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ANIQ VA TABIIY FANLAR *** EXACT AND NATURAL SCIENCES *** ТОЧНЫЕ И ЕСТЕСТВЕННЫЕ НАУКИ

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SIMULATION OF A FREE JET USING SEKUNDOV'S ONE-PARAMETER TURBULENCE MODEL

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Annotation: *In the work, a technique is carried out, where the scale of turbulence in the one-parameter model of A.N. Sekundova is determined through analytical equations, which is used to calculate the width of the jet. For numerical implementation, the equations of the boundary layer are written in physical variables and an implicit absolute stable difference scheme of the second order in the transverse and first order in the longitudinal directions is used. To compare the obtained numerical results, experimental data from known sources were used. The distributions of axial velocity and turbulent viscosity, profiles of axial, radial velocities, turbulent viscosity in various radial sections are determined. It is shown that the boundaries of the expansion are generally rectilinear, but at the end the jet narrows slightly.*

Keywords: *Turbulent jet, isothermal flow, turbulence scale, differential equation for turbulent viscosity, boundary layer, jet expansion angle, numerical solution.*

МОДЕЛИРОВАНИЕ СВОБОДНОЙ СТРУИ С ИСПОЛЬЗОВАНИЕМ ОДНОПАРАМЕТРИЧЕСКОЙ МОДЕЛИ ТУРБУЛЕНТНОСТИ СЕКУНДОВА

Аннотация: *В работе проводится методика, где масштаб турбулентности в однопараметрической модели А.Н. Секундова определяется с помощью аналитических уравнений, по которым рассчитывается ширина струи. Для численной реализации уравнения пограничного слоя записываются в физических переменных, и используется неявная абсолютно устойчивая разностная схема второго порядка в поперечном и в продольном направлениях первого порядка. Для сравнения полученных численных результатов использовались экспериментальные данные из известных источников. Определены распределения осевой скорости и турбулентной вязкости, профили осевой, радиальной скоростей, турбулентной вязкости в различных радиальных сечениях. Показано, что границы расширения в целом прямолинейны, но в конце струя немного сужается.*

Ключевые слова: *турбулентная струя, изотермическое течение, масштаб турбулентности, дифференциальное уравнение для турбулентной вязкости, пограничный слой, угол расширения струи, численное решение.*

SEKUNDOVNING BIR PARAMETRLI TURBULENTLIK MODELI FOYDALANISHDA BEPUL JETNI SIMULATSIYA QILISH

Annotatsiya: *Ishda texnika amalga oshiriladi, bu erda A.N.ning bir parametrli modelidagi turbulentlik shkalasi. Sekundova analitik tenglamalar orqali aniqlanadi, bu jetning kengligini hisoblash uchun ishlatiladi. Raqamli amalga oshirish uchun chegara qatlamining tenglamalari fizik o'zgaruvchilarda yoziladi va bo'ylama yo'nalishlarda ko'ndalang va birinchi tartibdagi ikkinchi tartibli yashirin absolyut barqaror farq sxemasi qo'llaniladi. Olingan raqamli natijalarni solishtirish uchun ma'lum manbalardan olingan eksperimental ma'lumotlardan foydalanildi. Eksenel tezlik va turbulent qovushqoqlikning taqsimlanishi, eksenel, radial tezliklarning profillari, turbulent viskozitenin turli radial kesmalarda taqsimlanishi aniqlanadi. Kengayish chegaralari odatda to'g'ri chiziqli ekanligi ko'rsatilgan, ammo oxirida jet biroz torayadi.*

Kalit so'zlar: *turbulent reaktiv, izotermik oqim, turbulentlik shkalasi, turbulent qovushqoqlik uchun differensial tenglama, chegara qatlami, reaktiv kengayish burchagi, sonli yechim.*

Introduction.

Turbulent mixing and propagation of free turbulent jets in a concurrent flow is widespread in chemical and technological processes, the food industry, irrigation of fields by drip irrigation, energy and other branches of technology and the national economy. Recently, the scope of intensive research and application of jet flows in the processes of heat and mass transfer has expanded enormously. It includes both leading areas of technology (chemical technologies, oil development, etc.) and basic natural sciences (biology, statistical physics, etc.).

