Experimental Study of Wind Flow in a Street Canyon between High-Rise Buildings Using PIV

Herlien D. Setio, Prasanti Widyasih Sarli*, Yongky Sanjaya & Doni Priambodo

Department of Civil Engineering, Faculty of Civil and Environmental Engineering,
Institut Teknologi Bandung, Jalan Ganesa No. 10, Bandung 40132, Indonesia
*E-mail: pw.sarli@itb.ac.id

Highlights:

- There was an increase from 7 to 44% in wind speed in between the high-rise buildings
- Wind flow experiences an interaction flow in all central areas, which translates into an increase in speed
- The change in distance between buildings changes the behavior of the flow in the cross area
- A change in the angle of attack of the wind does not influence the amplification factor
- The highest amplification occurs with a wind angle of attack of 0°

Abstract. In recent years there have been several occasions of failure of non-buildings such as billboard towers and pedestrian bridges around high-rise areas in urban Indonesia. Most cases did not occur during any particular high-speed wind gusts but rather during normal wind speed. This research aimed to show the increase in wind load for structures built between high-rise buildings. A simplified cluster of 4 symmetrical high-rise building was investigated. The study used a wind tunnel and a Particle Image Velocimetry (PIV) device in the experiment. Several angles of attack and also different distances between buildings were investigated to see the impact of these parameters on the wind flow between the buildings. Wind flow experiences an interaction flow in all central areas, which translates into an increase in speed. The change in distance between buildings changes the behavior of the flow in the cross area while a change in the angle of attack of the wind does not influence the amplification factor. The results show that there was an increase from 7 to 44% in wind speed due to the street canyons and that the highest amplification occurred with an angle of attack of 0°.

Keywords: *high-rise building; street canyon; PIV; wind flow; wind tunnel*.

1 Introduction

In recent years there have been several occasions of failures in non-buildings such as billboard towers and pedestrian bridges in high-rise areas in urban Indonesia. Most cases did not occur during particularly high-speed wind gusts, but rather during normal wind speed. To further develop the design code of these structures, it is important to understand the wind characteristics in street canyons between high-rise buildings.

Received October 28th, 2019, 1st Revision March 27th, 2020, 2nd Revision July 14th, 2020, Accepted for publication July 31st, 2020.
ISSN: 2337-5779,
DOI: 10.5614/j.eng.technol.sci.2020.52.5.3

A significant increase of wind speed inside street canyons has been observed by Stathopolous & Storms [1], Chang & Meroney [2] and Baskaran & Kashef [3], with an amplification factor of up to 1.4 reported at the passage centerline on the pedestrian level. The amplification factor is defined as the ratio of mean wind speed at a certain location between buildings (U) and the mean wind speed at the same location without the buildings being present (U_{reff}), so that this can be a direct indicator of the effect of buildings on wind speed. The amplification factor observed is typically attributed to the Venturi effect, meaning that the increase of wind speed is due to a decrease in the flow section. However, this has only been specifically shown at pedestrian level height. Blocken, *et al.* [4] have shown that the increase in flow rate is at most only 8% higher than the free-field flow rate at elevation height higher than the pedestrian level, indicating that the Venturi effect is rather weak. Further investigation of this is needed.

The study by Tsang, *et al.* [5] has shown that the maximum wind speed ratio at the pedestrian level increases with building height. This is due to a strong downwash effect, as taller buildings catch upper-level wind and direct it to the pedestrian level. Meanwhile, studies by To and Lam [6] on different two-building orientations, i.e. side by side, parallel and at an angle, showed that when wind flow is perpendicular to the row of buildings, the windiest condition occurs in the upstream corners due to flow channeling and suppressed horseshoe vortices.

