Wind Pressure Coefficient and Wind Velocity around Buildings in High Density Block of Metropolis for Natural Ventilation Design

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ABSTRACT

The ventilative cooling by natural ventilation is important technology for the buildings in urban area for the sake of energy saving and BCP (Business Continuity Plan). In fact, a large number of high-rise buildings in urban area in Japanese metropolises are equipped with natural ventilation apparatus such as openings and chimneys or shafts. In design stage of the building, generally, building engineers have to decide the size and number of ventilation devices, but it is not easy because the data of wind pressure coefficient are not ready for engineers to use easily especially for the buildings in high density block of metropolis. In designing the natural ventilation devices, a wind guide or a wind vane sticking out from walls of the building is useful device to introduce natural wind from outside into the rooms. The wind velocity around the building, however, is essential to predict the performance of these devices. Here, the wind velocity around building depends on the distance between buildings, height above ground and wind speed of approach flow and so on. It can be said that the data of wind pressure on building wall and wind velocity around buildings are necessary for natural ventilation design of the buildings in high density blocks of metropolis.

In this study, in order to provide the data for natural ventilation design of buildings in metropolis, the distribution of wind pressure coefficient on the building walls and wind velocity distribution between the buildings were measured by wind tunnel test with 1:1000 scaled models and CFD analysis by LES. In CFD analysis, the dependency of wind pressure and velocity on Reynolds number between buildings, that is so-called Reynolds Number Effect, was examined.

As a result of CFD by LES, it was turned out that Reynolds number effect is inevitable to some extent in the wind tunnel test with 1:1000 scaled models under 10m/s of approaching wind, but the basic data of wind pressure coefficient and wind velocity were obtained by the wind tunnel test. Additionally, a simple method to predict the pressure loss and airflow rate based on the pressure boundary of the block without the gap between buildings were presented.

In the presentation of AIVC conference, some movies of airflows around buildings simulated by LES will be presented with many important data of wind pressure or wind velocity.

KEYWORDS

wind tunnel test, LES, critical Reynolds Number, wind pressure coefficient, wind velocity around buildings

1 INTRODUCTION

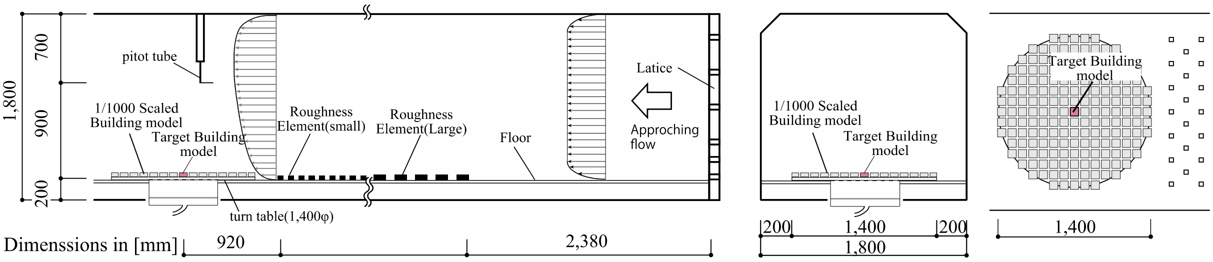
In urban district of metropolises, there are often many buildings in a block surrounded by streets with quite narrow gaps between buildings. In order to utilize natural ventilation for the

sake of energy saving and BCP (Business Continuity Plan), it is essential to predict the airflow rate through openings due to natural wind force or buoyant force based on the pressure difference between openings for natural ventilation. The data of wind pressure coefficient on the building walls facing narrow gaps between buildings are not yet prepared enough for the calculation of natural ventilation, so the wind tunnel test or reliable CFD (Computational Fluid Dynamics) will be necessary every time you design the natural ventilation of a building in a high-density block. In addition, the data of wind velocity in the narrow gaps between buildings are also important to estimate the discharge coefficient of openings on the wall, especially for wind scoop projecting from the wall.
There are many studies on the wind pressure or wind velocity in urban street canyon such as (Gromke et al., 2008)(Buccolieri at al., 2010)(Antoniou et al.,2017), but the narrow gaps have not been covered yet.
So in this study, the wind pressure coefficient on the wall and wind velocity are measured by wind tunnel test and CFD analysis using LES is conducted to investigate the effect of Reynold’s number on these values.

