Studying the Effect of Longitudinal Pressure Gradient on the Onset and Length of the Laminar-Turbulent Transition Zone Using of a Perot Non-equilibrium Turbulence Model and Programming of the Model UDF to the Fluent Software

Mahmoud Salari[1], **Hadi Etezadi**[2]

Imam Hossein University - Faculty and Research Institute of Engineering- Marine Research Institute

Abstract

In this paper, the effect of two important parameters affecting the transition process in the boundary layers, namely, the intensity of free flow turbulence and the pressure gradient along to the flow on the transition onset position and length of the transition zone/region, have been numerically investigated. Perot turbulence potential model has been used to capture turbulence and flow transition characteristics. This model has appropriate structural relationships for analyzing non-equilibrium flows, which is a suitable capability for simulating the transitional flows. In this research, the governing equations of this new turbulent model have been applied to the fluent software in the form of programming of UDF. Numerical analyzes for eleven different types of different flows have been carried out under a wide condition of pressure gradient and turbulence intensity of free flow and compared with experimental data. The results show that increasing the turbulence intensity of the inlet/input free flow as well as the reverse pressure gradient leads to begin transition onset position sooner and the length of the transition zone is also smaller and vice versa. Another important result is that, in flows with turbulence intensities of more than 5%, the effect of the pressure gradient on the transition onset position in the boundary layers is negligible.

Keywords: Laminar-Turbulent Transition Process; Numerical Modeling; Pressure Gradient; Perot Non-equilibrium Turbulence Model; Transition Onset.

1. Introduction

Today, one of the most important challenges in fluid mechanics is to detect and predict the position of the laminar-turbulent transition zone. Factors affecting on the transition process, physics inside the transition zone and transitional phases still have many unknowns. The heat transfer rate and shear stresses on the wall during the transition process are continuously increasing along the flow direction, so a proper design based on heat loads and shear forces can be made when the properties of the transition process are known. Analysis of heat transfer issues in the cone nose of missiles, more accurate analysis of air vehicles aerodynamics, designing and analyzing heat transfer issues for airfoils and gas turbine blades, and issues related to drag reduction for moving bodies in fluid are just some of the issues that are directly needed to recognizes the transition process of flow and predicts the onset position and length of the zone. The historic Reynolds experiment in 1883 marks the beginning of the experimental research of the transition process in the boundary layers. Linear stability analysis for non-viscous flow is one of the first methods of studying the theory of transition process. Later, Orr [1] and Sommerfeld [2], independently of each other, examined the effect of viscosity on the flow stability of the flat plate, which is known as the Orr-Sommerfeld equation as their research work result. Tollmien and Schlichting [4] analyzed the Orr- Sommerfeld equation for two-dimensional unstable stir/disturbance waves in the Blasius boundary layer, which later these two-dimensional stir waves known as name of two researchers (T-S waves). Exact empirical experiments by Stubbier and Skramstad [5] confirmed the T-S waves. They, with the help of theoretical analysis, were able to calculate a neutral curve of stability for the transition process. Based on the above studies, the first scenario for the transition process was introduced, whereby very small stir of free flow and wall were introduced into the boundary layer and in the zone of the flow layer, they form and grow linearly in the form of two-dimensional T-S waves. With the gradual amplification of the T-S wave amplitude, the nonlinear growth phase of the stirs begins and the amplitude of the stirs grows rapidly and provides the necessary conditions for the production of turbulence points. Interference and overlapping of turbulence points of the flow leads to complete flow turbulent. This type of process is known as the natural transition.

Experimental studies of Mayle [6] showed that for boundary layers adhering to the surface, if the turbulence intensity of the inlet free flow is less than 0.1%, the transition process is a natural transition type.

Other studies show that, in addition to the natural transition process, different types of transitional processes in the flows may also occur in terms of the type and size of the effective parameters. Mayle [6] also showed that, if the initial turbulence intensity of the free flow is more than about 0.1%, the phase of linear growth of the flow and the occurrence and amplification of other TS waves are no longer visible and the stirs in the boundary layer from the beginning are non-linear and rapidly grow and the other phases of the transition process continue until complete turbulent of the flow. Today, this type of transition process is known as bypass transition. In engineering, two other types of transition processes are known as laminar-bubble transition and vortex induction transition, which are beyond the scope of this paper.

The onset position of the transition and the length of the transition zone are the most important engineering parameters that directly depend on the flow conditions. Free flow stirs, flow gradient along to the flow, compressibility effects, surface roughness, curvature of surfaces, the three-dimensional effects of medium flow and the effects of heating or cooling of the wall, the effects of sound waves of the environment, the effects of thermal masses, so on are the most important factors affecting on the type of transition process, the onset position and the length of the flow transition zone. Mayle's extensive research [6] has shown that among the many parameters that affect the transition process, two parameters of turbulence intensity of the inlet free flow and pressure gradient along to the flow have the most effect, respectively. On the basis of this, this paper also examines these two parameters.

