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An Improved Empirical Correlation for Boundary Layer Transition Considering the Effects of Both the Streamwise Pressure Gradient and Freestream Turbulence Intensity

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Abstract

The empirical correlation for prediction of the onset of boundary layer transition, presented previously by authors, Taghavi et al.(2009), was extended by taking into account the effects of both the streamwise pressure gradients and the freestream turbulence intensity. The correlation was derived based on experimental data of transitional boundary layers subjected to different freestream turbulence intensities and streamwise pressure gradients, obtained in this study as well as from other researchers. The experiments were carried out in two different free stream turbulence levels and four different pressure gradients. A single hot-wire probe was used for measurements of instantaneous flow velocities within the boundary layer. Experiments were conducted in an open circuit wind tunnel of suction type. For each pressure gradient in a distinct free stream turbulence level, the mean longitudinal velocity and root mean square, RMS, of the velocity fluctuations were obtained at several streamwise locations. Experimental results were used to determine the variations of streamwise skin friction coefficient and boundary layer shape factor versus the local Reynolds number. Based on the available measurements and mathematical models, an improved empirical correlation was developed. Comparisons with other existing empirical correlations showed that the new correlation was more consistent with experimental data.

Keywords*:* Boundary layer transition, Hot wire anemometry, Turbulence intensity, Pressure gradients, Empirical correlation.

1. INTRODUCTION

Laminar to turbulent transition in boundary layers plays an important role in various applications of aerospace engineering, propulsion systems and especially design of turbomachines [1]. The transition is affected by disturbances in the external flow such as streamwise pressure gradient and freestream turbulence intensity. It is also affected by Reynolds number variations, flow separation, unsteady wake/blade interactions, surface roughness, surface temperature, and curvature [2]. The location of the onset and the length of transitional region are of major importance. Throughout the transitional region, heat transfer and skin friction increase dramatically from their low laminar values at the onset of transition to their corresponding high fully-turbulent values at the end of transition [3]. In order to calculate heat transfer and skin friction in the transitional region, accurate prediction of the onset and length of transitional region of the developing boundary layer are required. In addition, the behavior of laminar to turbulent transition has a dominant effect on the separation behavior of boundary layers. As a consequence, accurate prediction of onset and length of the transitional region plays an important role in the design of efficient turbomachinery components, particularly for low-pressure turbines [4].

In addition, for the low Reynolds number fluid flows at low-freestream turbulence intensity condition, the boundary layers tend to remain laminar; hence the boundary layer may experience a separated condition before the laminar-to-turbulent transitional region. This phenomenon reduces the airfoil efficiency and increases the fuel consumption of their airplanes. It has been reported that an improvement of about 1% in the efficiency may result in considerable savings in cost [5]. Laminar-to-turbulent transition occurs on blade surfaces of low-pressure compressor and turbine stages of turbomachines and in some circumstances, the transitional region covers about 80% of the blade surface in very low turbulence intensity conditions of the inlet flow [6].

Many physical factors influence the onset and length of the transitional region, which can be summarized as: the streamwise pressure gradient, Reynolds number, surface roughness, heat transfer, freestream turbulence intensity and unsteady wake-boundary layer interactions. Due to these highly influential factors, all of the existing theoretical or semi-empirical correlations presented in the literature for prediction of the onset of transition have some limitations; hence, there is not a unique solution to model all different kinds of the transitional flows [7].

Because of the importance of the transition phenomenon, many investigations have been

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conducted to recognize its physics and effects, from experimental and theoretical points of view [8, 9, 10, 11]. Two distinct transitional mechanisms were identified by Mayle [12] through extensive studies on transitional flows. The first, which occurs at the freestream turbulence levels less than about 1%, is due to amplification of Tollmien-Schlichting (T-S) waves, so called as *natural transition*. At higher freestream turbulence levels of about 1%, where there is little evidence of these T-S waves, transition takes place through a second mechanism, known as bypass transition. In this mechanism, amplification of fluctuations occurs rapidly, and then, directly results in turbulent spots [8]. In other words, the stage of conventional two-dimensional Tollmien-Schlichting instability is bypassed in this type of transition process.

One of the most popular methods for prediction of the natural transition is the popular e^N method developed more than 50 years ago by van Ingen [13]. The e^N method is a semi-empirical method developed based on using the linear stability theory and experimental observations. As the use of the e^N method is often time-consuming for numerical computation of complex flows, the development of simplified methods is of unquestionable practical interest. For example, Krumbein [14] used the e^N transition prediction method to perform Reynolds-averaged Navier–Stokes computations of three-dimensional, finite wings using a local linear stability code and a database method.

