# Separation Control and Heat Transfer over a Fence inside an Asymmetric Diffuser

# التحكم في الأنفصال وانتقال الحرارة فوق حاجز (نتوء) داخل ناشـــــر متسع الزاوية

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**ملخـص البحـث**

يهتم هذا العمل بالتحقيق المعملي فى التدفق و انتقال الحرارة خلال حاجز وضع داخل ناشر متسع الزاوية ثنائي الأبعاد. تم قياس متوسط السرعة والمجال المتأرجح بواسطة مجس ذو سلك حراري وذو درجة حراره ثابتة. لكن ،تم قياس الضغوط في مناطق التدفق العكسي بمجس ذو الخمس ثقوب. و باهتمام خاص عن تأثير الحاجز علي قياس السرعة و الضغط للتدفق وعلاقة ذلك على متغيرات انتقال الحرارة عند خمسة مواضع مختارة بشكل جيد في الناشر.
البيانات المعملية التى تم الحصول عليها تستخدم لتقديم مقارنة باستخدام و بدون استخدام الحاجز للتحكم في انفصال السريان و من ثم تحديد القيم المختلفة لأعداد ستانتون و ناسلت ، و خصوصا في مناطق انفصال السريان. أيضا،أفاد التحقيق في تقديم بعض الخواص حول حساسية مناطق انفصال السريان و التدفق الراجع ، التي تمثل نوع من التد فق حيث ان ميكانيكية التحكم فية مجهولة إلى حد كبير.

## ABSTRACT

The present work is concerned with an experimental investigation of flow and heat transfer through a fence located in an asymmetric plane two-dimensional diffuser. The average velocity and fluctuation fields have been measured with a constant temperature hot-wire anemometer (CTA). However, pressures in reversed flow regions have been measured using 5-hole-probe. Of special interest is the influence of the fence on measuring the velocity and the pressure of the flow in relation with heat transfer parameters at five well-chosen stations of the diffuser.
The obtained experimental data are used to provide a comparison between the cases of using and not using the fence for the sake of separation control and consequently the determination of the variation of Stanton and Nusselt numbers, particularly in the separated regions. Also, the investigation is reported for some attributes about the sensitivity of the separated and reversed flow regions, that represent a range of flows in which the controlling mechanisms are largely unknown.

## KEY WORDS:

Wide-angled diffuser, fence, Stanton number, Nusselt number, separated region, velocity and pressure gradient parameters.

Accepted December 16, 2007

## 1. INDRODUCTION

Past studies of the internal flow over a single fence or an obstacle helped to establish the influence and effects of Reynolds number, blockage ratio, upstream conditions, and, in the case of the obstacle, the length to height ratio. Reviews of wall-reattaching separated flows have been provided, among others, in references [1 to 4]. In some situations, turbulence generation and mixing associated with separation are desirable, whereas in others, separation is to be avoided as the fence causes a pressure loss and makes the considerable pressure gradient less effective [5 to 11]. Also, heat transfer characteristics behind a two-dimensional fence have been investigated extensively in the past. Such geometry appears in several designs of heat exchanging devices, such combustion chambers, electronic equipment, and cooling passages of turbine blades. Reviews dealing with the heat transfer characteristics of separated flows have been reported through (12 to 17). Most of the published studies have been numerical in nature and have dealt mainly with forced convection flows. Experimental results for heat transfer in separated flows are lacking, and measurements of the effect of the flow control devices on separated flows do not seem to have appeared in the literature. This has motivated the present study, which explores experimentally the effects of the fence on the flow and heat transfer characteristics in separated boundary layer flow downstream of a two-dimensional fence. In the present work, an asymmetric two-dimensional diffuser is well designed and manufactured to have flow separation at a determined distance. A small fence is located normal to the wall of the diffuser at the position where the flow separation would expect to occur. Measurements of velocity and pressure of hot air flow at three well-chosen locations are made. Of special interest are the influence of the fence on separation control and consequently the determination of the variation of Stanton and Nusselt numbers, particularly in the separated regions. Also, the comparison of using and non-using the fence is reported.

## NOMENCLATURE

$A_1$ Cross-sectional area at inlet, ($m^2$)
$A_2$ Cross-sectional area at exit, ($m^2$)
$A_r$ Area ratio, = ($A_2/A_1$)
$C_p$ Specific heat at constant pressure, (J/kg. K)
h Heat transfer coefficient, (W/m$^2$. K)
k Thermal conductivity, (W/m. K)
N Diffuser axial length, (m)
Nu Nusselt number, = hW/k
$P_1$ Static pressure at inlet, (Pa)
$P_2$ Static pressure at exit, (Pa)
Pr Prandtl number, $=\mu.\ C_p/k$
Re Reynolds number, $= \rho\ U_o\ W/\mu$
St Stanton number, = h/ρ. u. Cp
U Mean velocity in the diffuser, (m/sec)
U (x) Core velocity, (m/sec)
$U_o$ Mean velocity in the inlet cross-section, (m/sec)
$u^+$ Friction velocity, $=\sqrt{\tau_w/\rho}$, (m/sec)
u Mean local velocity component, (m/sec)
U* Dimensionless velocity, = u/U
X Axial distance measured from diffuser inlet, (m)
y Normal distance to wall, (m)