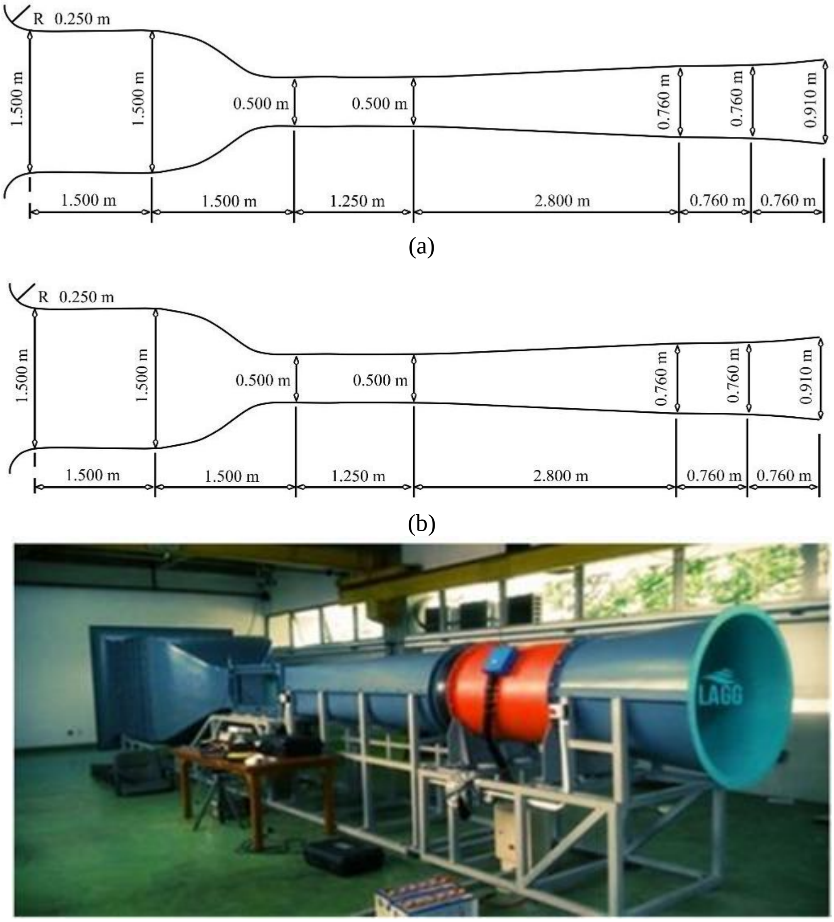
The study by Iqbal & Chan [7] proposed that a configuration with squared central space with the prevailing wind direction towards the windward open side face offers a better pedestrian level wind environment because this configuration contains airflow movements more effectively. However, the majority of past studies mainly focused on pedestrian level winds at 1.75 to 2 m above ground [2-5, 7-10], whereas many observed failures of pedestrian bridges and billboard towers occurred in vast city landscapes of developing countries, so there is a need to understand the behavior of wind at the height of a typical pedestrian bridge (5.1 to 6.5 m above the ground level [11]). Kuo, *et al.* [8] have shown through experimental results that pedestrian street-level wind can be categorized into three different flow regimes. Further investigation is required to determine whether this is extendable to higher levels.

This study considered the behavior of wind between four adjacent buildings at a height above pedestrian level. The mean wind speed at various points of the centerline was compared to discover the significance of different widths between passages and different angles of attack to clarify its impact.

2 Research Method

2.1 Experimental Setup

The experiments were conducted at the open-circuit Wind Tunnel Laboratory of BPPT-BBTA3 in Jakarta, Indonesia. The wind tunnel is a low-speed wind tunnel with a maximum wind speed of 45 m/s. It has a test section length of 1.25 m, with a rectangular cross-section of 0.5 m x 0.5 m at the inlet, which protrudes to 0.51 m x 0.51 m at the outlet (a schematic diagram of the wind tunnel can be seen in Figure 1(a) and (b) and an image of the wind tunnel can be seen in Figure 1(c).

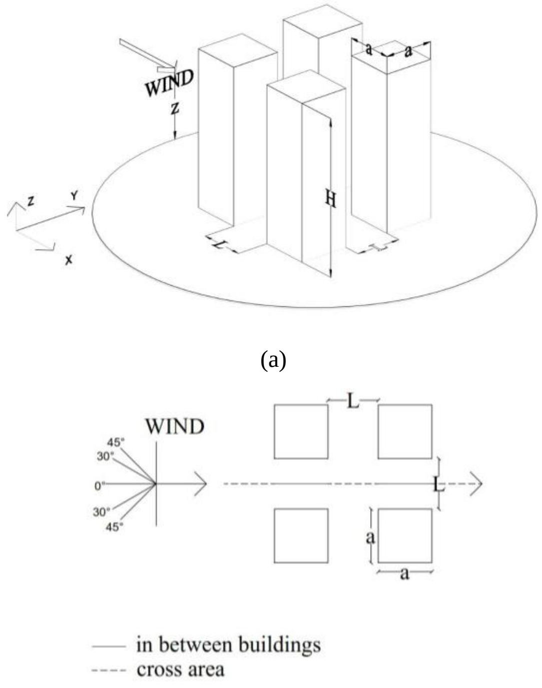


(a)

(b)

(c)

Figure 1 Schematic diagrams of the wind tunnel: (a) side view and (b) top view; and (c) photo of the wind tunnel used at the National Laboratory for Aerodynamics, Aeroelastics, and Aeroacoustic Technology.