Among various factors affecting the occurrence of transition, freestream turbulence intensity and streamwise pressure gradient are known as the most dominant factors, so the onset of transition and its length are mostly dependent on them [15]. Biau et al. [16] proposed a transition prediction model for boundary layers subjected to only the free-stream turbulence. The model was based on this phenomenon that in the upstream region of the transition onset, the fluctuations inside the boundary layer are dominated by such elongated wavy structures, in which their amplitude are growing in the streamwise direction. a linear and parabolic approach, inspired by the hydrodynamic stability theory, was used to describe the streaks dynamic of fluctuations and predict the transition position.

Numerical simulation of the transitional regions using traditional computational fluid dynamics (CFD) methods has been challenging in the recent decade. The TRANSPRETURB European network on transition prediction (http://transition.imse.unige.it/) reported that there are mainly two concepts for developing a computational model for numerical simulation of bypass transition in the industry (Menter et al.[17]). The first is the application of low Reynolds number (Re) turbulence models. However, the ability of these models to predict transition seems to be coincidental [18]. The reason is that the calibration of the damping functions is based on reproducing the viscous sublayer behavior, and not on predicting transition from laminar to turbulent flow. The second approach, which is favored by the industry over low-Re models, is the use of empirical correlations. The correlations usually relate the free stream turbulence intensity, *Tu*, to the transition Re, where the length scale is based on the momentum thickness. There are a number of transition models based on empirical correlations. Considerable progress has been made in the development of transition models, but existing models are still not always robust, because they do not capture all the physics of the transition process well.

Intermittency-based models, such as those proposed by Steelant and Dick [19], Suzen and

Huang [20], and Solomon et al. [21] are attempts to model the transition region by treating the zones separately. The transition model developed by Menter et al. [17] was based on two transport equations, one for intermittency and one for transition onset. The model used the concept of vorticity Re to link transition onset correlations with intermittency and was based only on local variables. The new model can be used for unstructured grids and parallel processing and is a significant improvement over the existing transition models. Today, this transition model is extensively used for modeling of such complex flows. Robitaille et al. [22] used the γ-$Re_{\theta t}$ model of Menter et al. [17] to examine the design of adaptive laminar airfoils in the transonic flow regime a transition prediction method. Predictions from the model are then compared to an extensive set of experimental results containing transition measurements on a morphing airfoil.

The new transition model of Menter et al. [17] used an important empirical correlation to estimate the transition Re based on the momentum thickness, Re_θ. It is clear that the accuracy of this correlation can affect that of the transition model. Based on all the explanation above, the literature lacks a perfect model suitable for both low and high turbulent intensity.

In this paper, the effects of both the freestream turbulence intensities and the streamwise pressure gradients on the onset of transition region were experimentally investigated. Based on the data obtained from the experiments and other investigator's results, which includes the effects of both the freestream turbulence intensity and streamwise pressure gradients, a new correlation was proposed for Re_θ. The novelty of this research is related to improvements in the prediction of onset of fluid flow transition for flows with lower values of turbulence intensities, where natural transition occurs. In while the combined effects of both the freestream turbulence intensities and the streamwise pressure gradients were considered in this study.

2. EXPERIMENTAL SETUP

Schematic layout of the test setup is shown in Fig 1. The wind tunnel was an open circuit of suction type with a test section of 62 by 62 cm^2 and length of 2 meters. An aluminum flat plate of 110 cm in length spanning the total width of the test section was used as the test model. The leading edge of the plate was sharped to reduce undesirable effects of the impinging flow. A suitable number of pressure tapings were mounted along two axially parallel lines at the top side of the plate centerline. Manipulation of the flow incidence at the leading edge of the test-plate was facilitated through partial blockage of the flow passing over the test plate with a perforated steel (51% open area) installed 50 mm upstream of the test-plate trailing edge, as well as through the use of a 200-mm-long flap mounted on the test section floor, the leading edge of which was located 300 mm downstream of the leading edge of the test plate. An additional means of incidence control was provided through adjustment of the pitch of the test plate relative to the longitudinal axis of the test section using the four threaded rods that carry the test plate. A plane-type rigid ceiling was also pivoted at the top of the test section near to the turbulence grid to provide favorable streamwise pressure gradients.