2 WIND TUNNEL TEST

2.1 Outline of wind tunnel test

In Figure 1, the section and layout of the used models of building in wind tunnel with atmospheric boundary layer of power of 1/4.2 are shown. The scale of the buildings was set at 1/1000. Used building models are shown in Figure 2. Case 1 is the case that one block consists of one building. This case is actually uncommon, but the wind pressure on the wall at the location of building gaps can be estimated from the data of Case1. The size of the block ($W80 \times D80 \times H40$) was decided from the average size of blocks in urban area of Osaka city (Japan). Three kinds of gaps, that is the distance between buildings are tested as seen in Figure 2. Each gross BCR (Building Covering Ratio) in four cases is 64%, 57.8%, 51.8%, 41.0%. In Figure 3, the layout of target block and Surrounding blocks are shown. The target block was exchanged in turn, but the surrounding block with the gaps of 8mm is not



(a)Section of wind tunnel

(b) Layout of building models

Figure 1: Outline of wind tunnel test

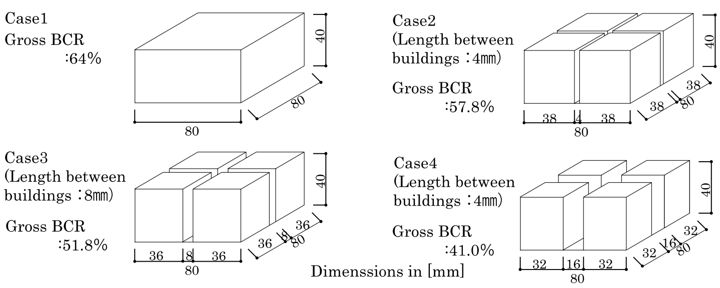


Figure 2: Tested cases of the target buildings (BCR: Building Covering Ratio)

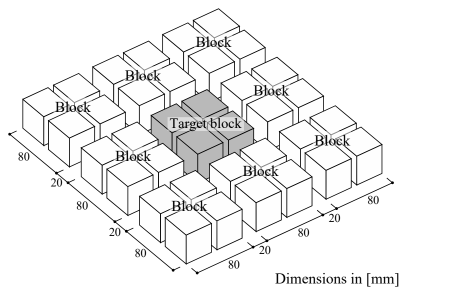
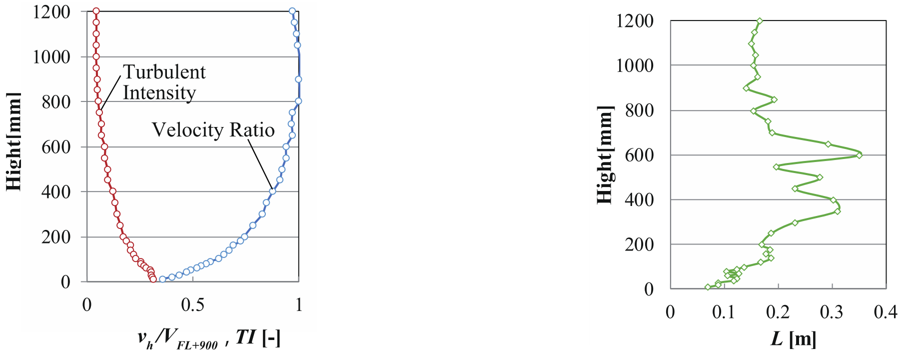


