EXPERIMENTAL STUDY OF THE FRICTION FACTOR IN EQUILATERAL TRIANGULAR DUCT WITH DIFFERENT TYPES OF VOREX GENERATORS (OBSTACLES)

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Abstract:

Friction factors for fully developed flow in an equilateral triangular duct containing built-in vortex generators of delta wing, rectangular wing, pair of delta winglets, and pair of rectangular winglets have been investigated experimentally for Reynolds numbers ranging from (24 500) to (75 750). The ratio of the cross- sectional area of the test duct to that of the vortex generator (A_D/A_{VG}) was remaining constant during experiments. The variable parameters were; type of vortex generator, vortex generator angle of attack, and Reynolds number. The friction factor values for the smooth triangular duct are in good agreement with the existing data. The present results show that the friction factor is affected strongly by the wing greater than the winglet pair of vortex generators. The delta wing causes flow loss greater than the rectangular wing, while the flow loss accompany with the existence of the pair of delta- winglets is less than that of the pair of rectangular winglet. It is also observed that the friction factor is affected remarkably by the angle of attack of vortex generator.

Keyword: Triangular Duct, Fully Developed, Friction Factor, Obstacle.

دراسة تجريبية لمعامل الاحتكاك كامل النمو في مجرى مثلث المقطع باستخدام أنواع مختلفة من مولدات الدوامية (عوائق)

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الخلاصة:

تم اجراء دراسة تجريبية لبيان تاثير غرز مولدات الدوامية نوع الجناح المثلث، والجناح المستطيل، والجنيح المثلث، والجنيح المستطيل على جريان الهواء داخل مجرى مثلث المقطع ولقيم عدد رينولدز تراوح بين (500 24) و (75 750). تم تثبيت نسبة مساحة المقطع العرضي للمجرى الى مساحة مولد الدوامية خلال التجارب، وكانت المتغيرات في هذا البحث هي: نوع مولد الدوامية، وزاية ميل مولد الدوامية، وعدد رينولدز. كانت نتائج الاختبارات للجهاز بدون وجود مولدات الدوامية جيدة مقارنة مع نتائج البحوث السابقة. بينت النتائج الحالية ان معامل الاحتكاك يكون متاثراً بشكل كبير بالمولدات نوع الجناح اكثر منه من نوع الجنيح. كما وان المولد نوع

الجناح المثلث يولد هبوط ضغط اقل من الجناح المستطيل، في حين ان خسائر الجريان المرافقة لوجود الجنيح المثلث هي اقل من تلك المرافقة لوجود الجنيح المستطيل. كما ولوحظ ان تغيير زاوية ميلان مولد الدوامية تؤثر بشكل واضح على معامل الاحتكاك.

الكلمات المفتاحية: مجرى مثلث، تام النمو، معامل الاحتكاك، عائق.

NOMENCLATURE

Lest of symbols

A	**Internal cross-sectional area of the orifice plate (m^2).**
A_D	**Internal cross-sectional area of the test duct (m^2).**
A_{VG}	**Vortex generator area (m^2).**
C	**Constant.**
d	**Constant.**
D_h	**Hydraulic diameter (m).**
f	**Darcy's friction factor.**
f_o	**Standard friction factor(without obstacle).**
h	**Height of the vortex generator (m).**
L	**Distance between two tandem static pressure taps (m).**
l	**Length of the vortex generator (m).**
$m^{\bullet}$	**Air mass flow rate (kg/s).**
p	**Wetted perimeter of the walls of the duct (m).**
ΔP	**Pressure drop between the static pressure taps (pa).**
Re	**Reynolds number.**
S	**Distance between tips of winglet pair (m).**
$T_b in$	**Inlet air bulk temperature (^oK).**
$T_b out$	**Outlet air bulk temperature (^oK).**
T_f	**Air bulk film temperature (^oK).**
$\overline{U}$	**Mean velocity of the air (m/s).**

W	**Length of the side of the test duct (m).**
X_z	**Distance of wingtip from the leading edge of the test section (m).**

Greek symbols

β	**Angle of attack of vertex generator (degree).**
ρ	**Air density (kg/m^3)**
μ	**Absolute viscosity (pa.s).**
υ	**Kinematic viscosity (m/s^2)**

Introduction:

In the development of recent industrial world, the reduction in the heat exchanger size and enhancement in their performance for heat transfer had a great interest of investigators. But there are always economical factors to reduce the costs of heat transfer process. The need for high performance thermal systems due to study the increase in the pressure drop associated with the augmentation operations in heat transfer. Use of vortex generators for heat transfer enhancement is one passive method that generates vortices which creates high turbulence in fluid flow over heat transfer surfaces.