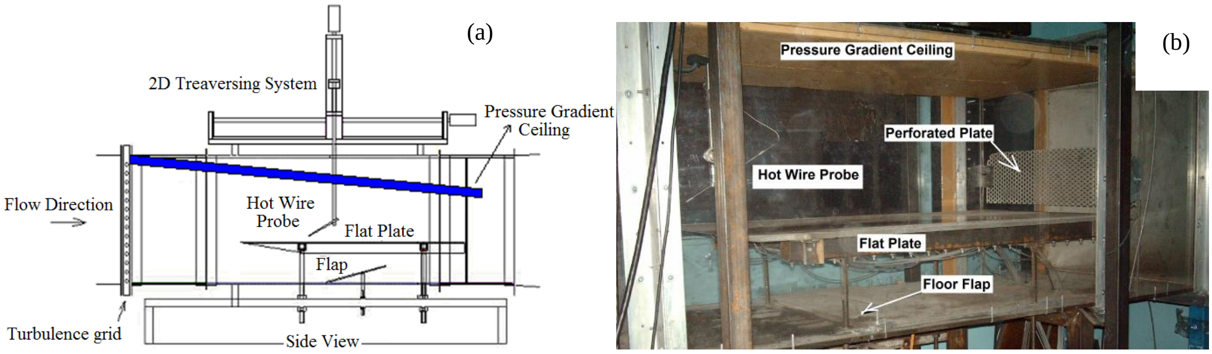
A traversing system with accuracy of 0.01 mm was used for traversing the hot-wire probe within the test section. A special technique developed by the authors was used to position the hot-wire probe at the closest possible distance from the plate.

The proposed method is for initial positioning of hot-wire sensors with respect to the wall based on utilizing the features of the jet flow generated by a high-aspect-ratio (HAR) rectangular nozzle. It is founded on the characteristics of jet flows from HAR rectangular nozzles. There is no need for any expensive or complicated devices such as advanced microscopes or laser devices and this method is a straightforward procedure for determining the location of the hot wire sensor with the precision of $\pm 5\,\mu m$. More details on this wall positioning technique are explained by Salari et al. [23].

Inlet freestream turbulence intensity at the leading edge of the plate,

$$\mathrm{Tu} = \frac{u}{U} \times 100 \qquad (2)$$

, varied using square mesh grids of circular bars, installed upstream at a proper distance from the leading edge of the plate. A single-channel hot-wire probe was utilized for measuring the streamwise velocity and its fluctuations. The wire was made of tungsten, 5 μm in diameter and 1.2 mm in length. An A/D card with a maximum data-sampling rate of 100 KHz and a resolution of 12 bit was applied for digitizing the analogue signals transmitted by the sensor. The frequency response (based on the square wave test) of the constant temperature anemometry (CTA) unit with the selected probe had a maximum sampling rate of about 15 kHz. A cut-off frequency of 10 kHz was used for the measurements, which seems adequate for acquisitioning of transitional and turbulent flows. More information about the details of the test setup was presented by Taghavi and Salari et al. [24].



Layout and a picture of wind tunnel test section

The suction-type wind tunnel and some components of test section

Fig. 1. Schematic layout of the test section of the experimental setup

2.1. TEST CASES

Test conditions under various favorite streamwise pressure gradients, including turbulence intensity, uniform air velocity at the leading edge of the plate and pressure gradient parameter,

$$\lambda_\theta = \frac{\theta^2}{\nu}\frac{dU}{dx} \qquad (1)$$

, are introduced $A = \pi r^2$ in Table 1.

Table 1. Conditions for streamwise pressure gradient test cases

Test case	Tu at the plate leading edge (%)	Uniform air velocity at the plate leading edge (m/s)	Pressure gradient parameter λ_θ
PG-B1	3.3	10	0.014-0.018
PG-B2	3.3	11	0.02-0.03
PG-C1	4.9	10	0.018-0.022
PG-C2	4.9	9	0.018-0.03

3. TEST VALIDATIONS

To check the trustworthiness of the results, initially, two important test cases were carried out. These test cases focused on laminar and turbulent boundary layers in the absence of turbulence generator grids. Inherently, these flows were accompanied by freestream turbulence intensities as low as about 0.2%. As shown in Fig. 2, current laminar experimental results are in a good agreement with Blasius' results. Turbulent results are presented in Fig. 2 (right). The results of Musker [25] and the well-known wall law results were superimposed in this figure. As can be seen, the current experimental results coincide with Musker's. For the regions very close to the wall surface, i.e., $y^+\leq 5$, the wall law of $u^+=y^+$ had excellent agreement with these experimental results.

Profiles of the measured mean velocity, U, and RMS velocity fluctuations, u, for the PG-C2 test case (see Table 1) are plotted in Figs. 3, at different axial positions from the plate leading edge. It is clear that streamwise pressure gradient has made the velocity profile become noticeably distorted from Blasius' and Musker's solutions in the laminar region and the turbulent region, respectively. Favorable pressure gradient made the velocity profile more stable than the level of zero pressure gradients, hence the onset of transitional region was postponed. It can be realized from these figures that the pre-transitional region of the boundary layer resembled a laminar boundary layer in terms of the mean velocity profile. As the local Reynolds number increased, the profile became noticeably distorted from the typical Blasius solution, which was associated with an increase in momentum in the inner region and a decrease in the outer region. This shift in mean velocity profile was accompanied by a development of relatively high-amplitude streamwise fluctuations, where the magnitude of which was several times that of the freestream level. This process resulted in an augmentation of skin friction and heat transfer in the pre-transitional region, and eventually led to bypass transition through the eventual breakdown of the streamwise fluctuations. The results presented in **Figs. 3** were in a reasonable agreement with those reported by Matsubara et al. [26], Klebanoff [27], and Jacobs et al. [28].

