Comparison of Turbulence Models for the Problem of an Asymmetric Two-Dimensional Plane Diffuser

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ABSTRACT

In this paper, the turbulent flow in an asymmetric two-dimensional diffuser is investigated. In many applications, it is important to know whether the boundary layer (laminar or turbulent by calculating the Reynolds number, which is the ratio of the inertia force to the viscous fluid flow force) will separate from the surface or inside a particular body. If this happens, it is also important to know exactly where the flow separation will occur. The separation can be internal or external. This is quite important in many tasks.

KEYWORDS: *Navier-Stokes equations, SIMPLE, RANS approach, control volume method.*

Introduction

Currently, high-performance computers allow engineers to simulate turbulent flows in areas with complex geometry by numerically solving the equations of hydrodynamics, including the equations of momentum, continuity and energy using one of the existing methods of computational fluid dynamics CFD (Computational Fluid Dynamics). CFD codes are a powerful tool for researching practical problems and give satisfactory results. As a rule, CFD has become the basis for understanding the basics of flow processes, such as fluid flow, heat transfer, mass transfer, and has recently found application in medical fields [1].

Flow separation occurs when the boundary layer passes far enough away from the unfavorable pressure gradient, so that the velocity of the boundary layer relative to the object drops to almost zero [2,3]. The fluid flow breaks away from the surface of the object and as a result takes the form of vortices. The boundary layer closest to the wall or leading edge is flipped in the direction of flow. The point between the forward and reverse flow is called the separation point, where the shear stress is zero. Initially, the entire boundary layer thickens rapidly at the point of separation, and then is repelled from the surface by the reverse flow [4]. Sebechi et al. [5] accurately calculated the separation points in incompressible turbulent flows using four prediction methods, the Goldschmid, Stratford, Head and Chebechi-Smith method, and then confirmed them experimentally. Knob et al . [6] studied the dynamics of boundary layer separation using the PIV method and time-resolved biorthogonal decomposition in order to theoretically study the rapid structure of the separation region, its development and coherent structures, as well as the simple case of an unfavorable pressure gradient. Gustavsson [7] and Yan et al. [8] experimentally studied flow separation using a high-resolution PIV (Particle Image Velocimetry) system to study the rapid structure of the separation region, its development and the attachment of a turbulent flow. The results obtained were compared with conventional measurements using static pressure taps [8], a hot-wire anemometer and a Preston tube. Chandavari et al., [9] investigated the flow flow in a flat diffuser by changing the cone angle of the diffuser for axisymmetric expansion to delay separation. Thornblom et al. [10] experimentally and numerically studied a new approach to controlling flow separation using longitudinal vortices. Studies of flows in diffusers or channels with sudden expansion are important from the point of view of fundamental fluid mechanics and many practical applications because they present all the difficulties of separating and reconnecting a turbulent flow in the presence of an unfavorable pressure gradient [11-13]. Turbulent fluid flows through an asymmetric geometry or a sudden expansion channel are common in many technical applications, such as combustion chambers, aircraft, pipelines, nuclear reactors, turbomachine heat exchangers, building fairings, etc. [12,13]. Buis and Eaton [14] experimentally investigated the flow in an asymmetric flat diffuser, and their diffuser has so far been widely recognized as a reference. Numerous studies of the flow in an asymmetric flat diffuser using various turbulence models have been carried out numerically. Berdanier [13] was the first to apply the one-parameter Spalart-Almares turbulence model. Then such models as k-ε, k-ω and the Reynolds stress model with five equations were used. Salehi et al . [15] used the low-Reynolds model k-ε, k-ω, v2 - *f* and a modified version of the Reynolds stress model. Similarly, Kumar and Kabbur [16] used k-ε, k-ω and RNG models. Elbehery [14] and Laccarino [17] used low-Reynolds models k-ε, k-ω. In a similar study, Jamil et al. [18] came to the conclusion that it is possible to use turbulence models in relation to flow in a rectangular channel and in a channel with partitions. All models are consistent very close to the experimental data. In another study, Saqr et al., [19] numerically investigated a limited vortex flow using a modified k-ε turbulence model. The modified k-ε turbulence model shows better performance compared to the RNG k-ε and the standard k-ε model. Obi et al. [20] experimentally and computationally studied the separation in an asymmetric flat diffuser, and their work received wide attention. Others who have studied this phenomenon both experimentally and computationally include Klistafani [21] and Tornblom [22], and their results are consistent with these two methods when compared.