(a)

(b)

Figure 2 (a) 3D view of a schematic of a simplified configuration of four high-rise buildings, and (b) as seen from above.

It must be noted that this experimental model does not perfectly represent a real urban setting and that the simplicity of the model is a limitation of this study. However, the objective of this study was to explore the effect of the distance between the buildings with fluid behavior; for this purpose the experimental model is considered sufficient. Additional models should be investigated in the future.

Table 1 Different parameters investigated in this study.

Parameters	Symbol	Value taken for investigation
Distance between buildings	L	30 m, 70 m
Height of buildings	H	100 m
Width of buildings	a	32 m
Angle of attack	α	0°, 30° and 45°
Wind speed	U_{reff}	4 m/s, 8 m/s, 13 m/s

Three different wind speeds were taken at 4 m/s, 8 m/s and 14 m/s. The angle of attack of the wind was taken at 0°, 30°, and 45°. Thus, 18 different cases were investigated in total. All results from the experiments were taken at a normalized value for each wind speed. A picture of the model for 0° inside the wind tunnel can be seen in Figure 3.

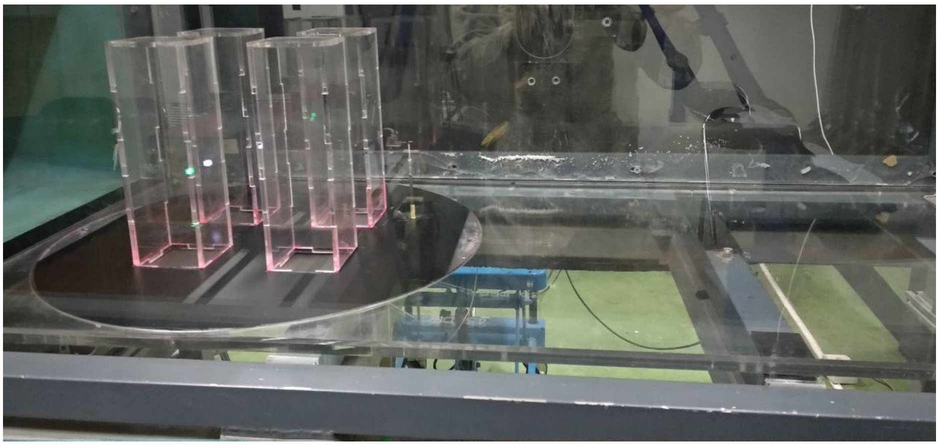


Figure 3 The model for a 0° angle inside the wind tunnel.

2.2 Particle Image Velocimeter (PIV)

Measurements were taken with a particle image velocimeter (PIV) device, which is an optical method of flow visualization that uses a laser to create a grid on the model to better investigate the flow of the fluid. PIV was used due to its non-intrusive nature, high spatial resolution, and directional sensitivity [9,10,14], all of which were in line with the objective of the study.

The main components of this PIV system consisted of a charge-coupled device camera, a high-performing laser which produces a traversing system, a particle generator, and a particle tracer in the form of a programmable timing unit. A short description of each of these components is given in Table 2.

Table 2 PIV components used in this study.

Components	Description
Laser system	Double-pulse Nd:YAG Litron
Traversing system	2D
Aerosol/particle generator	Pressure of 1 bar
Charge-coupled device camera	3312 pixel x 2488 pixel
Programmable timing unit	

Table 3 shows the details of the PIV parameters used in this study. The airflow was captured using a high-speed camera with a frequency of 100 Hz; 50 frames were taken per 0.5 seconds. The field of view of the PIV measurements was 400 mm x 300 mm.

Table 3 PIV parameters used in this study.