The occurrence of the transition is usually identified by the inspection of variations of the skin friction coefficient, Cf, along the surface. The skin friction coefficient is a very sensitive indicator of transition that increases dramatically as it occurs.

Variations of skin friction coefficient with local Re are presented in Fig. 4 for all of the test cases introduced in Table 1. Results for the boundary layer flows, presumed in the fully turbulent regimes along the whole surface, were also superimposed in these figures. The friction coefficient correlations for laminar and turbulent flows, Cf,lam=0.664 Rex-0.5and Cfturb= 0.027Rex-1/7, respectively, were also brought in Figs. 4 for comparison, and were used to determine the onset and end points of the transitional zone for the current experiments.

It can be concluded from Fig. 4 that in constant free stream turbulence intensity, as the pressure gradient parameter increases, the onset of boundary layer transition is delayed. As expected, increasing the freestream turbulence intensity made the onset of transition region occur earlier.

turbulence levels and the streamwise pressure gradients in the prediction of the onset of transition region. It should be noted that this correlation was in close agreement with Mayle's [12] and Abu-Ghannam and Shaw's correlations [29] at high freestream turbulence intensities (Tu > 3.0) and was comparable to the Abu-Ghannam and Shaw's correlation at moderate turbulence intensities (1.0 < Tu < 3.0). At lower turbulence intensities (Tu < 0.5%), the proposed correlation was in agreement with zero pressure gradient results presented by Drela's [30] e^n type model and experimental results of other studies [31, 32, 33, 34, 37]. The results of the proposed correlation in comparison with other correlations and experimental data are presented in Fig. 5.

4. DEVELOPING A NEW EMPIRICAL CORRELATION

The correlation presented by Taghavi and Salari et al. [24] was extended to consider both the free stream turbulence levels and the streamwise pressure gradients in the prediction of the onset of transition region. It should be noted that this correlation was in close agreement with Mayle's [12] and Abu-Ghannam and Shaw's correlations [29] at high freestream turbulence intensities (Tu > 3.0) and was comparable to the Abu-Ghannam and Shaw's correlation at moderate turbulence intensities (1.0 < Tu < 3.0). At lower turbulence intensities (Tu < 0.5%), the proposed correlation was in agreement with zero pressure gradient results presented by Drela's [30] e^n type model and experimental results of other studies [31, 32, 33, 34, 37]. The results of the proposed correlation in comparison with other correlations and experimental data are presented in Fig. 5.

Based on the experimental results obtained for different cases of streamwise pressure gradient, in the current work and other studies, an improved empirical correlation was proposed. The new correlation that includes the effects of both the freestream turbulence intensity and the streamwise pressure gradient was produced by a curve fitting technique over the available measurement data and mathematical models published in the literature [17, 29, 31, 32, 34, 36]. The new correlation (Eq. 1) is expressed as follows:

$$\mathrm{Re}_{\theta t} = F(\lambda_\theta).(\,3346e^{-(\frac{Tu+0.3656}{0.2825})} + 879.9e^{-(\frac{Tu+0.8927}{1.782})} + 419.5e^{-(\frac{Tu+12.93}{18.29})}) \quad (1)$$

Where

$$F(\lambda_\theta) = 1-\left(-6\lambda_\theta + 25.5\lambda_\theta^2 + 10.\lambda_\theta^3\right) e^{-\left[\frac{Tu}{4}\right]}, \quad \lambda_\theta \leq 0 \quad (2)$$

$$F(\lambda_\theta) = 1 + 0.556\left(1-e^{-40\lambda_\theta}\right)e^{-[2.5Tu]}, \quad \lambda_\theta \succ 0 \quad (3)$$

