Effects of Angle of Attack on Turbulent Near Wake Flow, Using Hotwire Anemometer

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ABSTRACT

In this paper, the effects of angle of attack on flow behavior in the near wake of a flat plate, using a hot-wire anemometer are reported. The symmetric flat plate used has a rounded leading edge and a sharp trailing edge with a sweep angle of 45°. All measurements were carried out in a wind tunnel with a cross sectional area of 305×305 mm and a maximum velocity of $40\,m/s$. The Reynolds number, based on the chord length, was 6×10^{5}. The model was placed at angles of attack 5, 10, 15, and 20 degrees. It was concluded that, although it has been shown that the logarithmic law for angle of attack of zero is validated up to distances in near wake, its validity there is decreased by increasing the angle of attack. However, this law will not be validated by going away from the trailing edge. Also, the effect of angle of attack on turbulence kinetic energy in shear layer and on drag coefficient has been investigated. The results show that the turbulent kinetic energy is enhanced by increasing the angle of attack in a certain distance from the trailing edge and its value is reduced by going away from the trailing edge at a particular angle of attack. Also, the results show how the drag coefficient is increased when angle of attack gets larger.

Key Words: Hot Wire, Turbulence, Near Wake Flow, Drag Coefficient

اثرات زاویه حمله بر جریان آشفته نزدیک دنباله با استفاده از جریان سنج سیم داغ

عبدالله شادآرام[۱]، نورالله رستمی[۲] و سید آرش سید شمس طالقانی[۳]
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چکیده

در مقاله حاضر، اثرات زاویه حمله بر رفتار جریان آشفته نزدیک یک دنباله در پشت یک صفحه مسطح به کمک جریان سنج سیم داغ بررسی شده است. صفحه مسطح متقارن بوده، دارای لبه حمله گرد و لبه فرار تیز با زاویه اریب ۴۵ درجه می باشد. اندازه گیری ها در یک تونل باد با سطح مقطع ۳۰۵ × ۳۰۵ mm و سرعت ماکزیمم ۴۰ m/s انجام شده است. عدد رینولدز بر مبنای طول وتر ۶×۱۰^۵ بوده است. مدل در زوایای حمله ۵, ۱۰، ۱۵ و ۲۰ درجه قرار داده شده است. گرچه نشان داده شده که قانون لگاریتمی برای زاویه حمله صفر درجه در دنباله نزدیک تا فاصله ای از لبه فرار اعتبار دارد، لیکن نتایج این تحقیق نشان می دهد که اعتبار این قانون در ناحیه نزدیک دنباله با افزایش زاویه حمله در یک مقطع ثابت کاهش می یابد. همچنین، در یک زاویه حمله ثابت، با دور شدن از لبه فرار این قانون اعتبار خود را زودتر از زاویه حمله صفر درجه از دست می دهد. از طرف دیگر، اثر زاویه حمله روی انرژی جنبشی آشفتگی در لایه برشی بررسی شده است. همچنین، افزایش ضریب درگ با افزایش زاویه حمله نشان داده شده است.

واژه های کلیدی: سیم داغ، آشفتگی، جریان نزدیک دنباله، ضریب درگ

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Nomenclature

C_D	Drag Coefficient
D	Drag per Unit Length of Plate
k	Turbulence Kinetic Energy
l	Chord Length of Model
Re	Reynolds Number
t	Plate Thickness
U_∞	Free Stream Velocity
u', v', w'	Streamwise and Transverse Components of Velocity Fluctuations
V	Mean Velocity
V_τ	Friction Velocity
x, y	Streamwise and Transverse Coordinates Measured from the Centre of the Trailing Edge

Greek Letters

ν	Cinematic Viscosity
μ	Dynamic Viscosity
ρ	Density
θ	Angle of Attack

1. Introduction

The motion of objects through fluids is extensively encountered in engineering problems. Also, the profile and angle of attack of the moving objects play a very important role in order to estimate the flow field and consequently its efficiency. Air foils, turbine and compressor blades are examples of moving objects where the object is in motion inside a stationary fluid medium. Velocity and pressure fields which determine the drag forces have been studied by researchers in the flow wake around the moving objects components mentioned above [1].

