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Effect of Employing Vortex Generator on Curve Diffuser Performance

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Abstract: A diffuser is commonly applied in fluid-flow engineering applications with its simplest form of expanding area in the flow direction. A curve diffuser is one of its kinds often associated with secondary flow separation, thus improvement via installing passive flow control devices such as a vortex generator is to explore. The present work aims to numerically investigate the potential of four (4) types of vortex generators, i.e. triangle, rectangle, tapered, wishbone to improve the 90° curve diffuser performance. The results suggest that using vortex generators on a curve diffuser can improve performance. Triangle vortex generator provides the most optimum pressure recovery and flow uniformity of respectively 0.250 and 2.14. This promises improvement of approximately 31.3% and 25.4% relative to the benchmark case, without vortex generator.

Keywords: Curve diffuser, vortex generators, flow separation, pressure recovery, flow uniformity index

1. Introduction

A diffuser is a common engineering device which has the simplest design of an expanding area in the flow direction. The main and basic function of a diffuser is to reduce the velocity of the flow. A wind tunnel is one of the many installations that incorporates a diffuser [1]. A typical closed-circuit wind tunnel would normally incorporate a wide-angle diffuser before the nozzle in order to transform the geometry from a smaller to a larger area [2]. An additional diffuser is also installed behind the working section to recover static pressure from the kinetic energy to increase the efficiency of the power source. Similarly, higher propulsion efficiency can be achieved as a result of pressure recovery obtained by installing a diffuser at the inlet of an aircraft engine. The use of diffusers to increase the handling stability of racing cars is also well established. Unfortunately, the desired performance of a diffuser is often compromised by detrimental flow phenomena induced by the very nature of its geometry.

Bernoulli's principle implies that an increasing area along the path of an incompressible flow, as in a diffuser, causes the velocity to decrease $\left(\frac{\partial u}{\partial x} < 0\right)$ and the pressure to increase $\left(\frac{\partial p}{\partial x} > 0\right)$. Under a strong adverse pressure gradient, the boundary layer on the diffuser wall is likely to separate because the flow cannot sustain the momentum required to maintain a stable boundary layer [3-4]. Ultimately, flow detachment occurs because the fluid particles at the near-wall region experience a greater retarding shearing force than the pressure force pushing it. Flow separation is undesirable in many fluid systems as it would increase the pressure drag, decrease the core flow area, reduce the handling stability, and enhance the structural vibration.

A curve diffuser is regularly companion with secondary flow separation that calls for improvement [5-7]. Despite enormous literature on diffusers are available, much less attention has been given to improve performance of curve

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diffuser by means of applying passive flow control devices. Vortex generator is one of its kinds that has already been proven to provide significant improvement of fluid flow in many engineering applications such as aircraft wings and car bumpers [4-9]. A specific configuration and arrangement of the vortex generator is used to produce delayed flow separation, which would reduce the drag force [10, 11]. In this study, the potential of 4 types of vortex generator (rectangle, triangle, tapered, wishbone) to improve performance of a sharp 90º curve diffuser is numerically investigated. The most optimum configuration of vortex generator to resolve flow separation and improve pressure recovery is proposed.

Nomenclature:	
ρ	Air density (kg/m^3)
σ_{out}	Flow uniformity index
Cp	Pressure recovery coefficient
N	Number of measurement points
P_{in}	Average static pressure at inlet (Pa)
P_{out}	Average static pressure at outlet (Pa)
V_i	Local air velocity at outlet (m/s)
V_{in}	Mean air velocity at inlet (m/s)
V_{out}	Mean air velocity at outlet (m/s)
VG	Vortex generator

2. Methodology

This study involves the designing of 90° curve diffuser and 4 types of vortex generator models using Solidworks 2018 software. The model will be used in Ansys FLUENT 19.2 to simulate the data and obtain the result when employing vortex generator on curve diffuser performance.

2.1 Modeling and Meshing

The 90° curve diffuser design was based on the previous study by Nordin et al. [12]. To analyze the design in Ansys, only path flow of the fluid was designed in Solidwork as shown in Fig. 1. Basic dimensions applied are shown in Table 1. In this study, 4 types of vortex generators which are rectangle, triangle, tapered and wishbone were considered. The model and configuration of each vortex generator is shown in Fig. 2. Table 2 presents the dimension of each VG design.