In this paper, after reviewing the available numerical methods for the analysis of transitional flows, using the Perot turbulence potential model [7, 8 and 9], which has strong bases and less hypotheses, the effects of the free flow turbulence intensity and pressure gradient on the transition onset position and the length of the flow transition zone were investigated. This turbulence model, which is a family of RANS models, uses a new approach in which, instead of modeling the

Reynolds stress tensor divergence, Reynolds stress tensor is directly modeled and does not use a Boussinesq relation. In order to obtain the Reynolds stress tensor divergence, a combination of two vector and scalar potential fields related to the turbulence forces is used. Due to the fact that in this model, the divergence filter has been removed, it is expected to be able to control and model complex non-equilibrium flows such as transitional flows.

2. Numerical Methods Review for Analyzing Transitional Flows

Estimating the onset position of the transition zone and also estimating the length of the transition zone on the moving bodies in the fluid is one of the most important basic needs of engineering. The use of experimental relations is one of the first methods to estimate these two parameters. In these methods, there is usually an explicit relation between the Reynolds number of the flow in the transition onset position according to the flow inlet parameters. As simple as these relations, their application to numerical codes analyzing the fluid flow field on the bodies is very difficult and, of course, the scope of validity of this type of relations is also very limited.

One of the most commonly used methods for predicting transition positions is the e^N method, which is most often used to predict the natural transition on the airfoils. This method uses linear stability theory [10]. Another method to apply the transition process properties to numerical solving in computational fluid dynamics is to enter the transition onset position to a numerical solving by the user. In this method, the computational domain is divided into two different computational zones, that is, laminar and turbulent zones, and in each computational zone, the equations related to the laminar or turbulent flows are numerically solved. The first problem of this method is to estimate the position of these computational zones correctly, and the next problem is how to activate the turbulence model embedded in the numerical code after the transition position of the flow to the turbulence. It should also be noted that in this method, the length of the transition zone is not modeled. Another method that has been widely used to analyze transitional flows is the use of the nature of well-known turbulence models and the correction of some of the terms of these models to model the transition zone. Savill has done a good review of the performance of a number of turbulent modified models of $k-\varepsilon$ to predict transition processes [11]. He concludes that each of these turbulent models does not have the appropriate responses for all flows, and each of them provides acceptable responses for specific flows. In this context, Salari and Chaboki [12] examined the performance of five different Low Reynolds Number (LRN) turbulence models for predicting transitional flows. They stated that Mr. Abyed's model had the best prediction than other LRN models to predict the bypass transition process, both in terms of the transition onset position and in terms of the length of the transition zone.

In another category of numerical work, it is assumed that the transition onset position is known and only the modeling of the changes in the characteristics of the flow inside the transition zone and the prediction of the length of the transition zone is investigated. Intermittency model by Suzen and Huang [13] has achieved relatively good successes in this field. The focus of this research has been on the flow analysis on the gas turbine blades, because experimental measurements have shown that when the inlet free flow has few initial stirs, the transition zone created on the blade of a gas turbine will be taken about 50 to 80% of the length of the blade.

The experimental measurements by Mayle and Schulz [14] showed that the instantaneous velocity of the boundary layer in the pre-transition zone has large fluctuations that are known today as laminar fluctuations of the flow [14]. These experiments show that before the transition zone, the profile of the boundary layer of the flow is significantly different from Blasius profile, as the inner layer momentum of the boundary layer is high and the outer layer momentum of the boundary layer is low. Mayle and Schulz [14] argued that the growth of laminar fluctuations in the pre-transition zone is due to the pressure fluctuations induced by free flow turbulence. These compressive waves like the T-S waves propagate inside the boundary layer, which stimulate and accelerate the velocity fluctuations. One of the most interesting method transition modeling methods recently introduced is based on the modeling and expanding the aforementioned laminar fluctuations in the pre-transition zone. This idea was first proposed by Mayle and Schulz in the form of a definition of a transport equation for the laminar kinetic energy of the pre-transition zone. Walters and Leylek [15] proposed a new formulation for the energy transport equation of the laminar fluctuations using idea of Mayle and Schulz [14]. Walters and Leylek [15] model is a three-equation model with transport equations for kinetic energy, K_l, turbulence kinetic energy, K_t and energy depreciation rate, ε. This model has a good potential for expansion in future.

