# A PARAMETRIC STUDY OF PASSIVE FLOW CONTROL DEVICES FOR 90° CURVED DIFFUSER

## MUHAMMAD ZAHID FIRDAUS BIN SHARIFF

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> Faculty of Mechanical and Manufacturing Engineering Universiti Tun Hussein Onn Malaysia

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#### ABSTRACT

The 90° curved diffuser has been widely utilised in various applications. The sharp curved angle and diffusing have simultaneously tackled the problem of space restrictions in some applications. However, due to the nature of its geometry, the curved diffuser's performance is compromised and disrupted. The potential of the flow treatment device, vortex generator (VG), to improve the performance of curved diffusers in terms of pressure recovery,  $C_p$  and flow uniformity,  $\sigma_{out}$  was experimentally and numerically investigated in this research. Experiments have been done to obtain data in terms of  $C_p$  and  $\sigma_{out}$  for bare curved diffuser and curved diffuser with triangle vorter generator attached. Three (3) types of vortex generators (triangle, rectangle, tapered-fin) with varying geometrical and operating parameters (height, spacing, distance, length, angle, inlet Reynolds Number) were considered. It had been demonstrated that the triangle VG offered the most promising improvement of  $C_p$  and  $\sigma_{out}$  at 43.1% and 9.7%, respectively. Height (2.75d and 3.85d), Spacing (5.5h), Inlet Reynolds Number (5. 786  $\times$  10<sup>4</sup>), Length (3.0h), Distance (6.0h) and Angle (18°) have been recommended as the optimal configuration of geometrical and operating parameters of the VG. The onset flow separation was discovered to have varied outcomes. However, the velocity vector distribution at the diffuser outlet showed that the flow was considerably more distorted; the flow deficit region observed at the diffuser inner wall had more core flow present when compared to the curved diffuser without VG installed.



#### ABSTRAK

Peresap melengkung 90° telah digunakan secara meluas dalam banyak aplikasi. Sudut melengkung tajam dan meresap terbukti secara serentak menangani masalah berkaitan dengan sekatan ruang dalam sesetengah aplikasi. Walaubagaimanapun, disebabkan sifat geometrinya, prestasi peresap melengkung terjejas dan terganggu. Potensi peranti rawatan aliran, penjana pusaran (VG) untuk meningkatkan prestasi peresap melengkung dari segi pemulihan tekanan,  $C_p$  dan keseragaman aliran,  $\sigma_{out}$  telah dikaji secara eksperimen dan numerik dalam penyelidikan ini. Eksperimen telah dilakukan untuk mendapatkan data dari segi  $C_p$  dan  $\sigma_{out}$  untuk penyebar melengkung kosong dan peresap melengkung dengan penjana vorter segitiga dipasang Kajian ini mengambilkira tiga (3) jenis penjana pusaran (segi tiga, segi empat tepat, sirip tirus) dengan parameter geometri dan operasi yang berbeza-beza (tinggi, jarak, jarak, panjang, sudut, Nombor Reynolds masuk). VG segi tiga terbukti paling berpotensi meningkatkan  $C_p$  dan  $\sigma_{out}$  masing-masing pada kadar 43.1% dan 9.7%. Ketinggian (2.75d dan 3.85d), Jarak (5.5h), Nombor Reynolds Masuk (5.786  $\times$  10<sup>4</sup>), Panjang (3.0h), Jarak (6.0h) dan Sudut (18°) disyorkan sebagai konfigurasi optimum bagi parameter geometri dan operasi VG. Didapati bahawa hasil pengasingan aliran permulaan adalah berbeza-beza. Namun, taburan vektor halaju di salur keluar peresap menunjukkan bahawa aliran itu jauh lebih herot; kawasan defisit aliran yang diperhatikan pada dinding dalam peresap mempunyai lebih banyak aliran teras hadir berbanding dengan peresap melengkung tanpa dipasang VG.



