# EXPERIMENTS ON A FLAT SQUARE PLATE AT HIGH INCIDENCE AND DIFFERENT REYNOLDS NUMBERS

**M. O. Budair*, M. Mahmood**

*Department of Mechanical Engineering*
*King Fahd University of Petroleum & Minerals*
*Dhahran, Saudi Arabia*

**and**

**M. K. Abusaleh**

*Al-Zamil Industries*
*Dammam, Saudi Arabia*

## الخلاصة :

تتعلق هذه الورقة بدراسة تجريبية لحركة الهواء حول صفيحة مستوية مربعة حادّة الأطراف عند أرقام ( رينولد ) مختلفةٍ ، وكذلك عند زوايا للتصادم متغيرة .

ويحتوي البحث على إظهار مسار الجريان السطحي وقياس متوسط الضغوط . ويتراوح رقم رينولد بين ( ٠,٥ × ١٠° ) و ( ٣,٧ × ١٠° ) وكذلك عند زوايا للتصادم تتراوح بين ٢٠° و ٥٠° .

وقد جرت دراسة تأثيرات رقم رينولد على الزاوية الحرجة ، وقوة الرفع العمودية ، والانخفاض في قوة الرفع العمودية وقد أظهر البحث أن التغير في رقم رينولد ليس له تأثير مهم على قوة الرفع العمودية عند ثبوث زاوية التصادم .

## ABSTRACT

This paper deals with an experimental study of the air flow over a flat square sharp-edged plate, at various Reynolds numbers and angles of attack.

The investigation includes surface flow visualization, and mean pressure measurements. It is carried out at Reynolds numbers ranging between $0.5 \times 10^5$ and $3.7 \times 10^5$ and at angles of attack between 20° and 50°.

The effects of Reynolds number on the critical angle, the normal force, and the drop in the normal force are investigated. It is revealed that the change in Reynolds number hardly influences the normal force on the plate for the same angle of attack.

---

*Address for correspondence:
KFUPM Box No. 494
King Fahd University of Petroleum & Minerals
Dhahran 31261
Saudi Arabia

# EXPERIMENTS ON A FLAT SQUARE PLATE AT HIGH INCIDENCE AND DIFFERENT REYNOLDS NUMBERS

## 1. INTRODUCTION

It has been known for a long time that the force acting on low-aspect ratio flat plates as well as circular discs in low speed flow experiences an abrupt and considerable drop when the angle of incidence increases to a certain high value and that this is accompanied by specific changes on the wake side.

The results of normal force measurements on a square plate inclined to the wind between 0° and 90° were reported as early as 1890 by Dines [1]. He noticed a sudden drop in normal force when increasing incidence from $\alpha = 35°$ to $\alpha = 40°$. Similar results were reported by Prandtl in 1910 [2] and Hoerner in 1965 [3]. Ahlborn in 1904 [4] visualized the flow field about a thin rectangular flat plate in a water tank at angles of attack between 70° to 90° to the direction of the flow in order to get an insight into the origin of drag. Flow visualization pictures by Eden in 1912 [5] on the wake of an obstacle show the discharge of irregularly shaped vortex rings. Fage and Johansen in 1927 [6] measured the normal force distribution over an infinitely long thin flat sharp-edged rectangular plate at different angles of attack and at $Re_c$ of about $2.2 \times 10^5$. Winter in 1937 [7] investigated a number of flat rectangular sharp-edged plates covering a wide range of aspect ratios. His experimental results, obtained up to high angles of attack, show the occurrence of a more or less abrupt change in the normal force. The magnitude of the change and the angle at which it occurs is dependent on the aspect ratio. He showed that the normal force acting on a square flat plate drops abruptly by about 40% at the angle of attack of about 40°.

In 1959 Fail and Lawford *et al.* [8] studied the effects of changing the aspect ratio of flat plates on flow pattern, drag, and base pressure. Their study showed that as the aspect ratio is increased from unity, the drag coefficient rises, the base pressure falls and the bubble length decreases. Later in 1965 Hoerner [3] showed that a normal force coefficient value of 1.17 exists in the incidence range of 45° to 90°. Robert [9] in 1979 studied the effect of Reynolds number on the aerodynamic characteristics of a body with cruciform wings at angles of attack up to 50°. He showed that force and moment coefficients consisting of normal force, side force, pitching moment, yawning moment, and rolling moment were found to be independent of Reynolds number for the complete range of test conditions. Recent interest in the aerodynamic characteristics of fighter airplanes and missiles at high angles of attack led to investigations like that of Winkelmann and Barlow [10], who tried to model the flow field over a rectangular wing. Satyapal in 1981 [11] studied the effect of free stream turbulence on the characteristics of the turbulent wake developed from the trailing edge of flat plate.

Recently Stahl and Mahmood in 1985 [12] studied the flow phenomenon, over a square flat plate, associated with the abrupt loss in normal force at some high angle of attack at a Reynolds number of $1.1 \times 10^5$. They observed that the fall in the normal force acting on the plate is accompanied by sudden disappearance of the tip vortices from the plate surface; a value of about 15% in the drop in the normal force was measured at an angle of incidence of about 30°, which they called a critical angle.

In view of the previous investigations and as an extension of the study in [12], it was felt that the effects of Reynolds number on the different aspects of the flow field on a square plate, such as the critical angle of attack which separates the subcritical region from the supercritical region [12], the normal force, pressure distribution on the plate, and the change in the normal force as the flow changes from a subcritical regime to a supercritical regime are important. This constitutes the scope of the present paper.

## 2. EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The investigation was conducted in the King Fahd University of Petroleum and Minerals low-speed wind tunnel facility. The test section of the tunnel has a rectangular cross-section of dimensions $1.1 \times 0.8\,\mathrm{m}^2$ and a length of 3 m. The tunnel is of the open-return type, with a maximum wind speed in the empty test section of about 35 m/sec. A variable-speed motor drives an axial flow with constant-pitch blades. Models, built by Mahmood [13], consist of two square plates, one used for the surface flow visualization and the other for mean pressure measurements. The plates are of 22 cm chord length and made of plexiglass. The plate used for flow visualization has a thickness of about 4% of the chord and cambered edges kept at an angle of about 15°. The pressure model was provided with 144 holes of diameter 0.8 mm spaced on only one surface of the plate. The coordinate system and plate orientation with respect to flow direction are shown in the schematic of Figure 1. The side of the plate facing the flow is referred to as a pressure side. The wake side is referred to as a suction side. The mean pressure was measured by means of a water manometer of the projection type. Such manometer reads the mean pressure to within 0.5 mm of water.