Of particular importance is the determination of the boundaries of movement in heat and mass transfer processes in the above industries, which mainly occur according to the rules for the propagation of turbulent gas jets in isothermal and non-isothermal cases.

Such flows have been studied quite extensively in order to determine their transport properties. Of theoretical and practical interest is the elucidation of one of the main characteristics of the transfer - the coefficient of turbulent viscosity. In the work of A.N. Sekundov proposed a differential equation for turbulent viscosity, which is quite simple and accessible for analysis. In this equation, the scale of turbulence for jet streams was assumed to be sufficiently large and was not taken into account in the calculations. In this work, a method is proposed for determining this parameter in a numerical solution using the jet boundaries.

Literature review.

A lot of works are devoted to the theory and modeling of turbulent flows [1-5]. When modeling turbulent flows, a problem arises to determine the turbulent viscosity.

The model for describing the distribution of turbulent viscosity ν_t was first proposed by L. Prandtl in 1925. and is known as the mixing path model. It has been proven to reproduce thin viscous layers quite well. Considering averaged shear flows without a pressure gradient, Prandtl postulated that ν_t is equal to the average velocity gradient multiplied by the characteristic length scale l_m

$$\nu_t = l^2 \cdot \left|\frac{\partial u}{\partial y}\right|$$

Since then, the main focus for researchers has been on finding this scale of turbulence, which was later called the "mixing path", which with this name is often used in free flows.

The nature of the flow in turbulent flows is greatly influenced by the hydrodynamic "prehistory" of mixing flows, i.e., the different level of preliminary turbulence in them. The influence of these factors cannot be taken into account within the framework of semi-empirical theories based on algebraic models of turbulence, which cannot be used to obtain more detailed data on the structure of the turbulence field The above considerations became the initial premise for the development of semi-empirical theories of turbulence in an incompressible fluid based on the use of differential equations.

Among these models is the so-called one-equation differential models, which have shown that, in practice, models with respect to turbulent viscosity are preferable to other models.

In [7], a differential equation was obtained for the coefficient of turbulent viscosity, which is quite simple and accessible for analysis, describes a fairly wide class of non-self-similar turbulent flows in the following form

$$u\frac{\partial \varepsilon}{\partial x} + v\frac{\partial \varepsilon}{\partial y} = \frac{\partial}{\partial y}\left((\chi\varepsilon + \nu)\frac{\partial \varepsilon}{\partial y}\right) + \varepsilon k_0\left|\frac{\partial u}{\partial y}\right| - \frac{k_1\varepsilon}{L^2}(\beta\varepsilon + \nu) \qquad (1)$$

As can be seen from equation (1), and here there is a coefficient L representing the scale of turbulence. As indicated in [7], in free flows in equation (1), the influence of the last term can be neglected, since the turbulence scale L is considered large. But still, if this value is calculated in the calculations, it can also be taken into account.

In [8], using empiricism and arguments of size analysis, Galilean invariance, and selective dependence on molecular viscosity, a transport equation for turbulent viscosity was constructed. This model is constructed in such a way that it is not required to set the turbulence scale here. It bears resemblance to the models of Nee and Kovazhny, Sekundov et al., Baldwin and Barth. The equation includes an inviscid fracture term that depends on the distance to the wall. A very good agreement with experiment was obtained on this model for the flow around airfoils and in separated flows.

Using these equations, various processes of turbulent flows were investigated.

The work [9] is devoted to numerical simulation using turbulence models that include a differential equation for turbulent viscosity. Numerical calculations are carried out for self-similar flows in a subsonic jet and boundary layer. Combinations of velocity gradients were used for the turbulence scale. Good agreement is obtained with experiment (for the jet) and analytical solutions (for the boundary layer). Numerical modeling of supersonic jet flows in off-design cases and comparison with experimental data for various turbulence models has been carried out.