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## LIST OF SYMBOLS AND ABBREVIATIONS

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The following list gives the meaning of abbreviations used in this thesis unless otherwise defined in the text and appendices:

L <sub>in</sub>	-	Inner wall length
W	-	Width
$C_p$	-	Pressure recovery coefficient
$\sigma_{out}$	-	Flow uniformity index
Re <sub>in</sub>	-	Inlet Reynolds number
Vout	-	Outlet velocity
X	-	Length
D	-	Duct inlet diameter
D <sub>h</sub>	-	Hydraulic diameter (m)
Ν	-	Number of measurement points
$p_{dyn}$	-	Dynamic pressure (Pa)
p <sub>in</sub>	-	Average static pressure at the inlet (Pa)
<i>p</i> <sub>out</sub>	15	Average static pressure at the outlet (Pa)
TDERY	<u> </u>	Operating temperature (°C)
U	-	Mean velocity (ms <sup>-1</sup> )
V <sub>i</sub>	-	Local outlet air velocity (ms <sup>-1</sup> )
V <sub>i max</sub>	-	Maximum local outlet air velocity $(ms^{-1})$
V <sub>in</sub>	-	Mean inlet air velocity (ms <sup>-1</sup> )
AR	-	Area ratio
AS	-	Aspect ratio
HVAC	-	Heating, ventilation and conditioning
2-D	-	Two dimensional
3-D	-	Three dimensional
VG	-	Vortex generator
SVG	-	Submerged vortex generator

KVG	-	Karman vortex generator
CFD	-	Computational Fluid Dynamics
AOA	-	Area of attack
PIV	-	Particle image velocimetry
FLT	-	First layer thickness
MMS	-	Mesh maximum size
k-e	-	k-epsilon turbulence model
k-e realizable	-	k-epsilon realizable turbulence model
RNG k-e	-	Renormalization-group k-epsilon turbulence model
k-ω	-	k-omega turbulence model
RSM	-	Reynolds stress model
ACFD	-	Asymptotic Computational Fluid Dynamics

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#### **CHAPTER 1**

#### INTRODUCTION

#### **1.1 Background of Study**

Diffuser has been commonly used and applied in aero-engineering, oil and gas, automotive and other industries that benefit from their fluid mechanic capabilities. The employment of diffusers with turbines has been a growing interest for their ability to increase the axial hydrodynamic load on the powertrain of the turbine as it presents a challenge to start the turbine due to its frictional torque [1]. A diffuser's simplest and basic form is a straight duct with an expanding cross-section on its end. Diffusers are mainly used to decrease flow velocity while increasing pressure. Many diffusers have been designed with different parameters such as area ratio (AR), divergence angle, length-to-width ratio ( $L_{in}/W_1$ ) and aspect ratio (AS) to make improvements for its performance characteristics such as pressure recovery, flow uniformity and pressure losses.

Theoretically, expanding a straight duct would easily increase static pressure at the end of the expansion. Unfortunately, this is not the case due to the fact that there is a phenomenon known as flow separation and secondary flow, which its geometry would create. They would still occur even with the most optimum divergence angle of the diffuser [2]. Moreover, the curved diffuser would have a higher degree of secondary flow than the simple straight diffuser because of its complex geometry.

A diffuser performance is measured in terms of the pressure recovery coefficient( $C_p$ ) and outlet flow uniformity ( $\sigma_{out}$ ). A higher  $C_p$  value represents high-pressure recovery, while the lower value of  $\sigma_{out}$  represents high flow uniformity. Some



diffusers are curved and bent to meet their space availability and applications. A standard wind tunnel would incorporate the curved diffuser to save space. In order to increase its power source efficiency, diffusers were installed in wind tunnels to convert the kinetic energy of the stream to the potential energy of pressure [3]. Calautit et al. [4] utilised a highly porous safety mesh and guide vanes to prevent parts from entering the axial fan section and improve flow characteristics.

El-Askary and Nasr [5] considered using a bend-straight diffuser as the system required a diffuser with optimum divergence angles and the right spacer length, which can produce a uniformly distributed flow depending on the inflow Reynolds number. However, this would significantly increase the duct length, thus, increasing the energy wasted on skin friction. The utilisation of a curved diffuser would be a more viable option for this case, while it can simultaneously save space and reduce the effect of skin friction in the duct.

In order to further improve the performance of the turning diffuser in terms of pressure recovery and flow uniformity, obtaining the optimum design for the flow control device is essential. This would mean reducing flow separation to achieve maximum efficiency for the curved diffusers. Several past studies have reported that the diffuser's performance can be increased by introducing flow control devices such as vortex generators, mesh screens, honeycomb and guide vanes [6]. Therefore, this study investigated the flow control device's potential to improve the curved diffuser's recovery and flow performance.