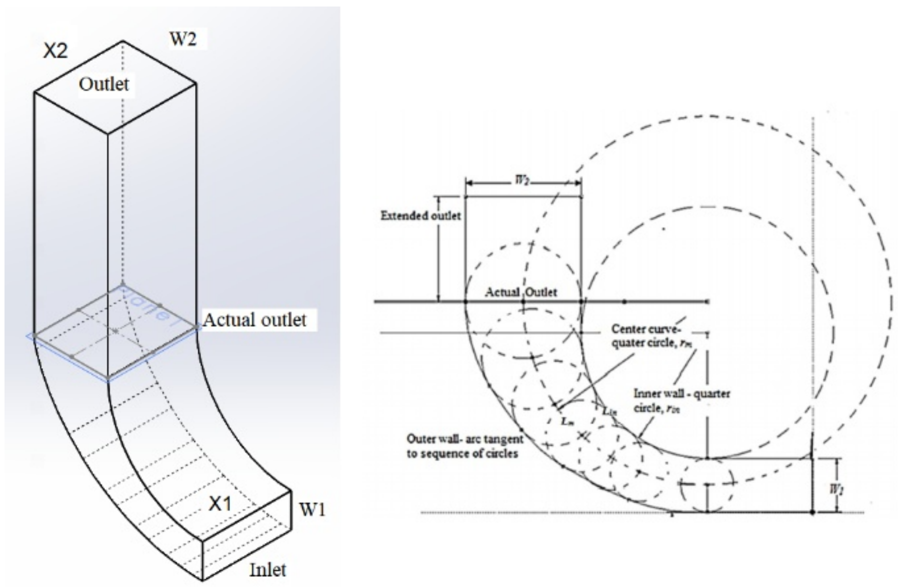
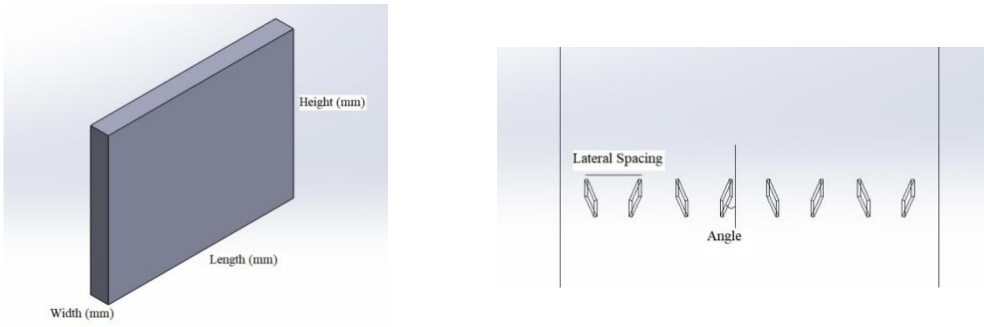


Fig. 1 - 90° curve diffuser model

Table 1 - Basic dimension of curve diffuser

Angle (°)	W_1 (mm)	X_1 (mm)	W_2 (mm)	X_2 (mm)	r_{in} (mm)	L_{in} (mm)	r_m (mm)	L_m (mm)
90	50	130	108	130	120	199.5	175	245.1



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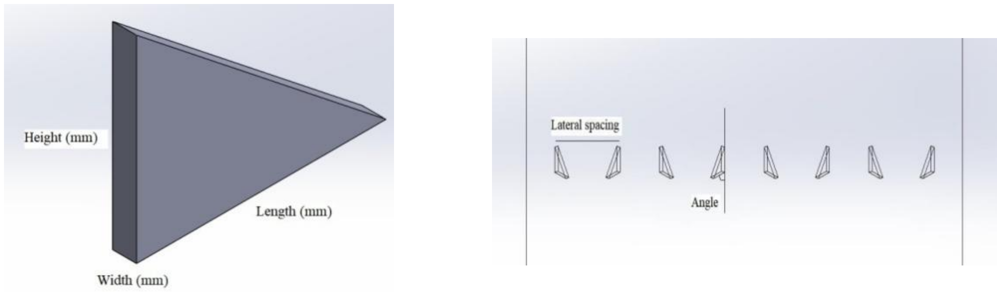