As far as the authors know, insufficient studies of the flow in a standard asymmetric two-dimensional Buice diffuser have been carried out. Therefore, the purpose of this study is a numerical analysis of flow asymmetric two-dimensional diffusers using various turbulence models and a comparison of their results. The results of this study can be useful for understanding turbulence, separation and attachment, as well as for selecting suitable turbulence models that are important for the study of practical engineering applications.

Mathematical statements and computational methods

For the numerical study of the problem, a system of equations averaged by Reynolds Navier-Stokes equations is used, which has the form

$$\begin{cases} \rho\dfrac{\partial\overline{U_i}}{\partial t}+\rho\overline{U_j}\dfrac{\partial\overline{U_i}}{\partial x_j}+\dfrac{\partial\overline{p}}{\partial x_j}=\mu\dfrac{\partial^2\overline{U_i}}{\partial x_j\partial x_j}+\dfrac{\partial}{\partial x_j}\left(-\rho\overline{v_i'u_j'}\right), \\ \dfrac{\partial\overline{U_i}}{\partial x_j}=0. \end{cases} \qquad (1)$$

Here $\overline{U_i}$ – air flow velocity– $\overline{p}$ - hydrostatic pressure– ρ- gas density; μ - its molecular viscosity; $\overline{v_i'u_j'}$- components of the Reynolds stress tensor. This system of equations is open-ended and semi-empirical turbulence models are used to close it. In many models, a generalized Boussinesq hypothesis is used to close the system of equations (1), which is called the linear approach

$$-u_i'u_j'=v_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)-\frac{2}{3}k\delta_{ij}.$$

Here is ν_t - the turbulent viscosity that needs to be determined.

In this paper, seven turbulence models were used to determine the turbulent viscosity, which are embedded in the COMSOL Multiphysics software package.

Turbulence models

The Spalart-Allmaras model: This model belongs to the class of one-parameter turbulence models. Here there is only one additional equation for calculating the kinematic coefficient of vortex viscosity**.**

$$(\mathbf{U}\cdot\nabla)\tilde{\nu} = C_{b1}\tilde{S}\tilde{\nu} - C_{w1} f_w \left(\frac{\tilde{\nu}}{d}\right)^2 + \frac{1}{\sigma_\nu}\nabla([(\nu+\tilde{\nu})\nabla\tilde{\nu}]) + \frac{1}{\sigma_\nu}C_{b2}\nabla\tilde{\nu}\nabla\tilde{\nu}. \quad (2)$$

The turbulent vortex viscosity is calculated from: $\nu_t = \tilde{\nu} f_{\nu 1}$

k-ε turbulence model: k-ε *Two additional equations are written in the k-ε turbulence model to calculate the kinetic energy of turbulence k and the rate of dissipation of kinetic energy ε.*

$$\begin{cases} (\mathbf{U}\cdot\nabla)k = \nabla\left[(\nu + \frac{\nu_t}{\sigma_k})\nabla k\right] + P_k - \varepsilon, \\ (\mathbf{U}\cdot\nabla)\varepsilon = \nabla\left[(\nu + \frac{\nu_t}{\sigma_\omega})\nabla \varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{k}P_k - G_{2\varepsilon}\frac{\varepsilon^2}{k}. \end{cases} \quad (3)$$

The turbulent vortex viscosity is calculated by: $\nu_t = C_\mu \frac{k^2}{\varepsilon}$.