#### **1.2 Problem Statement**

Most of the time, diffusers are associated with flow separation and secondary flow. Flow separation occurs due to the more significant deceleration of shearing force than the pressure force pushing it at its boundary layer [6]. Riffat et al. [2] reported that flow separation would still occur even if the diffuser were at its optimum divergence angle. Fox and Kline [7] developed a correlation for the curved diffuser up until 90° and proved that a higher angle of curvature affects the diffuser's performance significantly. Thus, the diffuser with a high angle of curvature, such as 90°, which is widely used in various applications, should have some flow control device installed to assist the flow and increase the diffuser's performance.

The implementation of flow control devices in curved diffusers has been previously studied. It was observed that some flow control devices had more significant effects on the curved diffuser's performance than others [6]. However, this does not imply that one flow control device is better. This research investigated one of the flow control devices, namely the vortex generator, while determining its most optimum geometrical parameters for the 90° curved diffuser.

#### 1.3 **Objectives**

The main objectives of this study were as follows:

- 1. To assess the potential of several shapes of vortex generators installed in a 90° curved diffuser through experiment and CFD simulations.
- 2. To evaluate the effects of varying the geometrical and operating parameters of vortex generators on the performance of 90° curved diffuser.
- 3. To propose the most optimum geometrical and operating parameters of vortex generator for the best performance of 90° curved diffuser. AKAAN TU

#### Scope of Study 1.4

The scopes of this study were as follows:

- 1. A 90° curved diffuser with a rectangular cross-section with AR=2.16,  $L_{in}/W_1 = 4.37, Re_{in} = 5.786 \times 10^4 - 1.775 \times 10^5$
- 2. Various vortex generator shapes were considered, including triangle, rectangle, and tapered-fin.
- 3. The parameters considered to test the performance for each vortex generator shape were the height, spacing, length, distance, angle and inlet Reynolds number.
- 4. The performance of curved diffusers was evaluated primarily in terms of pressure recovery coefficient,  $C_p$  and flow uniformity,  $\sigma_{out}$ .

5. ANSYS version 19.2 intensively simulated the performance of a curved diffuser by employing different vortex generator geometrical parameters.

#### **1.5** Significant of study

The curved diffuser has been widely employed in numerous engineering applications, from wind tunnels to smaller devices such as centrifugal compressors. As technology improves, the capacity to save power and boost machine efficiency is becoming a significant characteristic to consider in the design process. Although it has inferior flow properties than a straight diffuser, a curved diffuser is employed when space is restricted and complex arrangements are complex. The current research focused on further establishing the most optimum geometrical parameters for the vortex generators to improve the performance of a 90° curved diffuser. Past research for existing vortex generator designs was evaluated and analysed to offer an improved vortex generator design for better flow performance. For this purpose, both numerical and experimental approaches were employed. With minimal flow distortion at the output, a vortex generator design that has been improved will increase pressure recovery.



#### REFERENCES

- J. R. P. Vaz *et al.*, "Powertrain assessment of wind and hydrokinetic turbines with diffusers ☆," *Energy Conversion and Management*, vol. 195, no. May, pp. 1012–1021, 2019, doi: 10.1016/j.enconman.2019.05.050.
- S. B. Guohui, Riffat, "Measurement and Computational Fluid Dynamics Prediction of Diffuser Pressure-Loss Coefficient," *Applied Energy*, vol. 54, no. 2, pp. 181–195, 1996.
- [3] Azad et al., "Turbulent Flow in a Conical Diffuser : A Review," *Experimental Thermal and Fluid Science*, vol. 1777, no. 96, pp. 318–337, 1996.
- [4] J. Calautit, Kaiser, H. Nasarullah, B. Richard, and L. Fang, "Journal of Wind Engineering A validated design methodology for a closed-loop subsonic wind tunnel," *Jnl. Wind Eng. Ind. Aerodyn.*, vol. 125, pp. 180–194, 2014, doi: 10.1016/j.jweia.2013.12.010.
- [5] M. Nasr and E. Askary, "Author's personal copy Performance of a bend diffuser system: Experimental and numerical studies," An International Journal Computer and Fluids, vol 38, issue 1, 2009 doi: 10.1016/j.compfluid.2008.01.003.
- P. O. A. L. Chong, Davies, "A Parametric Study of Passive Flow Control for a Short, High Area Ratio 90 deg Curved," *Journal of Fluids Engineering*, vol. 130, November 2008, doi: 10.1115/1.2969447.
- [7] R. W. Fox and S. J. Kline, "Flow Regimes in Curved Subsonic Diffusers," *Journal of Basic Engineering*, page 303, 1962.
- [8] M. K. Gopaliya, P. Goel, S. Prashar, and A. Dutt, "Computers & Fluids CFD analysis of performance characteristics of S-shaped diffusers with combined horizontal and vertical offsets," *Comput. Fluids*, vol. 40, no. 1, pp. 280–290, 2011, doi: 10.1016/j.compfluid.2010.09.027.
- [9] E. M. Sparrow, J. P. Abraham, and W. J. Minkowycz, "International Journal of