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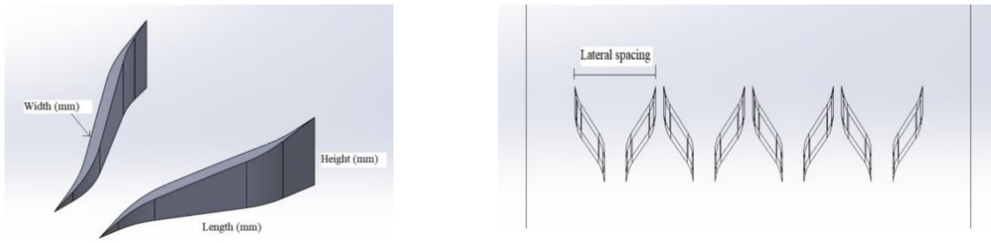

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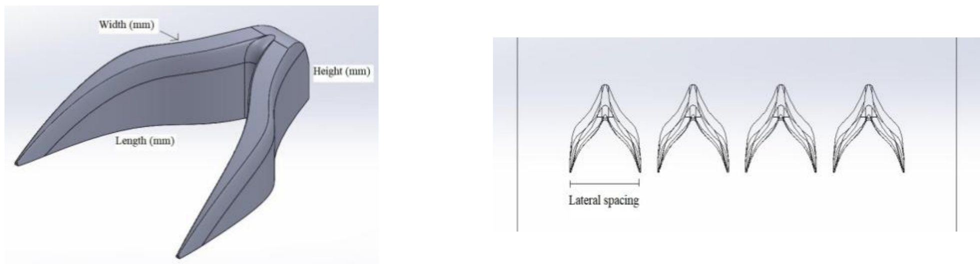


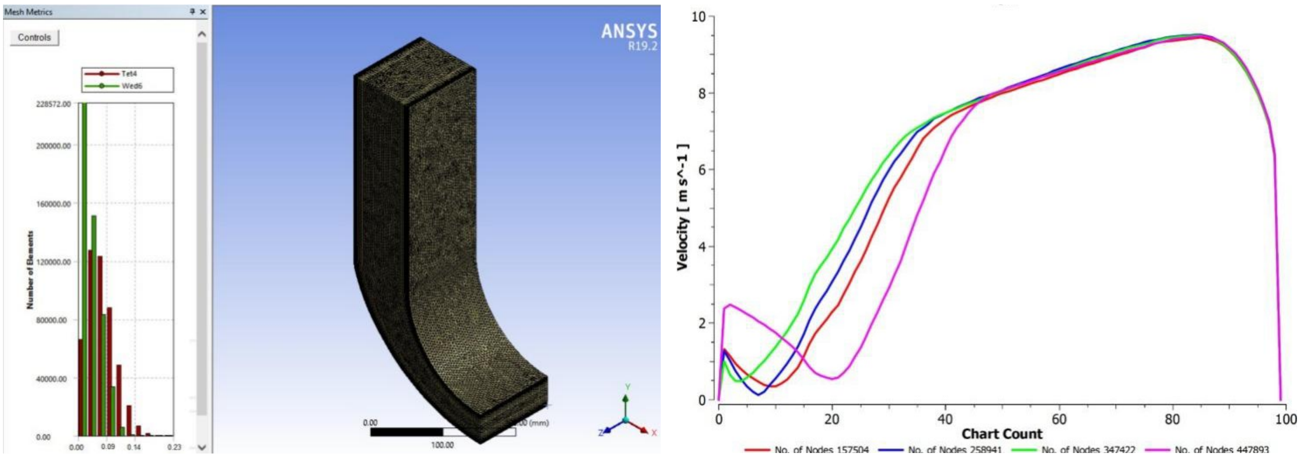
(d)

Fig. 2 - Types and configurations of vortex generator (a) rectangle; (b) triangle; (c) tapered; (d) wishbone

