Numerical Investigation intoVelocity and Temperature Fields Over Smooth and Rough Ducts for Several Types of Turbulators

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Abstract

Numerical study on a laminar and turbulent fluid flow and temperature distribution in a rectangular duct with six types of vortex generators has been carried out. A modified version of ESCEAT three-dimension code has been used to solve Navier-Stokes and energy equations. The effect of vortex generator type, geometrical configuration, and dimensions on flow and temperature in different planes has been presented. The purpose of the present investigation is to highlight the complex three-dimensional interaction of the vortices generated by wings and other vortex generators to understand how such vortices configurations structure the velocity and temperature fields. Experiment in terms of velocities and temperatures vectors and contours were performed on 6 configurations, which experiments are (fin, fence, rib, wing-type, rectangular-type, and winglet-type) vortex generators The results show good agreement with published data.

الخلاصة

تم إجراء دراسة عددية على توزيع الجريان ودرجة الحرارة للمائع لحالتي الجريـان الطباقي والاضطرابي داخل قنوات مستطيلة حاوية على ستة أنواع مــن مولـــدات الـــدوامات. واستخدم لذلك نسخة مطورة من برنامج (ESCEAT) بثلاثة أبعاد لحل معادلتي نفير–ســـتوك والطاقة. حيث تم دراسة تأثير نوع مولد الدوامات وشكله الهندسي وأبعـاده علــى الجريـــان ودرجة الحرارة في مختلف المستويات. ان الغرض من البحث الحالي هو لتسليط الضوء على التأثير المعقد ذو الثلاثة أبعاد للدوامات المتولدة بواسطة الجُنيّحات (wings) ومولدات الدوامات الأخرى لفهم كيف ان الأشكال الهندسية لهذه الدوامات تُشكّل مجالي السرعة ودرجة الحرارة. لقد أخذت النتائج بصيغة متجهات وكنتورات (منحنيات مقفلة) للسرع ودرجات الحرارة لســتة أشكال من مولدات الدوامة وهي الزعنفـــة (fin) والحـــاجز (fence) والنتـــوء (rib) وجُنـــيّح (wing) وعائق مستطيل (rectangular) وعائق نوع (winglet). وقد أثبتت النتائج توافـــق وتطابق جيد مع تلك المنشورة سابقاً.

Nomenclature

B	Width of the duct		**Greek Symbol**
Br	ratio of wing span to width of the duct, b/B	α	Inclination angle
b	width of the VG (wing span)	β	Angle of attack

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C_1, C_2, C_D	coefficient in turbulence models, =1.43, 1.92, 0.09 respectively	β_1	thermal expansion coefficient
C_p	specific heat	γ	aspect ratio of the duct , B/H
e	VG thickness	δ	aspect ratio of the wing , 2b/l
g	gravitational acceleration	Γ	diffusion coefficient $= \mu / \sigma$
G_B	buoyancy production	ε	energy dissipation
G_K	generation rate of turbulence energy	μ	dynamic viscosity
H	duct height	ρ	fluid density
h	VG height	σ	prandtl number
hd	hydraulic diameter		**Subscript**
k	turbulent kinetic energy	k, ε	refer to turbulence model equation
L	duct length	in	iInlet condition
l	VG length or chord	ref	reference condition
p	pressure	t	turbulent
s	distance between winglet-pair (narrow side)	wall	condition at wall
S_T	source term	x,y,z	refer to cartesian coordinates
q_w	wall heat flux		**Superscript**
T	temperature	+	dimensionless value
U,V,W	mean velocity components	'	fluctuations relative to the time-averaged values
u,v,w	component of Velocity vector in x,y,and z direction	—	time-average values of products of fluctuating quantities
x,y,z	Physical or Cartesian coordinates		**Abbreviation**
		ESCEAT	elliptic equation solver for convection and Heat Transfer
		k-ε	two-equations turbulence model
		PDES	partial differential equations
		SIMPLE	semi-Implicit Method for pressure Linked Equation
		VG	vortex Generator

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Introduction

Configurations involving arrangements of sequential baffles (ribs, thin obstacles etc.) attached to a wall are commonly used for supporting and mixing purposes in heat exchangers, nuclear reactors cores, air-cooled solar collectors, some electronic circuit boards, internally cooled turbine blades, wastewater aeration tanks as well as chemical mixers and other chemical engineering applications. In some situations, turbulence generation and mixing associated with separation are desirable whereas in others separation is to be avoided as it causes a pressure loss [1]. Turbulence promoters or roughness elements have been used to improve the heat transfer. These roughness elements have been set on a heat transfer surface. The mechanism augmented heat transfer is complicated since the effects of the extended surface and turbulence generation are combined [2]. The character of the surface of the walls which makes up a duct strongly influence fluid flows along the ducts. Consequently, it would be more difficult to predict the characteristics of the flow and of the heat transfer in noncircular ducts with rough surfaces [3]. The basic idea of the heat transfer augmentation is not only to disturb the velocity temperature profiles close to the walls, but also to create a secondary flow that will exchange heat and momentum between the wall regions and the core region [4].

There are multi-types of these turbulators or vortex generators, Fig.1 shows only six types that are used in this work.

Longitudinal vortices generated by wings at an angel of attack spiral the flow around their axes and persist to

hundreds of wing chords downstream of the wing. When longitudinal vortex generators are placed near a heat transfer surface or when they are part of the heat transfer surface, they increase the heat transfer by transporting fluid from the wall in to the free stream and vice versa. Essential for the effectiveness of a vortex generator in substantially enhancing the heat transfer over a large area is the vortex strength that can be generated per unit area of the vortex generator. From theory and experiment it is well known that slender delta wings are the most effective longitudinal vortex generators, Fig. 1-a, [5].

The purpose of this paper is to present numerical model for the velocity and temperature fields over a smooth and six type VGs roughened surfaces.

Vortex generators by means of delta wing and winglet-type and by rectangular winglet-type have been previously observed by [5 & 6]. They have studied laminar velocity and temperature fields with a row of built-in VGs with a range of Reynolds number. The experiment results and the analytical methods show a heat transfer enhancement because of the longitudinal vortices that are deformated. Also, the delta wing shows by far the best performance of all configurations. The increase in friction factor appears to be proportional to the projected cross flow area for all geometries.

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Fluid flow and heat transfer over a transverse ribbed surface in a rectangular channels were carried out by [7&8]. The computational and experimental studies undertake the effect of the channel aspect ratio on the distribution of the local heat

transfer coefficient in rectangular channels for a range of Reynolds number, channel width-to-height ratio and rib spacing. There is good agreement between prediction and measurements. Based on the law of the wall similarity and the application of the heat-momentum analogy, a general correlation of fraction factor and heat transfer was developed.

The turbulent flow over a well-defined rough surfaces, walls, and elements numerically and experimentally is presented by [2 , 3 & 9]. The researchers studied momentum - and heat - transfer characteristics.