$X^*$ Non-dimensional axial distance, = x/N
$Y^*$ Non-dimensional normal distance, = $y/y_s$
W1 Diffuser width at inlet, (m)
W2 Diffuser width at exit, (m)
$\Delta P$ Diffuser recovery pressure, = ($P_2$ - $P_1$), ( Pa)
du/dx Velocity gradient in x-direction, (1/sec)
dP/dx Pressure gradient in x-direction, ($N/m^3$)
du/dy Velocity gradient in y-direction, (1/sec)
$d^2u/dy^2$ Second derivative of velocity in y-direction, (1/m.sec)
$\tau_w$ Shear stress at the wall, = $\mu.(du/dy)_{y=0.0}$ ($N/m^2$)
$\rho$ Air density, ($Kg/m^3$)
$\mu$ Dynamic viscosity, ($N.s/m^2$)
$\nu$ Kinematic viscosity, = $\mu/\rho$, ($m^2$/sec)
$\theta$ Wall angle, (degree)
$\delta$ Boundary layer thickness, (m)

## 2. EXPERIMENTAL CONFIGURATION

### 2.1 Test Section

The asymmetric plane diffuser (test section) is made of wood except one side is made of plexiglass to facilitate flow observations during experiments. The inlet and exit cross-sections are (0.3*0.3) $m^2$ and (0.775*0.3) $m^2$, respectively. The length (N) is 1.73 m with wall angle of $\theta \cong 15^\circ$ and ratio of, N/W1$\cong$ 6.0. The geometry of the flat wide angled diffuser and the positions of the available stations for measurements are illustrated in Fig. (1). The five stations of the diffuser have five drilled holes on periphery of the diffuser wall for positioning hot-wire anemometer and 5-hole probe for measuring velocity and static pressure respectively.

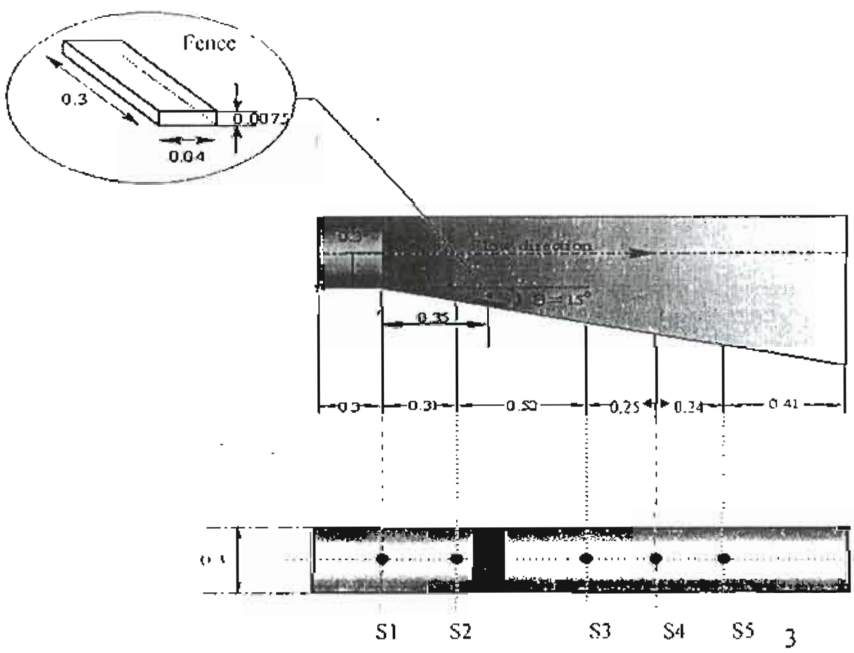
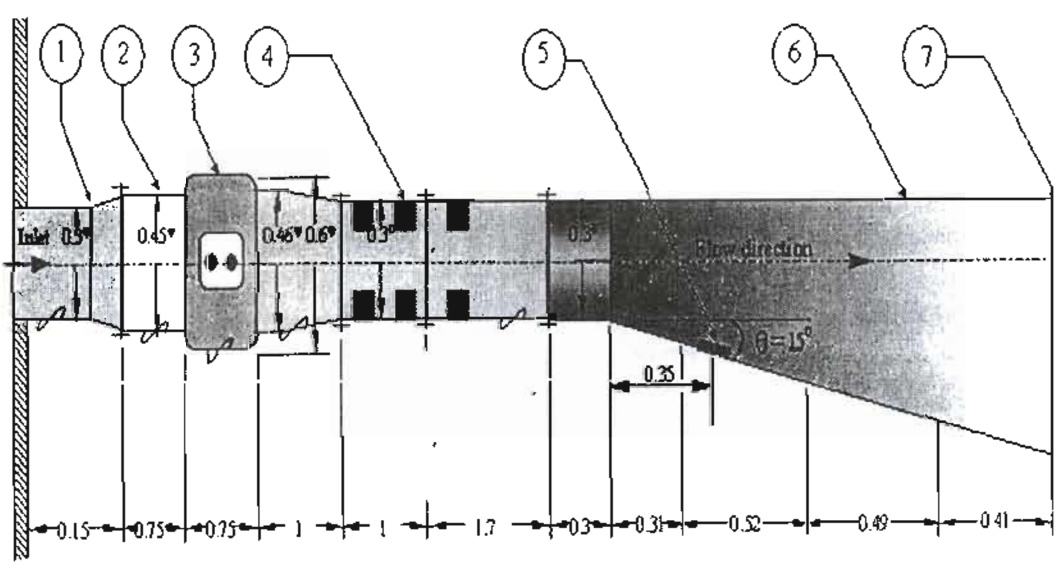



Fig. 1 Geometry of an asymmetric diffuser and positions of measuring stations

The diffuser is divided into five regions, the first region, x ≅ 0.0 – 0.3 m, where x is the axial distance from the inlet of the diffuser measured in the downstream direction; the second region, x ≅ 0.3 – 0.61 m, the third region, x ≅ 0.61 – 1.13 m, the fourth region ,x=1.13 – 1.38 and the last region , x= 1.38 – 1.62. A simple and effective empirical method was developed to determine the location of the point of separation. However, the point of separation locates at a distance of 0.36m measured from the first station, S1. A fence of dimensions (0.3*0.04*0.0075) m made of plastic is placed where the separation would be expected to take place.