Aly et al. (1978) performed a numerical and experimental study for fully developed airflows through an equilateral triangular duct for high values of Reynolds number. They have found that the measured and predicted friction factor have a good agreement with the Blasius[1] equation for friction factor in smooth circular tubes. An experimental study was performed by Altemani et. al. (1980) to determine the entrance region, fully developed heat transfer and fluid flow characteristics for turbulent airflow in an unsymmetrical heated equilateral triangular duct. They have found that the circular –tube friction factor results deviate from those of equilateral triangular duct, even when the hydraulic diameter is employ. In (1986) Chegini et. al. studied theoretically and experimentally the friction factors for fully developed flow in triangular duct for two apex- angles with and without fins for a wide range of Re number. This study showed that the equilateral triangular duct has smaller scatter of friction factor data compared with the isosceles. A numerical and experimental study of flow and heat transfer characteristics in a rectangular channel with built-in wing vortex generator was investigated by Biswas et. al. (1992) and Laith (2008). Biswas et. al. have seen that the combined spanwise average friction factor (*f*xRe) increases approximately linearly with the angle of attack of generator, and more affected with Re number. Laith found that the friction factor changes significantly when Re numbers increased. As an extension of the work of Biswas et. al. (1992), Dep et al. (1995) and Biswas et al. (1994) studied the effect of the delta-wing and winglet-pair type vortex generator on a fluid flow and heat transfer characteristics through a rectangular channel. Biswas et al. (1994) have found that the loss (corresponding to the combined spanwise average friction factor coefficient) due to the winglet-pair is less than that due to the wing. Kotcioglu et al. (1998) investigated the rectangular-wing in the rectangular channel as in a way of divergent and convergent arrays. They observed that the pressure drop is influenced strongly by the inclination angle of vortex generator. Sabah et. al. (2007) studied numerically the effect of exist of

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[1] $f = 0.316/Re^{0.25}$

multi–types of turbulators on the fluid flow and temperature distribution for laminar and turbulent flow in a rectangular duct. The influence of vortex generators angle and louver angle on heat transfer and flow loss in laminar channel flows was numerically studied by Chung (2003).

The purpose of this paper is to highlight the effect of the four basic types of the vortex generators experimentally on the pressure drop gradient in a triangular duct. These four basic types of the vortex generators are shown in **Figure (1).**

Experimental apparatus:

The experiments were performed in an open–loop airflow circuit. The first air is encountered of regulator valve upstream wise of the blower, and then ducted to a circular tube which is provided by an orifice plate flowmeter in the axial mid-length to measure the air flow rate. The upstream end of the circular tube is coupled with the blower by using a flexible tube to minimize the vibration that occurs during blower operation and the downstream end mated with a hydrodynamic development section. The hydrodynamic development duct has an equilateral triangular cross section. A convergent contraction aluminum part was used to transit from circular tubing of the upstream piping system to the downstream triangular cross-section. The air exiting the hydraulic development section passes through the test section which they mated together at the same horizontal straight line and have an identical cross-section. The scheme of the current experimental apparatus is shown in **Figure (2).** During a course of experiments, Reynolds number was varied between (24 500) and (75 750). The development and test section were of identical internal dimensions; side of triangle=15 (cm), and hydraulic diameter=8.66 (cm). The respective axial lengths of the development and test sections were (24 D_h) and (15 D_h). The experiments tests were performed in the fluid laboratory, engineering college, university of Anbar.

The volumetric flow rate of air was measured by an orifice plate meter whose pressure taps were located one diameter upstream and half-diameter downstream as published in Roberson et. al. (1997) and Spencer et. al. (1982). The internal diameter ratio of the orifice plate and the tube is (0.7).