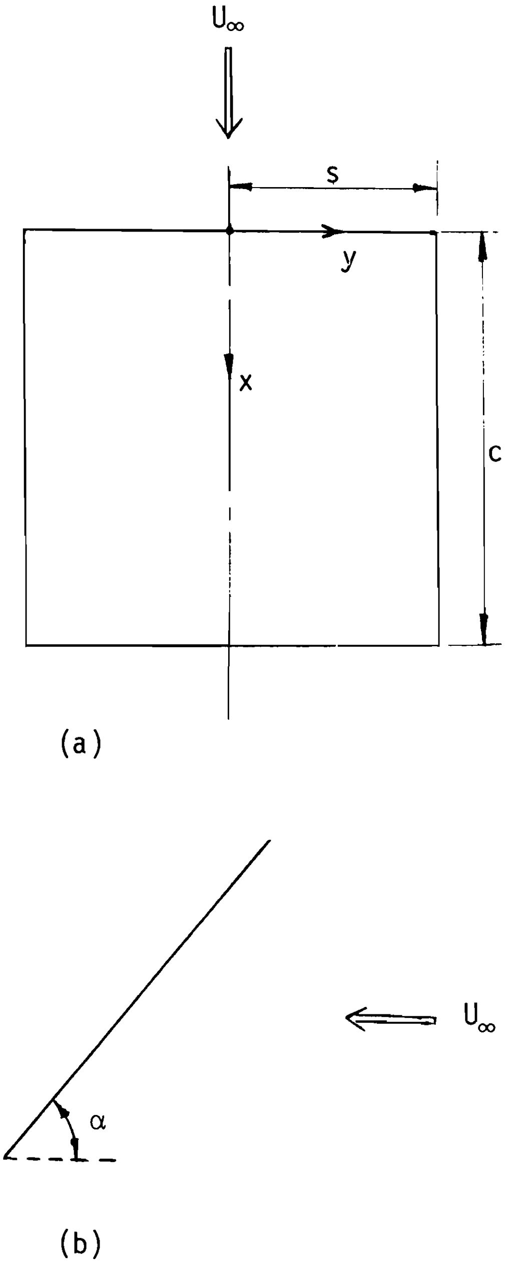


*Figure 1. A Schematic of (*a*) Coordinate System, (*b) Plate Orientation with Respect to Flow Direction.

The surface flow visualization was performed by spraying a mixture of kerosene and chalk powder evenly over the surface and then exposing the plate to the flow. After the flow patterns settled on a steady configuration, the plate was removed from the flow and examined.

Since it is well known that the drop in the normal force takes place at some angle of attack, $\alpha_{cr}$, it was necessary to determine such angle experimentally at each Reynolds number considered in this investigation. The surface flow visualization was used for this purpose. The flow regime over the plate for angles of attack less than $\alpha_{cr}$ is referred to as subcritical and that corresponding to angles of attack greater than $\alpha_{cr}$ is referred to as supercritical [12].

The angle of attack α was varied between $\alpha = 20°$ and $\alpha = 50°$. The Reynolds number based on the length of the chord ($Re_c$) was varied between $0.5 \times 10^5$ and $3.7 \times 10^5$. Table 1 shows the Reynolds numbers considered in this investigation and the corresponding wind speeds.

**Table 1. Reynolds Numbers of the Experiment.**

| $U_\infty$ m/s | $Re_c$ |
|---|---|
| 3.20 | $0.5 \times 10^5$ |
| 10.12 | $1.5 \times 10^5$ |
| 17.40 | $2.6 \times 10^5$ |
| 24.00 | $3.7 \times 10^5$ |

## 3. RESULTS AND DISCUSSION

### 3.1. Critical Angle of Attack

Since the investigation was conducted at different Reynolds numbers it was of interest to identify the critical angle of attack, $\alpha_{cr}$, at each Reynolds number. As the flow changes from a subcritical to a supercritical regime the most conspicuous change marking such a transition is the disappearance of the foci from the suction side of the plate as indicated by surface flow pictures [12]. Such was used as the criterion for identifying $\alpha_{cr}$. A series of flow visualization experiments were conducted at different angles of attack which showed that $\alpha_{cr}$ was in the neighborhood of 30°.

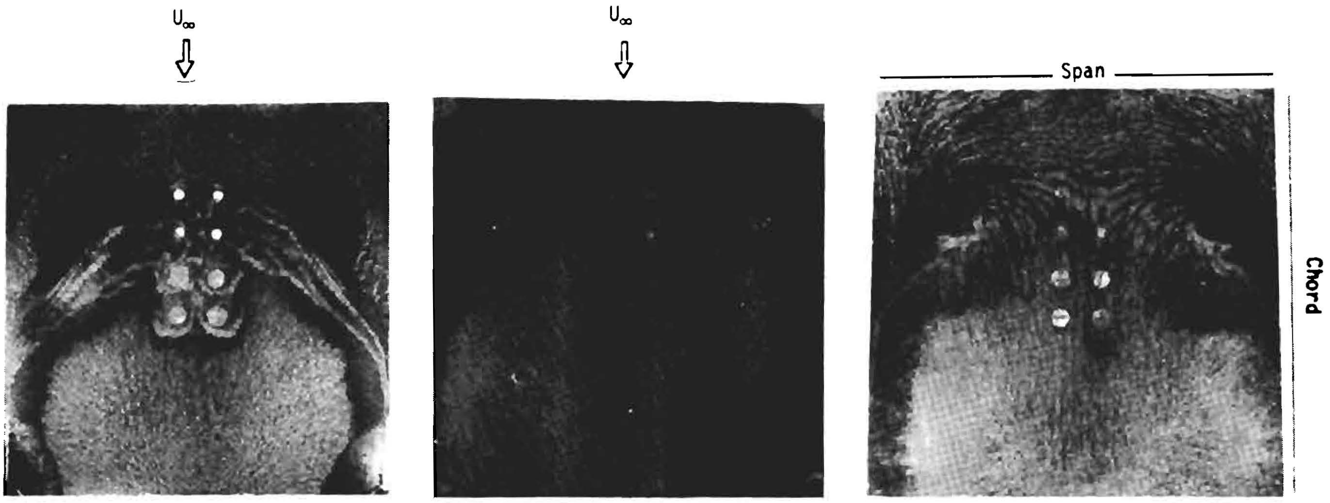
It was ascertained that when the plate is at $\alpha = 28°$, the flow regime was subcritical for all Reynolds numbers considered. On the other hand at $\alpha = 32°$, the flow regime was strictly supercritical for all Reynolds numbers considered as shown in Figures 2 and 3.