## 2.2 Wind Tunnel

A schematic diagram of the wind tunnel and instrumentation is shown in Fig. (2). Experiments were conducted in an open-circuit wind tunnel powered by a 7.5 Hp. The control valve installed, connected to the main parallel pipe through a contraction, provides a means of varying the test section speed (within the range 3-20 m/s). Twelve electric heaters (12 kW) are used to maintain airflow through the working section at different temperatures. The heaters are located apart 2.7m from the working section (wide-angled diffuser). The duct walls are insulated to reduce the heat losses through the walls. However, the heat losses, 3% of input heat to heaters, can be neglected.




1. Filter 2. Damper ( three screens ) 3. Main blower and control valve 4. Heaters
5. Plastic fence 6. Asymmetric plane diffuser 7. Diffuser exit

Fig. 2 General layout of the test rig and instruments, dimensions in (m), not to scale

## 2.3 INSTRUMENTS

In the present work the multi-channel CTA anemometer DANTEC, 54N80/81 and 5-hole- probe are used. The constant hot-wire anemometer works on the basis of convective heat transfer from a heated sensor to the surrounding fluid, the heat transfer being primarily related to the fluid velocity .It is possible to measure velocity fluctuations of fine scales and of high frequencies. The advantages of CTA over other flow measuring principles are ease-of –use, the output is an analogue voltage, which means that no information is lost, and very high temporal resolution. The hot-wire anemometer or CTA consists of a probe with probe support and cabling , a CTA anemometer, a signal conditioner ,an A/D converter , and a computer , and very often a dedicated application software for CTA set-up, data acquisition and data analysis is part of the CTA anemometer.

The present measurements are made using gold plated wire of 5μ m in diameter and 1.2 mm active length between two ends, and total length of 3mm long in order to minimize prong interference. However, gold plated wire is applicable for air flows with turbulence intensities up to 20-25%.

## 3.EXPERIMENTAL PROGRAMME

The experiments were performed in an asymmetric diffuser for airflow at Reynolds number approximately, $Re=0.75*10^5$, based on the inlet condition of the diffuser ($U_o$=4.5m/s, W1=0.3m). The electric heaters were used to maintain the mean temperature of the air inside the diffuser (T=55°C). The average velocity and fluctuation fields have been measured with a constant temperature hot-wire anemometer (CTA). However, pressures in reversed flow regions have been measured using 5-hole-probe (the diameter of five – hole probe =3 mm, and the first point near the wall at 1.5 mm), at five different locations of the diffuser. The results were averaged and used to calculate the mean velocity distribution of the airflow through the diffuser, (about 20 points, and 1.5 cm between each two points, except two points near the walls, such distance is 3mm ). A digital thermometer (measuring range –30 °C to 120 °C, resolution 0.1 °C) is used to measure the temperature distribution of the hot air at each station and at the inlet of the diffuser. The experimental readings of temperature were averaged to have mean air temperature through the diffuser. However, the physical properties of the air were taken at the mean temperature.

## 4.MEASUREMENTS UNCERTAINTY ANALYSIS

Velocity measurements are subjected to errors in the location of the measurement control volume of the working section. The other parameters recorded during the experimental runs and the respective measurement uncertainties are listed in Table (1). The least count limits seen in the table are the smallest interval between the scale markings of the perspective instruments. The bias limit for instruments was negligible. An error analysis including the effects of both bias and least count errors, using the root-sum-square method, showed that the uncertainty [18 to 20] in the measured mean velocity is ± 4.6 % (± 0.24 m/sec) within 95 % confidence. Other uncertainty values are summarized in Table (2).

Table1 The least count limits for the measured parameters

| Parameter | least count limit |
|---|---|
| Barometric pressure | ± 0.1 mm Hg |
| Static pressure gage | ± 5 % |
| Dynamic pressure gage | ± 5 % |
| Width, W1 | ± 0.1 mm |
| Length, N | ± 0.1 mm |
| Diffuser angle, θ | ± 1 % |
| Air density, ρ | ± 5 % |
| Inlet velocity, $U_o$ | ± 1 % |
| Pressure gradient, dP/dx velocity gradient, du/dx | twice the standard deviation of the slope of (P-x), (u-x) plots |
| Inlet air temperature | ± 0.5 °C |
| Dynamic viscosity, μ | ± 3 % |

Table 2 Estimated typical uncertainties

| Parameter | Uncertainty, % |
|---|---|
| u | ± 4.6 |
| P | ± 6.83 |
| Re | ± 4.74 |
| Nu | ± 4.74 |
| St | ± 4.74 |
| λ | ± 4.27 |