Estimating the forces exerted on objects like airfoils and different kinds of blade in industries is also one of the most important aim for many researchers who work experimentally in the laboratories to find it with aid of different parameters. The angle of attack of models mentioned above, has a significant effect on force values. So, in this paper we tried to show the effect of angle of attack on some parameters like turbulent kinetic energy, velocity profiles and drag coefficient that help us to know better the flow field behind the model. Since the wake flow in industrial parts is often turbulent, the experimental investigation of such flow field needs some equipment in order to have an accurate measurement of turbulence characters like velocity fluctuations and Reynolds stresses. The wake flow can be divided in two regions: (a) near wake region and (b) far wake region. Some studies have been done on far wake region that led to an appropriate description and reasonable results [1-2]. Patel [3], Subaschandar[4], Tummers .et al [5], and Lam .et al [6] have done some experimental studies on near wake region in where the flow is strongly affected by upstream flow. Also according to Patel [3], the near wake flow was divided to some regions based on geometry of blade and conditions of flow near the trailing edge. Subaschandar [4] has concluded that in near wake region, there is a transition at the turbulent structure that causes the adjustment of pressure field and thus causes the viscose- inviscid interaction. Although the near wake of a swept flat plate is one of the simplest examples of wake, but there are a few number of experimental studies in this field. The most useful study in this field is related to Subaschandar [7], Cousteix .et al [8] and Novak and Ramaprian [9]. Cousteix .et al [8] have investigated the wake behind a swept wing with a sweep angle of 22.5° and an angle of attack of 8°. Gordon Leishman [10] has studied the effects of angle of attack on drag coefficient of a blade in wind turbine. He has compared his work to other published works about the drag coefficient values versus increasing the angle of attack of blade. Other researchers such as Afzal [11] and Buschmann [12] have studied experimentally on logarithmic law and velocity profiles in fully developed turbulent boundary layer and wake flows. This paper deals with the analysis of flow in near wake region behind a swept flat plate. It also investigates the effects of different angles of attack on flow in the above mentioned region. We have also investigated the effect of angle of attack on drag coefficient. In this experimental study velocity profiles and turbulent energy have been measured at some different section normal to the stream wise flow at Reynolds number 6×10^5. Then the behavior of these characteristics has been shown at different angles of attack. Also the variation of drag coefficient respected to angle of attack for a flat plate with a sweep angle of 45° is shown.

2. Experimental Apparatus

All tests have been done in a wind tunnel with a square test cross section of 305 mm×305 mm. Test chamber, that consisted of 600mm-long duct was made of a 15 mm thick Plexiglas. An axial fan sucks the air through the wind tunnel. The inductive power of fan's motor was 5.7 kw and its speed was 2900 $R.P.M$. The maximum wind velocity in the tunnel was 40 m/s and we were able to change the wind speed by opening or closing the throttle valve at the end part of wind tunnel. Hot-wire probe was entered in the test section from top of it and can be transported by a traverse system toward a certain point. The ratio of the cross-sections of the entrance area for the wind tunnel to the test section was 9:1. In order to change the angle of attack, we have utilized some holes on the lateral walls of the test chamber in order to fix the model at angles of attack of 5, 10, 15, and 20 degrees. The model was a rather smooth flat plate with a chord length of 240mm, width of 280mm and thickness of 6.5mm. It was made of wood and its both leading and trailing edges were 45 degree swept respect to main flow. The leading edge had a rounded shape and the trailing edge had a sharp wedge shape. Schematic of the model is shown in Fig. **1** Measurements have been carried out by a 3-D wire probe at dimensionless cross sections of $x/l = 0,$ 0.0625, 0.125, and 0.1875. The origin was the point close to the trailing edge where the hotwire had no attachment to the model. Turbulent intensity at the inlet for free flow related to the measurements was approximately %1. Data acquisition rate for each point was 1000 data per second and data transmission lasted about 23 seconds. Velocity calibration of all tests has been done by a calibrator from Dantec Company, and the maximum error from this calibrator at different velocities was less than %1.5. Hotwire probe was calibrated at the velocity range of 0.5 to 45 m/s before data acquisition. All measurements have been carried out at central line (z=0) in the middle of test section (see Fig.1). Thus, the walls didn't influence the test field. Figure **2** exhibits the direction of angle of attack, coordination and the place of the probe.

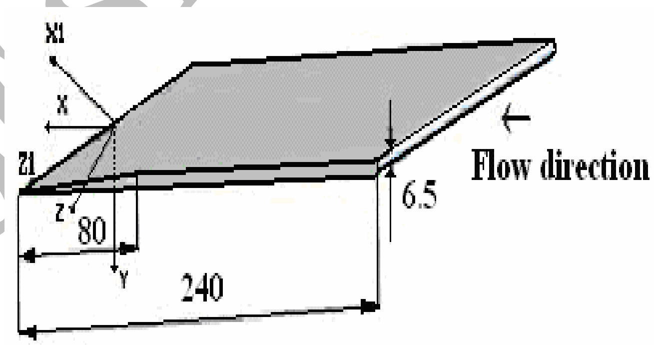

Fig. 1. Schematic of the model
(All dimensions are in mm**).**

3. Results and Discussion

Results presented in this paper were obtained under a bench mark experimental condition where the pressure was 650mm Hg and the average ambient temperature was $22^{\circ C}$. The results have been organized as follow: (1) dimensionless turbulent kinetic energy; (2) velocity profiles; and (3) drag coefficient.