Other methods of numerical modeling of transition in boundary layers, which are also applied to some CFD engineering codes, are the use of experimental relations for the transition onset position. Of course, in order to be able to use experimental relations to predict the transition onset in different flows and on different geometries (flat plate, airfoils, etc.), it is necessary to use the Reynolds number in experimental relations is arranged instead of the longitudinal position along to the flow (x) in terms of the boundary layer parameters (such as the thickness of the momentum, θ and etc.). For this purpose, in the main of the experimental relations, the turbulence intensity of the free flow (Tu) and the local pressure gradient (λ_θ) to the Reynolds number are usually related to the thickness of the momentum in the transition onset position ($\mathrm{Re}_{\theta t}$). Examples of this type of relationship are the relation by Mayle [6], the relation by Abu-Ghannam and Shaw [16], and the relation by Suzen and Huang [13], and the relation by Taghavi and Salari [24]. In order to develop this method, a valuable idea is presented to eliminate the need for non-local information in calculating the experimental model of transition process by Menter et al. (2002) [17]. In this formulation, a transport equation is presented for the intermittency coefficient (similar to the Suzen and Huang equation [13]), with the difference being that only local information of the flow is used to activate the term of production in the intermittency transport equation. The relationship between the experimental relations between the transition model and the intermittency equation has been established by using the Reynolds number based on vorticity. Therefore, the proposed model has two new transport equations for intermittency terms and Reynolds number of the momentum thickness (at the transition onset). In this computational model, the intermittency function is coupled to the turbulent model of $k-\omega(SST)$ by Menter [18], and the intermittency function is used to activate the turbulence kinetic energy production term at the bottom of the transition onset point. The second transport equation is arranged based on the Reynolds number of the momentum thickness of the $\overline{\mathrm{Re}_{\theta.t}}$ transition onset. This equation plays a fundamental role in the proposed transition model because it establishes the experimental relations between the transition onset with the activation of the intermittency equation and provides the use of a transition model for analyzing flow around different geometries. This formulation provides a flexible environment for predicting the transition in engineering processes, and due to its non-dependence on the non-local and integral quantities of the boundary layer, its computational frame is fully compatible with today's CFD numerical methods. Of course, since the experimental relations and calibrating functions of these models are usually obtained from the large experimental data analysis and by the high laboratory costs, therefore, these relations, if determined, are usually considered to be specific information of the institutions and generally not published [19 and 20]. One of the attempts to obtain a number of these model-calibrating experimental relations has been achieved in research work by Salari [21] and using several experimental measurements. In general, it can be said that this approach has a very good potential for developing transitional models.

3. Principles of Turbulence Potential Model

In the classical turbulence models based on the Unsteady Reynolds Averaged Navier Stokes (URANS) equations which is based on the vortex viscosity principle, a structural relationship between the Reynolds stress tensor and the average flow variables, that is, the average velocity and the kinetic energy of the flow are used. This relationship is established with the help of the definition of vortex viscosity (ν_T). The URANS equations are in the general form of the following:

$$\frac{\partial \vec{u}}{\partial t} + \nabla.(\vec{u}\vec{u}) = -\nabla p + \nabla.\nu\nabla\vec{u} - \nabla.\vec{R} \qquad (1)$$

In conventional turbulence models that use the principle of vortex viscosity, the structural relationship between stress tensor divergence and average flow quantities is defined as follows:

$$\nabla.R = \frac{2}{3}K.I - \nu_T(\nabla u + \nabla u^T) \qquad (2)$$

As the vortex viscosity in below form is related to turbulence parameters of the flow:

$$\nu_T = C_\mu k^2 / \varepsilon \qquad (3)$$

The relatively new turbulence model presented by Perot [7 and 8] uses the following equation to calculate the stress tensor divergence instead of using the principle of vortex viscosity and the above structural relation:

$$\nabla\phi + \nabla \times \psi = \nabla.R \qquad (4)$$

In this structural relation, the ψ vector potential and ϕ scalar potential functions is related to the turbulent body forces, and to ensure that these potentials are unique, the following relation should also be satisfied:

$$\nabla.\psi = 0 \qquad (5)$$

Also, these potentials are explicitly related to the below figure with stress tensor:

$$\nabla^2\phi = \nabla.(\nabla.R) \qquad (6)$$

$$-\nabla^2\psi = \nabla \times (\nabla.R) \tag{7}$$

Since these equations have elliptical nature, their boundary conditions should also have the same property. The values ψ and ϕ on the walls, the free surfaces and the very far distances of the flow are considered to be zero. In this model, instead of modeling the Reynolds stress tensor or providing a vortex viscosity, modeling of ψ vector potential and ϕ scalar potential functions related to turbulent body forces are discussed. This idea is based on the fact that a stress tensor divergence must be vector quantity and force type. This force, which is the result of the effects of the turbulent stress tensor of the flow, is called turbulent body forces. The ϕ scalar potential represents that part of the turbulence quantity that plays an important role in determining the average flow pressure, and has less effect on the average flow vorticities and only the ψ vector potential is capable of calculating and considering the effects of average vorticities of the flows.

Basically, the models of two turbulent equations, for example $k-\varepsilon$, are unable to analyze the physical processes in which the distribution of energy is occurred between the various components of the Reynolds stress. One of the assumptions of these models is that the Reynolds stress tensor divergence is in equilibrium with the average flow quantities. It is obvious that the laminar-turbulent transition process of flow is non-equilibrium process and during the transition process, the amplitude of the flow fluctuations grows exponentially in terms of time. The turbulence potential model, due to its basic relationship, maintains the physical state of the energy distributing phenomena and the non-equilibrium state in the flows, and due to its non-equilibrium formulation it is expected to be useful for analyzing transitional flows. In this paper, the ability of this model is examined for different condition of transitional flows.