Figure 3: Layout of eight blocks surrounding the target block with the gap of 8mm

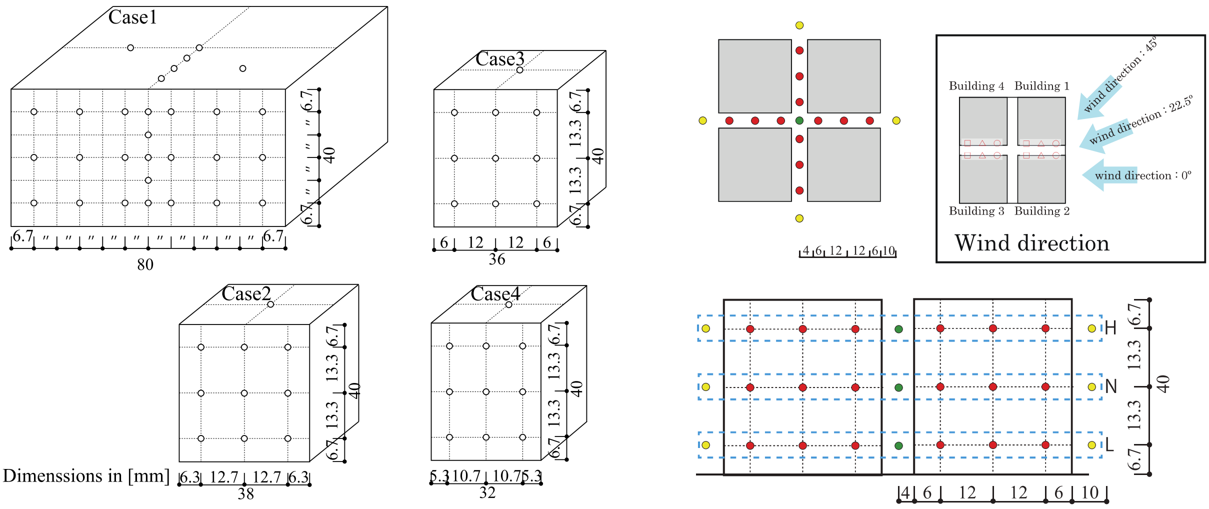
exchanged. The size of this gap is the mean value of three gap sizes of Case 2-4.
Figure 4 shows the profiles of wind velocity, turbulent intensity and turbulent length scale of approach flow (scaled atmospheric boundary layer) in the wind tunnel. The exponent of power law of wind velocity is almost 1/4.2. The wind velocity was set to 10 m/s using the pitot tube at the height of 900mm above the floor.



(a) Profile of wind velocity and turbulent intensity (b) Profile of turbulent length scale

Figure 4: Characteristics of approach flow

The wind pressure at the point in Figure 5 (a) was measured using pressure transducers (Validyne Engineering, DP45), and the wind velocity was measured at the points shown in Figure 5(b) using omni-directional anemometer (Kanomax Japan Inc., Model 1570). The wind direction was varied by 22.5 degree as the schematic figure in Figure 5, but the results in the case of 0 degree will be presented in this paper.



(a) Point for wind pressure coefficient (b) Point for wind velocity between buildings

Figure 5: Measurement point of wind pressure coefficient and wind velocity

2.2 Results and Discussions

Figure 6 shows the relationship between gap length and wind pressure coefficient on the center line in the walls perpendicular and parallel to wind direction. The wind pressure coefficient was calculated using dynamic pressure of approach flow at the height of building (40mm). The standard static pressure of kinetic pressure and wind pressure is the static pressure measure by pitot tube at the height of 900mm. From Figure 6, all the wind pressures have negative value. There is little difference between the pressures of both side (windward and leeward) of walls, and the wind pressure coefficient decrease as the length of building gap becomes larger. In almost cases, the higher the position is, the lower the wind pressure is. These results seem to be brought about by the change of wind velocity inside gaps between buildings.