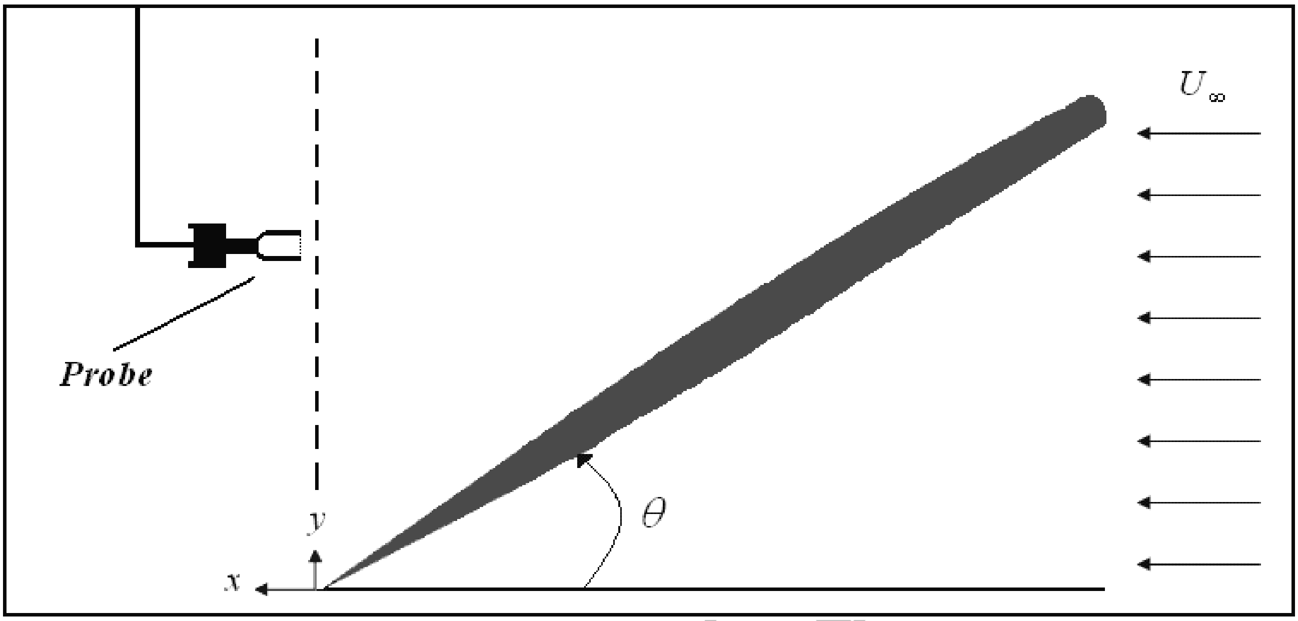

Fig.2. x-y coordinate and the place of hotwire probe.

3.1 Dimensionless Turbulent Kinetic Energy

Figure **3** shows the turbulence kinetic energy variations versus distances from central line of the model (y) in angles of 5, 10, 15 and 20 degrees for different cross sections. In this figure, k is the turbulence kinetic energy that can be calculated by the equation:

$$k = \frac{1}{2}\left(u'^2 + v'^2 + w'^2\right).$$

According to Fig. 3, at each section of x, the turbulence kinetic energy is increased by increasing the angle of attack. Also, it is observed that at any angle of attack, by increasing the distance from central line the turbulence energy approaches to its maximum value and then is decreased. For instance, according to Fig. **3** at section close to trailing edge ($x/l = 0.0$), the maximum value of dimensionless turbulence kinetic energy $((2k/U_\infty^2)\times 100)$, is increased from 3.3 at 5° to 5.5 at 20°. Also for $x/l = 0.1875$, the maximum value of turbulence kinetic energy is increased from1.9 at 5° to 7.2 at 20°. According to Fig. **4**, at a certain angle of attack, the maximum kinetic turbulence energy is decreased by going away from trailing edge. For example, at an angle of attack of 5°, the maximum dimensionless turbulence kinetic energy is decreased from 3.2 at trailing edge ($x/l = 0.0$) to 1.5 at $x/l = 0.1875$. Such decrease is also observed at an angle of attack of 20°.

When the angle of attack is increased, the main flow is deviated from its direction after attaching to the model. This deviation causes more turbulence, so it can increase the turbulent kinetic energy. The larger angle of attack that the model has, the more deviation from main direction is observed. On the other hand, the main flow senses the body more when we increase the angle of attack.

