DESIGN OF AN OPEN-CIRCUIT WIND TUNNEL WITH PIV (PARTICLE IMAGE VELOCIMETRY) SYSTEM

Rendi[1]
[1]Mechanical Engineering Study Program, Faculty of Engineering, Islamic University of Kalimantan Banjarmasin
Email: rendi.teknikmesin@gmail.com

This study aims to design a wind tunnel. The designed wind tunnel is an open-circuit wind tunnel with a Particle Image Velocimetry (PIV) system. The wind tunnel has dimensions of 8 meters in length, 1.75 meters in width, and 1.75 meters in height, with a maximum speed of 30 m/s. The design results show that the head loss in the test section is 1.28 meters, the head loss in the contraction chamber is 0.52 meters, and the head loss in the diffuser is 0.49 meters. Therefore, the total head loss is 2.29 meters, requiring a blower power of 11.94 Hp.

Keywords: Wind Tunnel, Open-Circuit System, Dimensions

1. INTRODUCTION

A wind tunnel, or terowongan angin, is an essential device in aerodynamic research, used to study the interaction between objects and airflow under controlled conditions. Since it was first introduced by the Wright Brothers in 1901 to test flight equipment, the wind tunnel has advanced significantly and become a vital tool in various applications, including the performance testing of wind turbines. Wind tunnels allow researchers to control air parameters such as speed, temperature, and pressure according to Bernoulli's principle, providing a deep understanding of the aerodynamic characteristics of the tested objects. [1,2]

In the context of wind turbine research, wind tunnels are used to test turbine performance by considering various factors such as rotational speed, torque, and aerodynamic characteristics. This is crucial for optimizing design and improving wind turbine efficiency, which in turn can contribute to the development of renewable energy technologies. [3,4]

The Islamic University of Kalimantan has a wind tunnel facility in the mechanical engineering department's laboratory, but its size and capabilities are still limited for student learning purposes. This limitation hinders more in-depth and comprehensive research in the field of wind energy utilization. To address this limitation, the development of a larger-scale wind tunnel equipped with advanced technology such as the PIV (Particle Image Velocimetry) system is necessary. The PIV system enables more detailed and accurate visualization and analysis of airflow, supporting more in-depth and applicable research. [5]

The aim of this research is to design an open-circuit wind tunnel equipped with a PIV system, which can be used for further research in the mechanical engineering department's laboratory at the Islamic University of Kalimantan. With a more advanced wind tunnel that meets research needs, it is expected to support the development of science and technology in the fields of aerodynamics and renewable energy, as well as serve as a reference for the creation of more modern and effective wind tunnels in the future.[6.7]

2. METHOD

2.1 Literature Review

The initial stage of this research involves conducting a comprehensive literature review on wind tunnel design, PIV systems, and their applications in aerodynamics research and renewable energy technology. A fundamental understanding of basic principles of aerodynamics and PIV technology is crucial for designing an effective and efficient wind tunnel.

2.2 Specifications

The geometric specifications include a length of 8 meters, width of 1.75 meters, and height of 1.75 meters. Utilizing a PIV System, integrating the PIV system for visualization and analysis of airflow velocity, and Main Components, designing the test section, contraction section, and diffuser to minimize head loss and maximize airflow velocity in the test section.

2.3 Head Loss Analysis

Conducting head loss analysis in the test section, contraction, and diffuser to ensure that the total head loss does not exceed the available blower capacity.

2.4 lower Selection and Power

Based on the head loss analysis, selecting a blower with adequate power to achieve the desired maximum velocity (30 m/s in this case).

3. RESULTS AND DISCUSSION

The wind tunnel design in this study, as shown in Figure 1, has dimensions of 8 meters in length, with width and height of 1.75 meters each. Generally, wind tunnel construction consists of three main parts: the Contraction

Chamber, Test Section, and diffuser, each serving the following functions:

1. Contraction Chamber: accelerates the airflow or fluid entering the wind tunnel. The contraction chamber has a larger cross-sectional area compared to the exit (test section) to increase flow velocity.
2. Test Section: where the model or object to be tested is placed. The dimensions of the test section can vary depending on the scale and purpose of the test.
3. Diffuser: used to decrease flow velocity and increase static pressure after the flow passes through the tested model. This allows the fluid to gradually slow down and return to velocities and pressures closer to free-stream conditions.