4. Turbulence Potential Model Equations

The turbulence potential model uses a set of transport equations for turbulent forces potentials and two auxiliary variables (k,ε) for modeling fountain terms in equations. Note that the auxiliary variables (k,ε) are not used to model the effects of turbulence on the average flow field. Therefore, this model has a fundamental difference with standard turbulence models of $k-\varepsilon$ from this perspective. Equations, quantitative derivatives, and the logic governing the model relations are the broad subject expressed by Perot. Perot has also examined the performance of the model for a variety of flows. The results show a good agreement with the results of the DNS and LES models or their data.

It is important to note that near the wall, the turbulence potentials of ψ,ϕ vary with the power 3 and 4 compared to the distance from the wall (y^3, y^4), respectively. As an example, in Fig. 1, the changes curve of these two quantities, along with turbulence energy changes of k, are shown perpendicular to the boundary layer of a flat plate and in the turbulent zone of the flow. It is clear that the direct calculation of these rapid changes with the help of second-order numerical methods is very difficult unless the computational grid near the wall is very tiny. Since the turbulent kinetic energy of k grows in a direction perpendicular to the wall, defining new quantities of $(\phi/k)^{1/2}$ and (ψ/k) can overcome the above problem to a large extent. These two newly defined quantities will be linearly changed in direction perpendicular to the wall. Changes of these two new quantities are also given in Fig. 1. On this basis, the transport equations of $(\phi/k)^{1/2}$ and (ψ/k) contain simpler and lesser terms.

More detailed information on other parameters and constants of the above equations is given in references [7] and [8]. The point to be taken into consideration is that although the transport equations of $k-\varepsilon$ are solved in this model, but there is not much similarity between this model and the standard model of $k-\varepsilon$. In this model, flow potentials of (ϕ,ψ) are defined with the help of a $\nabla.R=\nabla\phi+\nabla\times\psi$ precise relation, so that k,ε are used only for modeling fountain terms in the equations of this model and are not directly used to calculate the Reynolds stress tensor or to apply turbulence flow effects.

The final modified turbulent potential model by Perot [9] has the following transport equations:

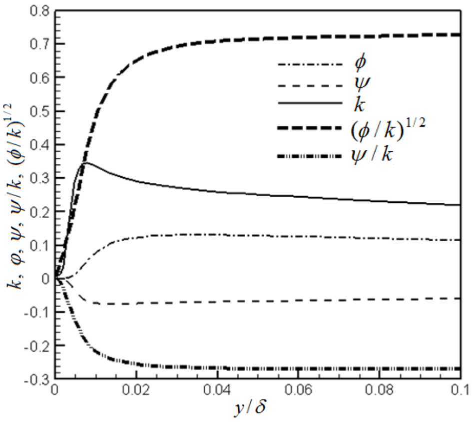


Fig. 1: $k,\ \varphi,\ \psi,\ \psi/k,\ (\phi/k)^{1/2}$ changes in terms of y/δ in perpendicular to the flat plate

$$\frac{Dk}{Dt}=\Delta.(\upsilon+\upsilon_t\overline{\sigma_\varepsilon})\Delta k+P-\varepsilon \tag{8}$$

$$\frac{D\varepsilon}{Dt}=\nabla.(\upsilon+\upsilon_t\bar{\sigma}_\varepsilon)\nabla\varepsilon+\frac{\hat{\varepsilon}}{k}(C_{\varepsilon1}P-C_{\varepsilon2}\varepsilon+C_{\varepsilon3}P_{3D}) \tag{9}$$

$$\frac{D(\phi/k)^{1/2}}{Dt}=\nabla.(\upsilon+\upsilon_t\bar{\sigma}_k)\nabla(\phi/k)^{1/2}+\frac{1}{2}C_{P1}\frac{\upsilon_t}{\upsilon_t+10\upsilon}\frac{\hat{\varepsilon}}{k}(2\alpha-1)\left(\frac{\phi}{k}\right)^{1/2}-\frac{1}{2}(1-C_{P2})\left(\frac{\phi}{k}\right)^{1/2}\frac{P}{k} \tag{10}$$

$$\begin{aligned}\frac{D(\psi/k)}{Dt}&=\nabla.(\upsilon+\upsilon_t)\nabla(\psi/k)+C_\mu(2\alpha-1)\frac{\phi}{k}\omega-C_{P3}2\alpha\frac{\psi}{k}P\\&-C_{P1}\frac{\upsilon_t}{\upsilon_t+10\upsilon}\frac{\hat{\varepsilon}}{k}(1-\alpha)\frac{\psi}{k}-(1-C_{P2})(\frac{\psi}{k}\frac{P}{k}-\frac{\phi}{k}\omega)\end{aligned} \tag{11}$$