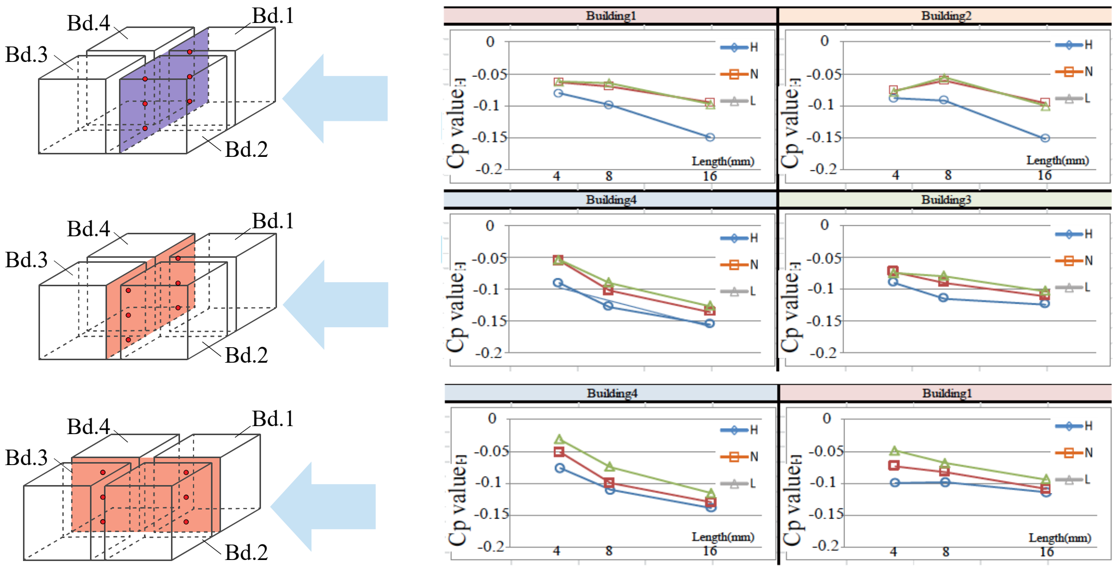


Figure 6: Relationship between gap length and wind pressure coefficient at the center on the wall

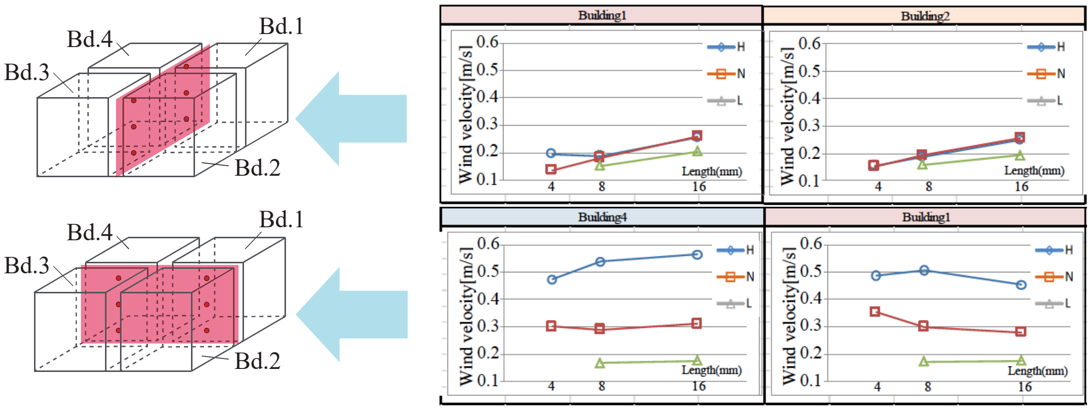


Figure 7: Relationship between gap length and wind velocity in the center of the gap between buildings