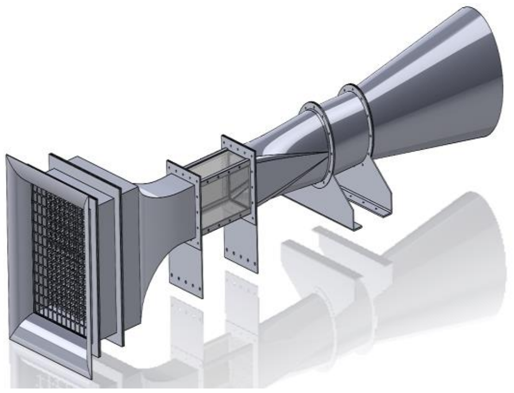


Figure 1. depicts the design of the wind tunnel

3.1 Test Section

The test section is one of the most important parts of the Wind Tunnel, which serves to place test objects or test specimens [1],[9]. The test section must have low turbulence levels. The specifications of the test section in this design are as follows:

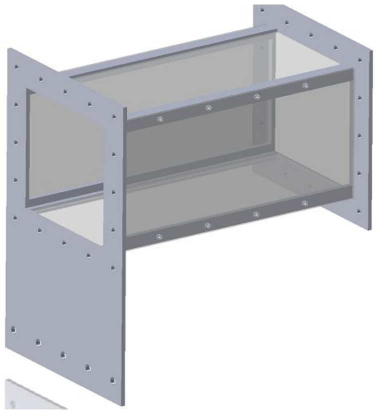


Figure 2. Test Section

Table 1. Test Section Specifications

Parameter	Magnitude	Unit
Length	100	cm
Width	50	cm
Height	50	cm
Maximum Velocity	30	m/s

Several commonly known factors that form the basis for wind tunnel planning are as follows:

Tr = Room temperature = 27°C = 300 K
G = Gravity = 10 m/s²
R = Gas constant = 29.72 kg·m / kg·K
Pr = Atmospheric air pressure = 1.013 × 10Pa
k = Perfect gas (adiabatic) = 1.4
μ = Viscocity = 1.56 x 10^{-5} kg/m.s
ρ = Air Density = 1.176 kg/m^3

The specific weight of air can be determined using the following equation:

$$\zeta = \rho \text{ x } g \quad (1)$$
$$= \frac{1.176 \text{ kg/m}^3}{9.81 \text{ m/s}^2}$$
$$= 11.54 \text{ N/m3}$$

The Reynolds number in the test section is

$$Re = \frac{\rho \text{ x v x } D_h}{\mu} \quad (2)$$
$$= \frac{1.176\frac{kg}{m^3} \text{ x } \frac{30m}{s} \text{ x } 0.5 \text{ m}}{1.86 \text{ x } 10^{-5}}$$
$$= 947580.6$$

To determine the type of flow, first find the Reynolds number (Re) over the test section length x (Rex), where x is calculated from the length of the test section.

$$Re_x = \frac{\rho \text{ x v x X}}{\mu} \quad (3)$$
$$= \frac{1.176\frac{kg}{m^3} \text{ x } 30\frac{m}{s} \text{ x 1 m}}{1.86 \text{ x } 10^{-5}}$$
$$= 1895161$$

The boundary layer thickness occurring on one side of the test section is determined when Rex is 1895161, which falls into the transitional flow category, hence it can be considered laminar flow.