## 5. RESULTS AND DISCUSSIONS

### 5.1 Velocity Results

Figure (3) shows the velocity distribution of hot air, at T= 50 °C, through the diffuser at Reynolds number, Re= $0.75*10^5$ based on inlet flow condition for two cases of the fence. As can be seen, in Fig. (3.a) that the velocity distribution at stations (1, 2) is full and complete but, not symmetric because of the geometry of the diffuser. At station (3), the effect of hot air on viscosity is clearly indicated that the viscosity of near wall boundary layer flow is insignificant and the flow separates. Also, there is a backflow that can be noticed at station (3). As a result of the wall angle of the diffuser, θ ≅ 15°, that causes the flow to separate with little backflow as can be seen at stations (4, 5). In Fig. (3.b), it is clear the effect of plastic fence to overcome much of the adverse pressure gradient, particularly at station (3), and the velocity profile seems to be full and complete. However, the influence of the fence does not reach to the end of the diffuser so, the velocity distribution has a little defect at stations (4, 5) in particular, in the near-wall boundary layer. Fig. (4) shows the velocity profiles of hot air for two cases of the fence at stations (1, 2). It can be seen in Figs. 4(a, b) that the velocity profiles are full and complete but asymmetric. In case of the fence the velocity profile shows to be large compared with the case of no fence, this is due to increasing the turbulence intensity due to fence. Fig. (4.c) shows the velocity profiles of hot air for the two cases of the fence at stations (3, 4 and 5). It can be seen that there is a backflow at the near-wall flow region, at (0 < Y* < 0.2), whereas the effect of using the fence is clearly indicated to prevent separation. However, details of the velocity profile, at ($0 < Y^* < 0.3$) can be seen in Figs.4 (f, g and h).

## 5.2 Heat Transfer Results and Discussions

In the present investigation, the following equations can be used to calculate Nusselt and Stanton numbers, respectively;

$$Nu = 0.023.Re^{0.8}.Pr^{0.4} \quad , \quad St = Nu/Re.Pr$$

The equations should be used only for small to moderate temperature differences with all the properties evaluated at the mean bulk fluid temperature.

The data are presented as the distribution of Nu, St, and Re numbers across each station of the diffuser and the relation between them for Reynolds number, $Re=0.75*10^5$ based on inlet condition of the diffuser, (u=4.5 m/s, W1=0.3 m).

For the sake of brevity, stations (2, 3 and 5) have been chosen for discussion. The results presented in Fig. (5) show the effect of hot air through the diffuser for the two cases (with and without fence) at station (2). As can be seen, in Fig. (5.a) St. number reaches a maximum value near the walls of the diffuser because the Reynolds in the near region of the boundary layer is very small. Also, St. number reaches to a small value at maximum Reynolds number at ($0.4<Y^*<0.8$). However, increasing St. number at the walls, does not mean that the heat transfer coefficient, h increases but, it is a matter of decreasing the Reynolds number due to viscous effects.

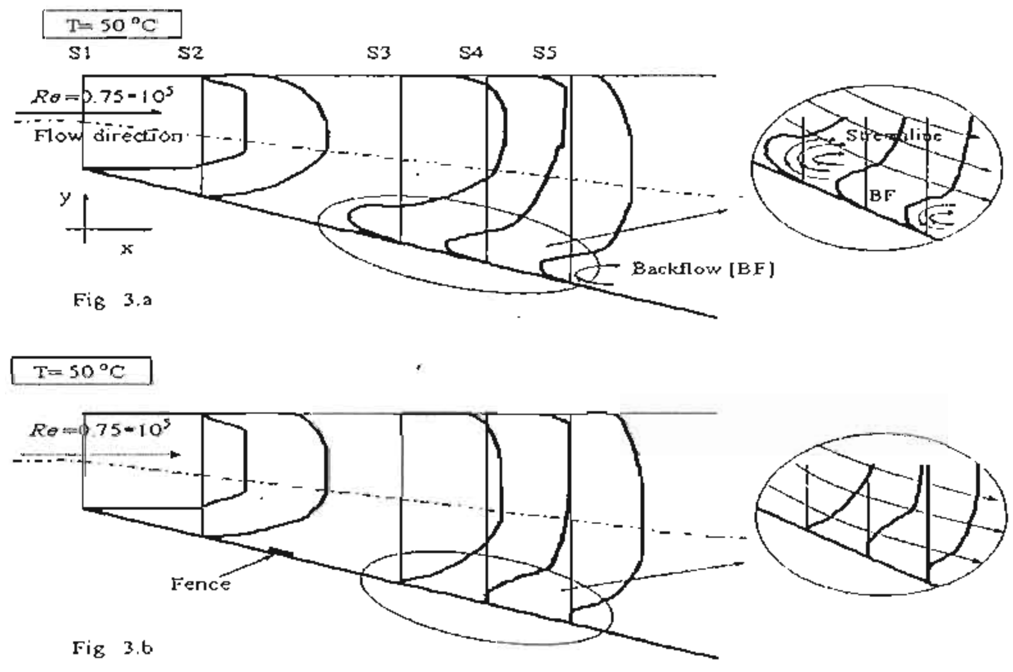



Fig. 3 Velocity distribution of hot air through the diffuser
a) without fence b) with fence