Works about heat transfer enhancement by using transverse and pin fins have been investigated by [10 & 11]. A numerical study was done on laminar fluid flow and forced convection heat transfer within horizontal channels to which one or two pairs of transverse fins are attached for different Reynolds numbers and various geometric arrangements. Experiments have been conducted to study the turbulent heat transfer and friction characteristics in pin fin channels.

Measurements and computations of the mean stream wise velocity and its fluctuation for an arrangement of two similarly fences mounted in tandem in fully developed channel flow have been reported by [1].

Mathematical and numerical Formulation

The mathematical formulation of fluid flow problems is governed by basic conservation principles namely the conservation of mass, momentum and energy. These principles can be expressed in terms of (PDES) for both laminar and turbulent flow regimes.

The numerical modeling of fluid flow is of a great significance in all applications. Finite volume method offers a great simplicity to numerical solution of partial, non-linear differential equations in Cartesian coordinate system [12 – 14].

General Conservation Equations

(i) Mass conservation
(continuity)

For steady incompressible, three-dimensional flows, for laminar flow:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0......... \ .(1)$$

and for turbulent flow, equation (1) is replaced by the sum of a time-mean component and a fluctuating component i.e.;

$$U = u + u', \ V = v + v', \ W = w + w'$$

then, the mass conservation equation becomes;

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 ....(2)$$

Since the fluctuating in
u', v', and, w' occurs over a short time interval so that
$u \approx U, \ v \approx V, and, \ w \approx W$.

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(ii) Conservation of momentum
(for turbulent flow)

X-direction (U momentum):

$$\frac{\partial}{\partial x}(u)+\frac{\partial}{\partial y}(v)+\frac{\partial}{\partial z}(w)=-\frac{1}{r}\cdot\frac{\partial p}{\partial x}+\frac{1}{3}\cdot$$

$$\frac{1}{r}\cdot\frac{\partial}{\partial x}(\mu\cdot\nabla N)+\frac{1}{r}\cdot\nabla^2\mu u+g_x+\frac{\partial}{\partial x}(-\overline{u'u'})$$

$$+\frac{\partial}{\partial y}(-\overline{u'v'})+\frac{\partial}{\partial z}(-\overline{u'w'})\ldots\ldots\ldots(3)$$

where: $\nabla N = \dfrac{\partial U}{\partial x}+\dfrac{\partial V}{\partial y}+\dfrac{\partial W}{\partial z}$ &

$$\nabla^2 = \frac{\partial}{\partial x}(\frac{\partial}{\partial x})+\frac{\partial}{\partial y}(\frac{\partial}{\partial y})+\frac{\partial}{\partial z}(\frac{\partial}{\partial z})$$

Y-direction (V momentum):

$$\frac{\partial}{\partial x}(u)+\frac{\partial}{\partial y}(v)+\frac{\partial}{\partial z}(w)=-\frac{1}{r}\cdot\frac{\partial p}{\partial y}+$$

$$\frac{1}{3}\cdot\frac{1}{r}\cdot\frac{\partial}{\partial y}(\mu\cdot\nabla N)+\frac{1}{r}\cdot\nabla^2\mu v+g_y+$$

$$\frac{\partial}{\partial x}(-\overline{u'v'})+\frac{\partial}{\partial y}(-\overline{v'v'})+\frac{\partial}{\partial z}(-\overline{v'w'})\ldots(4)$$

Z-direction (W Momentum);

$$\frac{\partial}{\partial x}(u)+\frac{\partial}{\partial y}(v)+\frac{\partial}{\partial z}(w)=-\frac{1}{r}\cdot\frac{\partial p}{\partial z}+$$

$$\frac{1}{3}\cdot\frac{1}{r}\cdot\frac{\partial}{\partial z}(\mu\cdot\nabla N)+\frac{1}{r}\cdot\nabla^2\mu w+g_z+$$

$$\frac{\partial}{\partial x}(-\overline{u'w'})+\frac{\partial}{\partial y}(-\overline{v'w'})+\frac{\partial}{\partial z}(-\overline{w'w'})\ldots(5)$$

and for laminar flow, the last three terms in equations (3),(4),and (5) do not exist and are replaced *u, v, and, w* by U,V,and W, assuming a similar

expression for the pressure P (i.e. $P = p + p'$).

(iii) Conservation of thermal energy(for turbulent flow)

$$\frac{\partial}{\partial x}(\Gamma\cdot\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\Gamma\cdot\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(\Gamma\cdot\frac{\partial T}{\partial z})+$$

$$\frac{\partial}{\partial x}(-\rho\cdot\overline{u'T'})+\frac{\partial}{\partial y}(-\rho\cdot\overline{v'T'})+\frac{\partial}{\partial z}(-\rho\cdot\overline{w'T'})$$

$$+S_T = 0\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

And for turbulence models:
$(\overline{u'^2} = \overline{v'^2} = \overline{w'^2})$ and:

$$-\rho\cdot\overline{u'u'} = 2\cdot\mu_t\frac{\partial u}{\partial x}-\frac{2}{3}\rho k$$

$$-\rho\cdot\overline{v'v'} = 2\cdot\mu_t\frac{\partial v}{\partial y}-\frac{2}{3}\rho k$$

$$-\rho\cdot\overline{w'w'} = 2\cdot\mu_t\frac{\partial w}{\partial z}-\frac{2}{3}\rho k$$

$$-\rho\cdot\overline{u'v'} = \mu_t(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x})$$

$$-\rho\cdot\overline{v'w'} = \mu_t(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y})$$

$$-\rho\cdot\overline{u'w'} = \mu_t(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x})$$

$$\ldots(7)$$

where:

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

and for laminar flow, the fourth, fifth, and sixth terms in equation (6) do not exist, and are again written $\tilde{T} = T + T'$, where T is the time-mean temperature and T' is the fluctuating from mean.

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The k - ε Turbulence Model

Two-equation turbulence model will be more appropriate for elliptic equation, such as the present case flows. For such flows a two-equation turbulence model (k - ε) has been adopted for the present work.

The transport equations for k and ε are as follow:

$$\frac{\partial}{\partial x}(\Gamma_k \frac{\partial k}{\partial x}) + \frac{\partial}{\partial y}(\Gamma_k \frac{\partial k}{\partial y}) +$$

$$\frac{\partial}{\partial z}(\Gamma_k \frac{\partial k}{\partial z}) + G_k - \rho \cdot \varepsilon + G_B = 0 ....(8)$$

where:

$$G_k = \mu_t \left\{ \begin{array}{l} 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] \\ + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 \end{array} \right\}$$

$$G_B = -\beta_1 g \frac{\mu_t}{\sigma_t} \cdot \frac{\partial T}{\partial y} \quad ,$$

$$\mu_t = C_D \cdot \rho \cdot k^2 / \varepsilon$$

$$\frac{\partial}{\partial x}(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial x}) + \frac{\partial}{\partial y}(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial y}) + \frac{\partial}{\partial z}(\Gamma_\varepsilon \frac{\partial \varepsilon}{\partial z})$$

$$+ \frac{\varepsilon}{k}\left[C_1 \cdot G_k - C_2 \cdot \rho\varepsilon\right] = 0 ....(9)$$

Wall function and heat flux

It should be mentioned that the heat flux across the viscous sub-layer is assumed to be constant. As in momentum transport treatment, the point Y^+=11.5 is also defined here for disposing buffer layer. For $Y^+ \leq 11.5$ the transport is assumed to be due to molecular activity and the expression for the heat flux parameter T^+ is a simple one.