$$\delta = \frac{4.91 \text{ x}}{Re_{x0.5}} \quad (4)$$
$$= 0.003567 \text{ m}$$

ISSN 2549-2888

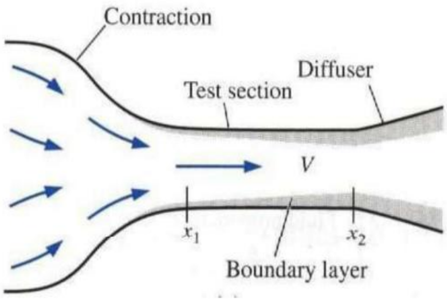


Figure 3. Boundary Layer Thickness Scheme in Wind Tunnel

Area of the test section after subtracting the boundary layer thickness:
Luas (A13) =

$$a-(2\,x\,\delta)x\,a-(2\,x\,\delta) \quad (5)$$

$$= 0.5\,m-(2\,x\,0.003567\,m)x\,0.5-(2\,x\,0.003567\,m)$$
$$= 0.2401\,m^2$$

Flow rate at the test section (Q), according to the law of continuity, is uniform throughout the wind tunnel system:

$$Q = A.V \quad (6)$$

= (0.2401 m^2) . (30 m/s)
= 7.26192 m^3/s

Mass flow rate at the test section also follows the law of continuity, so the mass flow rate across the entire wind tunnel system is the same:

$$\dot{m} = \rho\,x\,Q \quad (7)$$

$$= 1.176\frac{kg}{m^3}\,x\,7.26192\frac{m^3}{s}$$
$$= 8.540018\,kg/s$$

Pressure (P) inside the test section: Standard air pressure or external static air pressure (Po) (Torricelli's theory)
P_o = $101396.16\,Pa$
Dynamic pressure inside the test section (Pdy):

$$Pdy = ½.\,\rho\,.V2 \quad (8)$$

$$= \frac{1}{2}\,x\,1.176\frac{kg}{m^3}\,x\,30^2\,m/s$$
= 929.2 Pa

Static pressure inside the test section (Ps):

$$Ps = Po\,-\,Pdy \quad (9)$$

$$= 101866.92\,Pa$$

Speed of sound in the test section:

$$C^2 = k\,.g\,.R\,.T \quad (10)$$

$$= 1.4\,x\,9.81\frac{m}{s^2}\,x\,29.27\,kg.m\,kg.K\;\;x(\,27+273)$$
$$= 247.27\,m/s$$

Mach number at the test section:

$$M = \frac{v}{c} \quad (11)$$

$$= \frac{30\frac{m}{s}}{347.27\frac{m}{s}}$$
$$= 0.864$$

Since Mach number M < 1 at the test section, this wind tunnel operates in a subsonic flow regime.
Surface roughness of the channel, using acrylic material (= 0 mm), obtained from the Moody diagram table:

$$\frac{\varepsilon}{Dh} = \frac{0\,mm}{500\,mm} \quad (12)$$

= 0

Loss coefficient at the test section, with Revalue obtained as 947580.6 and surface roughness of 0, from the Moody diagram table:

$$K_{ts} = \lambda\,x\,\frac{L}{Dh} \quad (13)$$

$$= 0.014\,x\,1\,m\,x\,0.5\,m$$
$$= 0.028$$

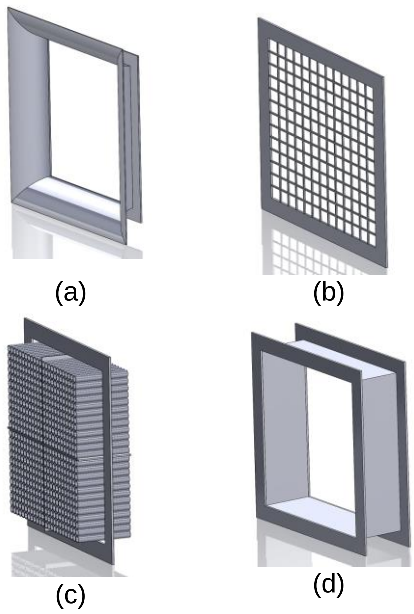
Loss calculation due to friction (Head) at the test section:

$$H_{ts} = K_{ts\,x}\,(\frac{v^2}{2g}) \quad (14)$$

$$= (0.028\,x\,302\,\frac{m}{s})\,x\,(2\,x\,9.81\,\frac{m}{s^2}\,)$$
$$= 1.28\,m$$

3.2 Contraction Chamber

The Contraction Chamber construction is divided into several parts, namely the belt mouth, inlet filter, setting chamber which contains honeycomb and diffuser. The parts of the Contraction Chamber are illustrated in Figure 4.