Some parameters were to be constant during the experimental apparatus design. These parameters are; the ratio of the cross-sectional area of the test duct to that of the vortex generators (AD/AVG), the distance of the wingtip from the leading edge of the test duct (XZ), the number of the VG punched in the duct, and the distance between the tips of winglet pairs (S). The geometry of the vortex generator was dependent upon the inclination angle (β) to keep the ratio (AD/AVG) is to be constant. This can be seen clearly in **Table (1)** and **Figure** (**3), (4), and (5).** The variable parameters are; the type of the vortex generator, the vortex generator angle of attack which is (20, 30, and 40) degree, and Reynolds number varying from (24 500) to (75 750). The vortex generator thickness is assumed negligible.

The test section has seven static pressure taps located at various positions along the axial direction. At any given axial location, the taps were also located in the circumferential direction to sense any pressure variation in that direction. The three taps at any given location jointed together to form one end. The difference in pressure was measured by connecting the inclined manometer two ends to each tandem two measuring points by PVC tubes.

A mercury thermometer is used to measure the input and output temperature of the test section. The air properties were estimated at the air bulk film temperature that is defined as follows, Holman (1976):

$$T_f = \frac{Tb_{in} + Tb_{out}}{2} \qquad \ldots(1)$$

The mass flow rate can be computed by the following equation:

$$m^{\cdot} = \rho A \overline{U} \qquad \ldots(2)$$

The experimental data are represented in the standard form of friction factor as a function of Reynolds number defined as follows. Streeter (1979):

$$\mathrm{Re} = \frac{\overline{U}\ D_h}{\nu} = \frac{4m^{\cdot}}{\mu P} \qquad \ldots(3)$$

The symbol (D_h) is the hydraulic diameter of the triangular duct that can be defined as follows, Streeter (1979):

$$D_h = 4\frac{A_D}{P} \qquad \ldots(4)$$

The friction factor *f*, known as Darcy friction factor in the literature, is defined as, Streeter (1979):

$$f = \frac{\Delta P}{[\frac{L}{D_h} \times \frac{\rho U^2}{2}]} \qquad \ldots(5)$$

Results And Discussion:

For checking the velocity of the experimental apparatus, **Figure (6)** shows the comparison between the current data without any obstacle and the literature experimental data. The results of Petukhov-Popov, Prandtl, and Blasius were developed for circular tubes, while the data of Altemani was for triangular duct as published in research of Altemani et. al.(1980). As shown in **Figure (6),** the present data over predicts that of Altemani by about (4.5) percent, whereas it is lower than that of Blasius, Petukhov-Popov, and Blasius by about (5, 6.86, and 8) percent respectively. This comparison indicates that the experimental rig is satisfactory.

Figure (7) shows the axial distribution of the (f x Re) along the test section for Re=24500 while keeping the angle of attack of vortex generator constant. It is apparent that the flow loss associated the existence of the wing-type is greater than that associated the winglet pair of VGs. This is because the wing-type causes a pressure drop region behind the trailing end of the vortex generator greater than that it is caused by the winglet pairs of vortex generators, and the air flow is circulated smoothly with the existence of winglet-pair type while if the wing-type is existence the air flow is circulated strongly. The pressure drop caused by RW is larger than that of DW. Also, we obtain a (f x Re) for the case of RWP greater than that of DWP. This performance gives a behavior similar to that of the rectangular channel as investigated by Tiggelback (1994). As expected, the friction factor value remains unchanged throughout in the duct for the flow without any obstacle. For example, at β=20 deg the (fxRe) for the case of DW at a location (X/D_h=2), is about (93.9%) more than that for the plane duct flow, while for the case of DWP over the (f x Re) value for plane channel about (57.4%). This behavior can also be clearly remarked in the **Figure (8)** when Re=75750 and β=40 degree.

Figure (9) shows the effect of the varying of the vortex generator angle of attack while keeping the ratio of (A_D/A_{VG}) constant. It is observed clearly that the friction factor increases monotonically with (β) because the vortex circulation increases which increases resistance and a higher value of friction is obtained. For example, at $\beta=30^o$, the friction factor for the case RW promotes by about (24.7) percent more than that for $\beta=20^o$ as shown in **Figure (9-a).**

Figure (10) exhibits the effect of Re number on the average friction factor through the test section. It seems that the friction factor is reversely proportion with Reynolds number. For example, in the case of RWP the (f) is about (56.7%) when Re=24 500 and $\beta=40^o$ greater than that for Re=75 750 as shown in **Figure (10-d).**

A correlation of the friction factor is determined as a function of Reynolds number to compare the fourth cases data. The correlation obtained from the current experimental data is:

$$f = \frac{C}{\mathrm{Re}^d}\frac{\beta}{\pi/2} \qquad \ldots(6)$$

The values of the variables C and d in Eq.(6) are tabulated in **Table (2).**

Concluding Remarks:

Depending on the results presented and discussed, the main conclusions of this study can be summarized as follows:

1. The flow loss in a triangular duct (corresponding to the friction factor) due to the

winglet-pair is less than that due to the wing.