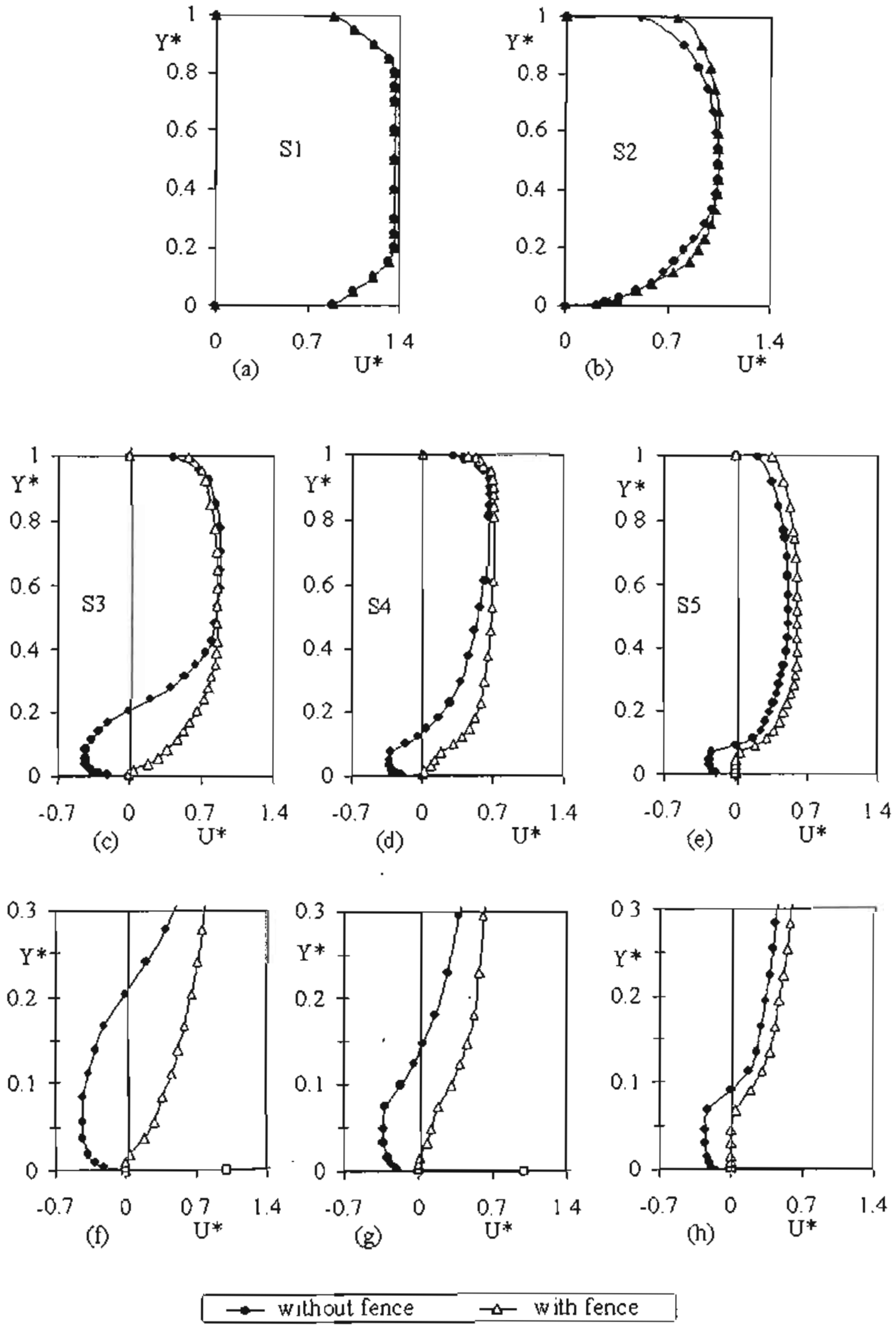



Fig. 4 Velocity profiles of hot air

In Fig. (5.b) the distribution of Nu. number across the width of the diffuser at station (2) is shown. It is clearly indicated that Nu. number reaches to minimum value at the walls as a result of decreasing the Reynolds number due to viscous effects. But, Nu. number reaches to maximum value and hence, the heat transfer coefficient, h increases due to increasing the Reynolds number in the core flow at ($0.4<Y^*<0.8$). In Fig. (5.c), Reynolds number increases for increasing the distance from the walls, it means that the viscous effects become insignificant for ($0.3<Y^*<0.8$), whereas the Reynolds number reaches to minimum value (about zero) near the walls. Fig. (5.d) shows the relation between Stanton number and Reynolds number. It can be seen that St. number increases for decreasing Reynolds number, it implies that the heat transfer coefficient (h) increases near the walls in spite of decreasing the velocity in the boundary layer. But, St. number decreases for increasing Reynolds number. The relation between Nu. number and Re number is clearly indicated in Fig. (5.e).