### 3.2. Pressure Measurements

Mean pressures were measured on the suction and pressure sides of the plate. The purpose of that was two-fold; to examine the variation of the mean pressure over both sides of the plate with regard to the change in $Re_c$, and to calculate the normal force coefficient at different $Re_c$.

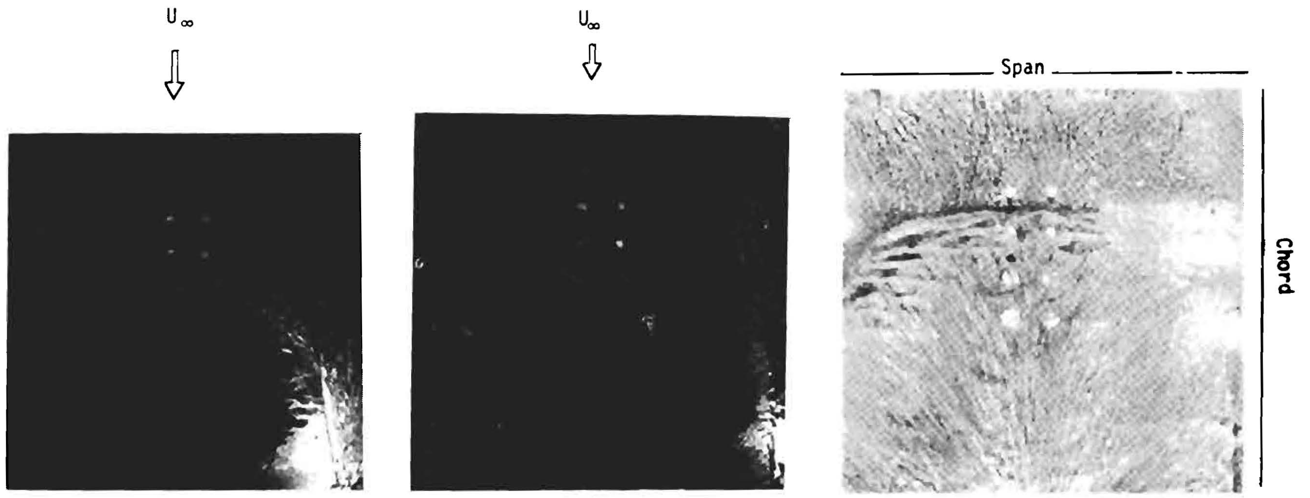
### *3.2.1. Subcritical Regime*

The local mean pressure coefficient ($C_p$) was measured over the suction and pressure sides of the



$Re_c = 1.5 \times 10^5$  $Re_c = 2.6 \times 10^5$  $Re_c$ $3.7 \times 10^5$

*Figure 2. Surface Flow Visualization on Suction Side for $\alpha = 28°$.*



$Re_c = 1.5 \times 10^5$  $Re_c = 2.6 \times 10^5$  $Re_c = 3.7 \times 10^5$

*Figure 3. Surface Flow Visualization on Suction Side for $\alpha = 32°$.*

plate at α = 25°, 28°, and 29° at all $Re_c$ considered in this investigation. A representative case for the mean pressure variation over the suction side of the plate at α = 28° is shown in Figure 4. The curves are plotted at different spanwise stations ($y/s$) where $s$ is the half-span length and $y$ is the coordinate in the cross-wise direction measured from the midpoint of the leading edge (see Figure 1). The pressure curves peak (signifying maximum suction) at about 40% from the leading edge at $y/s = 0.0$, 0.27, and 0.54. Towards the side edge of the plate, the pressure curves seem to show a more uniform distribution as indicated by the pressure curves at $y/s = 0.81$ and 0.89. It is also observed that the variation in $Re_c$ does not seem to have a significant effect on the basic behavior of the pressure curves. The surface flow pictures of the suction side at α = 28°, shown in Figure 2, indicate that the basic flow features, namely, the two foci, and the node remain visible as $Re_c$ is changed. The foci, however, seem to become more distinguished (suggesting more vortex circulation), and move closer to the leading edge as $Re_c$ is increased.

The mean pressure coefficient was measured over the pressure side of the plate at α = 25° and 28° for all $Re_c$ considered in this investigation. The chordwise distribution of pressure at α = 28°, Figure 5, shows a