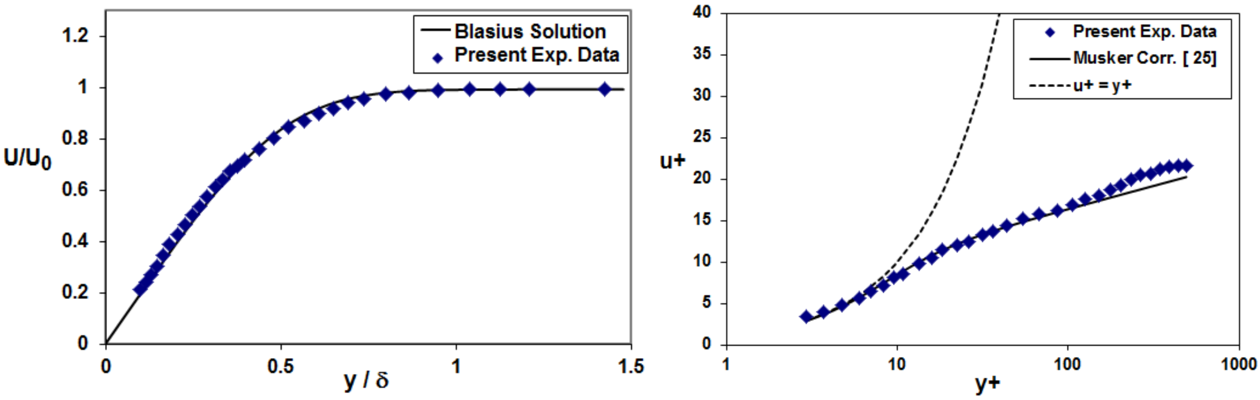


Fig. 2. Comparison of the a) laminar (left) and b) turbulent (right) test data at Tu=0.2% with other researches.

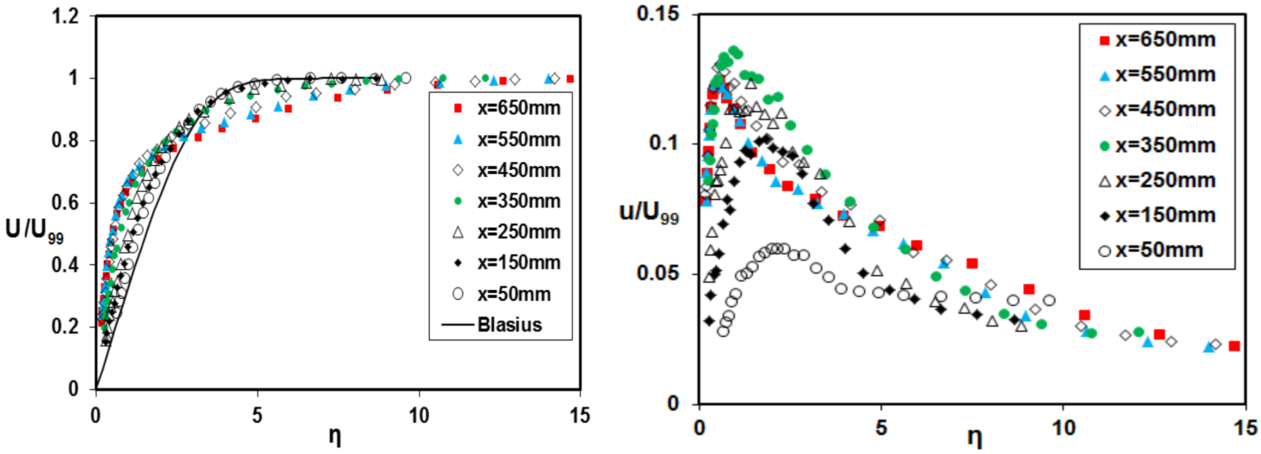


Fig. 3. a) Non-dimensional mean velocity profiles (left) and b) RMS fluctuations (right) for the PG-C2 test case at various axial distances measured from the plate leading edge

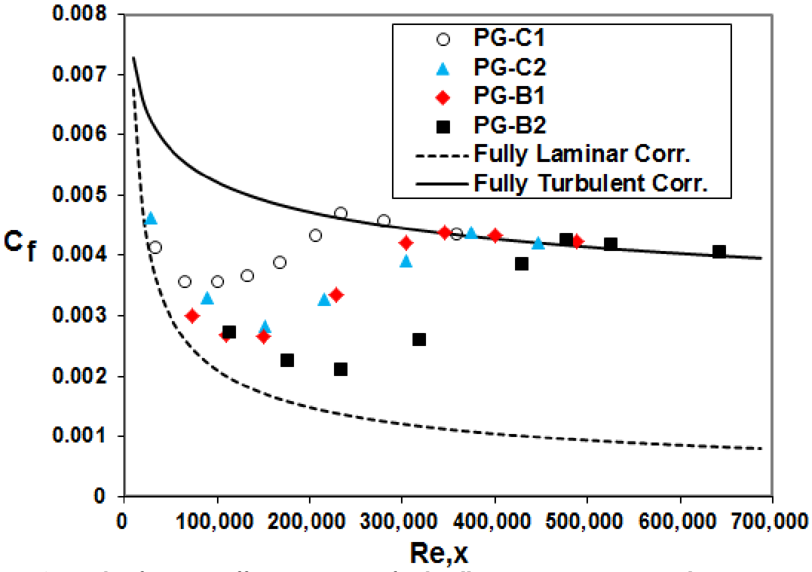


Fig. 4. Skin friction coefficient versus Re for the all streamwise pressure gradient test cases