Where the different terms are defined as:

$$P=\psi.\omega,\quad \upsilon_t=C_\mu\frac{\phi k}{\hat{\varepsilon}},\quad \alpha=\frac{1}{1+1.5\frac{\phi}{k}},\quad P_{3D}=\left|\psi\times\omega\right| \tag{12}$$

$$\hat{\varepsilon}=\varepsilon/\left[1+10\nu\left|\nabla k^{1/2}\right|/k\right]$$

Also, the constants of these equations are:

$$C_\mu=0.21,\quad C_{P1}=4.2,\quad C_{p2}=\frac{3}{5},\quad C_{p3}=1.0$$

$$
\begin{aligned}
&\sigma_k = 0.33 + 0.67P/\hat{\varepsilon} \\
&\sigma_\varepsilon = 0.33 + 0.5P/\hat{\varepsilon} \\
&\sigma_\phi = 0.33 \\
&C_{e1} = 1.45, C_{e2} = 1.83 - 0.16\exp\left(-0.1\frac{k^2}{\upsilon\varepsilon}\right),\ \ C_{\varepsilon 3} = 0.15
\end{aligned}
\tag{13}
$$

5. Numerical Solving Method

The scalar variables of $(\phi/k)^{1/2}, (\psi/k), k$ and ε, and transport equations of 4, 5 and 6 models have been applied to the fluent software by using capability of new User-Definition Scalar (UDS) and diffusion and fountains phrases by using capability of the new User-Definition Functions (UDFs). The second-order upwind difference scheme is used for discretization of displacement and diffusion terms of the model equations and momentum equations and, the simple algorithm is used for relationship between velocity and pressure fields. In all cases, the flow is considered incompressible with constant properties.

6. Presentation and Analysis of the Results

In order to analyze the effects of turbulence intensity of free flow and pressure gradient on the transition onset position and the length of the laminar-turbulent transition zone, several transition flows were analyzed, and each case is compared with the experimental data.

Numerical analytic states in non-zero pressure gradient conditions in this study are presented in table 1. These states include five states of flow under the influence of free flow turbulence intensity and different pressure gradient profiles along to the flow. In all of these analyzes, to determine the transition onset position and the estimation of the length of this zone, the change of the surface friction coefficient in terms of distance to the beginning of the plate is used as a criterion for the separation of the laminar flow zone from turbulent type.

Also, in order to ensure the independence of the solving results to the computational grid in each case, a proper grid is also conducted. In Fig. 2, a schematic of the computational grid for flow conditions on a flat plate is presented in the variable pressure gradient state.

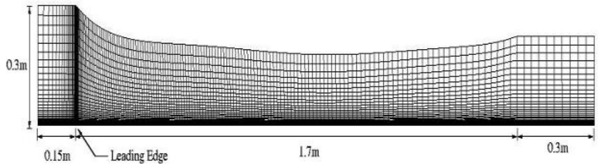


Fig. 2: T3Cx variable pressure gradient condition

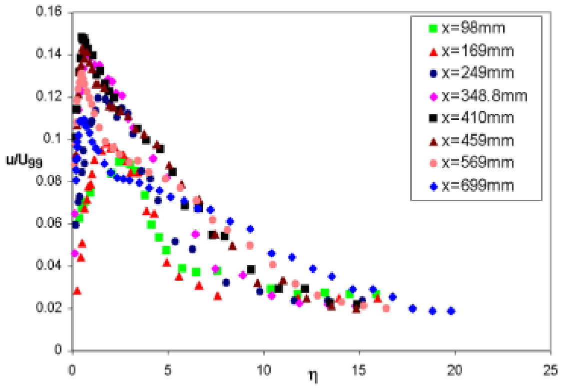


Fig. 3: Experimental measurements of size changes in root mean square of velocity fluctuations along the perpendicular to the wall and at different distances from the edge of the flat plate (end of transition zone, x = 410 mm) with the help of the hot wire sensor [22, 25]

6.1. Flow on flat plate under variable pressure gradient and different intensities of free flow turbulence

As mentioned in the introduction section, the two parameters of the turbulence intensity of the inlet free flow and the pressure gradient along to the flow have the greatest effect on the transition process in external flows. On this basis, there are five states of flow in which, in addition to the change in free flow intensity, the pressure gradient along to the flow is also non-zero, which is used to evaluate the turbulence potential model. The flow velocity in the inlet zone was uniform and equal to the U_0. The amount of turbulence kinetic energy is determined for the input zone by $k=3(Tu.U_0)^2/2$ relation. The initial turbulence loss rate of ε at the inlet boundary of the flow is obtained from the $\varepsilon = {C_\mu \rho k^2}/{\mu_t}$ relation. The input values of the potentials are at the input boundary of ϕ and ψ, are respectively obtained of relations $0.0529k$ and 0. The fluid has been considered air in all states, so the amount of kinematic viscosity of the flow is considered to be equal to the $\nu = 1.55\times10^{-5}$. Other inlet conditions of the flow for this situation are given in table (1).

