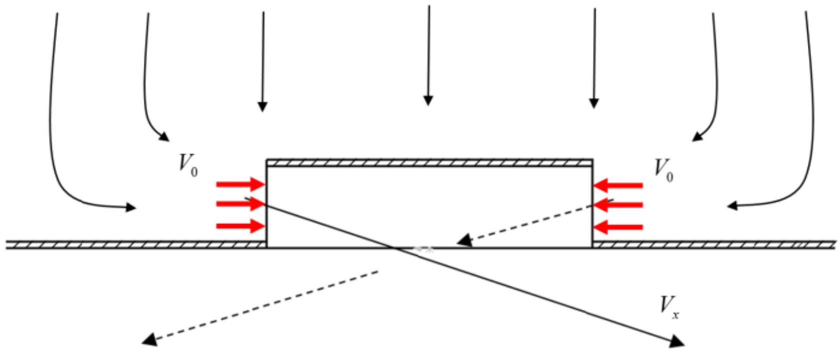

Figure: 2. Layout of the hole on the plane and the direction of flow.

To solve the problem, the computer software STAR-CCM + ver.8 was used. Spatial approximation of the transport equations (1.1-1.2) is performed using the control volume method. For time integration, an implicit scheme of the first order of accuracy is used. The approximation of the convective terms in the momentum transfer equation (1.1) is performed according to the scheme of central differences of the second order of accuracy. The solution of the systems of algebraic equations formed during the discretization of the transport equations is carried out by the algebraic multigrid method [15].

In the study area, a hexahedral unstructured computational mesh was built with a more detailed resolution in the hole area. The size of the computational grid element in the area of maximum density is 0.3 mm, and the maximum size of the computational grid element is 80 mm. The total number of cells in the computational grid is $22 \cdot 10^{66}$.

The* Mechanism *of the Occurrence of Self-Oscillations.

To understand the peculiarities of the mechanism of the occurrence of self-oscillations during the outflow of a liquid from the hole under consideration, it is necessary to accurately reproduce the picture of flows and interactions of flows with each other. The use of the LES approach allows one to obtain a detailed picture of the flow, directly resolving the largest vortex flow structures corresponding to the long-wavelength part of the inertial range of the energy spectrum. In fig. 3-4 shows the development of the flow from the hole during one half-period of its oscillations.

The observed phenomenon is a dynamically unstable periodic flow caused by a complex unstable interaction of counter-coaxial flows flowing through the hole.

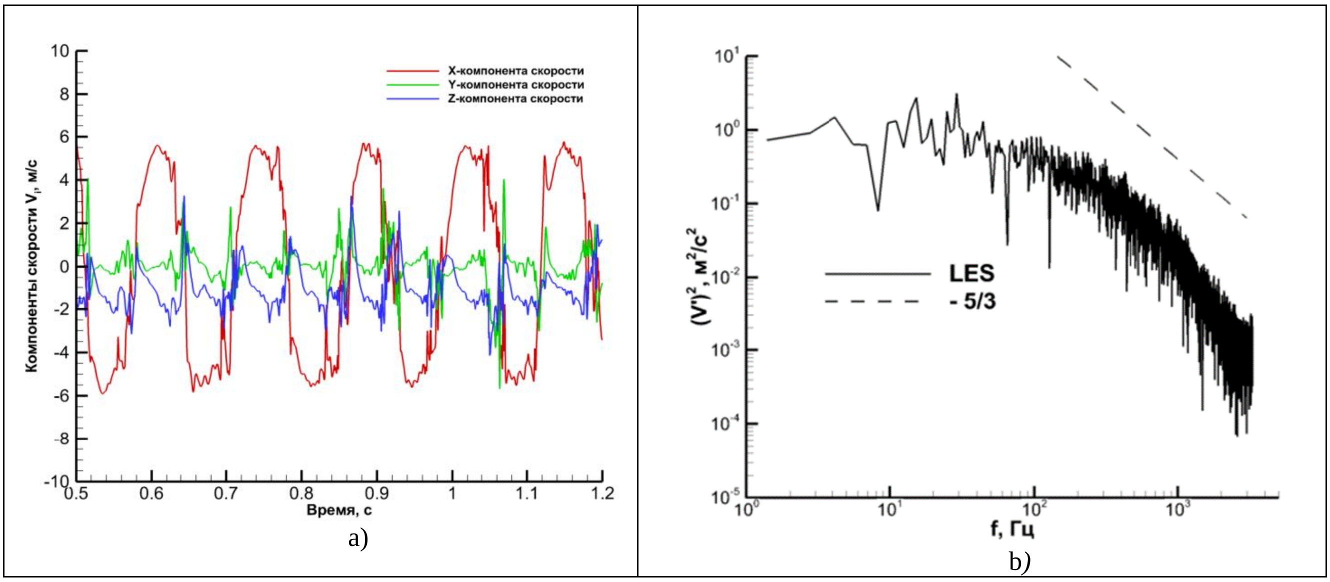

Figure: 3 . Time dependence of velocity components (a) and the energy spectrum of turbulent pulsations (b) at the point centered on the hole. Calculation by the LES method.