At a particular angle of attack, such variations are observed at different distances from trailing edge. According to Fig. **4**, by going away from trailing edge, model's effect on the flow will be less and less and the flow tends to approach to its initial condition. Therefore, the turbulent kinetic energy will be decreased at far distances from trailing edge.

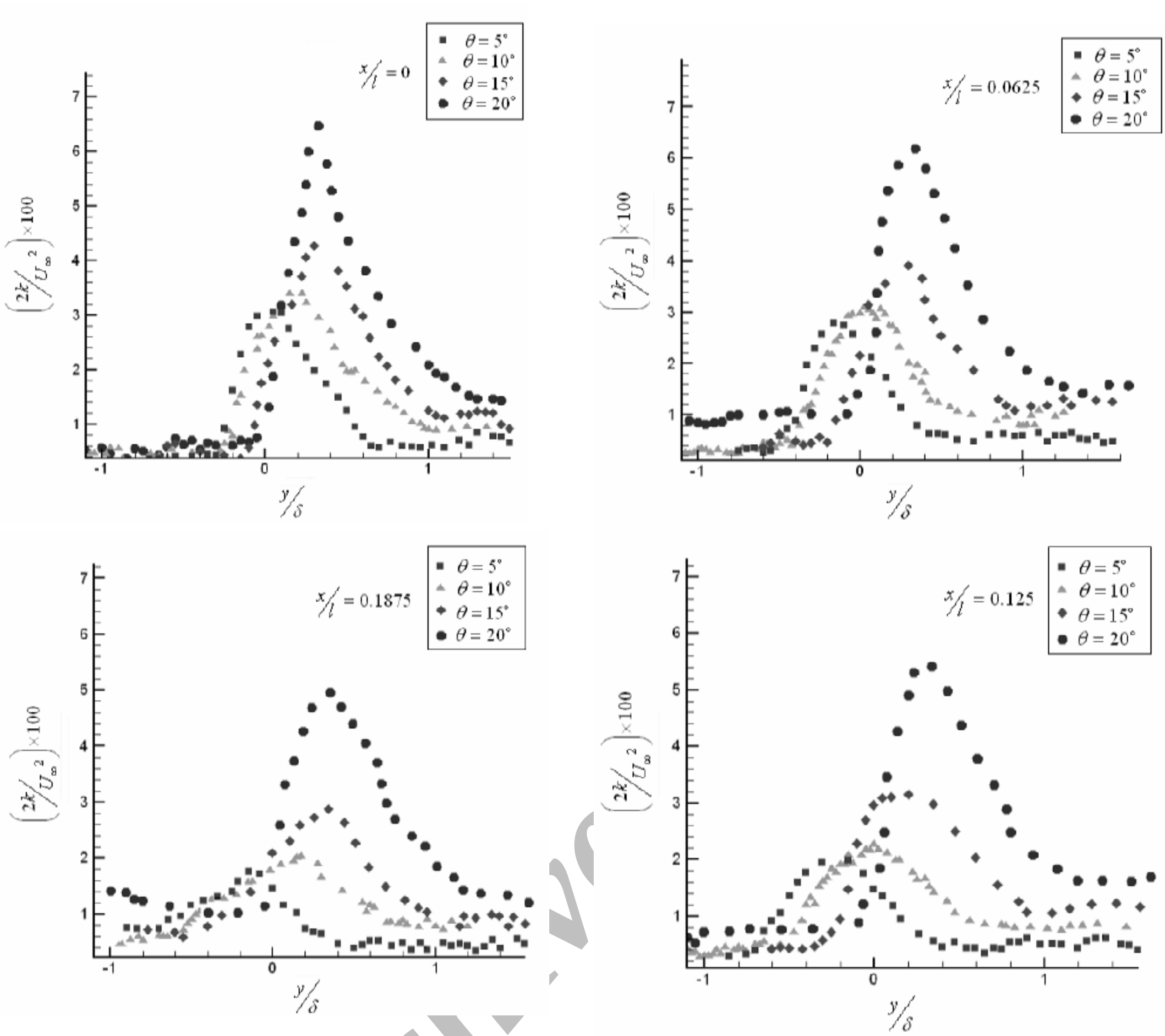

Fig. 3. Dimensionless turbulence kinetic energy at different cross section and at various angles of attack.

Considering Fig's. **3** and **4**, it is concluded that the maximum turbulence energy takes place generally at range of $y/\delta = 0.0$ to $y/\delta = 0.3$.