Table 1: Different conditions of the input flow in numerical analyzes for variable pressure gradient states

Case	Case Name	$U_0(m/s)$	Tu	μ_t/μ	Experimental Data
1	PG-T3C2	5.3	3%	11	ERCOFTAC[23]
2	PG-T3C5	8.4	3%	5	ERCOFTAC[23]
3	PG-SA	11.5	3.5%	15	Salari [21]
4	PG-SB	8.7	4.8%	30	Salari [21]
5	PG-T3C1	5.9	6.6%	30	ERCOFTAC[23]

It should be noted that the pressure changes profile along to the flow for empirical experiments of ERCOFTAC institute and in variable and for empirical experiments performed by Salari et al. [21 and 24] are as negative pressure gradients according to Fig. 5. The variable pressure gradient applied in the experimental tests of T3C1, T3C3, and T3C5 is designed to simulate the passing flow through the turbine blades. Therefore, in both of these cases, the pressure gradient is initially negative (desirable) and then positive (inverse). The profile of the pressure changes in the three above mentioned conditions is approximately the same as in Fig. 4.

In Fig. 5, the change of the coefficient of surface friction obtained from the numerical solving for flows with a pressure gradient along with laboratory data is plotted according to the Reynolds number. In this figure, the results of the flow solving are presented in two completely laminar and turbulent, and $k-\omega-SST$ model is also presented for comparison.

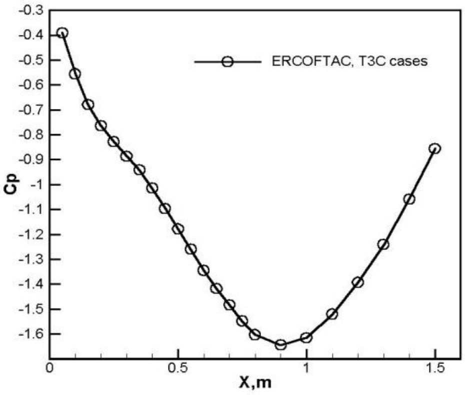


Fig. 4 (a): The pressure coefficient according to the distance from the beginning of the plate for T3Cx tests

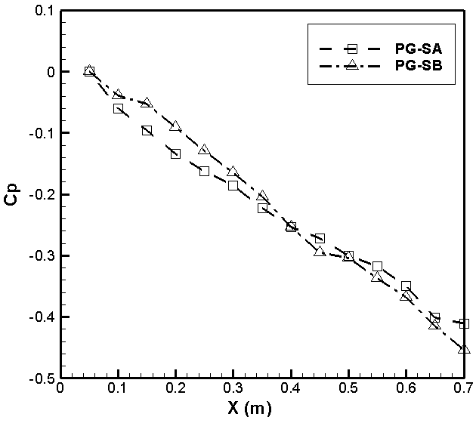
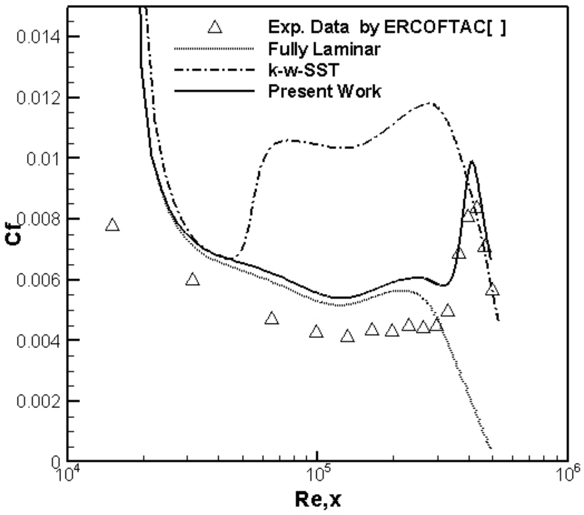
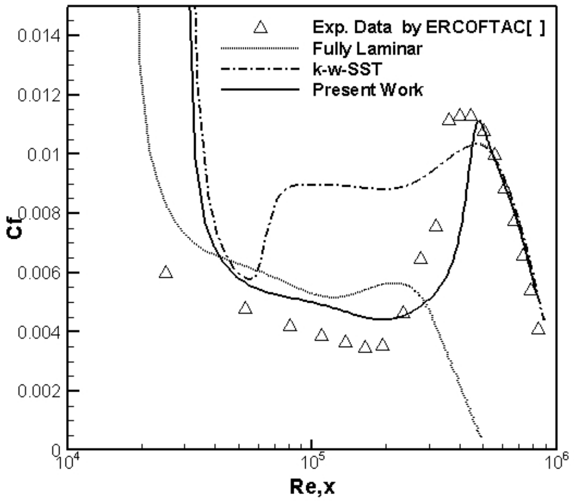


Fig. 4 (b): The pressure coefficient according to the distance from the beginning of the plate for PG-SA and PG-SB tests