Parameters	Values used for Experimentation
High-speed camera frequency	100 Hz
Field of view	400 mm x 300 mm
Interrogation window	64 x 64 pixels
Laser light sheet thickness	2.2 mm
Tracer particle size	$0.5 - 1.5\ \mu m$

Figure 4 shows a schematic of the experiment, which demonstrates the direction of the incoming wind, the position of the camera, the laser, and the model. Figure 5 shows pictures from the experiment, with Figure 5(a) showing the mounted camera on top of the wind tunnel section. The edges of the model were painted with Rhodamine B to reduce laser reflections, which could damage the camera sensor and hinder readings by the PIV.

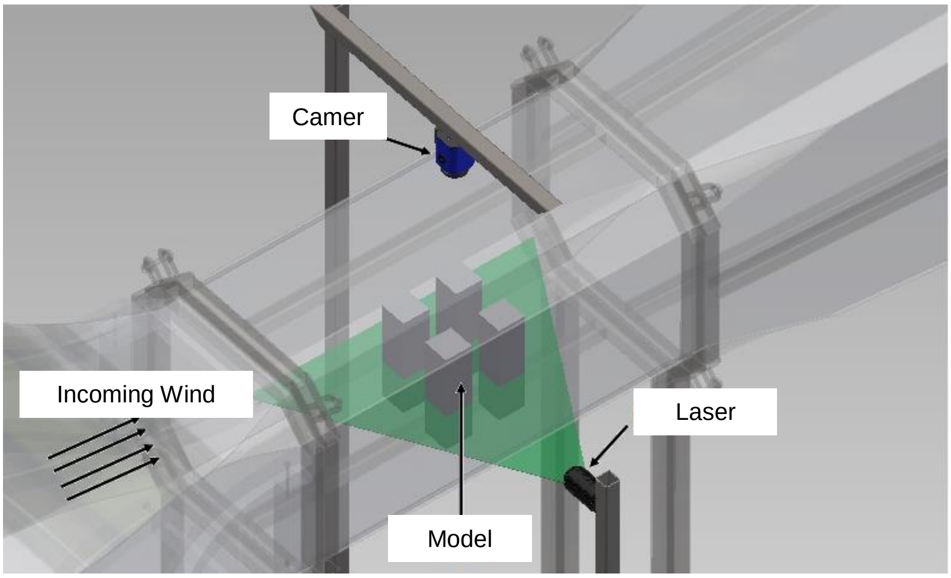


Figure 4 Schematic of the experiment with the model inside the wind tunnel, the laser from the side, and the high-speed camera from the top [15].

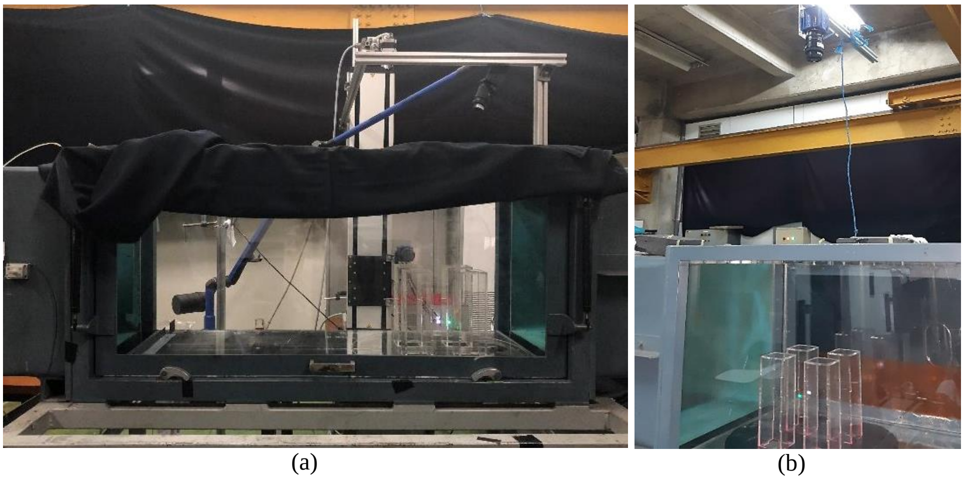

(a) (b)

Figure 5 Set-up of the experiment at the wind tunnel of BPPT-BBTA3 in (a) full view, and (b) with the camera positioned on top.