For $Y^+ \geq 11.5$ where

$$\frac{\Gamma t}{\Gamma} \gg 1, q \approx q_{wall} \quad \text{calculate}$$

q_{wall} from the following relation:

$$T^+ = \frac{(T_{wall} - T_p)\rho C_p u_t}{q_{wall}}$$

$$= \sigma_t \left[u^+ + P(\frac{\sigma}{\sigma_t}) \right] ....(10)$$

$$\frac{q_{wall}}{C_p} = \frac{\rho u_t(T_{wall} - T_p)}{\sigma_t \left[u^+ + P(\frac{\sigma}{\sigma_t}) \right]} .....(11)$$

$$P(\frac{s}{s_t}) = \frac{9.0\left[(\frac{s}{s_t}) - 1.0\right]}{\left[\frac{s}{s_t}\right]^{1/4}} ....(12)$$

Conditions

A. Initial u=v=0 , w=w$_{in}$, k=k$_{in}$=0.00135 * (w$_{in}$)^2 , $\varepsilon = \varepsilon_{in}$=0.09 * (k$_{in}$)$^{1.5}$ / (0.03 * hd) , T=T$_{ref}$

B. At inlet u=v=0 ,w=w$_{in}$, k=k$_{in}$, $\varepsilon = \varepsilon_{in}$, μ=μ$_{ref}$, T=T$_{in}$

C. At walls and VGs surfaces u=v=w=k= ε =0 , μ =μ$_{ref}$, T=T$_{wall}$

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D. At exit all variables equal to the same variables just before one plane.

The SIMPLE procedure that uses a staggered grid use a power-law differencing scheme with finite volume method to solve the (u , v , w , p , k , ε) equations.

Results and Discussion

A large number of computations have been performed at different VG

types, Reynolds numbers, ducts and VGs configurations and dimensions, which will be discussed below.

An important step in our code development is to validate its results using published data from other sources.

Fig. (2) shows a comparison of the computational result of Sabah [14], with the present result for laminar flow in a smooth duct for grid size (20x17x28). The results show a good agreement.

Fig. (3) shows another comparison of a computational result of Biswas et al. [15], for laminar flow in a channel with built-in wing-type VG for grid size (26x15x60) and channel's dimensions (0.4x0.2x1.68) m^3 and wing dimensions (h=0.156 m, l=0.316 m, b=0.15 m). The figure shows the first half of the channel length. Again the comparison appears to be fairly good.

As can be seen from fig.(2) & (3), the present code gives an acceptable simulation for both cases, i.e., the simplest one which is for smooth duct without turbulator and the more complex case, i.e., the rough duct with wing-type VG. Therefore, the present code could be used to handle

other complicated flows using several VG configurations as shown in fig. (1). One of such VG configurations is presented in fig. (4) which shows a finned duct (0.5x0.15x0.75) m^3 with grid size (21x17x29) with l=0.26 m (x=0.12-0.38) m and h=0.03 m. The obtained heat and flow pattern for this finned duct are presented in this figure. The presence of fins causes the flow to detach from the wall surface so that recirculation occurs in the rear of each fin. Owing to the vortex motion, temperature of recirculation

flows becomes rather high for perfectly conductive fins.

Airflow and isothermal contours in a fenced duct configuration are shown in Fig. (5). The related dimensions are the same with the finned duct but with different height fences (e=27 mm, h=28 & 56 mm and l=0.5 m), the shorter one placed at z=0.24 m and the other at z=0.515 m. The inlet temperature was $16C^o$ and the wall and fences surfaces at $40C^o$. It can be seen, how the VGs distribute the temperature and then enhance heat transfer.

The effect of ribs and its locations are presented in Fig. (6-a to 6-d). Fig. (6-a) gave the velocity vectors for staggered ribbed duct (0.16x0.08x0.6) m^3 and (10x19x60) grid size and (l=0.16 m, e=10 mm, and h=13mm), for laminar case at Re=2119. It shows a recirculation flows near the upper surface. Fig. (6-b) shows the flow at two-ribbed duct placed at the lower surface with the same duct dimensions and (19x15x31) grid size and (l=0.16, e=20 mm, and h=17 mm), and Re=2119. The developing

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flow in the entrance region is clear in the figure. The turbulent flow (Re=6293) is tackled in figure (6-c & 6-d), where Fig. (6-c) highlighted the velocity image (w/w_{in}) for staggered configuration for the same duct and (11x21x31) grid size. The dark color shows the small values of the velocity lie behind the ribs due to the vortex generated at that location. The temperature distributions, (T/T_{wall}) are given in fig. (6-d) with staggered configuration and $T_{in}=7C^o$ and $T_{wall}=27C^o$. The effect of the previously maintained flow vortices on temperature gradient is very clear in this figure.

For slender delta wings in a free stream, fig. (7, 8) show the vortex and flow structure and temperature distributions. Fig. (7-a & 7-b) represents the laminar case of the wing. Since Fig.(7-a) represents velocity contour for v-velocity component at Re=500, the symmetry of the flow is very clear in this figure. This location is very close to the beginning of the wing. Fig. (7-b) shows the isotherms for thermally and hydro dynamically developing duct flows with a built-in delta wing. It can be seen that the variation of temperature before the wing is very large while the temperature values after the wing is approximately constant. The turbulent behavior is presented in Fig. (7-c & 7-d). Fig. (7-c) shows the velocity along the duct at Re=153846, while Fig. (7-d) shows temperature field, the vortex generator disturbs the temperature field strongly. The difference in temperature field between laminar

case and the turbulent one is large as can be in for Fig. (7-b & 7-d). Near the top wall, then,appears a small temperature gradient above and behind the wing, which was not in the laminar case. And Fig. (7-e & 7-f) shows a comparison between the laminar and turbulent temperature distributions at the given location. The difference is quite clear between the two figures, which can be attributed to the turbulent effect (vortices). Fig. (7-e) shows temperature contours in cross section for laminar flow with delta wing geometries as in Fig. (3), while Fig. (7-f)is for turbulent flow. In the wing tip region the vortices suck low-velocity fluid into the vortex and bring it close to the wing, which leads to a thickening of the temperature

boundary downstream of the wing base.

Fig. (8) shows the formation of vortex pair for delta wing previously given in Fig. (3). The leading edge vortices have a circular structure and disappear gradually up to the end of the duct.