Heat and Mass Transfer Flow separation in a diverging conical duct : Effect of Reynolds number and divergence angle," *Int. J. Heat Mass Transf.*, vol. 52, no. 13–14, pp. 3079–3083, 2009, doi: 10.1016/j.ijheatmasstransfer.2009.02.010.

- [10] R. T. K. Raj and M. P. D. Shankar, "Effect of Convergent Angle on Flow Characteristics of Y-Shaped Diffusers using CFD," *Applied Mechanics and Materials*, vol. 594, pp. 1909–1913, 2014, doi: 10.4028/www.scientific.net/AMM.592-594.1909.
- [11] Nguyen, "A flow analysis for a turning rapid diffuser using CFD." *The Fourth International Symposium on Computational Wind Engineering (CWE2006)*.
- [12] H. K. Versteeg, "Effect of geometry on the performance of intermingling nozzles," *Textile Research Journal*, Vols. 69(8) 545-551, 1999.
- [13] M. A. Aziz, I. A. M. Gad, E. S. F. A. Mohammed, and R. H. Mohammed, "Experimental and numerical study of influence of air ceiling diffusers on room air flow characteristics," *Energy Build.*, vol. 55, pp. 738–746, 2012, doi: 10.1016/j.enbuild.2012.09.027.
- [14] A. Zamiri, B. J. Lee, and J. T. Chung, "Numerical Evaluation of Transient Flow Characteristics in a Transonic Centrifugal Compressor with Vaned Diffuser," *Aerosp. Sci. Technol.*, no. August, 2017, doi: 10.1016/j.ast.2017.08.003.
- [15] P. Moonen, B. Blocken, S. Roels, and J. Carmeliet, "Numerical modeling of the flow conditions in a closed-circuit low-speed wind tunnel," *Journal of Wind Engineering*, vol. 94, pp. 699–723, 2006, doi: 10.1016/j.jweia.2006.02.001.
- [16] B. Majumdar, R. Mohan, S. N. Singh, and D. P. Agrawal, "Experimental Study of Flow In a High Aspect Ratio 90 Deg Curved Diffuser," *Journal of Fluids Engineering* vol. 1, pp. 3–9. March 1998,.
- [17] B. Djebedjian, "Numerical And Experimental Investigations Of Turbulent Flow In A 180° Curved Diffuser," *Proceedings of ASME FEDSM'01*, pp. 1–9, 2001.
- [18] Khong et al., "Effect of turning angle on performance of 2-D turning diffuser via Asymptotic Computational Fluid Dynamics Effect of turning angle on performance of 2-D turning diffuser via Asymptotic Computational Fluid Dynamics," *IOP Conference Series: Materials Science and Engineering*, 243 2017, doi: 10.1088/1757-899X/243/1/012013.
- [19] T. W. Xian *et al.*, "Asymptotic Computational Fluid Dynamic (ACFD) Study of Three-Dimensional Turning Diffuser Performance by Varying Angle of Turn," *International Journal of Integrated Engineering*, vol. 5, pp. 109–118,

2019.