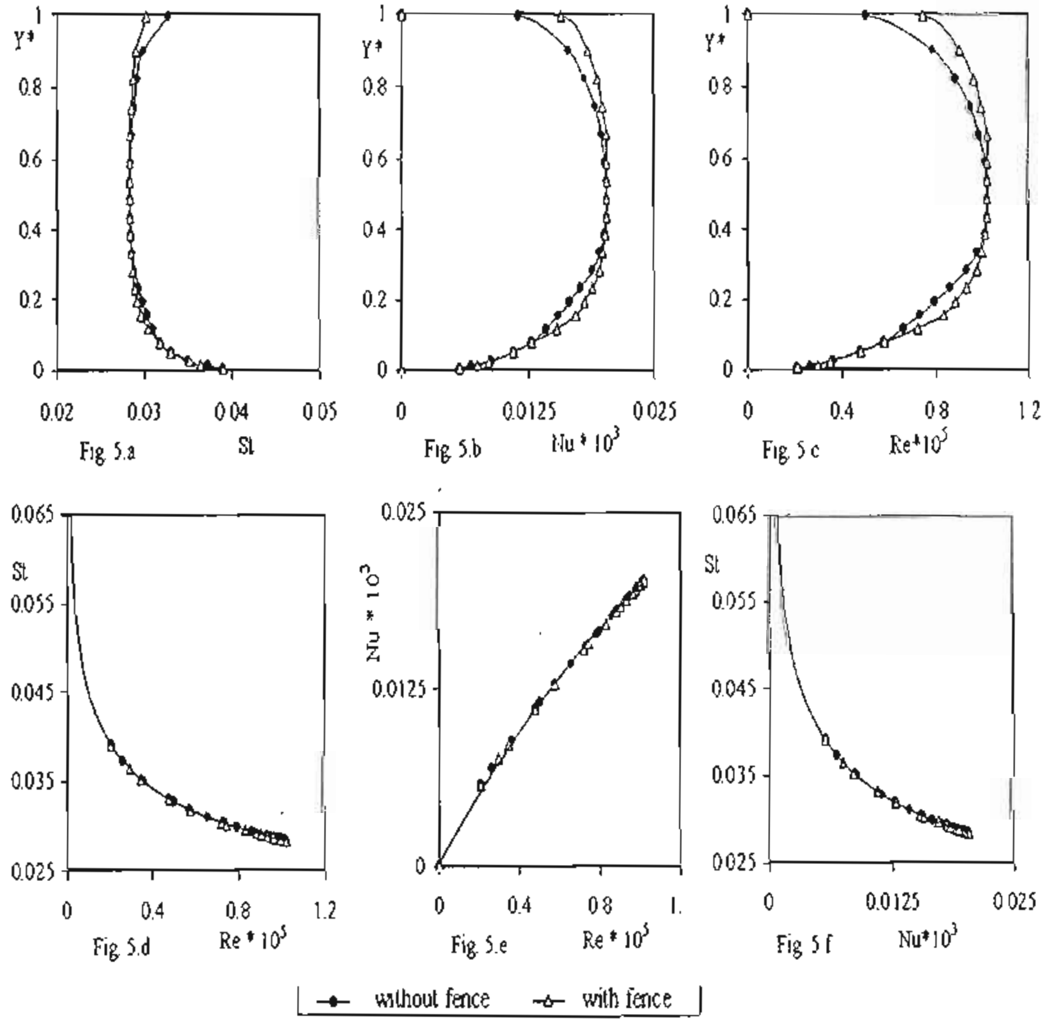



Fig. 5 Hot air without and with fence in diffuser at station (2)

It is clear that Nu. number increases for increasing Re number and vice versa. Fig. (5.f) shows the relation between St. number and Nu. number. It can be seen that the relation between St. number and Nu. number is similar as the relation between St. number and Reynolds number, Fig. (5.d).

Figure (6) indicates the distribution of St. number across the width of the diffuser with and without fence at station (3). The separation would expect to occur between station(3) and station (5), from experimental point of view the flows in separated zone represent a class of flows in which the controlling mechanism is largely unknown, particularly in the diffuser. Fig. (6.a) indicates the distribution of St. number across the width of the diffuser with and without fence. It can be seen that St. number increases near the walls whereas the Reynolds number reaches to minimum value, in case of no fence. But, St. number reaches to infinite value at $Y^*=0.2$ that is an unrealistic, this is due to the zero value of both St. number and Reynolds number. It implies the effect of reversed flow .But, in case of using the fence, there is no sign of flow separation, it means that the pressure gradient is less effective and St. number reaches to maximum value near the walls. However, the effect of fence on the distribution of St. number is like the case of no fence, in particular at $(0.4< Y^*<1)$. Figure (6.b) shows the distribution of Nu. number across the width of the diffuser at station (3). It can be seen that Nu. number reaches zero value at $Y^*=0.2$, in case of no fence, it means that Reynolds number equals zero. This is unrealistic. What would be expected to be thought, particularly in separated regions, is that the reading of the two limbs of the manometer is equal during the experiment; this is due to the effect of backflow. In case of using fence, the adverse pressure gradient becomes less effective and as a result, the velocity gradient increases and that lead to increasing Nu. number. At $(0.4<Y^*<0.9)$ where the non-viscous flow dominates, Nu. number increases as a result of increasing Reynolds number. However, the trend of Nu. number is similar for both cases of the fence. Also, the distribution of Nu. number is un-symmetric because the geometry of the diffuser is not symmetric. Fig. (6.c) shows the distribution of Reynolds number across the width of the diffuser for both cases of the fence. It is clear that the distribution of Reynolds number is like the distribution of Nu. number due to the direct relation between them. Fig. (6.d) shows the relation between St. number and Reynolds number for both cases of the fence. It can be seen that St. number increases for decreasing Reynolds number. However, there are some points, in particular in the separated regions, that can not follow the empirical formulation of heat transfer. Fig. (6.e) shows the relation between Nu. number and Reynolds number for the two cases of the fence. It is clear that this relation is nearly straight line. Fig. (6.f) indicates the relation between St. number and Nu. number for both cases of the fence. It can be seen that St. number increases as a result of decreasing Nu. number, it means that Reynolds number decreases, also St. number decreases for increasing Nu. number particularly, far from the wall regions. However, there are some experimental points which do not follow the empirical formulation of heat transfer i.e.the separated regions, where (0.06<St. <0.07).