SST-модель: The SST model is a combination of k-ε and k-ω turbulence models: to calculate the flow in a free flow, the equations are used k-ε models, and in the area near the walls — equations k-ω models:

$$\begin{cases} (\mathbf{U}\cdot\nabla)k = \nabla[(\nu + \sigma_k \nu_t)\nabla k] + P - \beta^*\omega k, \\ (\mathbf{U}\cdot\nabla)\omega = \nabla[(\nu + \sigma_\omega \nu_t)\nabla \omega] + \frac{\gamma}{\nu_t}P - \beta\omega^2 + 2(1-F_1)\frac{\sigma_{\omega 2}}{\omega}\nabla\omega\nabla k. \end{cases} \quad (4)$$

The turbulent vortex viscosity is calculated by: $\nu_t = \frac{ak}{\max(a\omega, Sf)}$.

k-ω turbulence model: The k-ω model is similar to k-ε, only here is the equation for the specific rate of kinetic energy dissipation solved ω.

$$\begin{cases} (\mathbf{U}\cdot\nabla)k = \nabla[(\nu + \sigma_k \nu_t)\nabla k] + P - \beta^*\omega k, \\ (\mathbf{U}\cdot\nabla)\omega = \nabla[(\nu + \sigma_\omega \nu_t)\nabla \omega] + \frac{\gamma\omega}{k}P - \beta\omega^2. \end{cases} \quad (5)$$

The turbulent vortex viscosity is calculated by: $\nu_t = \frac{k}{\omega}$.

L-VAL and yPlus: Algebraic turbulence models L-VEL and plus allow you to calculate the coefficient of turbulent viscosity depending on the local velocity of the liquid and the distance from the wall. No additional transfer equations need to be solved in these models. At the same time, they can be used to calculate the entire flow area.

$$\mu_t = \mu\left(\left(\frac{df}{dl_w^+}\right)^{-1} - 1\right),\ \mu_t = \mu\left(\frac{df}{du^+} - 1\right) \qquad (6)$$

v^2-f turbulence model: Near solid walls, the intensity of velocity fluctuations in the direction tangential to the wall is usually much higher than the intensity of fluctuations in the direction normal to the wall. In other words, velocity fluctuations are characterized by anisotropy. As you move away from the wall, the intensity of fluctuations in all directions becomes the same. The velocity fluctuations become homogeneous or isotropic. The anisotropy of turbulent fluctuations in the boundary layer is described v^2-f turbulence model by introducing two additional equations solved together with the equations for the kinetic energy of turbulence (k) and the rate of kinetic energy dissipation (ε).

$$\begin{cases} (\mathbf{U}\cdot\nabla)k = \nabla\left[(\nu + \frac{\nu_t}{\sigma_k})\nabla k\right] + P - \varepsilon, \\ (\mathbf{U}\cdot\nabla)\varepsilon = \nabla\left[(\nu + \frac{\nu_t}{\sigma_\varepsilon})\nabla \varepsilon\right] + \frac{1}{\tau}\left(C'_{\varepsilon 1}(\zeta,\alpha)P_k - C'_{\varepsilon 2}(k,\varepsilon,\alpha)\varepsilon\right), \\ (\mathbf{U}\cdot\nabla)\zeta = \nabla\left[(\nu + \frac{\nu_t}{\sigma_\zeta})\nabla \zeta\right] + \frac{2}{k}\left[\alpha^3\nu + \frac{\nu_t}{\sigma_\zeta}\right]\nabla k \nabla\zeta + \left(1-\alpha^3\right)f_w + \alpha^3 f_h - \frac{\zeta}{k}P_k, \end{cases} \qquad (7)$$

The turbulent vortex viscosity is calculated by: $\nu_t = C_\mu k\zeta\tau$.