- [20] R. Kumaraswamy, K. Natarajan, and R. B. Anand, "CFD Analysis of Flow and Performance Characteristics of a 90 ° curved Rectangular Diffuser : Effects of Aspect Ratio and Reynolds Number," *International Journal of Turbo and Jet Engines*, 38(4), p-p 451-463, 2019.
- [21] B. Djebedjian and M. Safwat, "Numerical Investigations Of Two-And Three-Dimensional," *ICFDP9: Ninth International Congress of Fluid Dynamics and Propulsion*-285 December, 2008.
- [22] M. Safwat and B. Djebedjian, "Performance Of Three-Dimensional," Mansoura Engineering Journal, vol 35, No 3 page 27, 2010.
- [23] N. Nordin, V. R. Raghavan, S. Othman, Z. Ambri, and A. Karim, "Numerical Investigation of Turning Diffuser Performance by Varying Geometric and Operating Parameters," *Applied Mechanics and Materials*, vols 229-231, pp 2086-2093, November, 2012, doi: 10.4028/www.scientific.net/AMM.229-231.2086.
- [24] N. Nordin, Z. Ambri, A. Karim, and S. Othman, "The Performance of Turning Diffusers at Various Inlet Conditions The Performance of Turning Diffusers at Various Inlet Conditions," *Applied Mechanics and Materials*, vols 465-466, pp 597-602, October 2015, 2014, doi: 10.4028/www.scientific.net/AMM.465-466.597.
- [25] N. Nordin, V. R. Raghavan, S. Othman, Z. Ambri, and A. Karim, "Compatibility Of 3-D Turning Diffusers By Means Of Varying Area Ratios And Outlet-Inlet Configurations," *ARPN Journal of Engineering and Applied Sciences*, vol. 7, no. 6, pp. 708–713, 2012.
- [26] N. Nordin, Z. Ambri, and A. Karim, "Flow Characteristics of 3-D Turning Diffuser," 1<sup>st</sup> Biannual Post Graduate Conference, May, 2014.
- [27] N. Nordin "Performance Investigation of Turning Diffusers at Various Geometrical and Operating Parameters" Ph.D. dissertation, Dept. Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, December, 2016, doi: 10.13140/RG.2.2.33037.13286.
- [28] A. R. Paul, P. Ranjan, R. R. Upadhyay, and A. Jain, "Passive Flow Control through Y-shaped Air Intake using Submerged Vortex Generators "Passive Flow Control through a Y-shaped Air Intake," *International Conference of Theoretical, Applied, Computational and Experimental Mechanics,* Vols. 148,

pp. 373-375, December, 2010.

- [29] A. R. Paul, S. Joshi, A. Jindal, S. P. Maurya, and A. Jain, "Experimental studies of active and passive flow control techniques applied in a twin air-intake," *Sci. World J.*, vol. 2013, 2013, doi: 10.1155/2013/523759.
- [30] B. A. Reichert, "Improving Curved Subsonic Diffuser Performance with Vortex Generators," *AIAA Journal*, vol. 34, no. 1, 1996.
- [31] Y. Zhang, H. Chen, and S. Fu, "A Karman-Vortex Generator for passive separation control in a conical diffuser †," *Science China Press and Springer-Verlag Berlin Heidelberg*, Vol. 55, pp. 828-836 May, 2012, doi: 10.1007/s11433-012-4708-7.
- [32] T. P. Chong, P. F. Joseph, and P. O. A. L. Davies, "A parametric study of passive flow control for a short, high area ratio 90 deg curved diffuser," *J. Fluids Eng. Trans. ASME*, vol. 130, no. 11, pp. 1111041–11110412, 2008, doi: 10.1115/1.2969447.
- [33] T. B. Gohil, "Effect of Submerged Vortex Generator in an S-duct Flow Effect of Submerged Vortex Generator in an S-duct Flow," 6<sup>th</sup> International and 43<sup>rd</sup> National Conference on Fluid Mechanics and Fluid Power, pp. 1–4, December 2016.
- [34] J. C. Lin, "Review Of Research On Low-Profile Vortex Generators To Control Boundary-Layer Separation", *Progress in Aerospace Sciences*, vol. 38. pp 389-420, 2002.
- [35] C. M. Velte, M. O. L. Hansen, and D. Cavar, "Flow analysis of vortex generators on wing sections by stereoscopic particle image velocimetry measurements," *Environmental Research Letters*, vol.3(1) 015006, doi: 10.1088/1748-9326/3/1/015006.
- [36] M. Corp and S. Louis, St, "A New Passive Boundary-Layer Control Device," J. Aircraft, vol. 14, no. 7, pp. 654–660, 1932.
- [37] W. H. Rae, A. Pope, and Barlow, "Low-Speed Wind Tunnel Testing" Wiley Interscience Publication. 1999.
- [38] A. V Johansson and B. Lindgren, "Design and Evaluation of a Low-Speed Wind-Tunnel with Expanding Corners," *Technical report. TRITA-MEK*. October, 2002.
- [39] A. Sahlin, A. V Johansson, A. Sahlin, and A. V Johansson, "Design of guide vanes for minimizing the pressure loss in sharp bends Design of guide vanes for

minimizing the pressure loss in sharp bends," AIP Physics of Fluids A: Fluid Dynamics, vol. 1934, no. 1991, 2011, doi: 10.1063/1.857923.