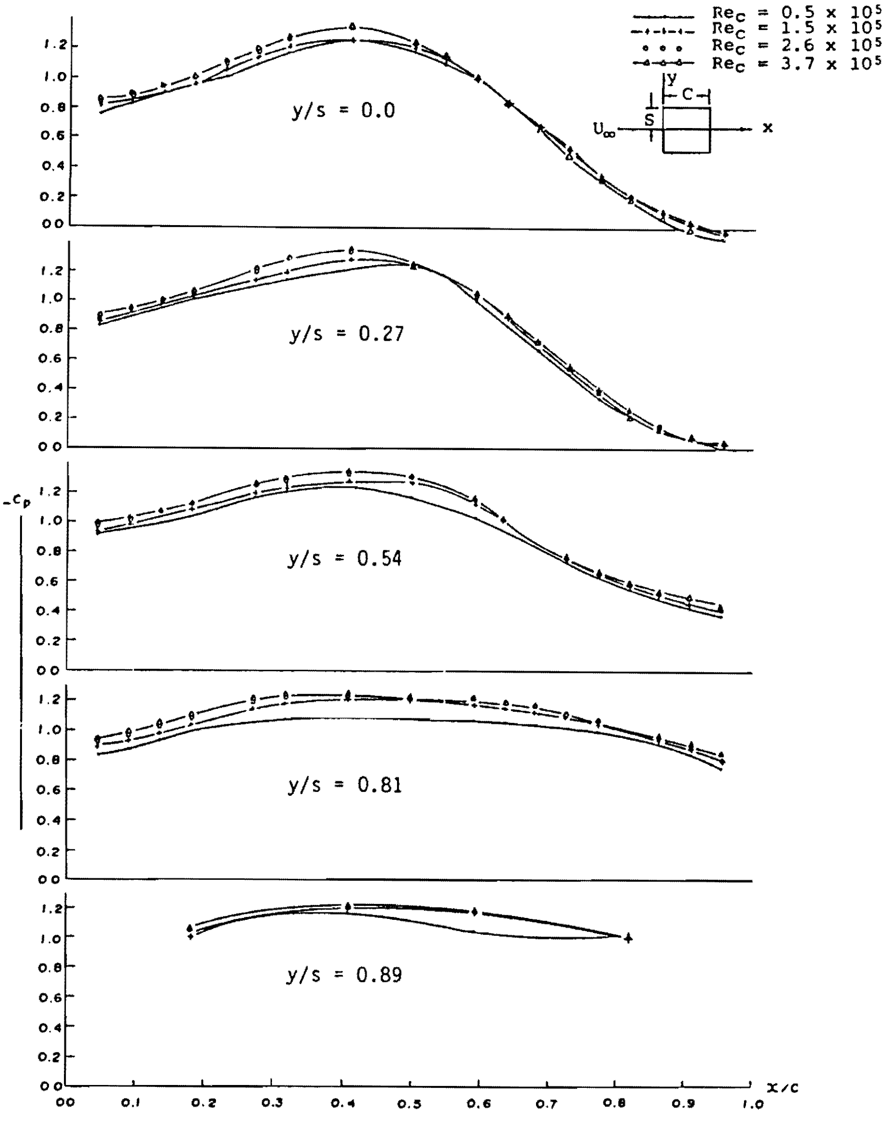


*Figure 4. Chordwise Pressure Distribution, α = 28°, Suction Side.*

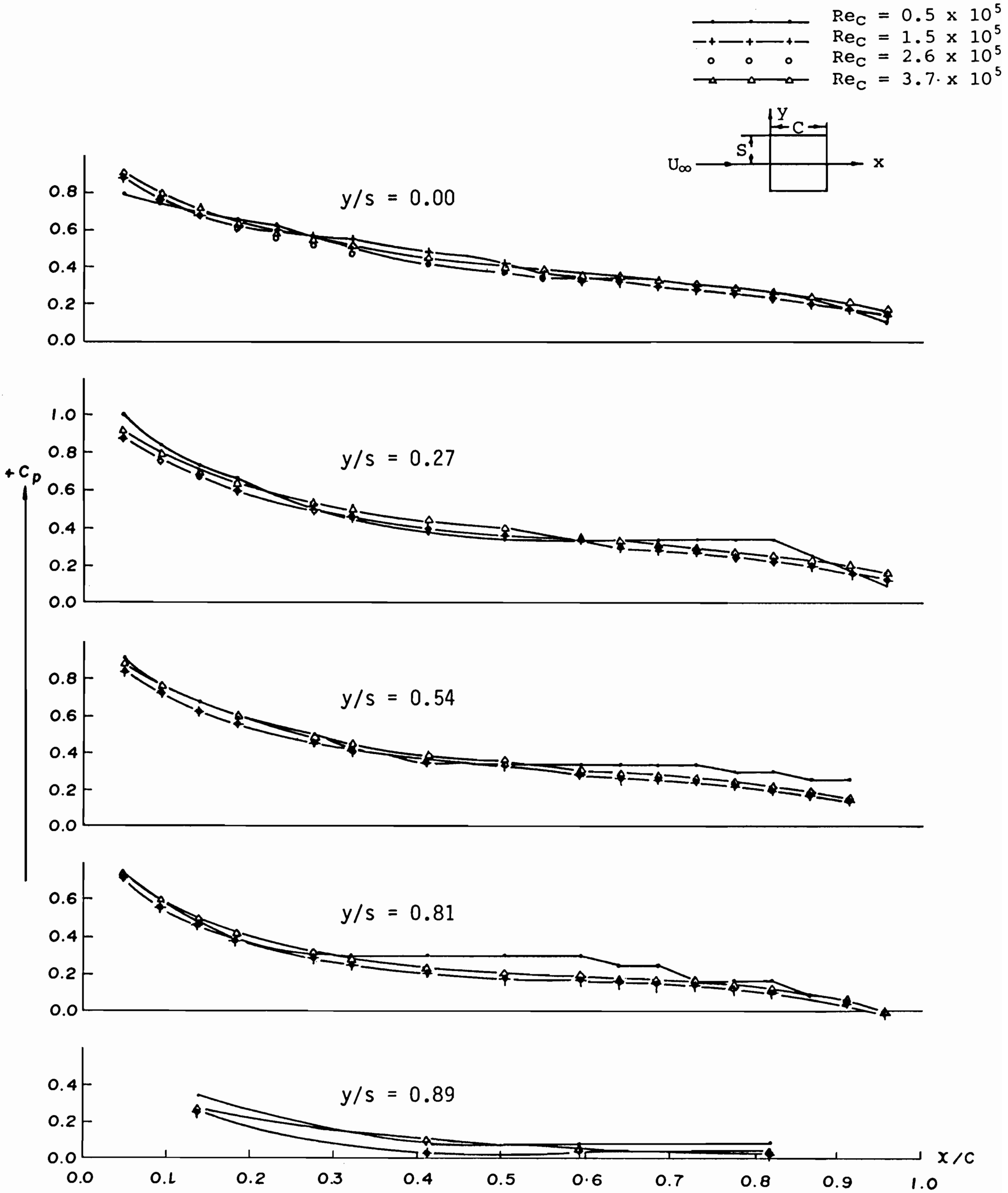


*Figure 5. Chordwise Pressure Distribution, α = 28°, Pressure Side.*

smooth decrease in pressure from leading edge to trailing edge for all *Re* considered. A similar trend was also observed for α = 25°. The influence of $Re_c$ seems to be small.