Initial and boundary conditions

The geometry of a two-dimensional asymmetric flat diffuser is shown in Figure 1, where the dimensions were in accordance with Buice and Eaton [14]. Input channel length (15H). The flow is considered incompressible, uniform, while the Uo value at the inlet is such that the Mach number is less than 0.3. Here Re is the Reynolds number 20000, ρ is the density (1,225 kg/m^3), H is the height of the diffuser inlet (0.01 m), and μ is the viscosity 1,789 × 10-5. 0-5. The density and viscosity values were obtained from the properties of the air in COMSOL.

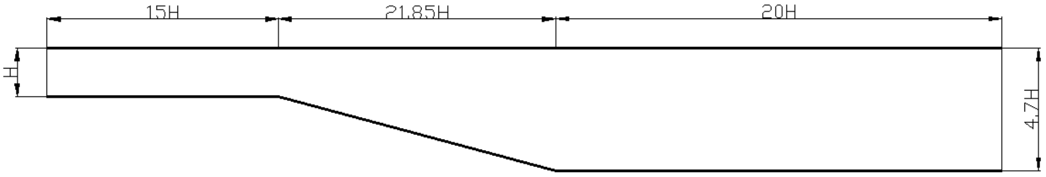
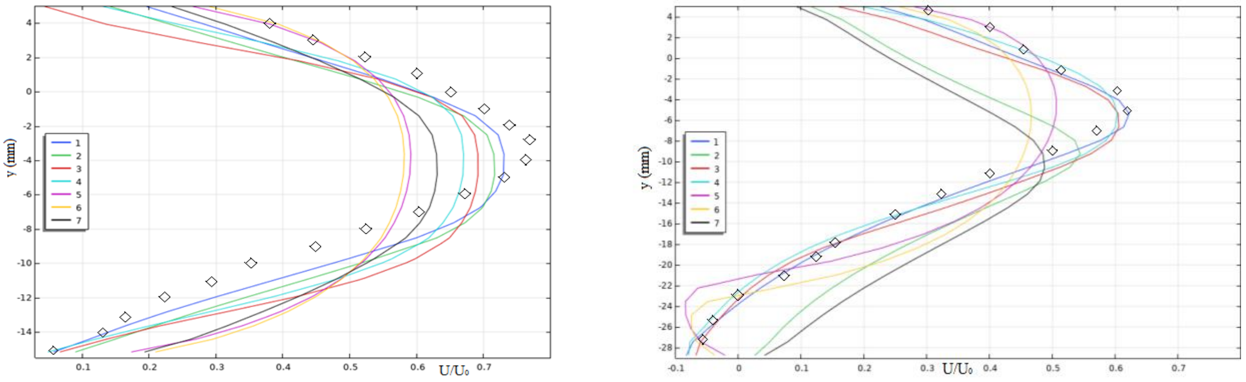


Fig. 1. Diagram of the design area of a flat asymmetric diffuser.

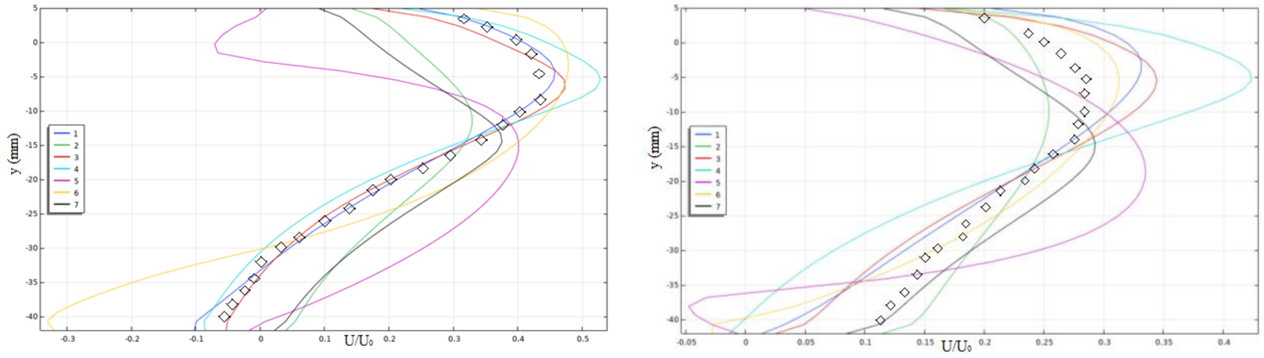
The calculation area was divided into three parts. The first vertical wall is the entrance and is configured for the boundary condition of the inflow. The last vertical wall is the outlet and is set to the outflow boundary condition. The upper and lower (horizontal) walls are installed in the boundary state of the wall. The same boundary conditions were used for all turbulence models.