3.2 Velocity Profiles

Figure **5** shows the dimensionless velocity variations versus dimensionless distance from central line, at different cross sections and at angles of 5, 10, 15and 20 degrees. In order to adapt with logarithmic law ($\frac{V}{V_\tau} = \frac{1}{k}\ln(y^+) + b$) at the origin point, the friction velocity has been obtained at range of 1.53 to 1.72 m/s for different angles of attack by trial and error. In the above equation, k is the Von Karmann constant. In this work, this constant has been considered as 0.4. Moreover, recent studies (e.g. [12]) have considered this constant as 0.38-0.39. Figure **5** shows that in a particular cross section, the deviation from logarithmic law will be increased by increasing the angle of attack. According to Fig. **5**, at sections closer to trailing edge

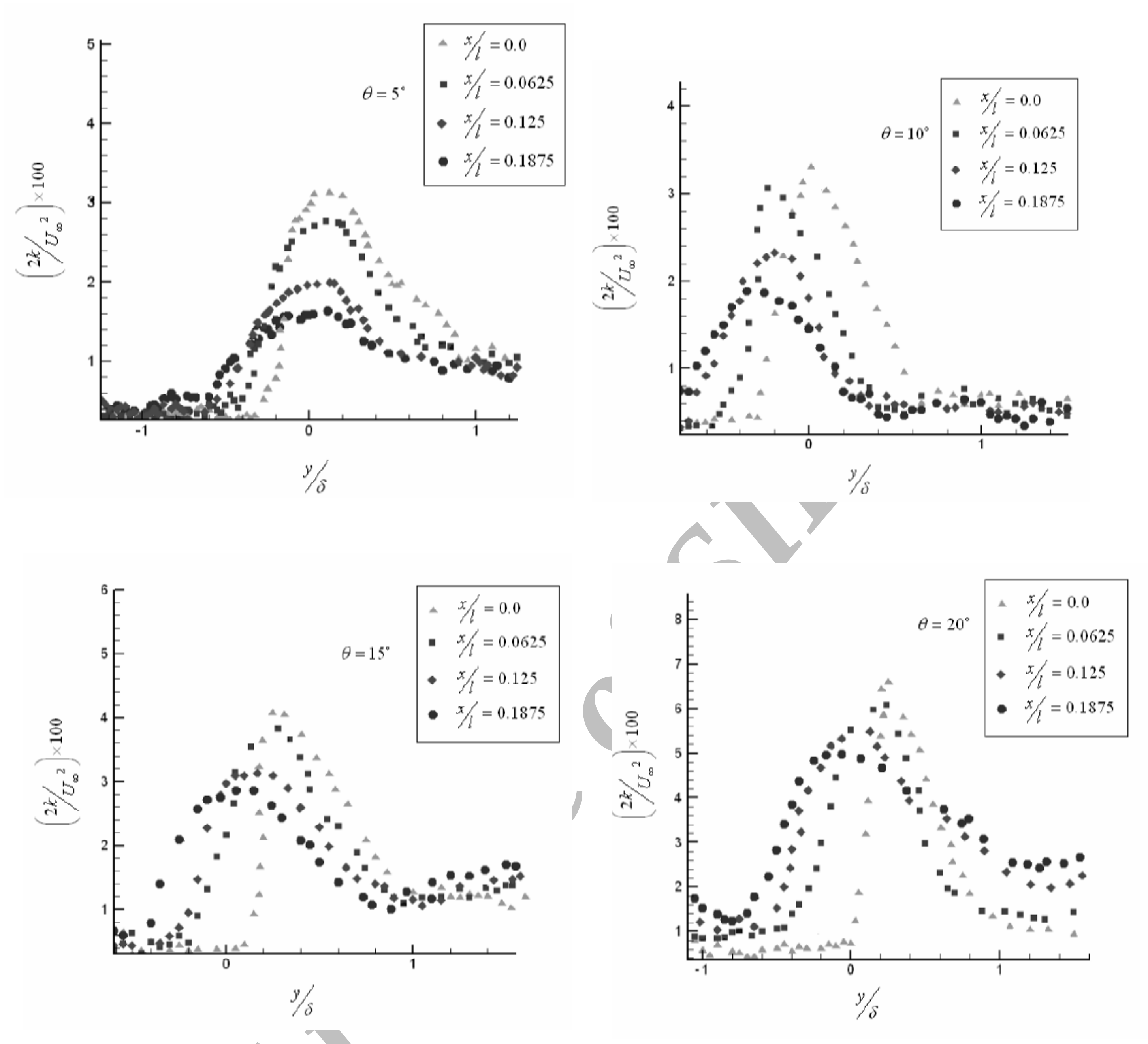

Fig. 4. Dimensionless turbulence kinetic energy at different angles of attack and at various cross sections.

and at angles of attack of 5° and 10°, the experimental results of velocity profile have acceptable agreement with logarithmic profile. But at larger angles of attack, i.e. $\theta \geq 15^\circ$, the deviation from logarithmic law will be increased. At distances far from central line, the velocity gets the values of logarithmic profile. Also according to Fig. **5**, by going away from trailing edge, the velocity and its deviation from logarithmic profile will be increased. The main reason of deviation from logarithmic profile at larger angles of attack is due to small reversing flow at the wake region behind the flat plate.