2. The pressure drop increases strongly with the angle of attack of vortex generator (> 30 degree).
3. The difference in the pressure drop caused by the delta-winglet pair and rectangular – winglet pair is very slightly.
4. The friction factor changes significantly when the Reynolds numbers increased.

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Table (1) Test model geometry, all values in mm.

	20 degree				30 degree				40 degree			
	RW	DW	RWP	DWP	RW	DW	RWP	DWP	RW	DW	RWP	DWP
Vortex height (h)	16	23	20	31	23	30	16	23	32	44	11	16
Vortex length (l)	46	65	33	46	44	63	32	44	50	70	35	50
Area A_{VG}(mm^2)	500	500	500	500	500	500	500	500	500	500	500	500
A_D/A_{VG}	20	20	20	20	20	20	20	20	20	20	20	20
Distance of the wingtip from leading edge (Xz)	$1D_h$	$1D_h$	$1D_h$	$1D_h$	$1D_h$	$1D_h$	$1D_h$	$1D_h$	$1D_h$	$1D_h$	$1D_h$	$1D_h$
Distance between tips of winglet pairs (S)			20	20			20	20			20	20

Table (2) Values of the variables C and d in Eq.(6)

case	var β	C	d
DW	20	0.723	0.549
	30	2.036	0.668
	40	1.762	0.666
RW	20	0.798	0.564
	30	1.254	0.612
	40	2.466	0.680
DWP	20	0.161	0.427

	30	0.408	0.538
	40	0.614	0.587
RWP	20	0.203	0.443
	30	0.367	0.523
	40	1.103	0.635

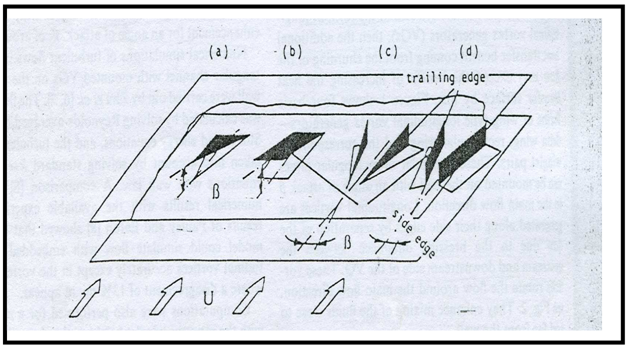


Figure (1) Schematic of longitudinal vortex generators types; a-delta wing, b-rectangular wing, c-delta winglet pair, d–rectangular winglet pair.

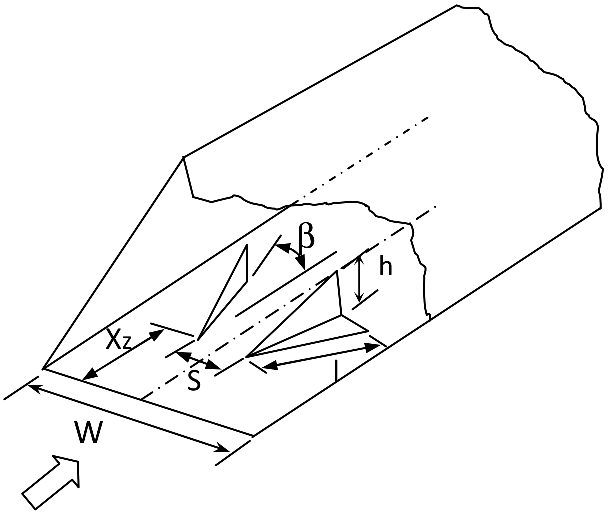


Figure (3) Schematic of the geometry of the duct with the delta-winglet pair.