Fig. (9) shows velocity vectors and temperature contours for duct flow with winglet pair (0.5x0.15x0.75) m^3 duct with (21x17x29) grid size. Winglet dimensions are: l=55 mm, h=19 mm, and $a = 43.7^o$, and the two winglets are from z=0.23 m to z=0.29 m. Fig. (9-a & 9-b) gives, the laminar case of Re=1538. Fig. (9-a) shows cross flow at Z=0.4 m, it shows two vortices at the same direction. And Fig. (9-b) shows cross-temperature contours at z=0.26 m. Fig. (9-c & 9-d) gives the turbulent counter part of the case at Re=153846. Fig. (9-c) shows

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cross flow at z=0.75 m. Two small vortices inside a big one appear in the figure, the small vortices shift to the direction of rotation. Fig. (9-d) shows the temperature distribution at z=0.26 m too. The differences between the temperature contours of Fig. (9-b) & (9-d) can explain the theory of force convection, i.e., the convection of heat is large for small velocities and vice versa.

Finally, fig. (10) describas the simulation of laminar and turbulent flow and heat for rectangular wing in a duct similar to that of Fig. (9) for the Re & temperature field. The VG dimensions are: l=55 mm, h=19 mm and $b = 19.1^o$, also from z=0.23 m to z=0.29 m. Fig. (10-a) shows u-velocity component contours at z=0.24 m for the laminar flow. Symmetrical values appear clearly in the figure. Fig. (10-b) represents

temperature contours at midplane for laminar flow. Fig. (10-c) shows v-velocity component contours at z=0.24 m for turbulent flow, and Fig. (10-d) represents temperature contours at midplane for turbulent flow.

Concluding Remarks

Based on the results presented and discussed ,the main conclusions are:

1- Numerical study was carried out to predict the velocities and temperatures for laminar and turbulent forced convection flows in internally roughened rectangular ducts.Six types of turbulators are used.The flow is characterized by recirculation zones and significant flow distortion.

2- The study includes the prediction of the presence of two-finned duct on the bottom surface of a duct.These fins interrupt the development of boundary layers,and hence exhibit great influence on the local flow behavior.

3- The ribbed-rough ducts also perdicted the influence on the secondary flow.This gives a peculiarity in the contours map which is similar to that observed in the contours of the mean velocity.

4- The study on the delta-wing's effect shows the generation of a pair of counterrotating longitudinal vortices along their leading edges that diverg slightly depending on the aspect ratio of the wing.The longitudinal vortices follow somewhat the wing inclination until they are redirected by the duct walls.

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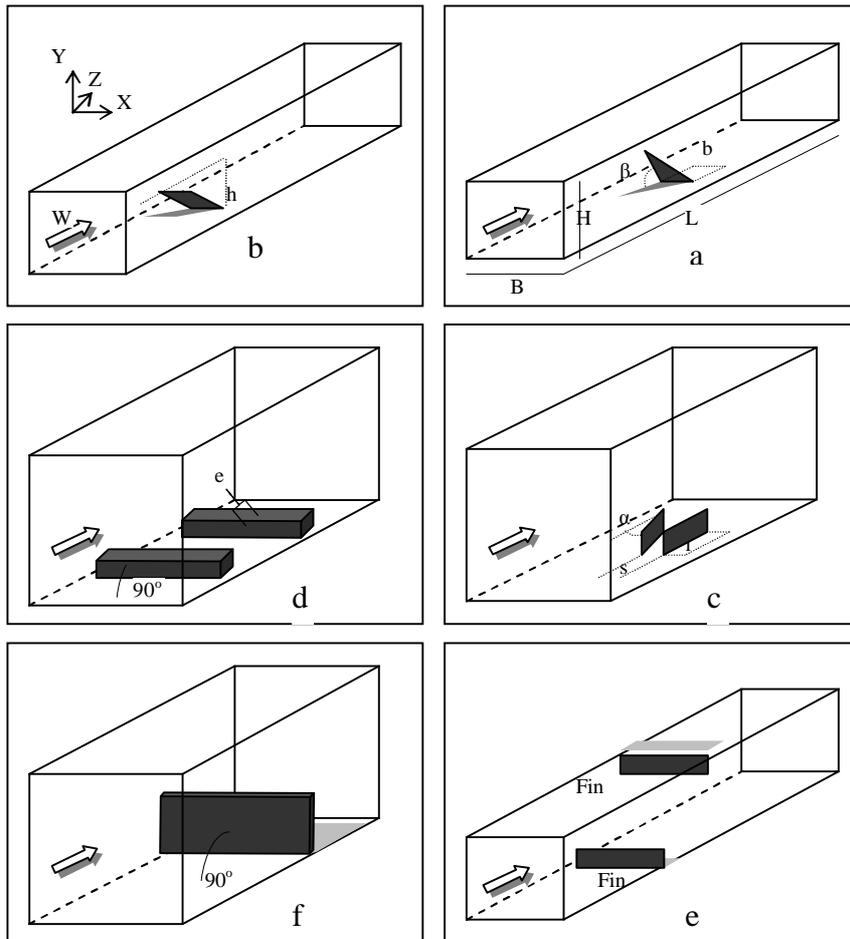Ducts for Several Types of Turbulators

Fig.(1) Some types of Vortex Generators (VGs) (the figures not to scale): a)
Delta wing, b) Rectangular wing, c) Winglet, d) Rib, e) Fin, and f) Fence.
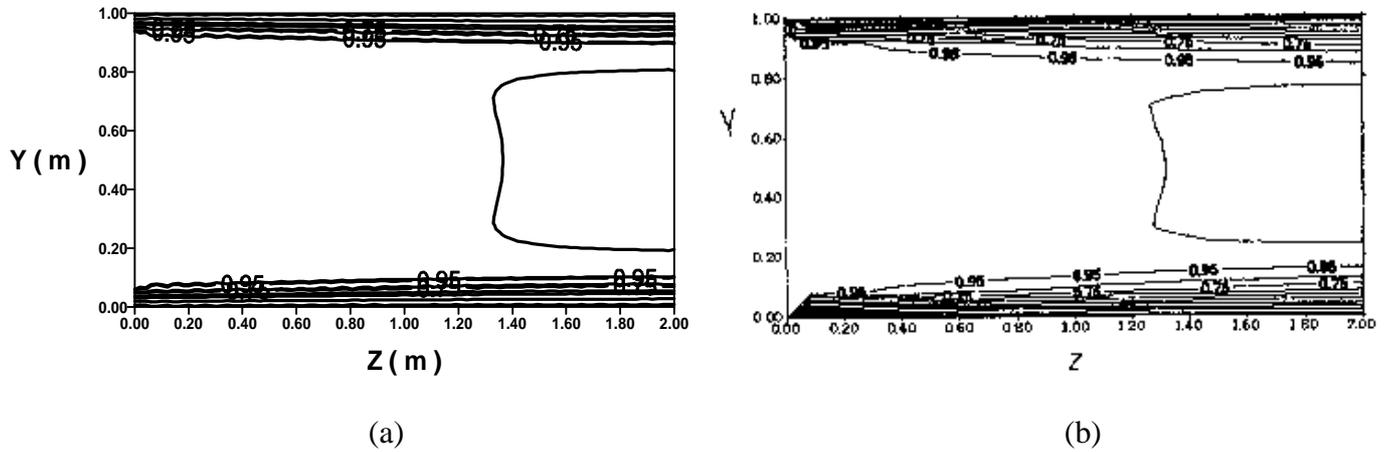
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(a)   (b)

Fig.(2) Variation in (w/w_{in}) at mid plane and Re=500 (a) Present result (b) Result
of [14].