The local mean pressure coefficients ($C_p$) were averaged over the whole plate surface. The value thus obtained is referred to as the average mean-pressure coefficient, $\bar{C}_p$. The variation of $\bar{C}_p$ with $Re_c$, Figure 6, shows that the suction, at the same angle of attack, is almost uniform over the suction side as $Re_c$ is varied. Uniformity of $\bar{C}_p$ with $Re_c$, at the same angle of attack, is also observed over the pressure side, Figure 7. However, in the subcritical regime a noticeable change in the average mean-pressure coefficient, $\bar{C}_p$ is observed on both sides of the plate at angles of attack α between 25° and 28° for the same $Re_c$.

### 3.2.2. Supercritical Regime

The mean pressures were measured on the suction and pressure sides of the plate at α = 32°, 35°, and 40° for all $Re_c$ considered in this investigation. The chordwise pressure distribution over the suction side at α = 32°, and 35° is shown in Figures 8 and 9. The

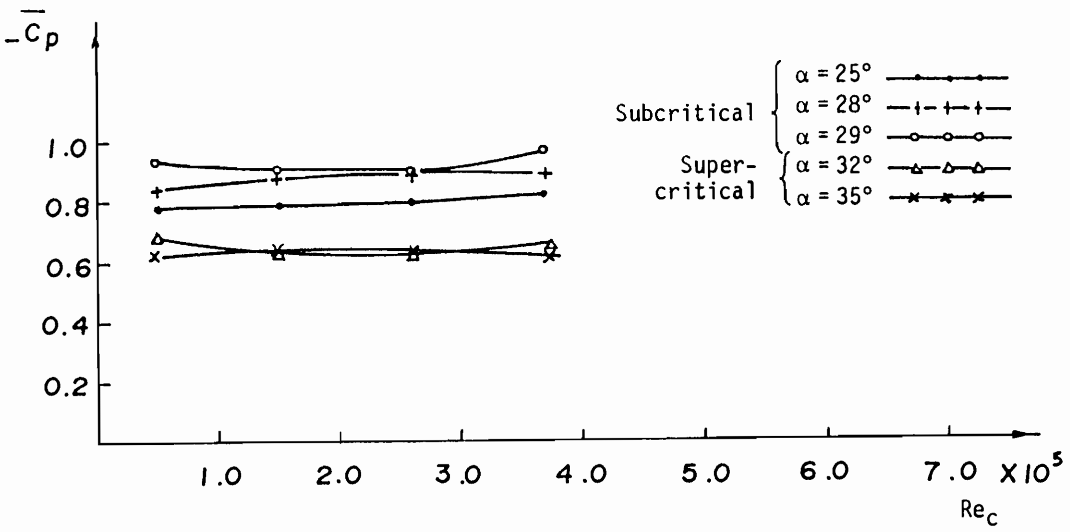


*Figure 6. Average Mean-Pressure Coefficient* versus *Reynolds Number, Suction Side.*

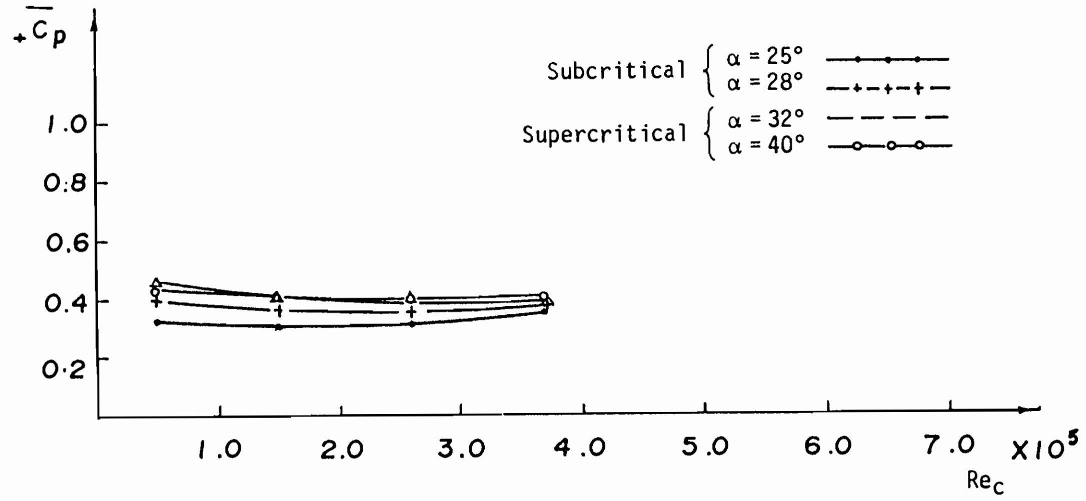


*Figure 7 Average Mean-Pressure Coefficient* versus *Reynolds Number, Pressure Side.*