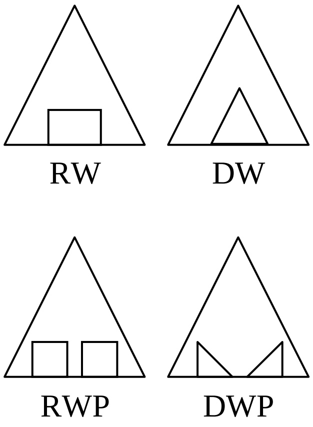


Figure (4) Shows the ratio of (A_D/A_{VG}) that is equal to 20.

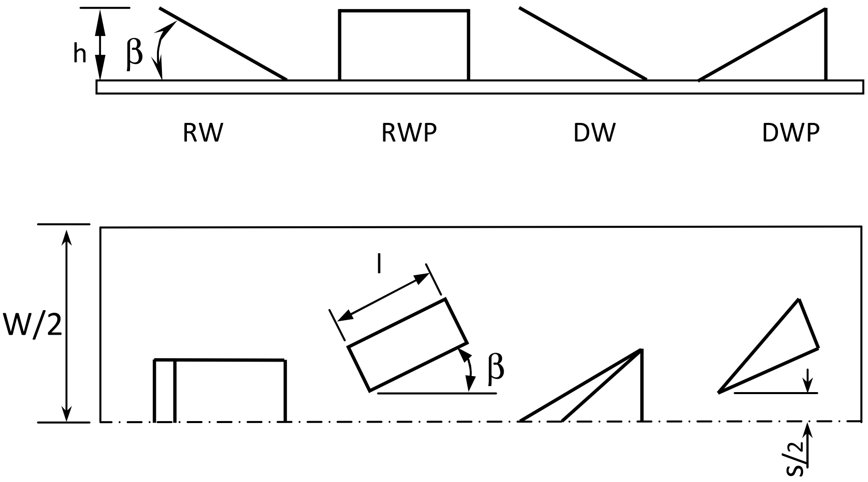


Figure (5) Shows elevation and plan view of different VGs.