Self-Oscillation Characteristics.

Interest in this type of self-oscillating flows is caused by the anomalously high relative amplitude of flow oscillations, which, as follows from Fig. 3 a, takes values from 5 to 6 units. To determine the energy spectrum of turbulent flow pulsations (Fig. 3 b) and the amplitude of oscillations along the perpendicular and longitudinal axes (respectively Y and X in Fig. 2) of the hole, the time dependence of all velocity components is determined (Fig. 3 a). As a result of the analysis of the data obtained, the distribution of the amplitude of self-oscillations is determined (Fig. 4). The value of the oscillation amplitude corresponding to the maximum relative transverse velocity component V_x to the velocity of average holes at specified conditions $A = {}^{V_x}\!/\!_{V_{\text{pacx}}}$.

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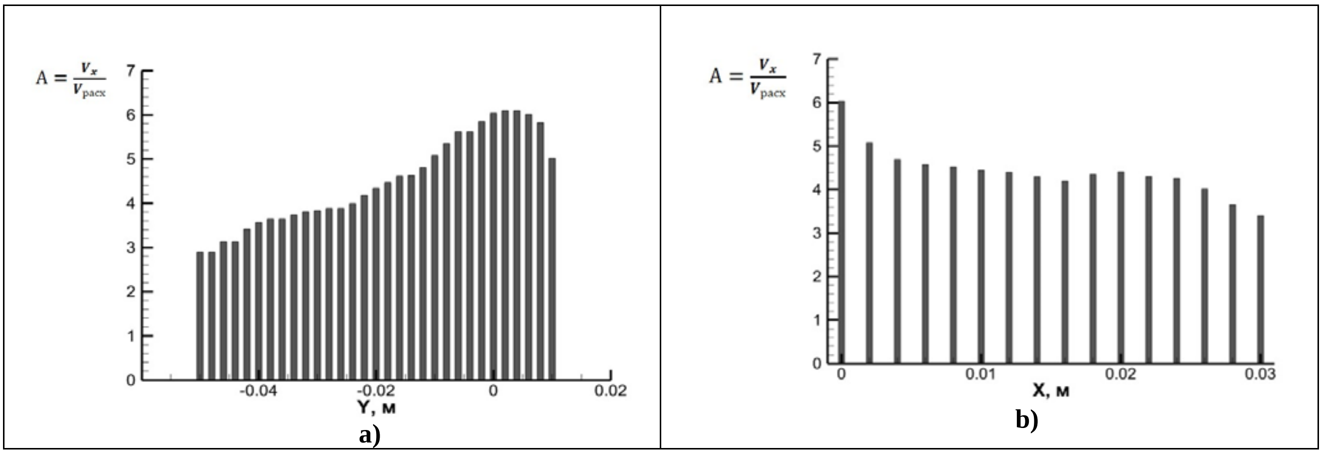

Figure: 4 . Distribution of relative values: a) along the Y axis; b) along the X axis. The point with coordinates X = 0, Y = 0 is located in the center of the hole.

It was found that the maximum value of the vibration amplitude is achieved in the center of the hole, at a distance from 0 to 4 mm from the plane of the hole (along the Y axis in Fig. 4 a). Taking into account that the area of a rectangular hole is formed as $d_0 \cdot L = 0.05 \cdot 0.1$ m^{2,} it can be assumed that the maximum fluctuations are found in the plane of this hole.

II.CONCLUSION

A self-oscillatory process is numerically investigated when it flows out of a rectangular hole with an aspect ratio of 2: 1, covered by an arched element. In the considered version, the hole with the ratio l/d_0=2. An explanation is given to the mechanism of occurrence of the self-oscillatory nature of the flow. The complex interaction of two counter-coaxial flows provides a periodic backwater of one of them, as a result, organizing a stable oscillatory nature of the flow. It turns out that the points of maximum values of the amplitude of the oscillatory process lie practically in the plane of the hole, retreating from it at a distance of 2-4 mm.

The relative amplitude of self-oscillations of the flow under consideration is anomalously high, and takes values of 5.0-6.0, while in other known self-oscillating flows it is 0.4-0.9. It can be seen that a commensurate increase in the amplitude is 5.0 - 15.5 times.

We have named the above-described phenomenon - AVAAC. Definition:

AVAAK is a phenomenon of an abnormally high amplitude of a self-oscillating process when a Newtonian fluid flows out from a rectangular hole covered by an arched element.

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