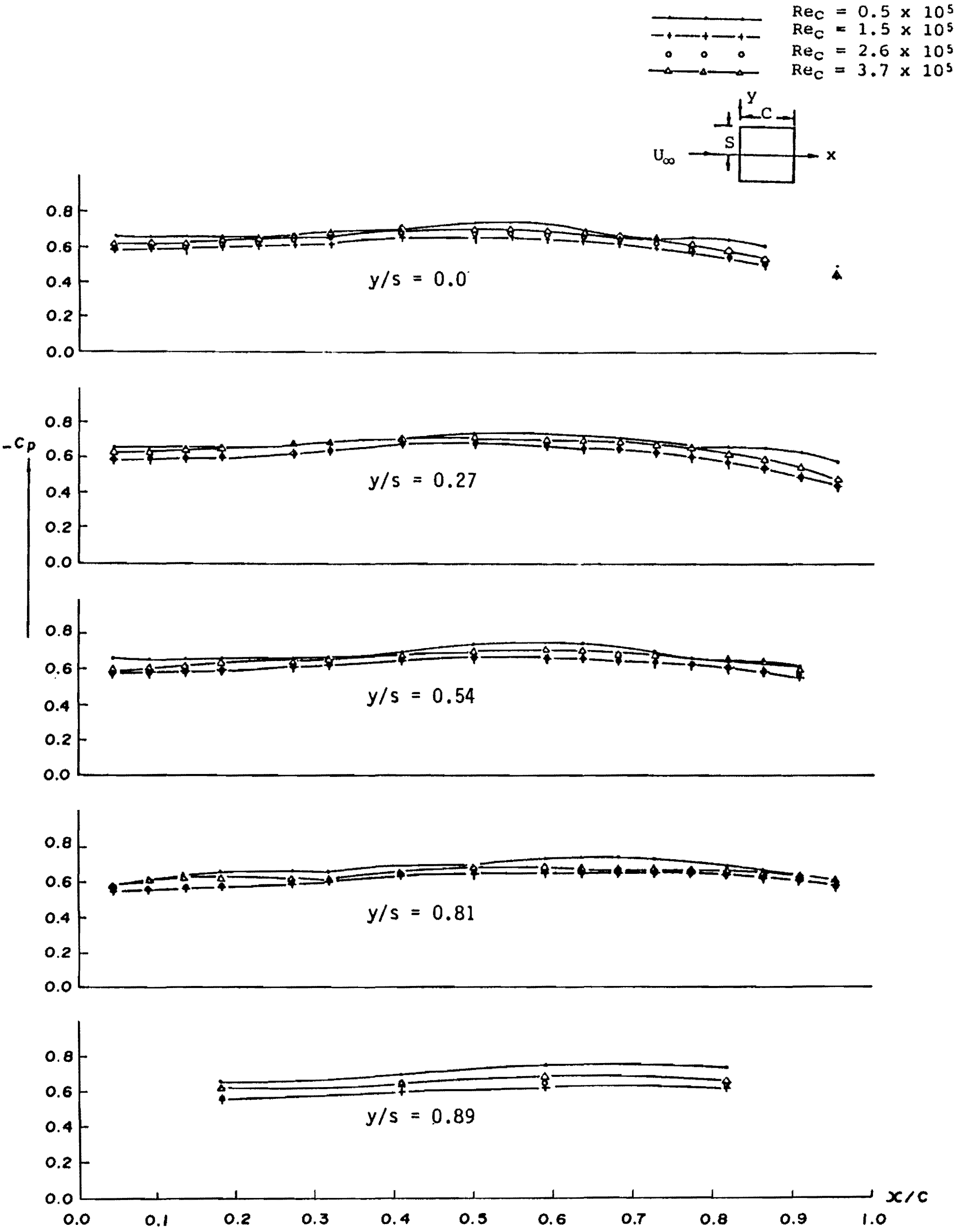


*Figure 8. Chordwise Pressure Distribution, $\alpha = 32°$, Suction Side.*

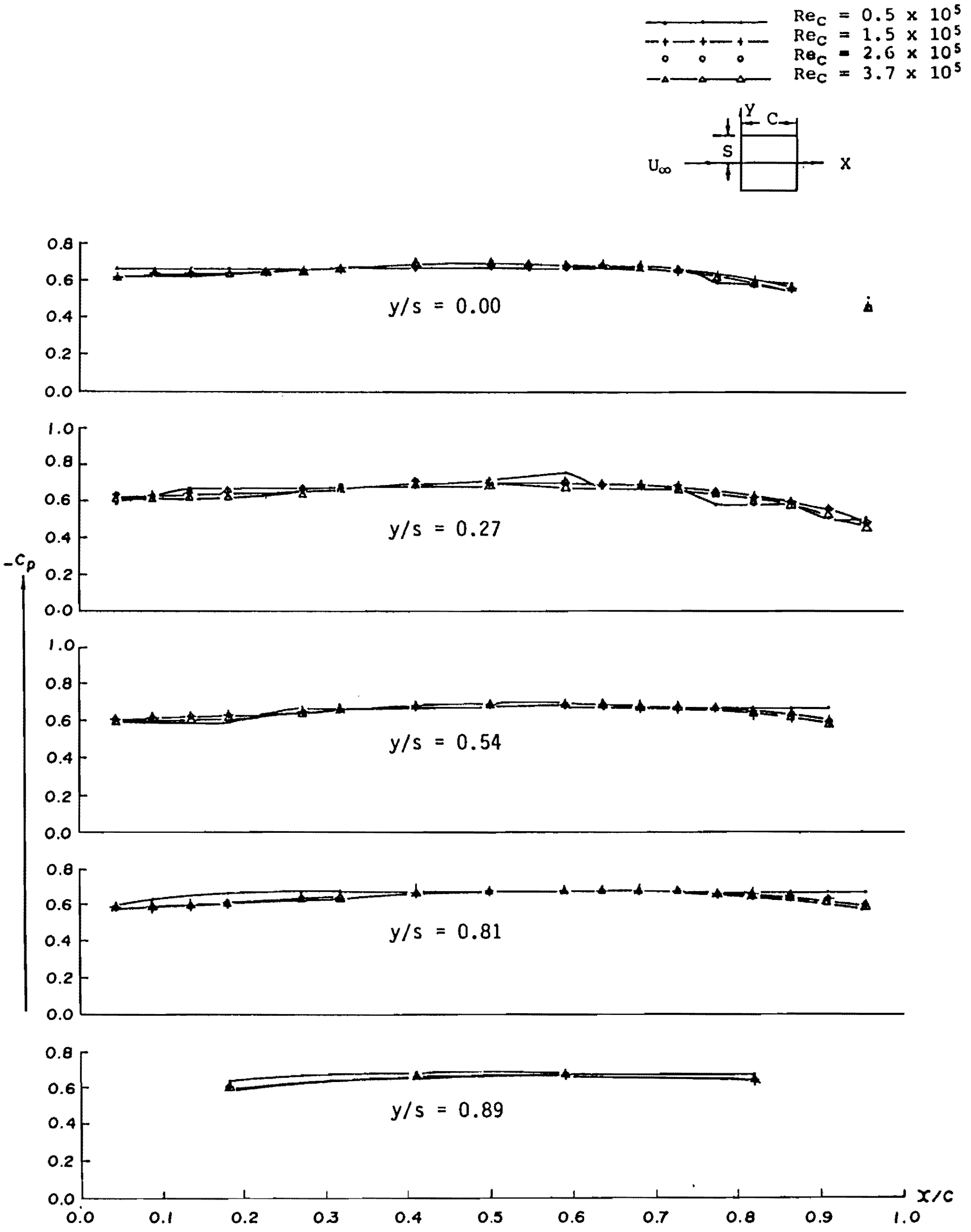


Figure 9. Chordwise Pressure Distribution, $\alpha = 35°$, Suction Side.

suction level is almost uniform over the suction side for different $Re_c$. This uniformity of suction was observed by Stahl and Mahmood [12]. The influence of $Re_c$, however, is more pronounced at $\alpha = 32°$ than at $\alpha = 35°$. Such influence does not seem to have a specific trend.