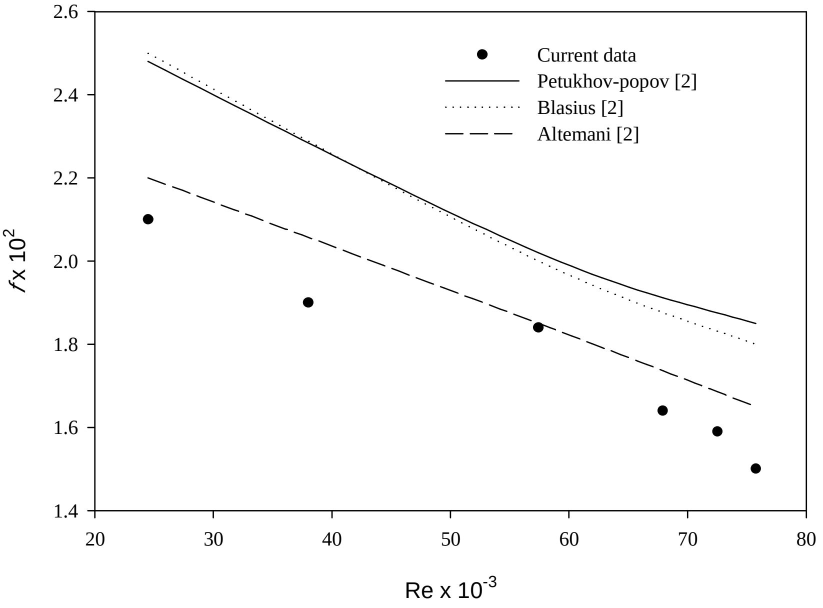


Figure (6) Friction Factor results

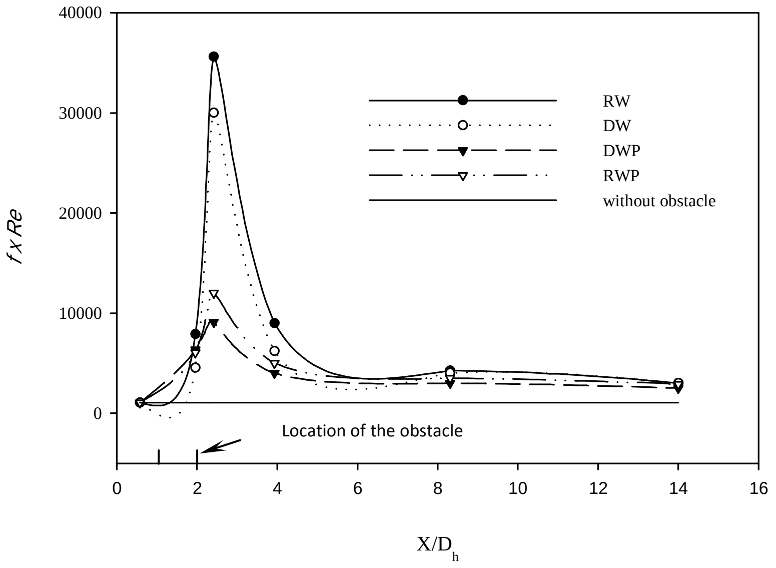


Figure (8) Axial Distribution (*f*xRe) along the Test Section

at β=40° and Re=77,500

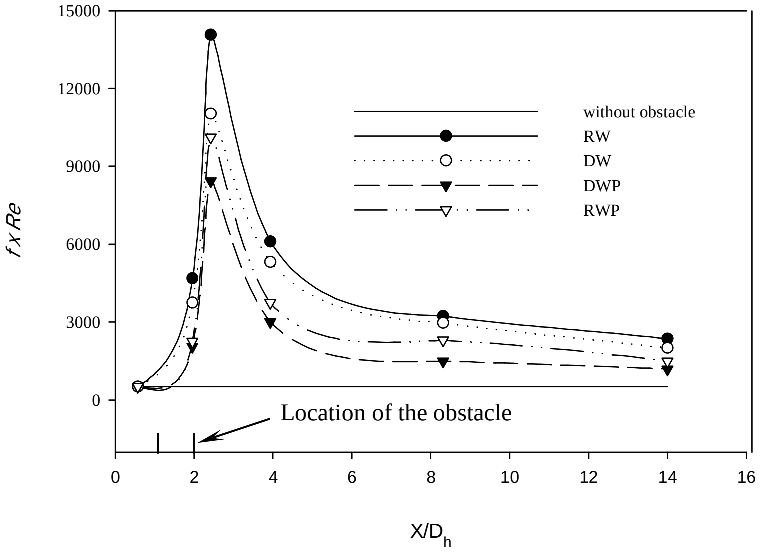
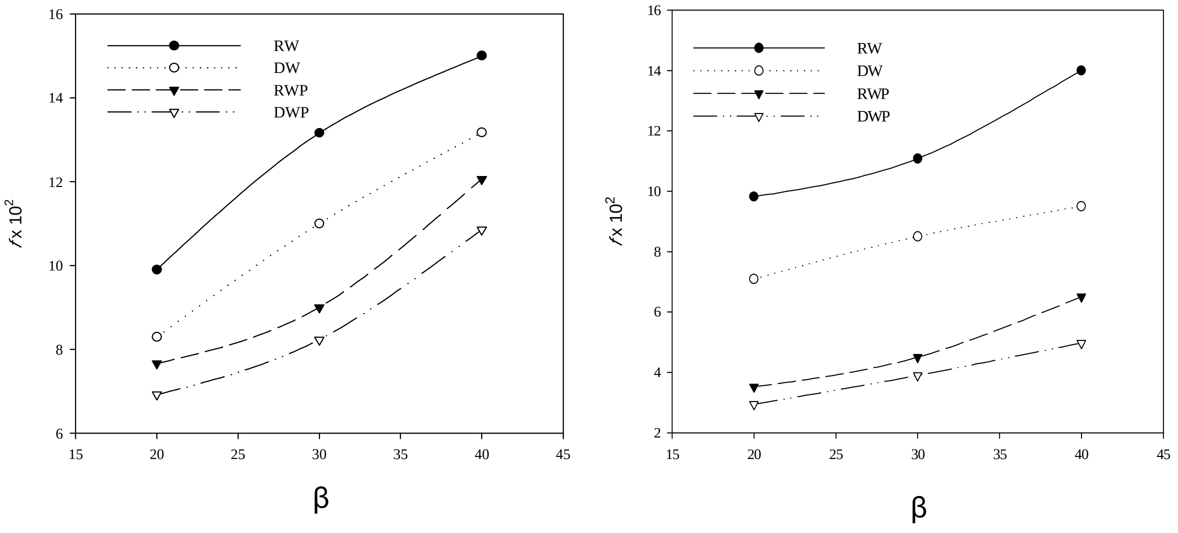