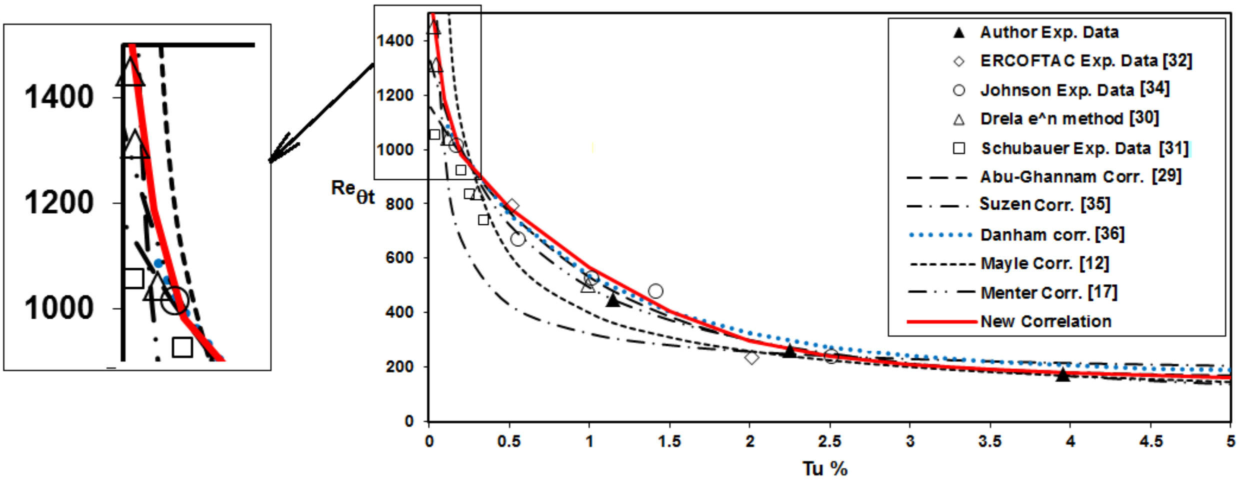


Fig. 5. Comparison of the new correlation with others for zero pressure gradient conditions

Based on the experimental results obtained for different cases of streamwise pressure gradient, in the current work and other studies, an improved empirical correlation was proposed. The new correlation that includes the effects of both the freestream turbulence intensity and the streamwise pressure gradient was produced by a curve fitting technique over the available measurement data and mathematical models published in the literature [17, 29, 31, 32, 34, 36]. The new correlation (Eq. 1) is expressed as follows:

$$Re_{\theta t} = F(\lambda_\theta).(3346 e^{-(\frac{Tu+0.3656}{0.2825})} + 879.9 e^{-(\frac{Tu+0.8927}{1.782})} + 419.5 e^{-(\frac{Tu+12.93}{18.29})}) \quad (1)$$

Where

$$F(\lambda_\theta) = 1 - \left(-6\lambda_\theta + 25.5\lambda_\theta^2 + 10.\lambda_\theta^3\right) e^{-\left[\frac{Tu}{4}\right]}, \quad \lambda_\theta \le 0 \quad (2)$$

$$F(\lambda_\theta) = 1 + 0.556\left(1 - e^{-40\lambda_\theta}\right) e^{-[2.5Tu]}, \quad \lambda_\theta \succ 0 \quad (3)$$

It should be noted the above equation is valid for $-0.1 \le \lambda_\theta \le 0.1$, $Re_{\theta t} \ge 20$ and $Tu \ge 0.027$ conditions.

It is clear that if λ_θ is equal to zero, $F(\lambda_\theta)$ will be equal to 1; so the new proposed correlation reduces to the correlation presented by Taghavi and Salari et al. [24]. It should be noted that the condition $\lambda_\theta = 0$ indicates the elimination of streamwise pressure gradient effects.

In Fig. 6, the new correlation is compared with experimental data of other studies [31, 32, 34] and correlations introduced in the literature [17, 29, and 36] for various streamwise pressure gradients. The current experimental results are also shown in Fig. 6. Before discussing the results presented in this diagram, it would be helpful to re-introduce the existing empirical correlations of the others as listed below.