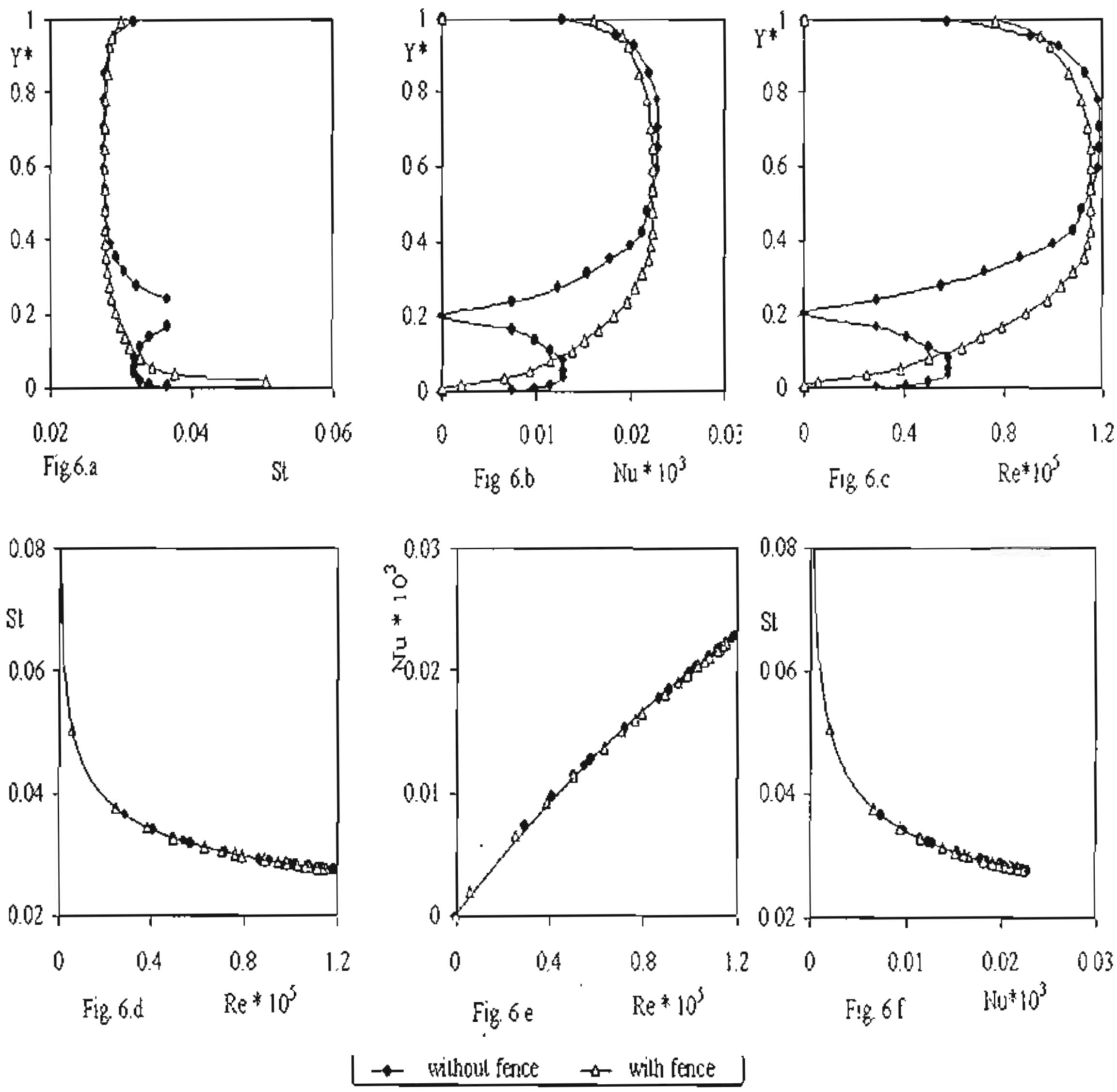



Fig. 6 Hot air without and with fence in diffuser at station (3)

Figure (7) shows the influence of hot air through the diffuser for two cases of the fence at station (5). In Fig. (7.a) the distribution of St. number the width of the diffuser is clearly indicated for both cases with and without fence. It can be seen that St. number reaches to a maximum value near the wall regions due to viscous effect (the streamwise velocity component is very small in the near-boundary layer flow regions). It is clearly indicated that St. number reaches to infinite value at (0<Y*<0.2). This is un unrealistic, but it is attributed to the value of St. and Reynolds numbers, as can be seen in

Figs.(7.b)and (7.c), respectively. Fig. (7.b) shows the distribution of Nu. number across station (5). It can be seen that Nu. number increases for increasing Reynolds number, in particular in the inviscid region. However, Nu. number reaches to zero value at (0.0<Y*<0.2) due to the effect of reverse flow in the separated regions for the case of using fence. But, in case of no fence there is no separation and St. number increases far from the walls.

Fig. (7.c) indicates the distribution of Reynolds number across station (5) for both cases of the fence. It can be seen that Reynolds number increases gradually up to the non-viscous region where the viscosity effect is very small. At (0.0<Y*<0.2) there are some experimental points locating in the separated regions where the backflow exists. These points do not obey the empirical relations of fluid flow and heat transfer.