3 Results and Discussion

PIV captures the flow of the fluid at each grid, in which the wind speed and the direction of the vector of the fluid flow for the whole duration of the test can be investigated. A view of the wind speed for each grid at one point in time can be seen in Figure 6. For each point of the grid, the wind flow can be observed. Using these data, the study investigated the effects of street canyon width and changes in the angle of attack towards the flow of the fluid.

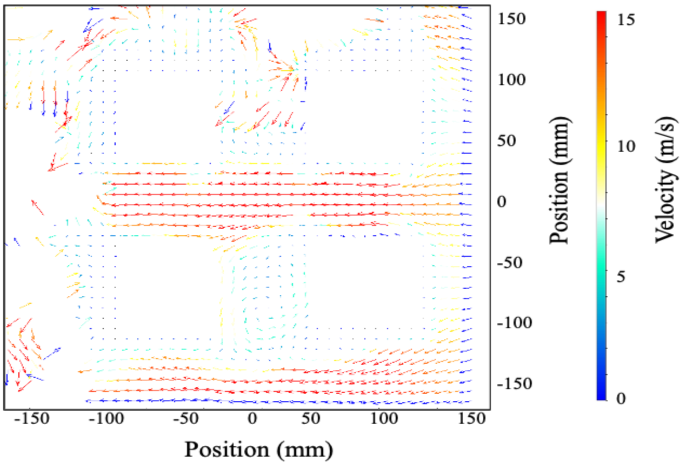
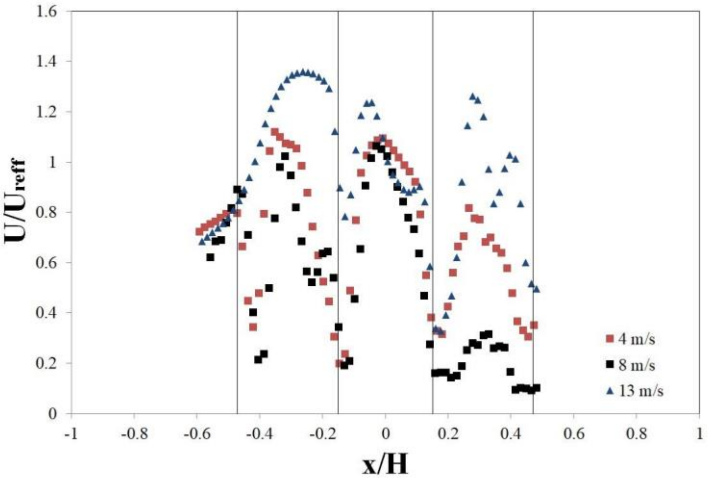
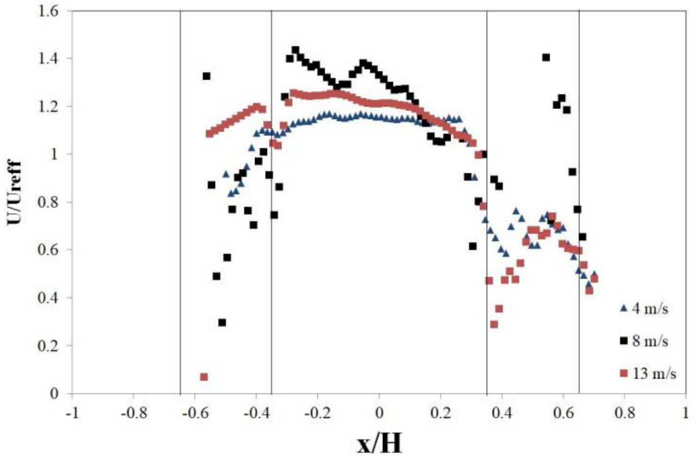


Figure 6 Wind speed at one point in time as captured by the PIV device for Model 1 at 4 m/s wind speed and 0° of angle of attack.

Blocken, *et al*. [4] proposed that there are three different wind flow regions between high-rise buildings that can be observed at the pedestrian level: (1) resistance flow, (2) interaction flow, and (3) isolated flow, all of which were observed in this study. The change in wind flow is a result of the change in the width of the passage.



(a)



(b)

Figure 7 Relationship between the dimensionless mean wind speed at height Z along the center passage of the building clusters for (a) L = 30 m and (b) L = 70 m.