Mayle's [12] correlation includes only the turbulence intensity, Tu, as:

$$Re_{\theta t} = 400 Tu^{-5/8} \quad (4)$$

Suzen et. al. [35] had also presented the following correlation for prediction of transition:

$$Re_{\theta t} = \left(120 + 150 Tu^{-\frac{2}{3}}\right) coth[4(0.3 - K_t \times 10^5)] \quad (5)$$

where:

$$K_t = (\nu/U^2)(dU/dx). \quad (6)$$

Abu Ghannam and Shaw [29] correlation was demonstrated as follows:

$$Re_{\theta t} = 163 + \exp\left(F(\lambda_\theta) - \frac{F(\lambda_\theta)}{6.91} Tu\right) \quad (7)$$

where:

$$F(\lambda_\theta) = 6.91 + 12.75\lambda_\theta + 63.64{\lambda_\theta}^2 \quad \text{for } \lambda_\theta < 0 \quad (8)$$

$$F(\lambda_\theta) = 6.91 + 2.48\lambda_\theta - 12.27{\lambda_\theta}^2 \quad \text{for } \lambda_\theta > 0. \quad (9)$$

Menter et. al. [17] also presented the bellow correlation:

$$Re_{\theta t} = 803.73(Tu + 0.6067)^{-1.027} F(\lambda_\theta, K) \quad (10)$$

where:

$$F(\lambda_\theta, K) = 1 - \left(-10.32\lambda_\theta - 89.47{\lambda_\theta}^2 - 265.51{\lambda_\theta}^3\right) e^{\left(\frac{-Tu}{3.0}\right)} \quad \text{for } \lambda_\theta < 0$$

$$F(\lambda_\theta, K) = 1 + (0.0962[K.10^6] + 0.148[K.10^6]^2 + 0.0141[K.10^6]^3)\left(1 - e^{\left(\frac{-Tu}{1.5}\right)}\right) + 0.556\left(1 - e^{(-23.9\lambda_\theta)}\right) e^{\left(\frac{-Tu}{1.5}\right)} \quad \text{for } \lambda_\theta > 0. \quad (11)$$

Dunham [36] 's correlation was rewritten as:

$$Re_{\theta t} = (0.27 + 0.73e^{-80Tu})(550 + \frac{680}{1-D}) \quad (12)$$

where:

$$D = min(21\lambda_\theta - 100Tu\,,\ 0.75)). \quad (13)$$

A lot of investigators, for example Suzen [35], demonstrated that Abu-Ghannam and Shaw's [29] correlation does not have sufficient sensitivity either in the adverse pressure gradient region or in fluid flows of very low turbulence intensities. In these cases, the Abu-Ghannam and Shaw's correlation predicted the onset of transitional region earlier than that of the real transitional region. These problems were eliminated in the correlation proposed in this study. The new correlation had sufficient agreement with the correlation presented by Abu-Ghannam and Shaw in the favorable pressure gradient region and turbulence intensities greater than 0.3% [29]. While, in fluid flows with turbulence intensities less than 0.3%, it had good agreement with experimental data on the contrary to the correlation presented by Abu-Ghannam and Shaw [29]. As shown in Fig. 5, it is clear that for $\lambda_\theta = 0$, the new proposed correlation had better agreement than the correlation presented by Abu-Ghannam and Shaw [29]. The experimental results showed that the position of the onset of transitional region had high sensitivity to Tu at very low pressure gradients (around $\lambda_\theta = 0$), But the correlation presented by Abu-Ghannam and Shaw [29] did show such sensitivity in the adverse pressure gradient region, and therefore, this sensitivity was taken into account in the new proposed correlation. Considering the bottom of Fig. 6, it is obvious that at the lower values of adverse pressure gradients especially at very low turbulence intensities, the relevant curves had a more abrupt slope than the correlation presented by Abu-Ghannam and Shaw [29]. Overall, it is clear that the new correlation had acceptable agreement with experimental data and the physical actualities of transitional process.

For comparison between the new proposed correlation and the correlation by Menter et. al. [17], it is worth mentioning that these two correlations were in good agreement for the Tu values higher than 0.3%, but there were inconsistency at lower values of Tu, especially for the favorable pressure gradient region. In comparison with experimental data for Tu < 0.3%, it can be seen that the new proposed correlation had better consistency with respect to the one by Menter et. al. [17]. Unfortunately, there are few sources of experimental data for lower values of Tu than 0.1%, in which the natural transition occurs.

As can be seen, all of the existing correlations, Dunham [36], Menter et. al.[17] Abu-Gannam et. al. [29] and the new proposed correlation were in good agreement with experimental data for Tu values higher than 1% and in the adverse pressure gradient region.