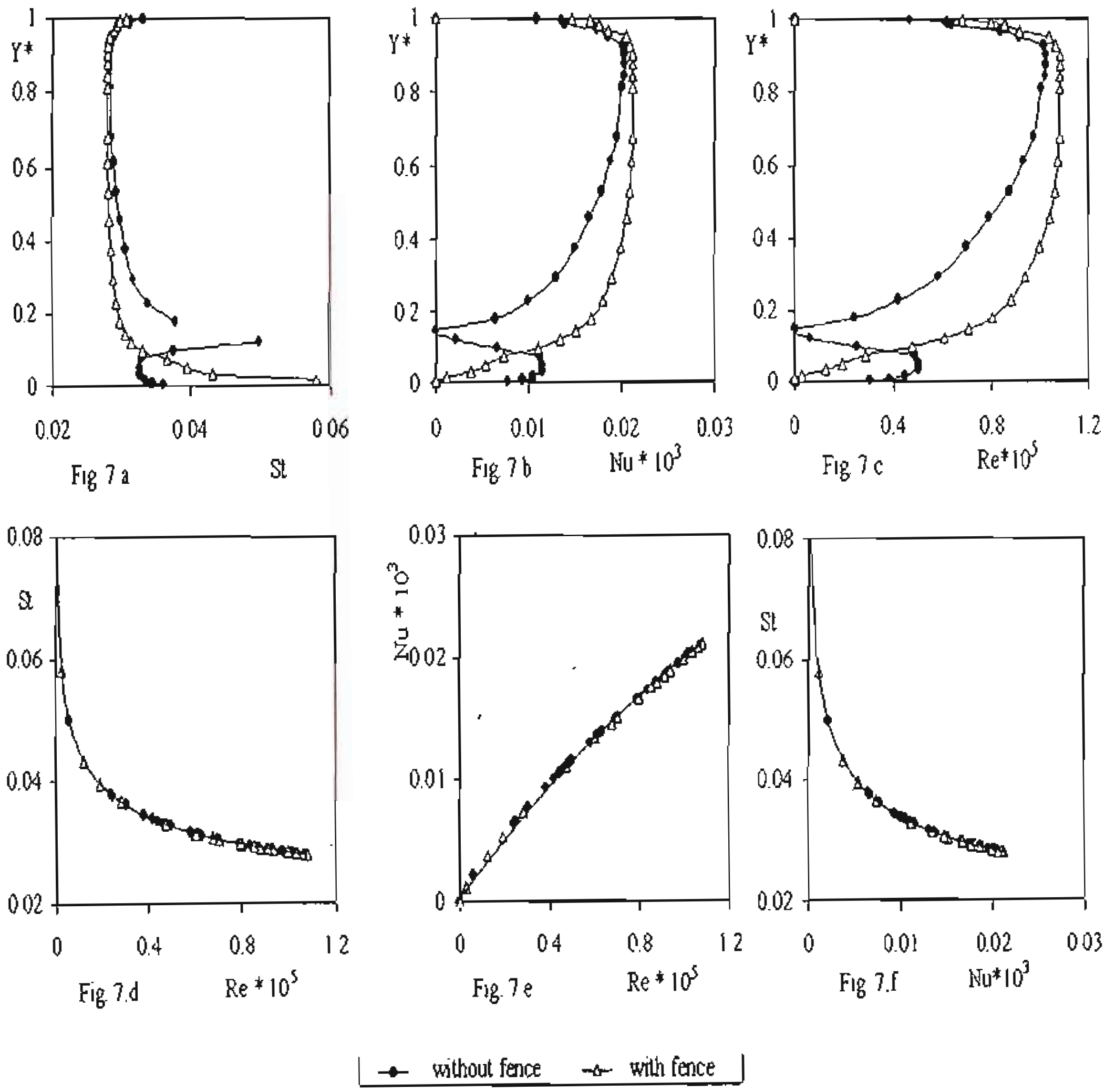



Fig.7 Hot air without and with fence in diffuser at station (5)

Fig. (7.d) shows the relation between St. number and Reynolds number. It can be seen that St. number decreases for increasing Reynolds number, but in separated region and where the reverse flow exists, Reynolds number reaches to zero and St. number becomes infinite( theoretically) this is not realistic. But, in case of using fence the effect of adverse pressure gradient decreases, and this leads to improve the characteristic of the flow in the boundary layer flow regions. Fig. (7.e) shows the relation between Nu. number and Reynolds number for the two cases of the fence. It is clear that the relation is nearly straight line, but there are some experimental points that do not follow the known empirical relation of heat transfer, due to the effect of reverse flow. Fig. (7.f) shows the relation between St. number and Nu. number for both cases of the fence. It can be seen that St. number increases for decreasing Nu. number, which means that Reynolds number decreases. Also, St. number decreases for increasing Nu. number. However, the relation between St. number and Reynolds number, Fig. (7.d) is similar as the relation between St. number and Nu. number, Fig. (7.f).

## 6. CONCLUSIONS

Based on the present experimental study of both the flow field and the heat transfer in an asymmetric diffuser including fence; the following conclusions may be drawn.

1- The fence causes a pressure loss and makes the considerable pressure gradient less effective. However, the effect of using fence becomes significant to improve the characteristics of the diffuser.
2- For naturally occurring separation, the streamwise of velocity component in reversed flow regions is fairly small compared with the maximum velocity found in viscous region.
3- An experimental evidence accumulated to date indicates that there are some results in separated regions that do not follow the known empirical relations of heat transfer.
4- In reversed flow regions, St. number reaches to an unrealistic value (infinite) for zero value of Reynolds number, whereas Nu. number equals zero.
5- The present work provides some attributes about the relevance of the relation between the fence and the wide angled asymmetric diffuser in controlling separation.

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