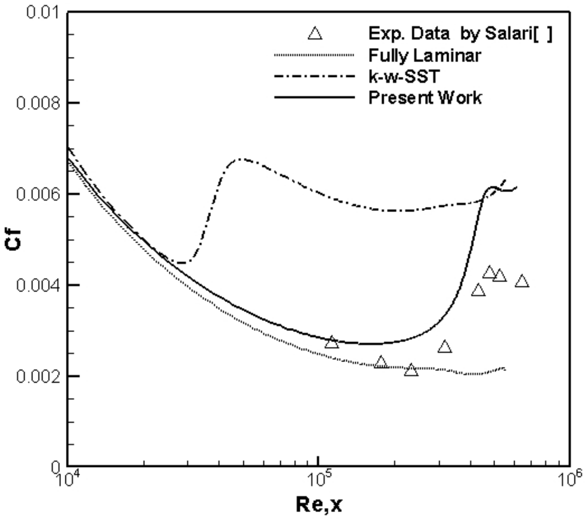
In these five cases of the flow of the numerical model, potential turbulence has been able to accurately follow the flow behavior, especially the ability of the model to predict the onset of the transition zone. Note that the desirable pressure gradient at the beginning of the plate in the T3C1, T3C2, and T3C5 states has made the onset position of the flow transition process compared to flat plate without the pressure gradient become later. As it can be seen, the turbulence model of $k-\omega-SST$ in the laminar and stir zones has a relative adaptation to the experimental results, but suggesting the flow transition position much earlier, that is, the it shows the length of the turbulent zone much larger than its real value.



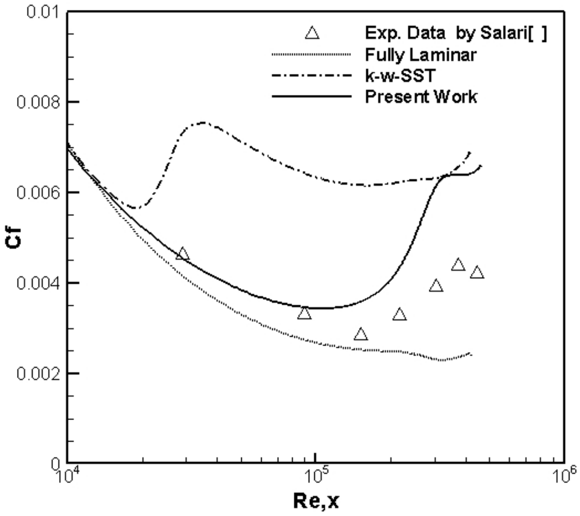
Case 1: PG- T3C2, (Tu=3%)



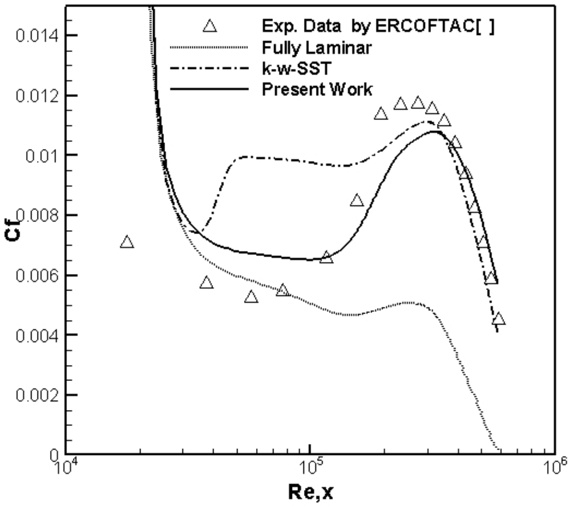
Case 2: PG-T3C5, (Tu=3%)



Case 3: PG-SA, (Tu=3.5%)



Case 4: PG-SB, (Tu=4.8%)



Case 5: PG-T3C1, (Tu=6.6%)

7. Conclusions

In this study, the effect of two important parameters on the laminar-turbulent transition process, that is, the turbulence intensity of inlet free flow and the pressure gradient along to the flow on initial position and length of the transition zone, was numerically analyzed. To this purpose, a wide range of changes of these two parameters, which their experimental data were available, were studied. Among the many methods used for numerical analysis of transitional flows, Perot turbulence potential model was used because of its fundamental difference with conventional turbulence models. The equations of this relatively new model have been applied to the fluent software by programming capabilities of this software and the use of UDF and UDS scalar equations. The results show that this turbulence model has been able to simulate flow behavior in all three laminar, transition, and turbulent zones due to its structural relations non-equilibrium nature, and in many cases the position and length of the transition process conforms to experimental data. Of course, in cases where the turbulence intensity of free flow is low and the transition process is of a natural type, the sensitivity of the results will be to the inlet values of the flow. With the help of the appropriate changes in the coefficient φ, this model can also be calibrated for these very sensitive conditions. Other details and results related to this model and the transition process are presented in the layers in reference [22].

8. Acknowledgments

We would like to thank the Aerodynamics Laboratory of the University of Science and Technology and Dr. Taghavi for providing experimental results.