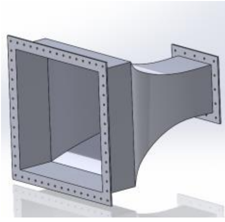

(e)

Figure 4. Componen Contraction Chamber (a) belt mouth, (b) inlet filter, (c) honeyoomb, (d) setting chamber dan (e) Diffuser-1

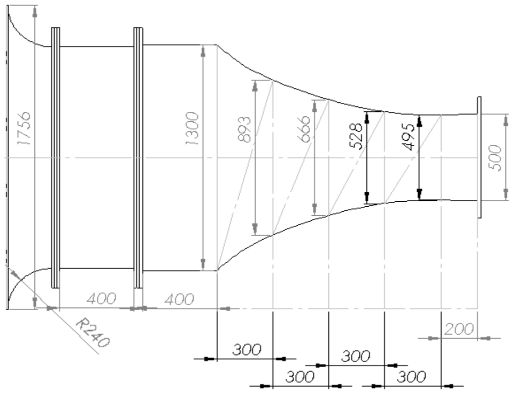


Figure 5. Contraction Chamber

To calculate the fluid flow velocity in the Contraction Chamber using the equation $A_1V_1 = A_2V_2$ = constant. To determine the type of flow, the Reynolds number (Re) is first calculated. Dynamic pressure is calculated using the equation $P_{dy}=\frac{1}{2}\,\rho\, V^2$, and static pressure is calculated using the equation $P_s = P_o - P_{dy}$. The calculation results are shown in the following

Table 3.1. Velocity and Dynamic Pressure in the Contraction Chamber.

Dh = (4*A)4L	A (m)	v (m/s)	P_{dy} (Pa)	P_s (Pa)
0.50	0.25	30.00	529.20	100866.96
0.50	0.25	30.00	529.20	100866.96
0.52	0.27	27.74	452.36	100943.80
0.66	0.44	17.22	174.31	101221.85
0.89	0.79	9.47	52.72	101343.44
1.30	1.69	4.44	11.58	101384.58
1.76	3.08	2.43	3.48	101392.68

Sound speed in the contraction chamber

$$C^2 = k\,.\,g\,.\,R\,.\,T \quad (12)$$
$$=(1.4)\ x\ (9.81\tfrac{m}{s^2})\ x\ (29.27\ kg.m/kg.K)\ x\ (27\ +273)$$
$$= 247.27\tfrac{m}{s}$$

The Mach number in the contraction chamber, using the average velocity (v) in the contraction chamber.

$$M = \frac{v}{c} \quad (13)$$
$$= \frac{17.33\frac{m}{s}}{347.27\frac{m}{s}}$$
$$= 0.049$$

Since Mach number M < 1 in the contraction chamber, this wind tunnel flows subsonically. Loss coefficient in the contraction chamber, Re value obtained from the notation as in the table, then the average Dh = 0.88 m, = 0.015.

$$K_{cc} = 0.32\ \lambda\ (\frac{L}{Dh}) \quad (14)$$
$$= \frac{(0.32)x\ (0.015)x\ (2.5\ m)}{(0.88)}$$
$$= 0.013636364$$

Calculation of friction loss (Head) in the contraction chamber

$$H_{cc} = \frac{K_{cc}\,(v_{1-}\,v_2)^2}{2g} \quad (15)$$
$$= \frac{(0.013636364)x\ (3o\ \frac{m}{s} - 2.43\ \frac{m}{s})}{2(9.81)}$$
$$= 0.52\ m$$

3.3 Diffuser

In this section, there are three parts: the first part of the diffuser, which is positioned close to the test section, is called diffuser-2. Next, the diffuser where the fluid exits is referred to as diffuser-3, and the diffuser housing the electric motor is known as the motor section, as shown in the following diagram.