Solution method. For the equation of momentum and turbulent quantities, a sampling scheme against the flow of the first order was used. As a rule, the properties of the numerical scheme - satisfactory accuracy or consistency, stability and convergence were provided. Caretto et al., [23] Patankar and Spalding [24] and Patankar [25] developed the SIMPLE algorithm defined as used for pressure-velocity coupling [26-29].

The values of U/U0 at various cross sections or curve lengths, namely at x/H=6, x/H=14, x/H=24 and x/H=34 measured from the expansion point, of various turbulence models are compared with experimental results for a 2D asymmetric diffuser, and are presented in Figures 15-17 below.



x/H = 6 x/H = 14

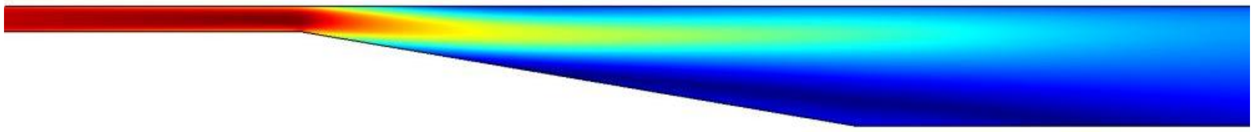


x/H = 24 x/H = 34

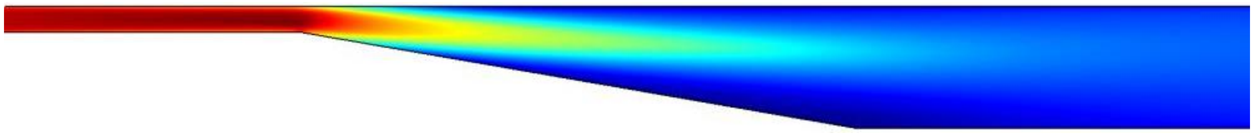
Fig.2. Comparison of the results of turbulence models with experimental data (rhombuses):*1-SA, 2- k-ε, 3-SST, 4- k-ω, 5- L-VEL, 6- yPlus, 7-* v^2*-f.*

Figure 2 shows that at the x/H=6 cross section, the results of all turbulence models do not describe the process well, except for the SA model. In the cross section x/H=14, the results of the SA, k-ω and SST models are closest to the experimental results. In addition, the results of the turbulence models SA, k-ω and SST are almost the same. In the cross section x/H=24, as shown in Figure 2, the results of the SA and SST turbulence models are close to experimental data. In the cross section x/H=34, all seven turbulence models describe the process poorly.

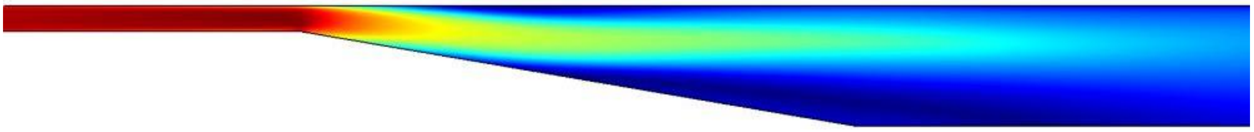
Figure 3 shows the isolines of the longitudinal flow velocity for various turbulence models.