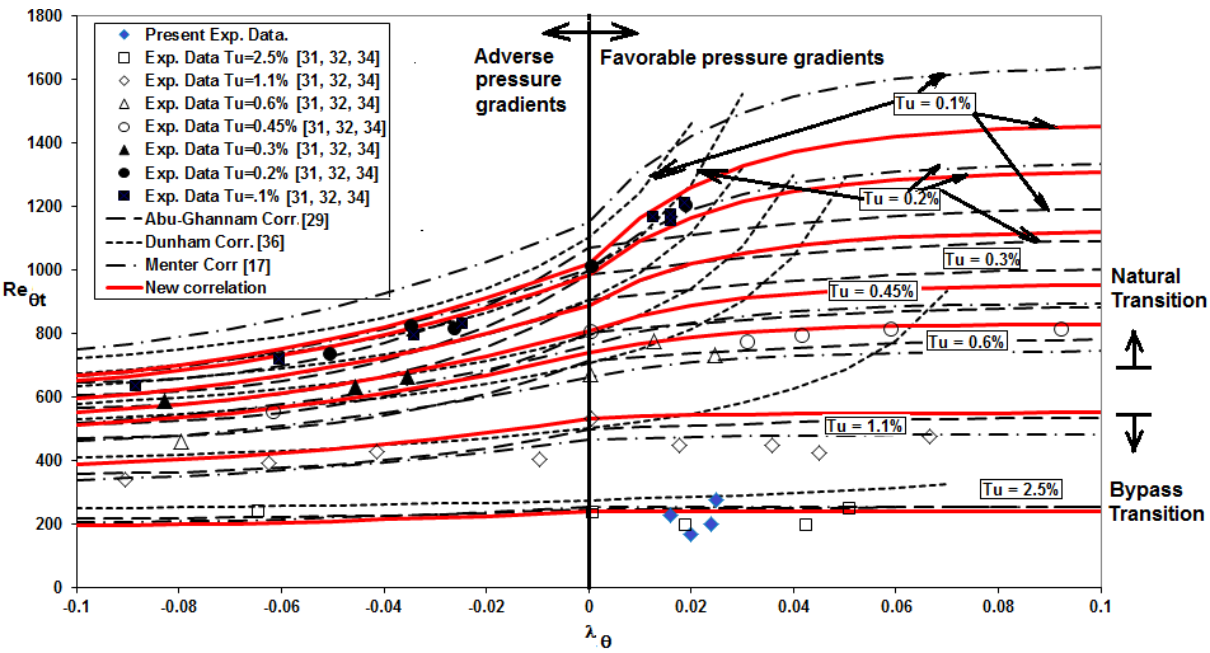


Fig. 6. Comparison of the new experimental correlation ($Re_{\theta t}$) versus Tu and λ_θ for nonzero streamwise pressure gradient conditions.

5. CONCLUSIONS

An improved correlation for the prediction of the onset of transitional region based on the momentum thickness of boundary layers was developed. The proposed correlation was derived based on experimental data derived from tests conducted in the study and data reported by other researchers found in the literature. This correlation was an extension of an earlier correlation presented by Taghavi and Salari et. al. [20] who focused only on the effect of the freestream turbulent intensity on the onset transitional region. The new proposed correlation includes both the effects of freestream turbulence intensity and streamwise pressure gradient. It is an algebraic function and was seen to have better agreement with experimental data than other existing correlations. Moreover, the results obtained for different cases of the streamwise pressure gradients confirmed that the onset of the transitional region was postponed by applying favorable pressure gradients. In addition, it could be seen from the experimental data that at the higher values of freestream turbulence intensity, Tu is greater than about 2.5%, or the relevant bypass transition cases the location of onset of transitional region was not affected by the pressure gradient. At the other side for natural transition cases, in which the Tu is less than about 1%, the location of onset of transitional region was highly sensitive to the pressure gradient.

NOTATIONS

a_i, b_i, c_i	Constants of the new correlation.
C_f	Local skin friction coefficient.
θ	Boundary layer momentum thickness.
$\mathrm{Re}_{\theta t}$	Reynolds number based on the boundary layer momentum thickness at the onset of transition.
λ_θ	$(=\frac{\theta^2}{\nu}\frac{dU}{dx})$, Pressure gradient parameter based on momentum thickness.
Re,x	Reynolds number based on streamwise distance from the plate leading edge.
Tu	$(=\frac{u}{U}\times 100)$, Local freestream turbulence intensity.
Tu_0	Local freestream turbulence intensity at the plate leading edge.
u^+	Mean velocity in wall coordinate.
U_o	Inlet freestream velocity.
U	Local mean velocity.
u	RMS velocity of fluctuations.
x_0	Distance between the turbulence generator grid and the plate leading edge.
x	Distance from the plate leading edge to specific location on the plate.
y	Normal distance from the wall
y^+	Wall distance in wall coordinates.
ν	Kinematic viscosity
η	Blasius similarity variable, $\eta = y(U_0/2\nu x)^{1/2}$

SUBSCRIPTS

0	Representing the values of any quantities at the plate leading edge.
t	Representing the values of any quantities at the onset of transition

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