Figure 7 shows the relationship between gap length and wind velocity at three points on the vertical center line in each building gap. It can be seen that in the gaps perpendicular to wind flow, the larger the gap length is, the larger the wind velocity, but in the gaps parallel to wind flow, wind velocity is almost the same regardless of the gap length. Also in the gaps parallel to wind flow, wind velocity at higher points are larger than lower points. These differences of wind velocity are larger than that of wind pressure coefficient.
From two figures of Figure 6 and Figure 7, there seems to be a tendency that at a point with high wind pressure has low wind velocity, which might mean that the total pressure of dynamic pressure and static pressure is preserved according to Bernoulli law.
So in order to examine the loss or gain of total pressure along the flow in the gap and to compare them with the static pressure on the wall of Case 1 at the position of the entrance and outlet of building gaps, Figure 8 shows the distribution of total pressure and wind pressure of a building in Case 1(´). Generally, the wind pressure at the point of opening location on the wall surface is equal to the total pressure of the airflow in the case that there is a pass way through an opening, and at the outlet the wind pressure is equal to the static pressure in the

airflow at the outlet. In the section parallel to wind flow, the right hand of the figures, it is true in Case 2 and 3, but there can be seen the difference between them in Case 4 of the gap of 16mm. From the figures on the left hand, in the section perpendicular to the wind flow, the wind pressure of the wall is not necessarily equal to the total pressure or static pressure depending on the case, that means the direction of the airflow is not consistent and symmetrical. A remarkable tendency is that the total pressure increases along the airflow in the parallel section on the right hand of these figures, which means the inflow of momentum from the airflow over the buildings. This phenomenon is quite interesting but will need detailed measurement of wind velocity and static pressure. The detailed CFD might be useful.