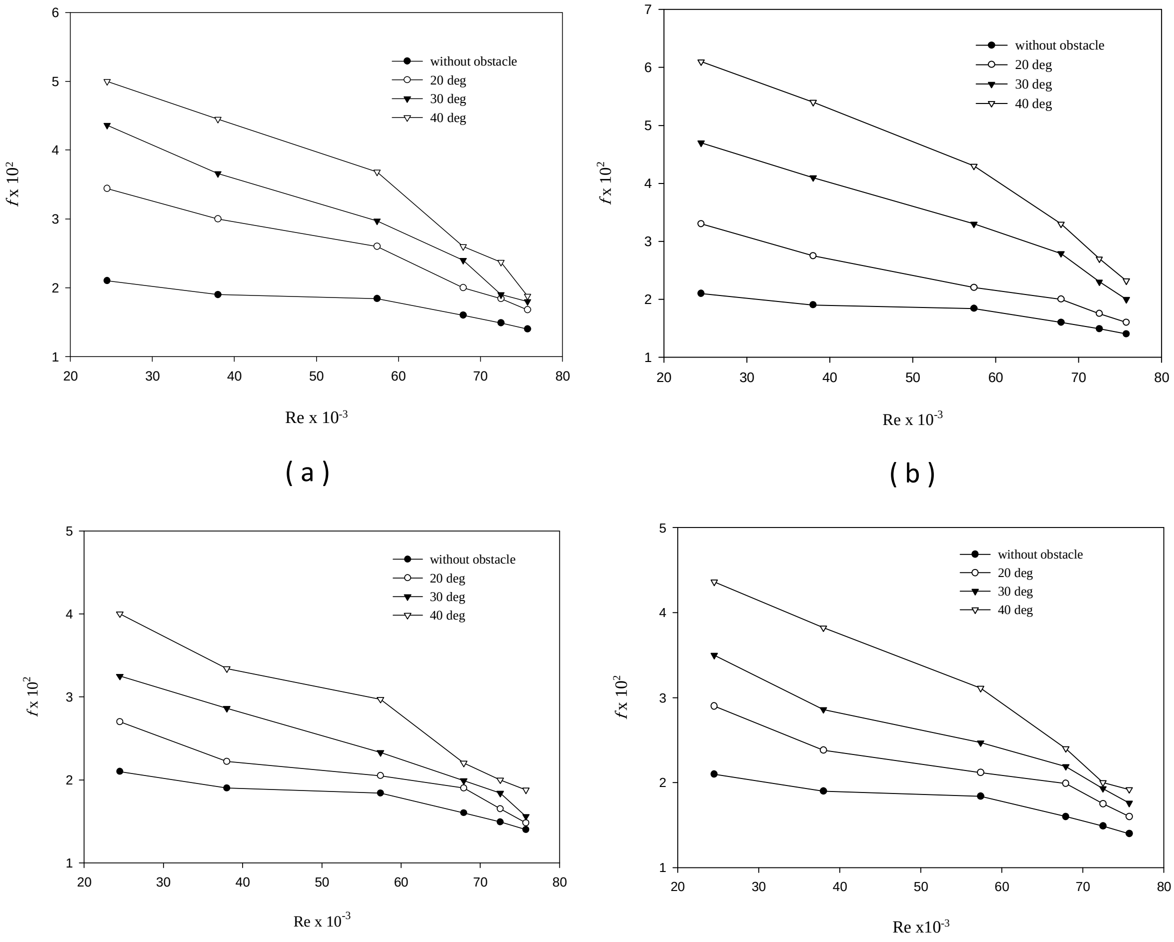
Figure (7) Axial Distribution of (*f*xRe) along the Test Section

at β=40^{o} and Re=24500.



(a) (b)

Figure (9) Effect of the Angle of Attack of Vortex Generators on the Average Friction Factor. (a) Re=24500, (b)Re=75750.



(a) (b)

(c) (d)

Fig (10) Effect of Reynolds Number on the Average Friction Factor in the Duct. (a)DW, (b)RW, (c) DWP and (d)RWP.