The chordwise pressure distribution on the pressure side at different angles of attack shows a similar trend to that observed in the subcritical regime with the maximum pressure occurring at the leading edge. A representative case for the pressure distribution on the pressure side is shown in Figure 10 for $\alpha = 32°$.

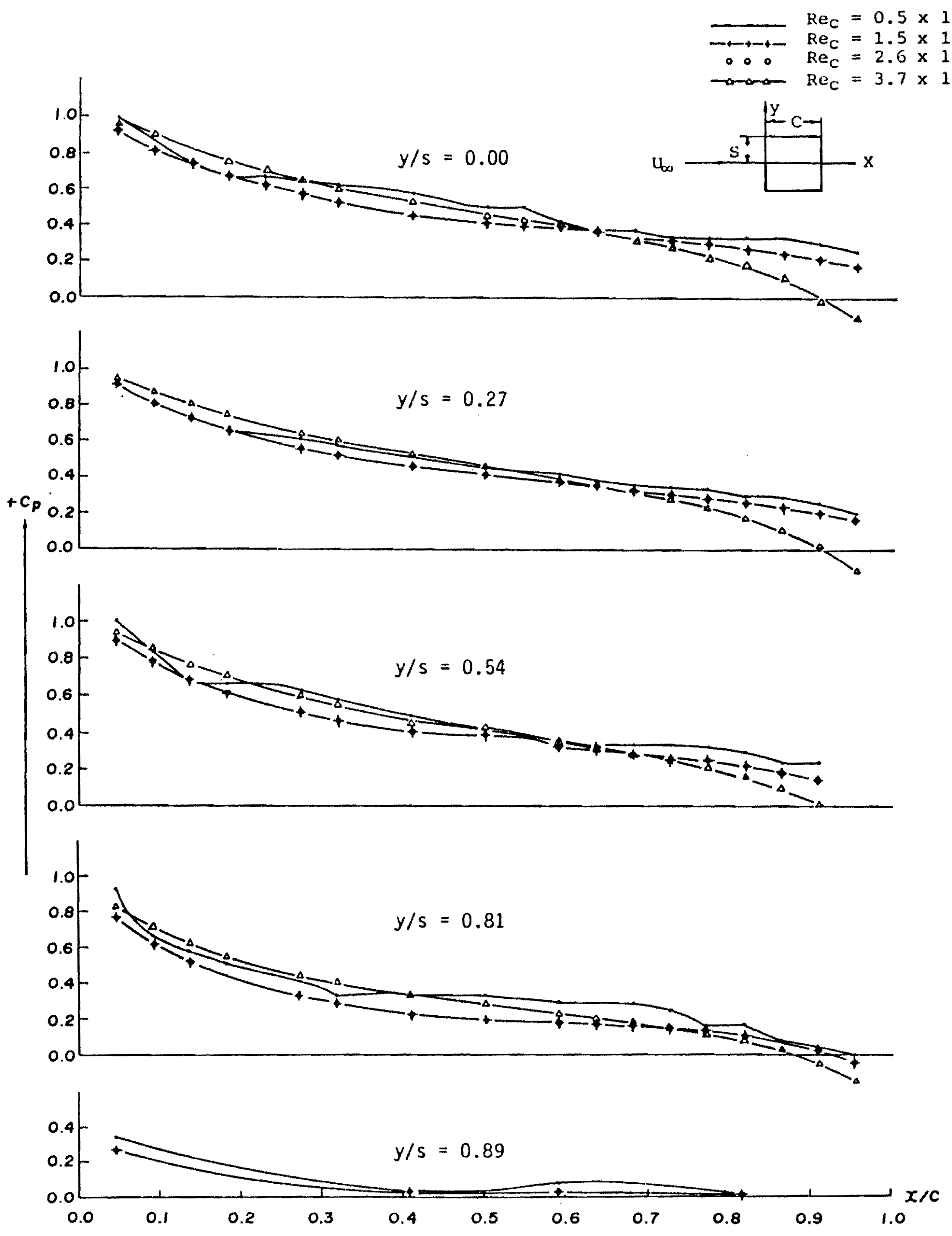


*Figure 10. Chordwise Pressure Distribution, $\alpha = 32°$, Pressure Side.*

The variation in $Re_c$ does not seem to change the basic behavior in the pressure distribution. However, as $Re_c$ was increased, the pressure lines collapsed on each other.

The average mean-pressure coefficient $\bar{C}_p$ over the suction side in the supercritical regime, Figure 6, shows that suction level does not significantly change with $Re_c$. The change in the angle of attack does not seem to influence the level of average suction. The same behavior is observed over the pressure side, see Figure 7.

The normal force coefficient, $C_n$ on the plate was computed from the average mean-pressure coefficient on both sides of the plate and is plotted against $Re_c$, Figure 11. It is observed that $C_n$ does not seem to vary with $Re_c$ for a particular angle of attack. The variation of $C_n$ with the angle of attack is more significant in the subcritical regime than it is in the supercritical regime, which is in agreement with the results reported by Hoerner [3].

The drop in the normal force ($\Delta C_n$%) *versus* Reynolds number ($Re_c$) is shown in Figure 12. The drop seems to increase with $Re_c$ over the Reynolds number range $0.5 \times 10^5$ to $2.6 \times 10^5$. Beyond this range a slight decrease in the normal force drop seems to occur. Such decrease is estimated from the reduced data to be of the order of 6%, which lies within the experimental error of the experiment. To establish an evidence for the real trend in the normal force drop beyond $Re_c = 2.6 \times 10^5$, greater values of $Re_c$ will have to be tested.