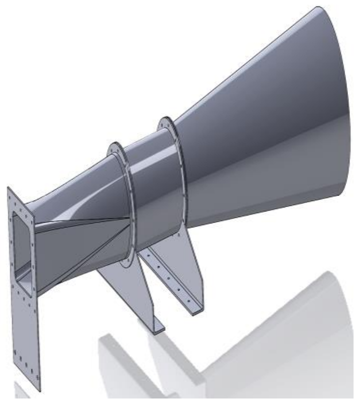


Figure 6. Diffuser

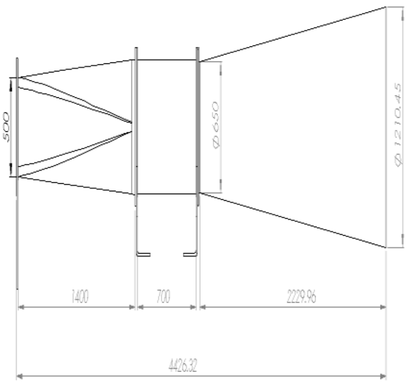


Figure 7. Diffuser

To calculate the fluid flow velocity in a diffuser using the equation $A_1V_1 = A_2V_2$ = constant, and to determine the type of flow, the Reynolds number (Re) is first calculated. The dynamic pressure is calculated using the equation Pdy = ½ρV^2, and the static pressure is calculated using the equation P_s = Po - P_{dy}. The calculation results are shown in the following Table 2.

Table 2. Velocity and dynamic pressure table in the diffuser

Dh = (4*A)4L	A (m)	v (m/s)	Pdy (Pa)	Ps (Pa)
0.50	0.25	30.00	529.20	100866.96
0.65	0.42	17.75	185.29	101210.87
0.65	0.42	17.75	185.29	101210.87
1.21	1.46	5.12	15.43	101380.73

Sound velocity in the contraction chamber

$C^2 = k\,.\,g\,.\,R\,.\,T$ (16)

$=1.4 \text{ x } 9.81 \frac{m}{s2} \text{ x } 29.27 \text{ kg.m/ kg.K x } (27 + 273)$

$= 247.27 \frac{m}{s}$

The Mach number in the contraction chamber, using the average velocity in the contraction chamber.

$M = \frac{v}{c}$ (17)

$= \frac{17.66\frac{m}{s}}{347.27\frac{m}{s}}$

$= 0.050$

Since Mach number M < 1 in the contraction chamber, the wind tunnel flows subsonically. The loss coefficient in the contraction chamber, with Re value obtained from the table notation, yields an average Dh = 0.75 m, = 0.015.

$K_{df} = 0.32\ \lambda\ \frac{L/Dh}{Dh}$ (18)

$=(0.32) \text{ x } (0.015) \text{ x } ((2.5 \text{ m})/(0.75))$

$= 0.016$

Friction loss calculation (Head loss) in the contraction chamber.

$H_{df} = \frac{Kcc\,(v_1 - v_2)2}{2g}$ (19)

$= \frac{(0.016)\text{x}\,(30\frac{m}{s} - 5.12\frac{m}{s})}{2(9.81)}$

$= 0.429 \text{ m}$

Total loss in the wind tunnel system Total loss due to friction (head loss)

$H_{Total} = H_{ts} + H_{cc} + H_{df}$ (20)

$= 1.28 + 0.52 + 0.49$

$= 2.29 \text{ m}$

Power lost due to friction within the wind tunnel is

$\dot{W}_{loss} = \frac{Q.\varsigma H_{Total}}{550}$ (21)

$= 7.26 \text{ x } 11.54 \text{ x} 2.29 / 550$

$= 191 \text{ W}$

3.4. Drive Motor

After obtaining the mass flow rate and kinetic energy in the test section, the required motor power can be determined, assuming motor efficiency is 90%.