In [10], the properties of the Sekundov νt-92 turbulent model for various jets were studied. Using this model, numerical studies of axisymmetric subsonic cold, hot and transonic jets were carried out. For numerical implementation, the equations of hydrodynamics are written in von Mises variables and an implicit absolutely stable scheme of the second order of accuracy in the transverse and first order in the longitudinal directions is used. The results are compared with known experimental data. It is shown that the model quantitatively well describes the main parameters of incompressible and compressible turbulent jets.

The differential equation of turbulent viscosity is also applied in other flows, for example, in combustion [11, 12]. In [11], the minimum distance to the wall is taken as the scale of turbulence.

As we can see, different approaches to obtaining the turbulence scale are used in the works cited. If one solves the equations in physical coordinates for the jet, one has to determine the values for the expansion of the jet in different radial sections. If it is defined, then it can be used as a displacement path, or as a turbulence scale. In this article, an attempt is made to determine this value for a stationary flow of a flat turbulent jet.

Methodology.

Consider a turbulent jet of isothermal gas flowing out of a round nozzle with a radius and propagating in a concurrent flow of the same gas. We assume that the jet outflow is stepped and uniform, the static pressure in the jet and in the concurrent are the same. To facilitate the solution of problems, we direct the x-axis along the jet, and the y-axis perpendicular to the jet, this allows us to consider one half of the jet.

With the assumptions made, the mathematical model of this process can be taken as a system of differential equations in the approximation of the turbulent boundary layer theory, which was used in jet flows, which for the axisymmetric case in a dimensionless form can be written as:

$$\left.\begin{aligned} \frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \\ u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{Re}\frac{\partial}{\partial y}\left(\nu_{ef}\frac{\partial u}{\partial y}\right) \end{aligned}\right\} \qquad (2)$$

In [14], it is indicated that the jet expansion angle for the initial and main sections is different (Fig. 1). For a flat isothermal jet, they are equal to $tg\alpha_i = 0{,}14$ and $tg\alpha_m = 0{,}22$.

This is preferable, since in the initial section, the angle of jet expansion is less than in the main section.

Thus, if somehow it is possible to keep the boundaries of the jet within the lines given above, then this length can be used as a mixing path when solving equation (2).

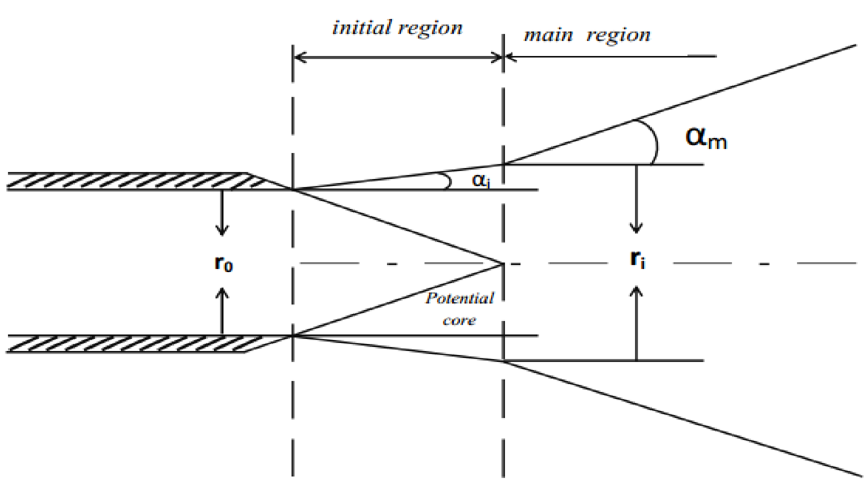

Figure.1. Free jet scheme

Results.

The boundary conditions for solving the system of equations (2), taking into account (1), can be written as:

$$x=0:\begin{cases}u=u_2,\ \nu_t=(\nu_t)_2,\ \vartheta=0 & \text{при}\ \ 0\le y\le r_0\\ u=u_1,\ \nu_t=(\nu_t)_1,\ \vartheta=0 & \text{при}\ \ r_0<y\le\infty\end{cases}$$
$$x>0:\begin{cases}\dfrac{du}{dy}=\vartheta=\dfrac{d\nu_t}{dy}=0, & \text{при}\ \ y=0\\ u\to u_1,\ \vartheta\to 0,\ \nu_t\to(\nu_t)_1 & \text{при}\ \ y\to y_\infty\end{cases} \qquad (3)$$

Here, the index "2" denotes the parameters of the jet, the index "1" the parameters of the concurrent flow. It is assumed that the concurrent flow will continue indefinitely. As can be seen from (3), the jet boundary is unknown; it is determined during the solution of the problem from the equations given in the methodology.