Table 2 - Main parameters of vortex generator

Vortex Generator Type	Height (mm)	Length (mm)	Width (mm)	Lateral spacing (mm)	Angle (°)
Rectangular	8.23	16.46	1	20.58	18
Triangle	8.23	16.46	1	20.58	18
Tapered	8.23	34.29	1.2	23.78	-
Wishbone	8.23	41.15	2.39	11.23	-

As shown in Fig. 3(a), hybrid mesh to consist of hexahedral and tetrahedral elements was generated to provide acceptable quality of skewness less than 0.3 [10]. Enhanced wall treatment of $y+\approx 1.0$ was applied to allow an optimum number of nodes obtained particularly close to the inner wall region to capture presences of flow separation. Failure to observe this essential flow phenomenon may disrupt the results. Grid independence test (GIT) was conducted, as shown in Fig. 3(b) to verify the most optimum mesh to represent the case.



(a) (b)

Fig. 3 - (a) hybrid mesh with enhanced wall treatment of $y+\approx 1.0$; (b) grid independence test result

2.2 Solver Setting

As depicted in Table 3, three types of boundary operating conditions were imposed. The inlet velocity, V_{in} was varied in the range 12.92 m/s corresponding to the Re_{in} = 5.786 x 10^4 until 39.66 m/s corresponding to the Re_{in} = 1.775 x 10^5. The inlet turbulent intensity, I_{in}= 3.5% - 4.1 % was estimated for fully developed turbulent flow. At the outlet boundary, the pressure was set at atmospheric pressure (0 gage pressure). At the solid wall, the velocity was zero due to the no-slip condition.

Table 4 lists the details of the solver setting applied. The governing equations were independently solved using a double-precision pressure-based solver with a robust pressure-velocity coupling algorithm, SIMPLE been applied. Second order scheme was employed for the discretization of the pressure and momentum equations, while first order scheme for the turbulent kinetic energy and dissipation rate equations. Standard k- ε (SKE) turbulence model equipped with enhanced near-wall treatments was applied for the simulation as it has been proven to be successful in simulating similar cases based on previous works [3, 5, 8, 12-17].

Table 3 - Boundary conditions

Inlet:	
Type of boundary	Velocity-inlet
Velocity magnitude, V_{in} (m/s)	12.92 (Re_{in} = 5.786 x 10^4)
	14.25 (Re_{in} = 6.382 x 10^4)
	22.94 (Re_{in} = 1.027 x 10^5)
	31.21 (Re_{in} = 1.397 x 10^5)
	39.66 (Re_{in} = 1.775 x 10^5)
Turbulent intensity, I_{in} (%)	4.1
	4.0
	3.8
	3.6
	3.5
Hydraulic diameter, D_h (mm)	72
Outlet:	
Type of boundary	Pressure-outlet
Pressure (Pa)	0 gauge pressure
Wall:	
Type of boundary	Smooth wall
Shear condition	No-slip
Working fluid properties:	

Working fluid	Air
Temperature (ºC)	30
Density, ρ (kg/m^3)	1.164
Dynamic viscosity, μ (kg/m.s)	1.872 x 10^{-5}

Table 4- Solver details

Solver Scheme	SIMPLE
Gradient	Least Square Cell Based
Pressure	Second Order
Momentum	Second Order Upwind
Turbulent Kinetic Energy	First Order Upwind
Turbulent Dissipation Rate	First Order Upwind
Turbulence models	Standard k-ε (SKE) model
Near wall treatment	Enhanced wall treatment (EWT)

Pressure recovery coefficient (*Cp*) and flow uniformity index (σ_{out}) are the parameters used to assess the curve diffuser performance [2, 3, 12]:

$$Cp = \frac{2(P_{out} - P_{in})}{\rho {V_{in}}^2} \tag{1}$$

$$\sigma_{out} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i - V_{out})^2} \tag{2}$$

The C_p indicates how much kinetic energy is successfully converted to pressure energy. The main problem in achieving high pressure recovery is flow separation, which results in dissipation of energy and non-uniform flow distribution [14-17]. The σ_{out} is used to measure the dispersion of local velocity from the mean velocity. It strongly depends on the distribution of the core flow and the presence of secondary flow. The flow is considered uniform with the presence of secondary flow of less than 10% [17-19].