(a)

(b)
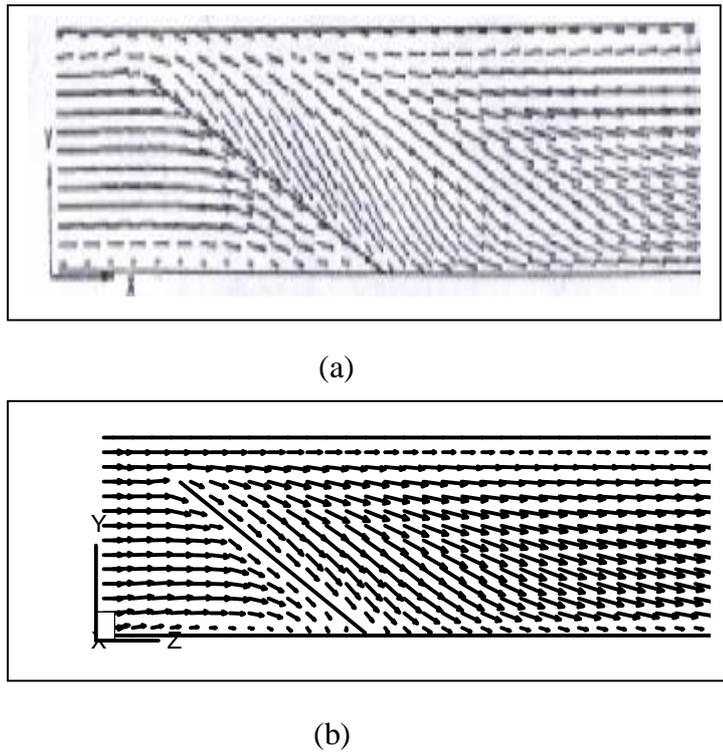
Fig.(3) Longitudinal velocity vectors at mid plane and Re=500 with σ =0.7 ,
Br=0.375, δ=1, γ=2, β=2° , x(or z in present result) = 0.0 - 0.84 m (a) Present
result (b) Result of [15].

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(a)

(b)

(c)

(d)
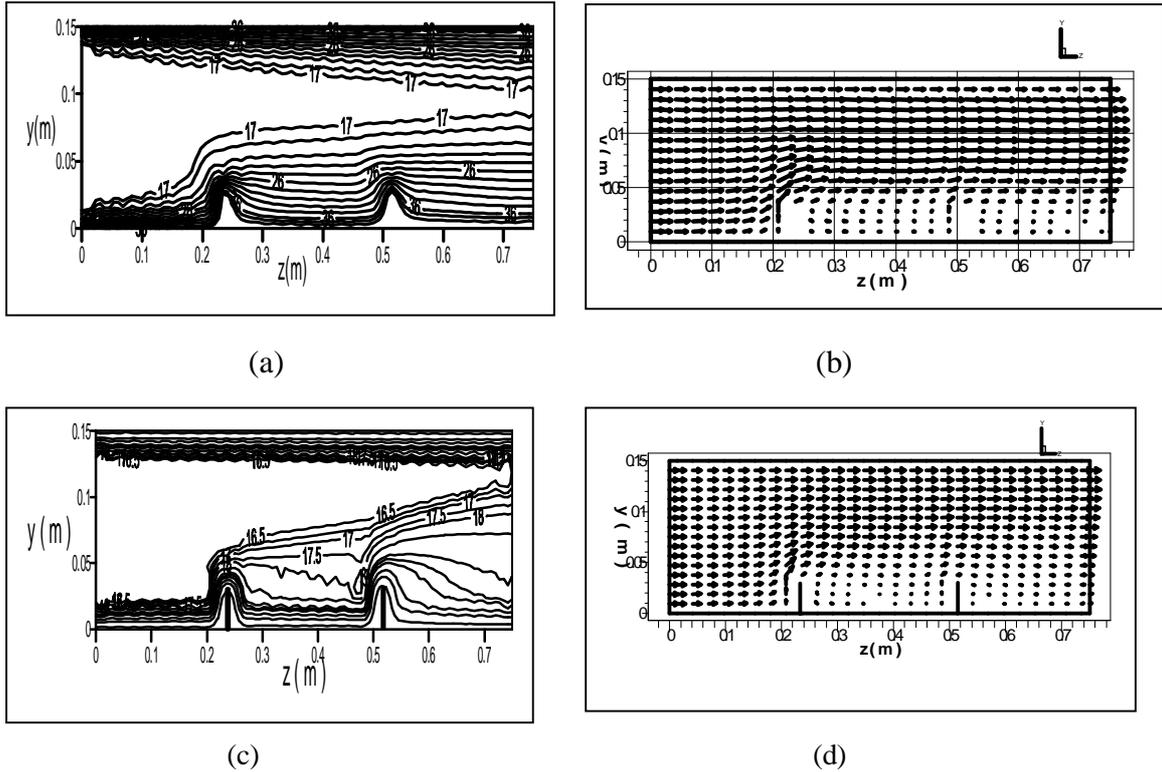
Fig.(4) Variation in isothermal contour and flow field at mid plane for laminar and turbulent flows At Re=1538 : (a) Isothermal contour T_{in}=16 C^o & T_w=40 C^o , (b) Velocity vector. At Re=135846 : (c) Isothermal contour T_{in}=16 C^o & T_w=40 C^o,and (d) Velocity vector.