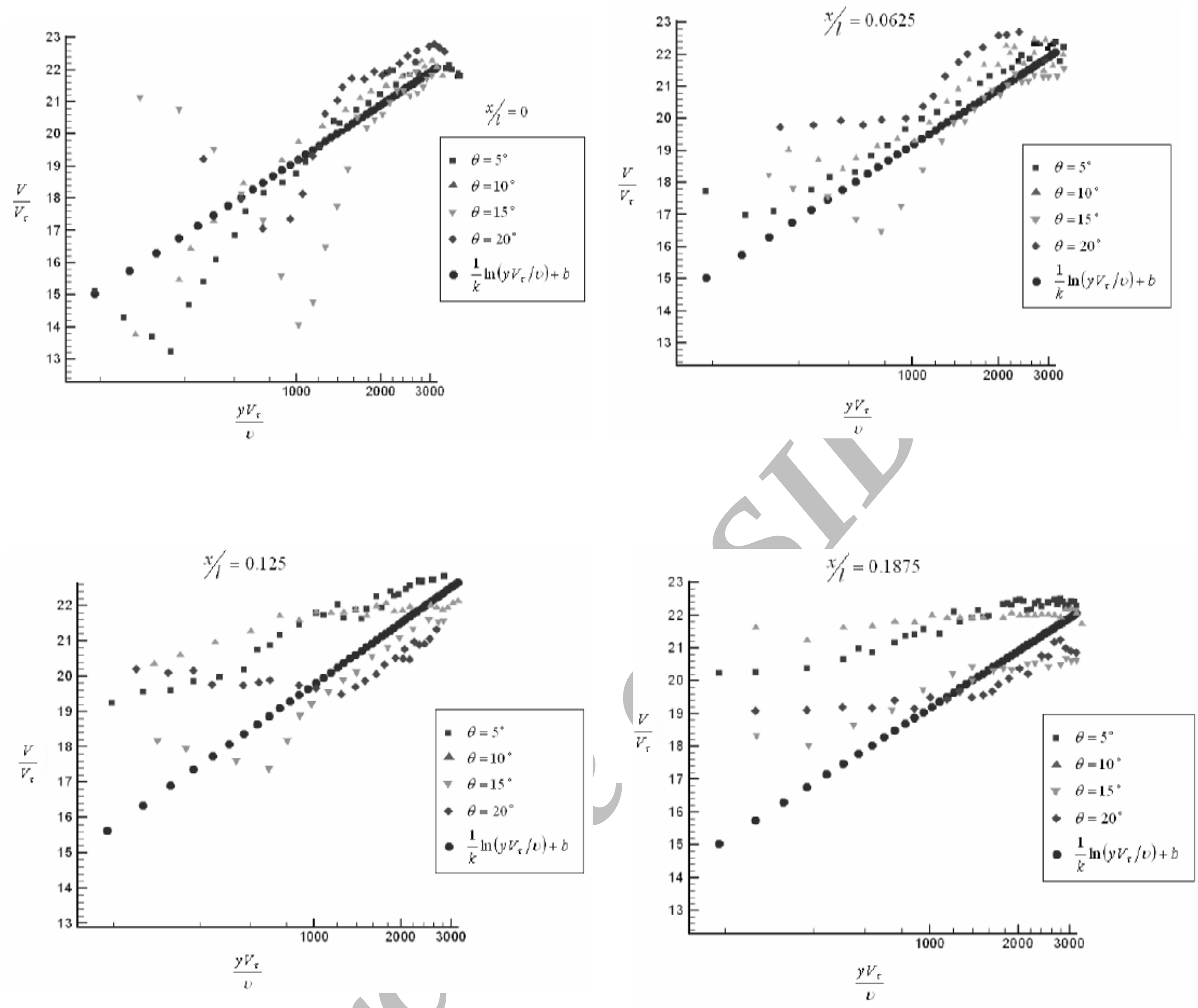

Fig. 5. Velocity variations at sections normal to stream wise flow and at different distances from trailing edge.