The system of differential equations (2) taking into account (1, 3) was solved numerically using a two-layer, implicit four-point finite-difference scheme and the sweep method with iterations [15, 16].

When defining the jet boundary, we adhere to the lines for the initial and main sections, with obligatory iterations between layers. The second condition for the iteration was the difference in speed between the main and concurrent streams.

On fig. Figure 2 shows the axial longitudinal dimensionless velocity (curve 1), the axial value of the turbulent viscosity (curve 2), and the characteristic jet thickness (curve 3), determined from the points at which the velocity is half the maximum value in comparison with the experimental data, given in [7]. It can be seen from the figure that after approximately half of the main section, the axial value of viscosity begins to decrease.

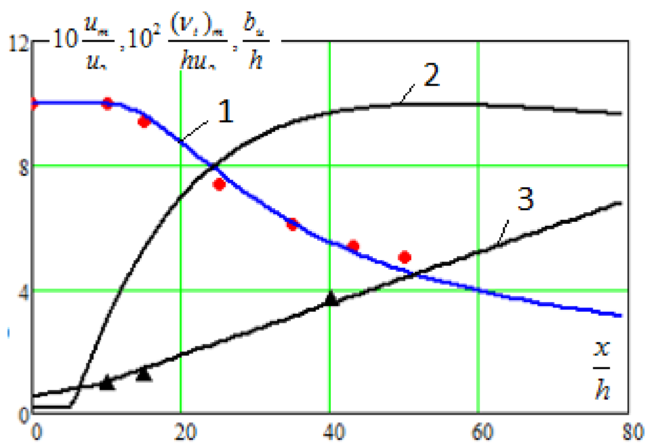

Figure.2. Axial values of longitudinal velocity (1), turbulent viscosity (2), and characteristic jet thickness (3) determined from points where the velocity is half of the maximum value.

The transverse values of the longitudinal velocity and viscosity in the cross section in $\bar{x}=60$ comparison with the experimental data from [7] are shown in Figs. 3.

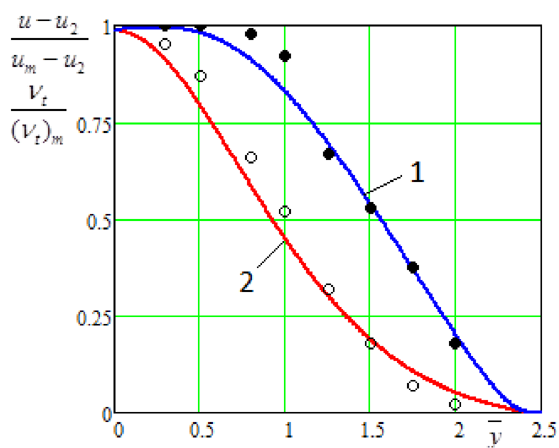

Figure.3. Transverse values of longitudinal velocity and viscosity in the section $\bar{x}=60$

Figure 4 shows the transverse velocity components at $\bar{x}=40$ and $\bar{x}=60$. It can be seen that as it approaches the outer boundaries, the jet draws a concurrent flow towards itself. When the jet velocity weakens, the degree of co-flow involvement also decreases.

Figure.4. Transverse velocity components at $\bar{x}=40$ and $\bar{x}=60$

Conclusion.

In this work, an attempt was made to determine the jet boundary using the formulas given in the literature. In general, the obtained calculated data are in good agreement with the experimental data. From the calculations made, it can be concluded that the boundary of the jet will be approximately rectilinear, but this linearity weakens as it approaches the end of the jet. Thus, it can be concluded that the expansion of the jet boundaries in the form of equations does not correspond to the end of the main section.

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