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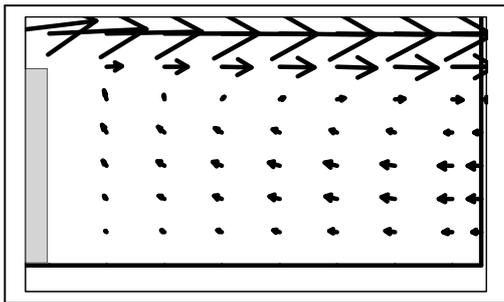
(a)
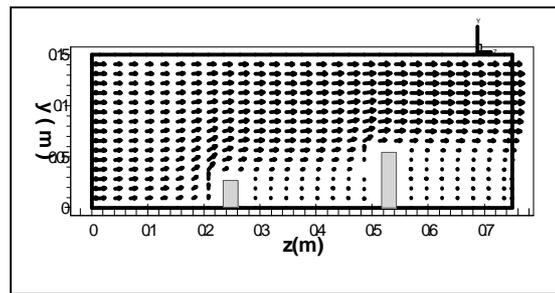
(b)
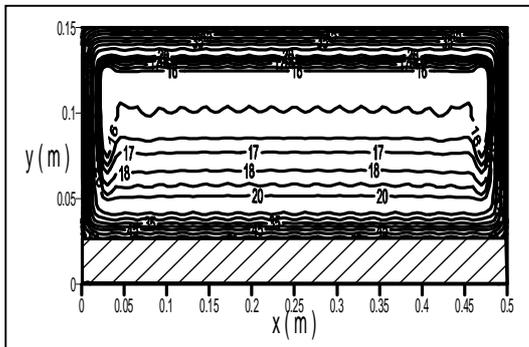
(c)
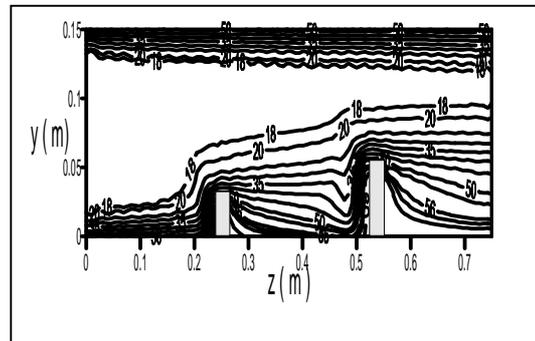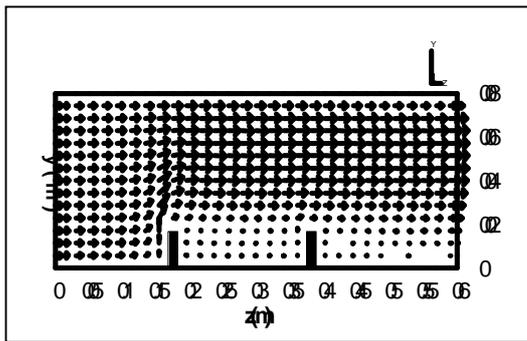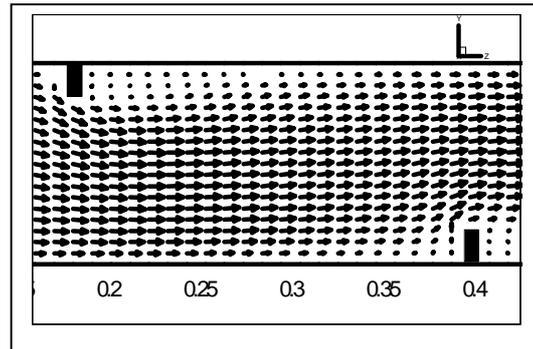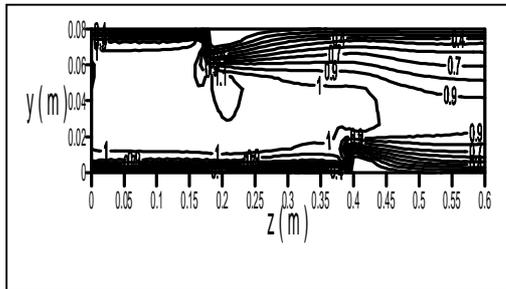
(d)

Fig.(5) Velocity vectors and temperature contours at Re=1538 : (a) Close view , (b)
Velocity vector at mid plane , (c) Temperature contours at cross section (z=0.23)m
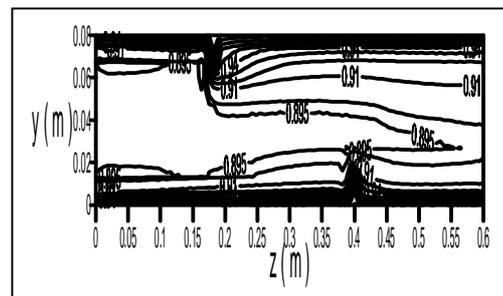and (d) Temperature contours at mid plane.

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(a)   (b)

(c)   (d)

Fig.(6) Velocity vectors and temperature contours for : (a) Staggered ribs (z=0.18
m & z=0.4 m) at x=66 mm for laminar flow, (b) Two ribs (z=0.19 m & z=0.39 m)
for laminar flow, (c) (w/w$_{in}$) at mid plane for turbulent flow , and (d) (T/T$_{wall}$) at
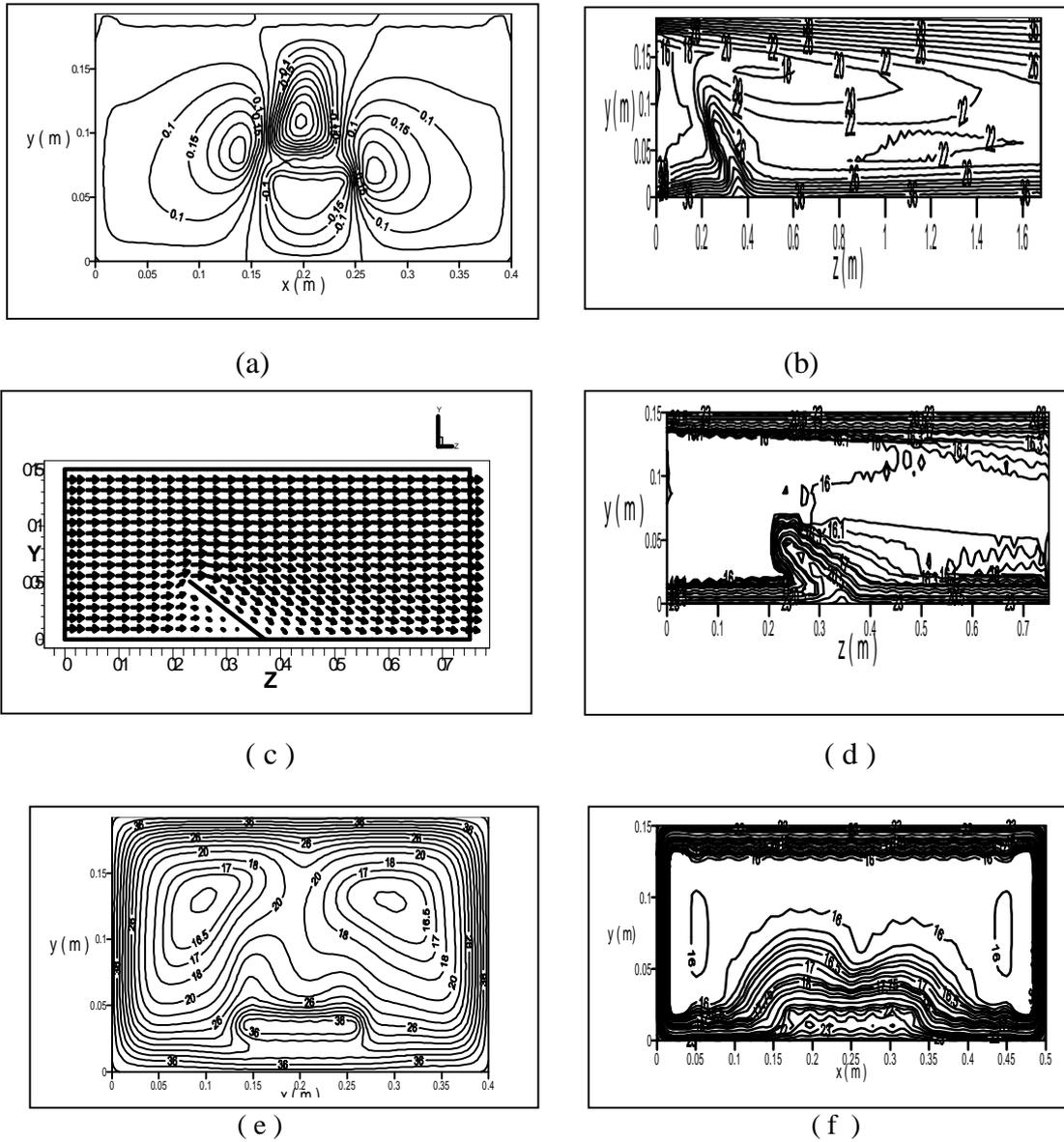mid plane for turbulent flow .