3. Results and Discussion

Effects of employing different types of vortex generator on curve diffuser performance are assessed. Ultimately, the most optimum configuration is proposed.

3.1 Numerical Validation

Previous experimental work by Shariff *et al.* [14] was referred to validate the present simulation. As shown in Fig. 4, the present simulation model resembles well the experimental case with an average deviation percentage of approximately 0.72%.

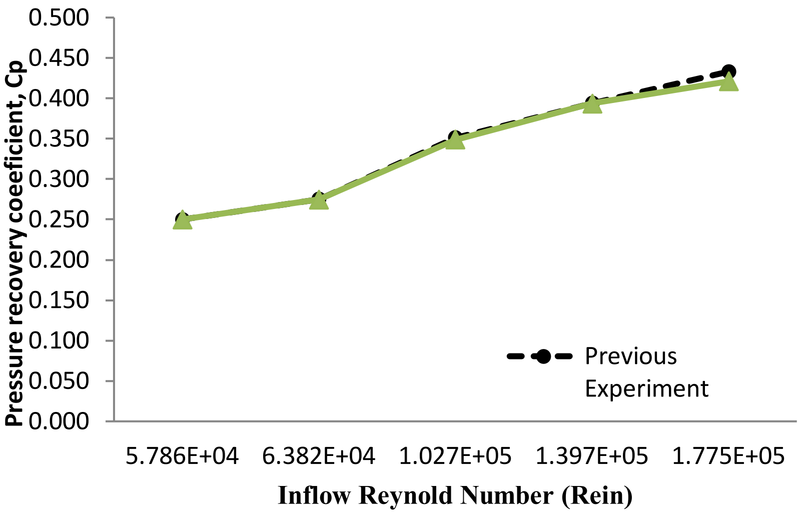
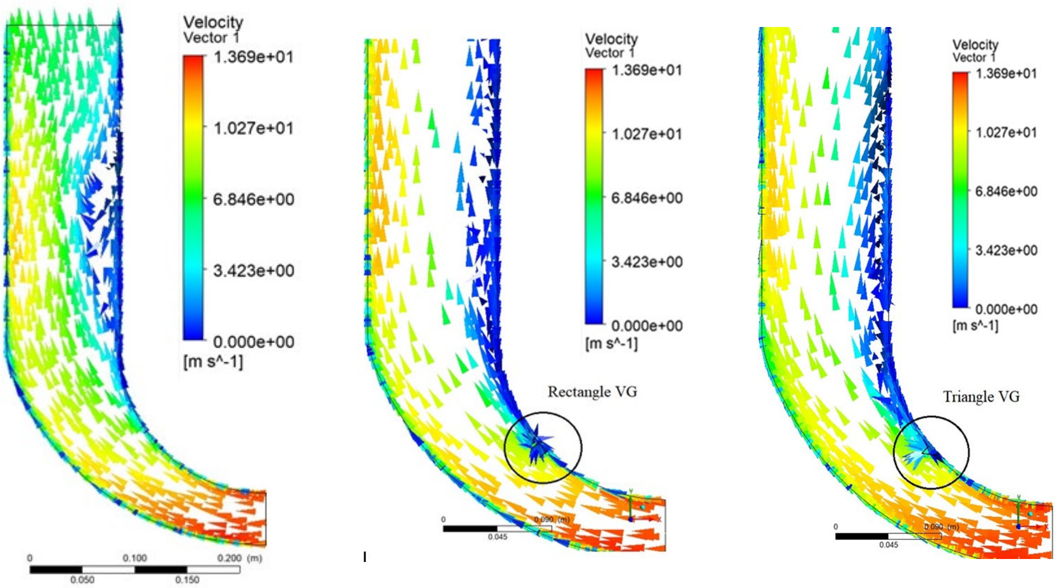