$\dot{W}_{fan} = \text{m x } a_2 (\frac{v2}{2})$ (22)

$= \left(8.54\frac{kg}{s}\right) \text{x } (2) \text{x} \frac{(30s)2}{2}$

$= 7686 \text{ W}$

$\dot{W}_{elect} = \frac{W_{fan}}{90\%}$ (23)

$= 8540 \text{ W}$

Power required for wind tunnel operation at maximum airspeed of $30 \text{ m}/s$ is

wp $= \dot{W}_{loss} + \dot{W}_{elect}$ (24)

$= 191 \text{ W} + 8540 \text{ W}$

$= 8731 \text{ Watt} = 8.731 \text{ kW}$

$= 11.94 \text{ hp}$

4. CONCLUSION

The planned wind tunnel is an open-circuit type with a piv (particle image velocimetry) system for testing wind turbines. The maximum wind speed in the test section is 30 m/s. The dimensions of the test section are 50 cm x 50 cm with a length of 100 cm. The determination of the required motor size and power was conducted using analytical methods. The obtained length of the wind tunnel is 8 m with a height of 0.75 m. The head loss in the test section is 1.28 m, in the contraction chamber is 0.52 m, and in the diffuser is 0.49 m, resulting in a total head loss of 2.29 m. Therefore, a pump power of 11.94 units is required.

REFERENCES

[1]. Kusumohadi, C.S., Yoga, N.G. And Arrozi, H., 2015, November. Perancangan Awal Terowongan Angin Kecepatan Rendah Untuk Pengujian Otomotif. In Sens.

[2]. Siregar, A.M., 2016. Rancang Bangun Wind Tunnel Sederhana Untuk Alat Pendukung Studi Eksperimental. Mekanik: Jurnal Ilmiah Teknik Mesin, 2(2).

[3]. Agni, M., Kirom, M.R. And Bethaningtyas, H., 2015. Analisis Kinerja Terowongan Angin Subsonik Dengan Menggunakan

Contraction Cone Polinomial Orde 5. Eproceedings Of Engineering, 2(3).
[4]. Yuniarsih, N. And Rossbandrio, W., 2015. Pengembangan Terowongan Angin Kecepatan Rendah (Low Speed Wind Tunnel) Untuk Tujuan Edukatif Di Politeknik Negeri Batam. Jurnal Integrasi, 7(1), Pp.19-22.
[5]. Handayani, S.U., 2014. Pengembangan Dan Analisa Keseragaman Aliran Terowongan Angin Tipe Terbuka Sebagai Sarana Pengujian Aerodinamika. Prosiding PNES II 2014, Pp.A-309.
[6]. Rendi, R. And Herlina, F., 2019. Penambahan Lingkaran Pelindung Pada Turbin Air Rotor Savonius. INFO-TEKNIK, 20(2), Pp.237-254.
[7]. Stefphanie, C., Rustana, C.E. And Nasbey, H., 2014, October. Pengembangan Desain Terowongan Angin Sederhana. In Prosiding Seminar Nasional Fisika (E-Journal) (Vol. 3, Pp. 347-351).
[8]. Arifin, J., 2019. Desain Diffuser Turbin Air Arus Sungai Untuk Meningkatkan Laju Arus Sungai. Al Jazari: Jurnal Ilmiah Teknik Mesin, 4(2).
[9]. Hatradi, B., Irfansyah, M. And Puteri, P., 2021. Desain Underwater Rotor Untuk Memanfaatkan Laju Aliran Sungai Sebagai Pembangkit Listrik Tenaga Air. Jurnal Engine: Energi, Manufaktur, Dan Material, 5(2), Pp.77-82.
[10]. Hartanto, A.S., 2005. Perancangan Dan Pembuatan Mekanisme Pengukuran Gaya Angkat Dan Gaya Hambat Untuk Terowongan Angin (Doctoral Dissertation, Petra Christian University).
[11]. Fitroh, A.J., 2011. Analisis Losses Pipa Lurus Berdiameter 40 Cm Pada Terowongan Angin LAPAN. Jurnal Teknologi Dirgantara, 9(1).
[12]. Rahman, A., Farid, A. And Suriansyah, S., 2014. Pengaruh Penggunaan Spoiler Pada Model Kendaraan Sedan Terhadap Tekanan Hisap Dalam Terowongan Angin. PROTON, 6(1)