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(a)

(b)

(c)

(d)

(e)

(f)

Fig.(7) Flow and temperature distirbution for wing-type VG :
(a) (v/w_{in}) at z=0.24 m for (0.4x0.2x1.68) m^3 duct with (26x15x60) grid size in (x-y) plane for laminar flow,(b) T at x=0.16 m in (y-z) plane for laminar flow,
(c) w at mid (y-z) plane for (0.5x0.15x0.75) m^3 duct with (21x17x29) grid size for turbulent flow, (d) T at mid (y-z) plane for turbulent flow, (e) T at z=0.33 m while ($T_{wall}=40C^o$ & $T_{in}=16C^o$) in (x-y) plane for laminar flow, and (f) T at z=0.31 m with wing properties : σ =0.7 , Br=0.5 , δ=3.7 , γ=3.3 , β=19.3^o (wing tip at z=0.23 m and wing base at z=0.37 m) while ($T_{wall}=25C^o$ & $T_{in}=16C^o$) in (x-y) plane for turbulent flow.

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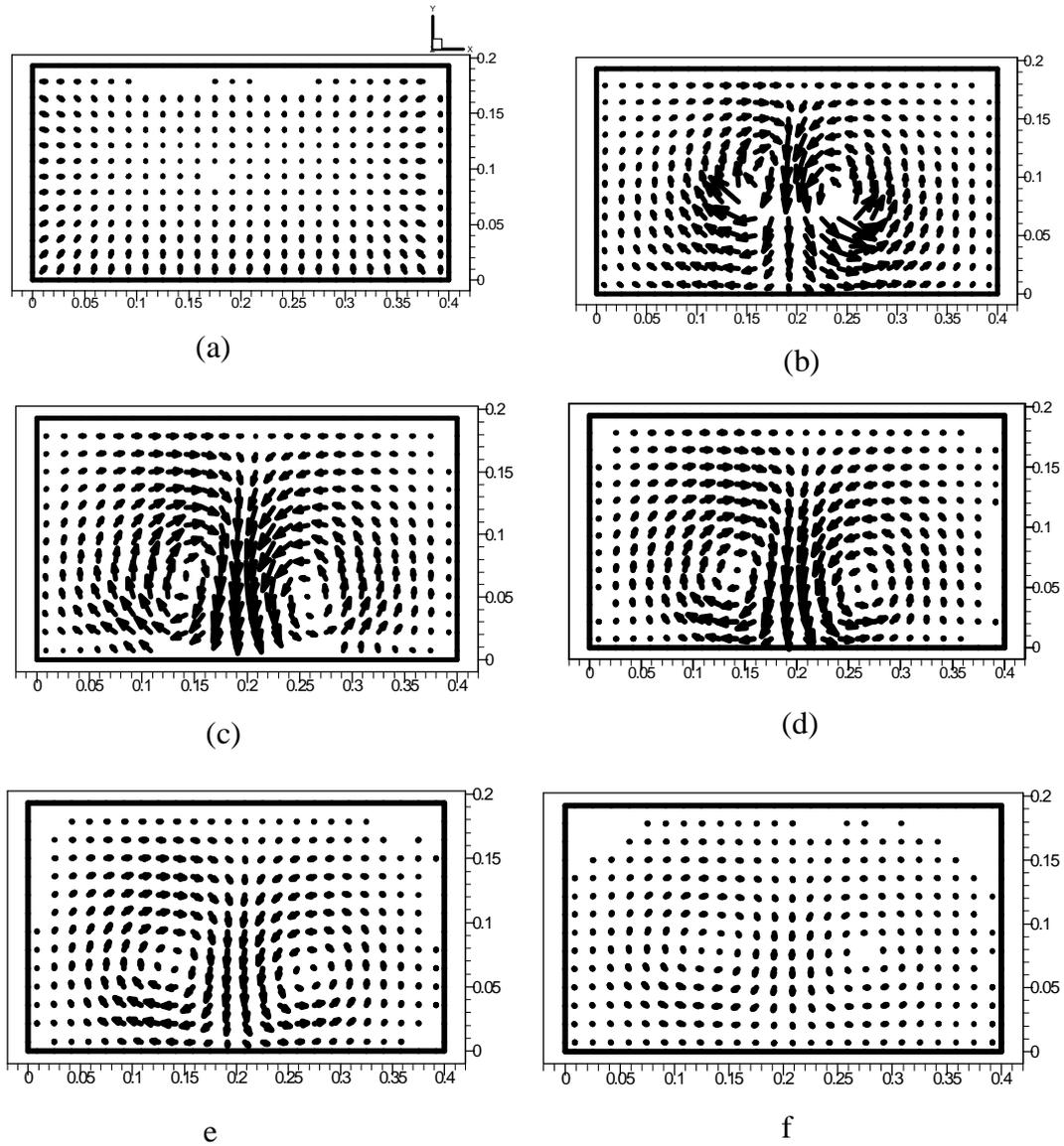Ducts for Several Types of Turbulators

(a)

(b)

(c)

(d)

e

f

Fig.(8) The development of the cross flow for wing-type
VG in (x-y) plane for laminar flow and wing dimensions (
h=0.156 m, l=0.316 m, b=0.15 m) while (wing tip at z=0.1
m and wing base at z=0.42 m) at : (a) z=0.04 m , (b)
z=0.24 m , (c) z=0.39 m , (d) z=0.53 m , (e) z=0.82 m , and
(f) z=1.68 m.