From Figure 7(a) and (b) it can be seen that there was an interaction flow in the area between the buildings, in the upstream cluster and the downstream cluster. However, for the cross area, the behavior of the flow changed with the change of the distance between the buildings; for L = 30 m (Figure 7(a)), the flow was still interaction flow, but for L = 70 m (Figure 7(b)), the flow was isolated. This shows that an increase in distance between buildings can change the behavior of the flow.

The amplification factor values for each case are summarized in Table 4, in which for each case the amplification factor for the area between buildings and the cross area was different. For each case, the maximum increase of mean wind speed can be seen, shown as a percentage in the table. It can be observed that the increase in wind speed ranged from 7% to 44% and that the highest increase mostly occurred in the area between the buildings. This is consistent with the findings of Stathopoulos and Storms [1], Chang and Meroney [2] and Baskaran and Kashef [3].

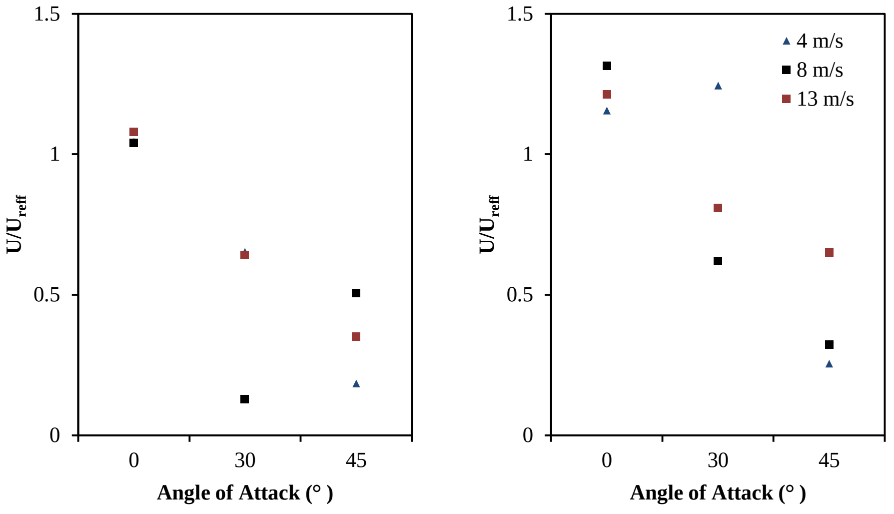
Table 4 Amplification factor for different street canyon widths in areas between buildings and at its cross area, and the increase in wind speed.

L (m)	**Wind Speed (m/s)**	**In between buildings** $(\frac{U}{U_{reff}})$	**Cross area** $(\frac{U}{U_{reff}})$	**Increase in Wind Speed (%)**
30	4	1.360	1.237	36%
	8	1.022	1.065	7%
	13	1.121	1.095	12%
70	4	1.196	1.170	20%
	8	1.404	1.436	44%
	13	1.255	1.253	25%

3.1 Effect of Approaching Wind Direction

The amplification factor at the center of the cross area was compared for a different wind angle of attack in Figure 8, (a) is for an *L* value of 30 m, while (b) is for an *L* value of 60 m. Normalized results from all runs at the center of the cross area are shown and clustered with the same angle of attack.

In both cases, the change in the angle of attack reduced the amplification factor at the center of the cross area. It can be seen that the highest amplification factor occurred at an angle of attack of 0°, which is in line with the results of Kuo, *et al.* [8] and Allegrini and Lopez [10]. This may be because the results show the value at the center of the cross area, where obstruction of the airflow by the building due to a change in wind direction is not so severe.



(a) (b)

Figure 8 Change of amplification factor with different angles of attack for buildings with a distance between building of (a) 30 m and (b) 70 m.

4 Conclusion and Future Research

This study investigated the behavior of wind between a cluster of 4 high-rise buildings. The wind flow experienced an interaction flow in all central areas, whether it is between the buildings or in the cross area, which translated to an increase in speed. The change in the distance between the buildings did change the behavior of the flow in the cross area. It was found that amplification happens in all cases and that the range of increase in wind speed was 7% to 44%. The change in the angle of attack of the wind does little to influence the amplification factor; the highest amplification factor still occurred at an angle of attack of 0°.

A continuation of this study will develop a simplified model of the behavior of the fluids between buildings, in which a simple relationship between the height to width ratio and its relationship to the amplification factor will be investigated. In addition, the results from this experiment will later be used to validate numerical computational fluid dynamics models.