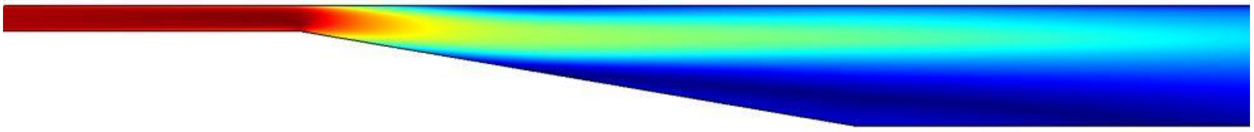
SA



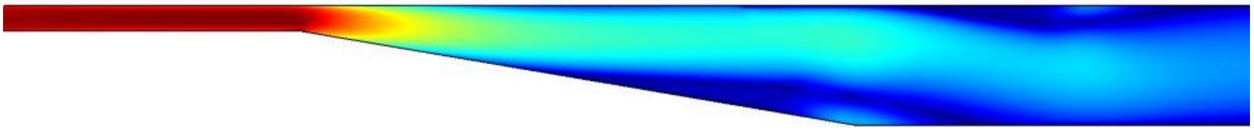
k-ε



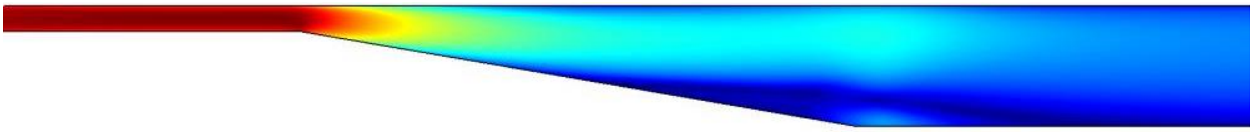
SST



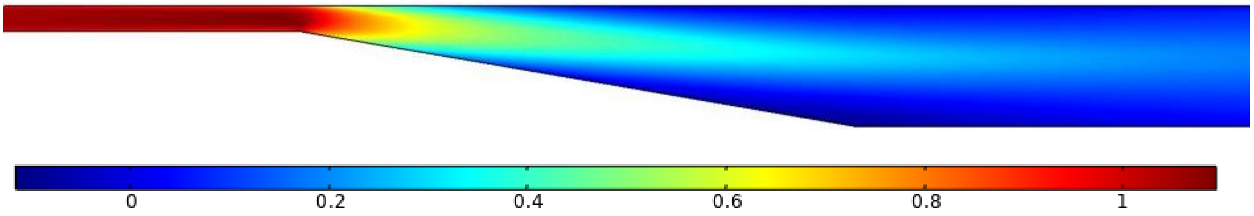
k-ω



L-VEL



yPlus



v^2-f

Fig. 3. Isolines of the longitudinal flow velocity for various turbulence models.

Conclusion

The main purpose of this study is to analyze various turbulence models of the COMSOL program for the numerical study of an asymmetric two-dimensional turbulent flow diffuser. The numerical study was carried out by such turbulence models as,SA, k-ε, SST, k-ω, L-VEL, yPlus and v2-f. The results obtained were compared with experimental results. The following conclusions can be drawn from the comparisons:

The turbulence models SA, SST and k-ω show the best characteristics at the cross sections x/H =14 and x/H =24. The separation of the boundary layer is more significant at distances x/H =14, and x/H = 24. The results of the turbulence models SA and SST on the cross section x/H = 24 are almost the same. Away from the diffuser, namely in the cross section x/H=34, all turbulence models describe the flow process unsatisfactorily.

The differences between numerical results and experimental data are related to the fact that errors in numerical results can come from many different sources, including turbulence models. Of course, this informal ranking of turbulence models depends largely on the user and the information of interest. However, these results have provided significant insight into the possibility of turbulence models, which are really invaluable to figure out which CFD turbulence model can be used for industrial design tasks.

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