9. References

[1] Orr, W.M.F., The stability or instability of the steady motions of a perfect liquid and of a viscous liquid, Part I: A perfect liquid; Part II: A viscous liquid, Proc. Roy. Irish Acad, 1907.

[2] Sommerfeld, A., Ein Beitrag zur hydrodynamischen Erkrung der turbulenten Flüssigkeitsbewegungen, Proc. 4th Int. Cong. Math., Rome, 3, 1908, pp.116-124.

[3]Tollmien,W., Uber die entstehung der turbulenz”.Nachr.Ges.Wiss. Gottingen, Eng ish trans ation NACA TM 609,1931.

[4]Schlichting,H.,Zur entstehung der turbulenz bei der p attenstr omung. Nachr.Ges.Wiss. Gottingen, 1933, pp. 181 –208,

[5]StubbierG.andSkramstad H.K. Laminarboundarylayerfluctuations and transition on a flat plate. NASA Report 909, 1948.

[6] Mayle, R.E. The role of laminar-turbulent transition in gas turbine engines,Journal of Turbomachinery, October 1991,Vol. 113, pp.509-537.

[7] Perot B., A new approach to turbulence modeling, Proceeding of the center for turbulence, Stanford university, 1997.

[8] Perot B. Turbulence modeling using body force potentials. Phys. Fluids Vol. 126, pp.45 –56 , 1999.

[9] Perot B and Taupier J. Modeling three-dimensional boundary layers using the turbulent potential model. AIAA 2000-0914 (Reno,Nevada,January 2000)

[10] Stock, H.W. and Haase, W., Navier-Stokes Airfoil Computations with eN Transition Prediction Including Transitional Flow Zones, AIAA Journal, Vol. 38, No. 11, 2000,pp. 2059 – 2066.

[11] Savill, A.M., (1993), some recent progress in the turbulence modeling of by-pass transition, In: R.M.C. So, C.G. Speziale and B.E. Launder, Eds.: Near-Wall Turbulent Flows, Elsevier, p. 829.

[12] Salari M.,Chaboki, Y., Studying the performance of low reynolds (LRN) turbulence models in the prediction of the laminar-turbulent transition process, Iranian Journal of Marine Science and Technology, No. 52, 2009

[13] Suzen, Y.B., Huang, P.G., Hultgren, L.S., Ashpis, D.E., 2003, Predictions of Separated and Transitional Boundary Layers Under Low-Pressure Turbine Airfoil Conditions Using an Intermittency Transport Equation,Journal of Turbomachinery, Vol. 125, No. 3, July 2003, pp. 455-464.

[14] Mayle, R.E. and Schulz, A., The Path to Predicting Bypass Transition, ASME Journal of Turbomachinery, Vol. 119,1997, pp. 405-411.

[15] Walters, D.K and Leylek, J.H., A New Model for Boundary-Layer Transition Using a Single-Point RANS Approach, ASME IMECE’02, IMECE2002-HT-32740.

[16] Abu-Ghannam B.J.and R. Shaw. Natural transition of boundary layers the effects of turbulence pressure gradient, and flow history. J. Mech. Eng. Science, 1980, Vol. 22, pp. 213-228.

[17] Menter, F.R., Esch, T. and Kubacki, S., Transition Modelling Based on Local Variables, 5th International Symposium on Engineering Turbulence Modelling and Measurements,2002, Mallorca, Spain.

[18] Menter, F.R., Two-Equation eddy-viscosity turbulence models for engineering applications, AIAA Journal, Vol. 32, No. 8, 1994,pp. 1598-1605

[19] Menter, F.R., Langtry, R.B., Likki, S.R., Suzen, Y.B., Huang, P.G., and V◌̨lker, S., A Correlation based Transition Model using Local Variables Part 1- Model Formulation, ASME-GT2004-53452, Austria, 2004.

[20] Menter F.R, Langtry R.B, Correlation- Based Modeling for Unstructured Alongized Computational Fluid Dynamics Codes, AIAA Journal, Vol. 47, 2009.

[21] Salari M., Experimental and numerical analysis of the bypass transition process in incompressible flows, Ph.D. thesis in Mechanics Engineering, Energy Conversion, Iran University of Science and Technology, May 2008

[22] Etezadi, H., Applying the proper model of laminar-turbulent transition process to the fluent software to analyze transitional flows, M.Sc. Thesis in Aerospace-Aerodynamics Engineering, Imam Hossein University, 2011

[23] ERCOFTAC (European Research Community on Flow, Turbulence, Combustion) Nexus. [online database], URL: http://ercoftac.mech.surrey.ac.uk/ [cited 15 Feb 2008].

[24] Taghavi R, Salari M, Tabar M, Omidi H, Hot Wire Anemometry of Transitional Boundary Layers Exposed to Different Freestream Turbulence Intensities, ImechE, Journal of Aerospace Engineering, Vol. 22, 2008.

[25] Salari M., Professional programming of fluent software, Andishehsara Publiction, 2012