- [40] B. Lindgren, J. O, and A. V Johansson, "Measurement and calculation of guide vane performance in expanding bends for wind-tunnels," *Experiments in Fluids*, vol. 24, pp. 265-272, 1998.
- [41] L. Z. P. Eugene, N. Nordin, S. Othman, and V. R. Raghavan, "A CFD Preliminary Study : Pressure Losses and Flow Structure in Turning Diffuser by means of Installing Turning Baffles Abstract," 2<sup>nd</sup> International Conference on Mechanical Engineering (ICME 2011), June, 2011.
- [42] N. Hazirah, N. Seth, N. Nordin, and S. Othman, "Investigation of Flow Uniformity and Pressure Recovery in a Turning Diffuser by Means of Baffles," *Applied Mechanics and Materials*, Vols. 465-466 pp 526-530, 2014, doi: 10.4028/www.scientific.net/AMM.465-466.526.
- [43] N. N. Seth, N. Binti, M. Isa, S. B. Othman, and V. R. Raghavan, "The Effects Of Angle Of Attack On 3-Dimensional Turning Diffuser On Baffle Performances," *ARPN Journal of Engineering and Applied Sciences*, vol. 11, no. 3, pp. 1536–1541, 2016.
- [44] N. Hazirah, "Parametric Study On The Design Of Baffle For Threedimensional Turning Diffuser," Ph.D. dissertation, Dept. Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, November, 2016.
- [45] N. Nordin, Z. Ambri, A. Karim, S. Othman, and V. R. Raghavan, "Effect of Varying Inflow Reynolds Number on Pressure Recovery and Flow Uniformity of 3-D Turning Diffuser," 3<sup>rd</sup> International Conference and Exhibition on Sustainable Energy and Advanced Material, 2013.
- [46] N. Nordin, Z. Ambri, A. Karim, and S. Othman, "Design and Development of Low Subsonic Wind Tunnel for Turning Diffuser" Advanced Materials Research Vols. 614-615 pp 586-591, December 2012, doi: 10.4028/www.scientific.net/AMR.614-615.586.
- [47] N. M. C. Martins, N. J. G. Carriço, H. M. Ramos, and D. I. C. Covas, "Velocity-Distribution In Pressurized Pipe Flow Using CFD: Accuracy And Mesh Analysis," *Computers and Fluids*, vol. 105, pp. 218–230, 2014, doi: 10.1016/j.compfluid.2014.09.031.
- [48] Y. T. Khong *et al.*, "Effect of turning angle on performance of 2-D turning diffuser via Asymptotic Computational Fluid Dynamics," *IOP Conf. Ser.*

Mater. Sci. Eng., vol. 243, no. 1, 2017, doi: 10.1088/1757-899X/243/1/012013.

- [49] N. Nordin, "Performance Investigation Of Turning Diffusers At Various Geometrical and Operating Parameters" Ph.D. dissertation, Dept. Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 2016
- [50] Y. A. Cengel, Fluid Mechanics: Fundamental and Applications. 2014.
- [51] J. Kim, P. Moin, and R. Moser, "Turbulence statistics in fully developed channel flow at low Reynolds number," *Journal of Fluid Mechanics*, Vols. 177, pp 133-166, April 1987, doi: 10.1017/S0022112087000892.
- [52] Dwyer, "Series 160 Stainless Steel Pitot Tubes: Specifications- Installation and operating instructions," 1999.
- [53] S. B. Schut, E. H. Van Der Meer, J. F. Davidson, and R. B. Thorpe, "Gas solids flow in the diffuser of a circulating fluidised bed riser," *Powder Technology* 11, pp. 94–103, 2000.

## VITA

The author was born in October 14, 1996, in Seremban, Malaysia. He went to Maktab Rendah Sains MARA, Alor Gajah, Melaka, and Kuala Klawang, Negeri Sembilan, Malaysia for his secondary school. He pursued his degree at the Universiti Tun Hussein Onn Malaysia, and graduated with the B.Eng. (Hons) in Mechanical and Manufacturing Engineering in 2015. Upon graduation, he continued to pursue his Masters degree in Mechanical Engineering by research at Universiti Tun Hussein Onn Malaysia in 2019. While conducting his research, he also started to work at Sunlight Switchgear Sdn. Bhd. as a design engineer and later switched to work at Dyson Manufacturing Sdn. Bhd in 2022 until now where he works as a design engineer which involved in designing machines parts as well as its performance.