In Fig. **6** it is observed that by deviating from trailing edge at a particular angle of attack, the logarithmic law will not be validated. At smaller angles of attack ($\theta \le 15^\circ$) this law will be validated in distances closer to trailing edge. Effects of going away from trailing edge on velocity profile and its deviation from logarithmic velocity at a particular angle of attack have been shown in Fig. **6.**

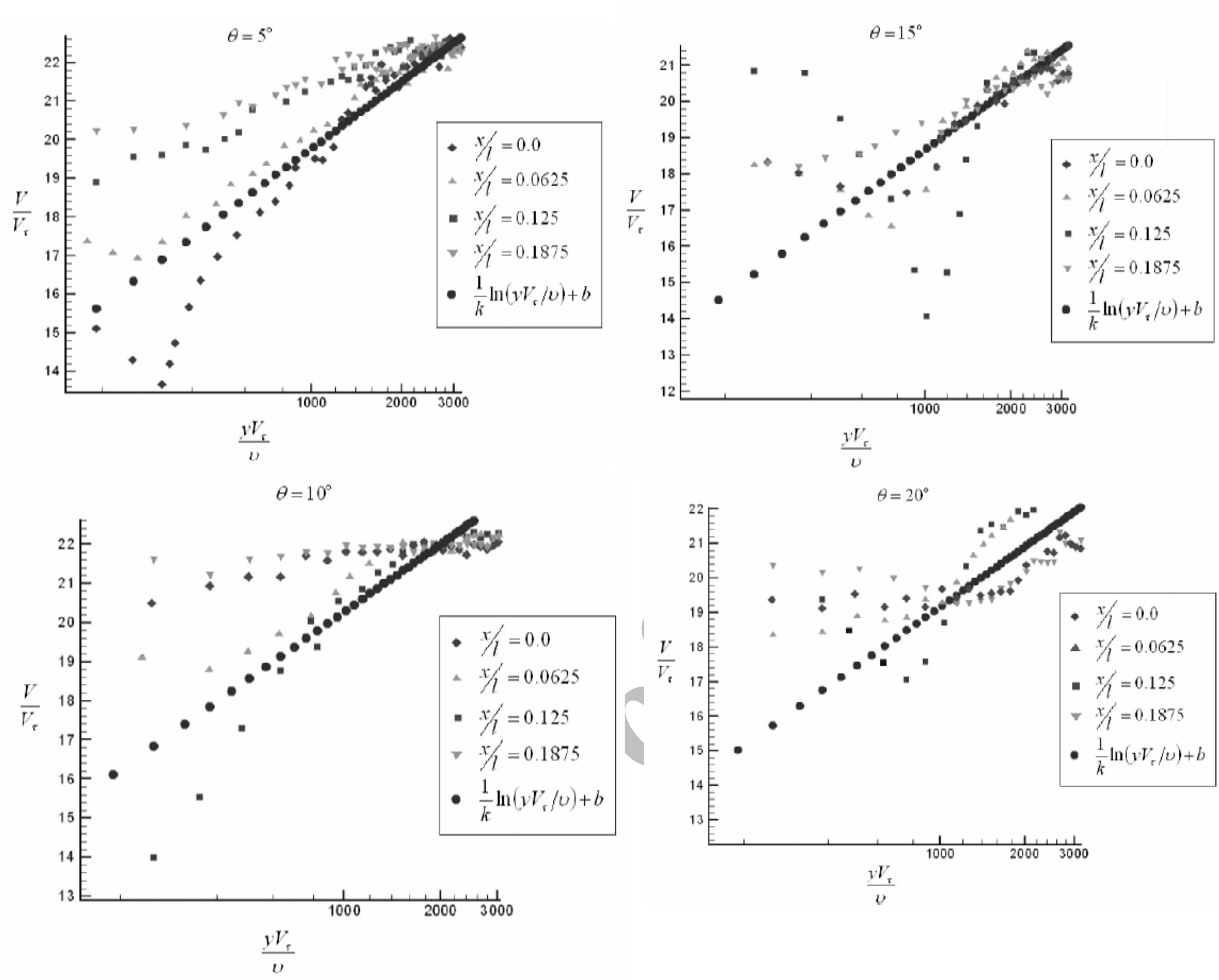

Fig. 6. Velocity variations at sections normal to stream wise flow and at different angles of attack.

3.3 Drag Coefficient

To show the accuracy of the measurement technique against published data, selected data were calculated at angles of attack of 5, 10, 15and 20 degrees.

Figure **7** depicts the comparison for the drag coefficient as a function of angle of attack. Data

available in the published literature are also included. The drag coefficient shows a smooth increase at 5 to10 degrees, and then has a sharp increase at 15 to 20degrees.

In this study, the drag coefficients are found to be at range of 0.02 to 0.21. These values are compared with experiments of Gordon Leishman [10].

The difference between the Leishman's work and the present work is related to a bit difference between aspect ratio of the models and to their roughness.