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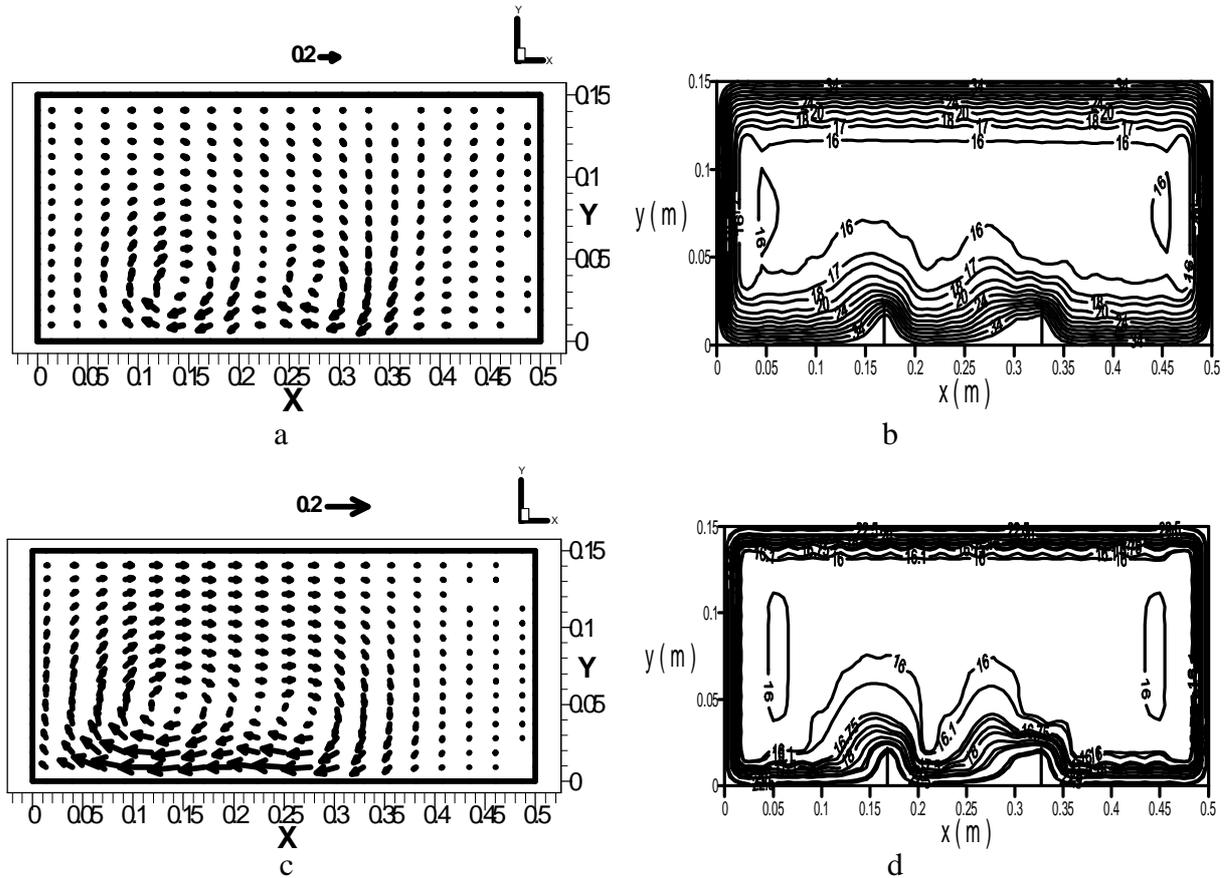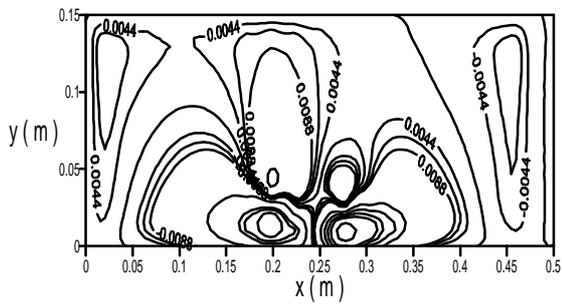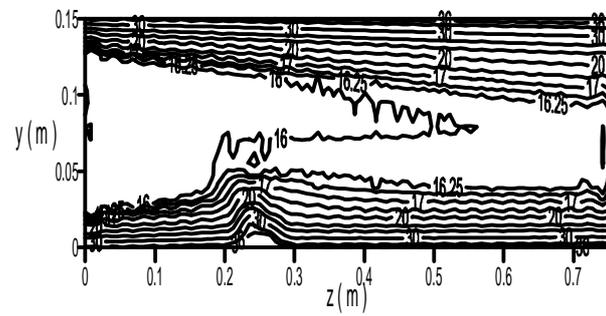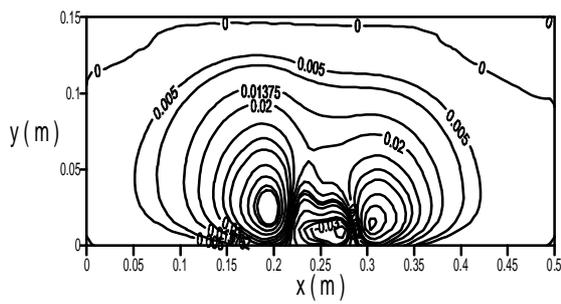Ducts for Several Types of Turbulators

Fig.(9) Velocity vectors and temperature contours for duct flow with winglet pair
in (x-y) plane: (a) Velocity vectors for laminar flow, (b) Temperature contours
where (T_{wall}=40C^o & T_{in}=16C^o) for laminar flow, (c) Velocity vectors for turbulent
flow , and (d) Temperature contours where (T_{wall}=25C^o & T_{in}=16C^o) for turbulent
flow.

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                                                          Temperature Fields Over Smooth and Rough
                                                          Ducts for Several Types of Turbulators
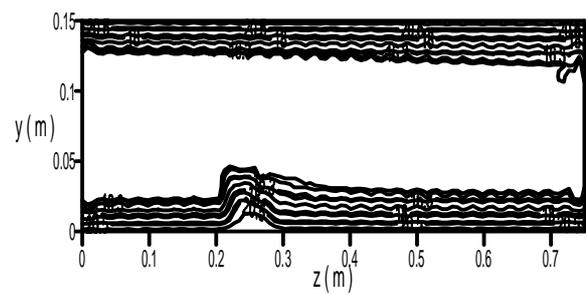
a

b

c

d

Fig.(10) Velocities and temperatures contours for duct flow with rectangular VG (represented in figure (1-b):
 (a) u / w_{in} in (x-y) plane for laminar flow, (b) T in (z-y) plane for laminar flow , (c) v / w_{in} in (x-y) plane
for turbulent flow , and (d) T in (z-y) plane for turbulent flow.

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