Acknowledgement

This research was done with the help of the P3MI-ITB (ITB Research, Community Service and Innovation Program) Grant Scheme 2017-2019 from ITB. The experiments were performed in the wind tunnel of BPPT-BBTA3, Jakarta.

References

[1] Stathopoulos, T. & Storms, R., *Wind Environmental Conditions in Passages between Buildings*, Journal of Wind Engineering and Industrial Aerodynamics, **24**, pp. 19-31, 1986.

[2] Chang, C.H. & Meroney, R.N., *Numerical and Physical Modeling of Bluff Body Flow and Dispersion in Urban Street Canyons*, Journal of Wind Engineering, and Industrial Aerodynamics, **89**, pp. 1325-1334, 2001.

[3] Baskaran, A. & Kashef, A., *Investigation of Air Flow around Buildings Using Computational Fluid Dynamics Techniques*, Engineering Structures, **18**(11), pp. 861-875, 1996.

[4] Blocken, B., Carmeliet, J. & Ted, S., *CFD Evaluation of Wind Speed Conditions in Passages between Parallel Buildings – Effect of Wall Function Roughness Modifications for the Atmospheric Boundary Layer Flow*, Journal of Wind Engineering and Industrial Aerodynamics, **95**(9-11), pp. 941-962, 2007.

[5] Tsang, C.W., Kwok, K.C.S. & Hitchcock, P.A., *Wind Tunnel Study of a Pedestrian-Level Wind Environment around Tall Buildings: Effects of Building Dimensions, Separation and Podium*, Building Environment, pp. 167-181, 2012.

[6] To, A.P. & Lam, K.M., *Evaluation of Pedestrian-Level Wind Environment around a Row of Tall Buildings Using a Quartile-Level Wind Speed Descriptor*, Journal Wind Engineering Ind. Aerodyn, **54**(55), pp. 527-541, 1995.

[7] Zahid Iqbal, Q.M. & Chan, A.L.S., *Pedestrian Level Wind Environment Assessment around Group of High-Rise Cross-Shaped Buildings: Effect of Building Shape, Separation and Orientation*, Building Environment, **101**, pp. 45-63, 2016.

[8] Kuo, C.Y., Tzeng, C.T., Ho, M.C. & Lai, C.M., *Wind Tunnel Studies of a Pedestrian-Level Wind Environment in a Street Canyon between a High-Rise Building with a Podium and Low Level Attached Houses*, Energies, **8**(10), 10942-10957, 2015.

[9] Mittal, H. & Sharma, A., *A Review on the Study of Urban Wind at the Pedestrian Level around Buildings*, Journal of Building Engineering, **18**, pp. 154-163, March 2018.

[10] Allegrini, J. & Lopez, B., *The Influence of Angular Configuration of Two Buildings on the Local Wind Climate*, Journal of Wind Engineering Ind. Aerodynamics, **156**, pp. 50-61, 2016.

[11] Department of Public Works Indonesia, Directorate General of Highways, Directorate of Technical Development, *Planning Procedures for Pedestrian Bridges in Urban Areas*, No.: 027/T/Bt/1995, Jakarta, 1995. (Text in Indonesian)

[12] Ishihara, T., *Guidelines for Design of Wind Turbine Support Structures and Foundation,* Japan Society of Civil Engineers, 2010. (Text in Japanese).

[13] Choi, C.K. & Kwon, D.K., *Wind Tunnel Blockage Effects on Aerodynamic Behavior of Bluff Body*, Wind and Structures, **1**(4), pp. 351-364, 1998.

[14] Conan, B., van Beeck, J. & Auburn, S., *Sand Erosion Technique Applied to Wind Resource Assessment*, Journal of Wind Engineering Ind. Aerodynamic, **104-106**, pp. 322-329, 2012.

[15] Center for Aerodynamics, Aeroelastics and Aerospace Technology, *Report on the Aerodynamic Studies of a Building Model Study using PIV in an ESWT*, Agency for the Assessment and Application of Technology (BPPT), 2020. (Text in Indonesian).

[16] Gandemer, J., *Wind Environment Around Buildings: Aerodynamic Concepts*, in Proc. Fourth International Conference on Wind Effects on Buildings and Structures, Heathrow, United Kingdom, pp. 423-432, 1975.