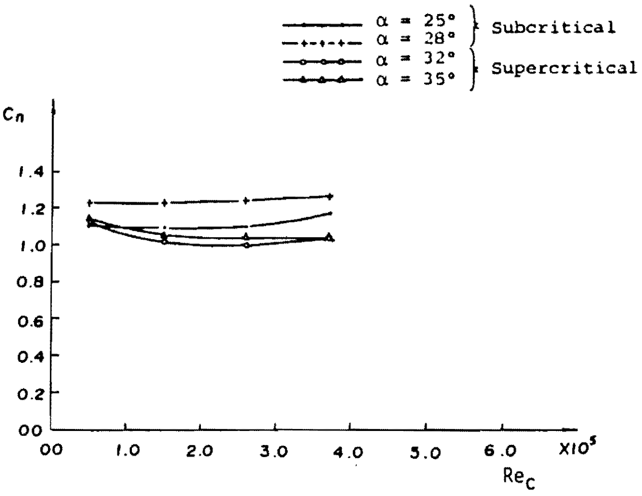


*Figure 11. Normal Force Coefficient* versus *Reynolds Number for Square Flat Plate.*

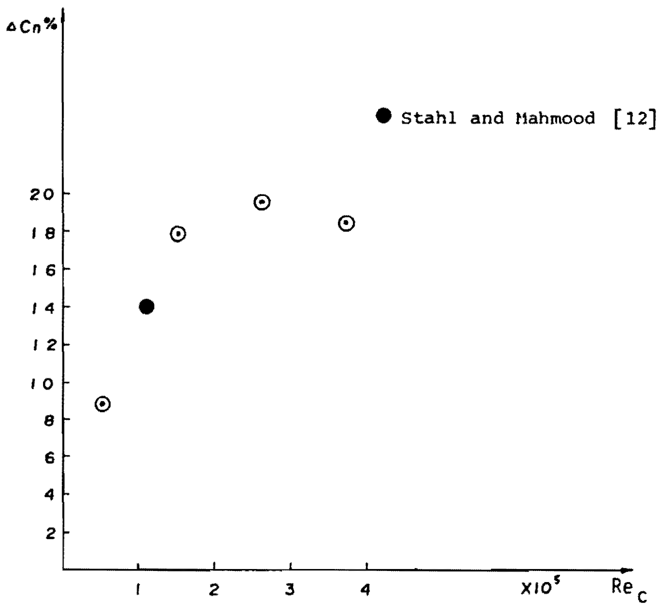


*Figure 12. Percentage Drop in Normal Force* versus *Reynolds Number for Square Flat Plate.*

## 4. CONCLUSIONS

The experimental investigation of the flow over a square sharp-edged plate conducted at different Reynolds numbers and different angles of attack reveals that the normal force on the plate is hardly influenced by the change in Reynolds number for the same angle of attack. However, for a fixed Reynolds number, the normal forces seems to be more influenced by the change in the angle of attack in the subcritical regime than it is in the supercritical regime.

As the angle of attack is changed between α = 28° and α = 32° the drop in the normal force is observed to increase with the increase in Reynolds number in the range $0.5 \times 10^5$ to $2.6 \times 10^5$.

The critical angle of attack was observed to be about 30° for all Reynolds numbers considered.

## REFERENCES

[1] W. H. Dines, "On Wind Pressure Upon an Inclined Surface", *Proceedings of the Royal Society of London*, **48** (1890), p. 235.

[2] L. Prandtl, "Einige fur die Flugtechnik Wichtige Beziehungen aus der Mechanik", Etwas Uber den Luftwiderstand, *Z. Flugtechnik Motorluftschiffahrt*, **1** (1910), pp. 3–6, 25–30, 61–64, 73–76.

[3] S. F. Hoerner, "Drag of Various Types of Plates", in *Fluid Dynamics Drag, Second Edition.* New York: Published by Author, 1965, p. 3.

[4] F. Ahlborn, "Hydrodynamisch Experimentaluntersuchungen", *Jb. Schiffbautechn, Ges.*, **5** (1904), p. 417.

[5] C. G. Eden, "Investigation by Visual Photographic Methods of the Flow Past Plates and Models", *Aero Club of America, Reports and Memorandum 58*, 1912.

[6] A. Fage, F. C. Johansen, "On the Flow of Air Behind Flat Plate of Infinite Span", *Aeronautical Research Council, Reports and Memorandum 1104*, 1927.

[7] H. Winter, "Flow Phenomena on Plates and Airfoils of Short Span", *NASA, Technical Memorandum 798*, 1937.

[8] R. Fail, J. A. Lawford, and R. C. W. Eyre, "Low-Speed Experiments on the Wake Characteristics of Flat Plate Normal to an Air Stream", *Aeronautical Research Council, Reports and Memorandum 3120*, 1959.

[9] L. Robert and J. Stalling, "Reynolds Number Effects on Aerodynamic Characteristics at Large Angle of Attack", *NASA, Langley Research Center, Hampton, Journal of Spacecraft,* **17(2)** (1980), Article No. 79-030IR, p. 129.

[10] A. E. Winklemann and J. B. Barlow, "Flow Field Model for a Rectangular Plan Form Wing Beyond Stall", *American Institute for Aeronautics and Astronautics Journal,* **18** (1980), p. 1006.

[11] Satyapal, "Free Stream Turbulence Effects on Wake Properties of Flat Plate at an Incidence", Department of Environmental Protection, New York, *American Institute for Aeronautics and Astronautics Journal,* **23(12)** (1985), p. 1868.

[12] W. H. Stahl and M. Mahmood, "Some Aspects of the Flow Past Square Flat Plate at High Incidence", *Z. Flugwiss. Weltraumforsch,* **3** (1985), p. 134

[13] M. Mahmood, "Low-Speed Experiments on a Flat Square Plate at High Angles of Attack", *M.S. Thesis, Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals,* 1984.

**Paper Received 29 April 1989; Revised 24 October 1989.**