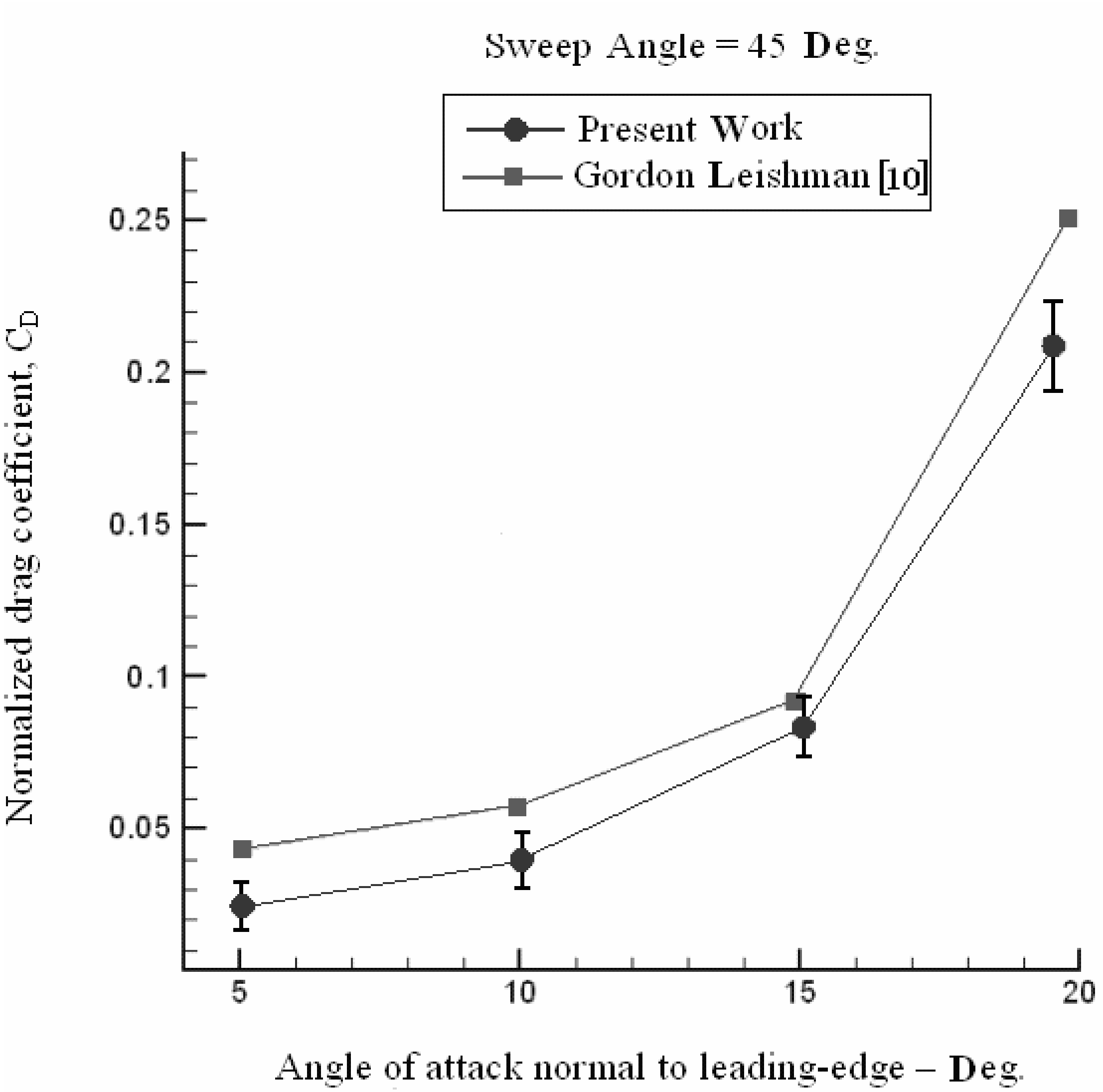

Fig.7. Comparison of measured drag coefficient with Gordon Leish. [8]

4. Conclusions

Hot-wire measurements, such as velocity profiles and turbulence kinetic energy, in the near wake of a flat plate with sweep angle of 45° at different angles of attack were performed at Reynolds number of 6×10^5. The conclusions of this experimental study are as follows:

a) the logarithmic style for velocity profiles is valid for normal sections from $x/l = 0$ up to nearly $x/l = 0.0625$. Also it is valid for small angles of attack from $\theta = 0^\circ$ to nearly $\theta = 10^\circ$. Therefore, at higher angles of attack such as $\theta = 15^\circ$ and $\theta = 20^\circ$, at sections far from trailing edge such as $x/l = 0.125$ and $x/l = 0.1875$, the logarithmic style is failed as well.

b) In a particular section, the maximum turbulent kinetic energy will be increased, when angle attack is increased Also at a particular angle of attack, maximum turbulent kinetic energy will be decreased by going away from trailing edge.

c) The drag coefficient for a flat plate with sweep angle of 45° is increased, when the angle of attack is increased. The investigation on drag coefficient also shows that the increasing intensity of drag coefficient at higher angles of attack is more than one at lower angles.

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