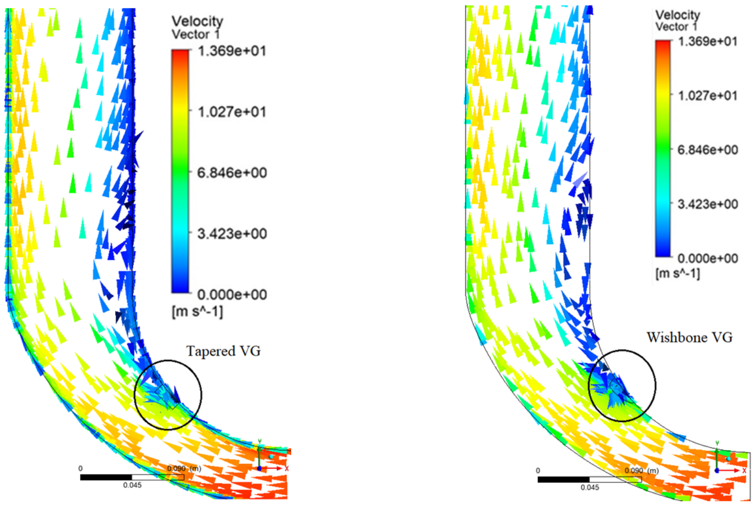
Fig. 4 - Numerical validation

3.2 Effect of Employing Vortex Generators on Flow Characteristics

Effects of employing VGs (rectangle, triangle, tapered and wishbone) relative to a benchmark case and without VG on flow characteristics were observed as in Fig. 5. There is substantial back-flow to form separation occurred in the diffuser without VG. The installation of VGs is seen to reduce back-flow and secondary flow separation. These VGs function to disturb the flow of air flowing on the inner-wall (convex region), producing a vortex of air between the high and low energy flows [8]. This attracts a flow of high energy air from the free flow down into the boundary layer, increasing the energy of the boundary layer. High energy air attaches to the inner-wall much more effectively and thus improves the flow attached. The triangle VG is seen to assist the flow well to produce minimal back-flow separation, ultimately leads to the best flow uniformity of 2.14, as depicted in Table 5. This promises 25.4% of improvement relative to the benchmark case, without VG.



(a) (b) (c)



(d) (e)

Fig. 5 - Flow characteristics of curve diffuser (a) without VG; (b) with rectangle VG; (c) with triangle VG; (d) with tapered VG; (e) with wishbone VG

Table 5 - Flow uniformity (σ_{out}) of curve diffuser with different vortex generators

Vortex Generator Type	Flow Uniformity Index, σ_{out}	Percentage of Improvement (%)
Without VG	2.87	-
Rectangle	2.26	21.3
Triangle	2.14	25.4
Tapered	2.61	9.1
Wishbone	2.39	16.7

3.3 Effect of Employing Vortex Generators on Pressure Recovery

Effects of employing VGs (rectangle, triangle, tapered and wishbone) relative to a benchmark case and without VG on pressure recovery are presented in Table 6. It is shown that the triangle VG produces the highest recovery of 0.25 corresponding to improvement of 31.3% relative to the benchmark case without VG. The triangle VG can minimize considerable losses due to form drag that often associates with flow separation. It was also observed that the vortex generators should be positioned exactly in the transition region of the boundary layer. However, the situation is complicated because of fact that the transition region depends on the flow conditions and the angle of attack. Therefore, future work shall be conducted to investigate the optimal mounting position of VGs.

Table 6 - Pressure recovery (C_p) of curve diffuser with different vortex generators

Vortex Generator Type	Recovery Pressure, C_p	Percentage of Improvement (%)
Without VG	0.190	-
Rectangle	0.243	27.6
Triangle	0.250	31.3
Tapered	0.205	7.6
Wishbone	0.230	20.7

4. Conclusion

In conclusion, the effects of employing vortex generators on curve diffuser performance have successfully been investigated. Results show that there is a potential performance of applying vortex generators on curve diffuser. Triangle vortex generator provides the most optimum pressure recovery and flow uniformity of respectively 0.250 and 2.14. This promises an improvement of approximately 31.3% and 25.4% relative to the benchmark case, without vortex generator. Future work should be conducted to investigate further the optimal mounting position of vortex generators as it really affects the overall performance of diffuser.

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