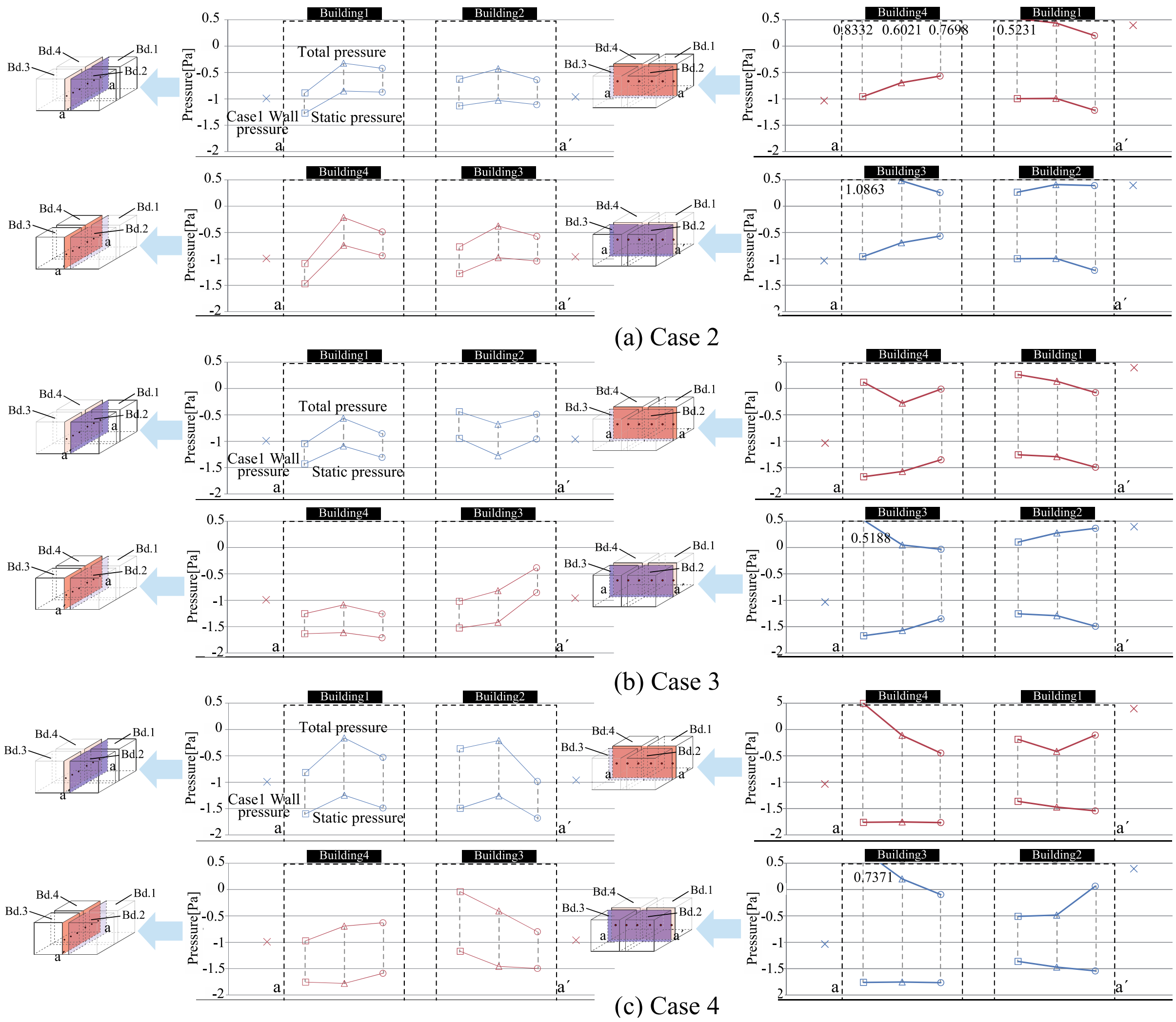


Figure 8: Distribution of total wind pressure coefficient of case 2 through 4 with the wind pressure coefficient on the building walls of the large building without gaps of case 1

3 CFD ANALYSIS

3.1 Outline of LES (Large Eddy Simulation)

In chapter 2, the results of wind tunnel test were presented. However, the similarity between wind tunnel test and actual phenomenon should be examined. The problem is whether critical Reynolds number was attained or not. Normally wind velocity of 10m/s is enough for measuring wind pressure or wind velocity in the case of bluff body in the wind tunnel test, but the gaps between buildings in this study are so narrow that the effect of Reynolds number could be essential, that is, the effect of viscosity could not be negligible. It is, however, not easy to examine the effect in wind test changing the model scale or wind velocity. So, by CFD analysis using LES was conducted to examine the effect of Reynolds number on the wind pressure and wind velocity. In order to change Reynolds number of the flow in the gaps of buildings, upper wind velocity V_0 (at the height of 900mm) in wind tunnel was changed. As the height of analyzed area is 400mm, the inlet velocity at the top of analysis area was calculated by power law of wind profile. In Table 1, the outline of CFD was listed, and six cases were examined as is shown in Table 2. In any cases, the product of time step and upper wind velocity V_0 at the height of 900mm above the floor was set to 0.01m taking account of time scale similarity.

Table 1: Outline of CFD analysis

CFD Code		Fluent19.1
Turbulence Model		Large Eddy Simulation WALE Model (Cw =0.325)
Algorithm		SIMPLE
Discretization Scheme for Advection Term		Central Differencing
Boundary Condition	Inlet	Velocity : Profile (experimental value)
	Outlet	Outflow
	Wall	Two Layer Model of Linear-Log Law
Total Number of Cells		2,275,875

Table 2: Analysis cases

	V_0	Time Step Size	Time Step
Case1	1.0m/s	0.01sec.(100Hz)	5000
Case2	5.0m/s	0.002sec.(500Hz)	
Case3	10.0m/s	0.001sec.(1000Hz)	
Case4	50.0m/s	0.0002sec.(5000Hz)	
Case5	100.0m/s	0.0001sec.(10000Hz)	

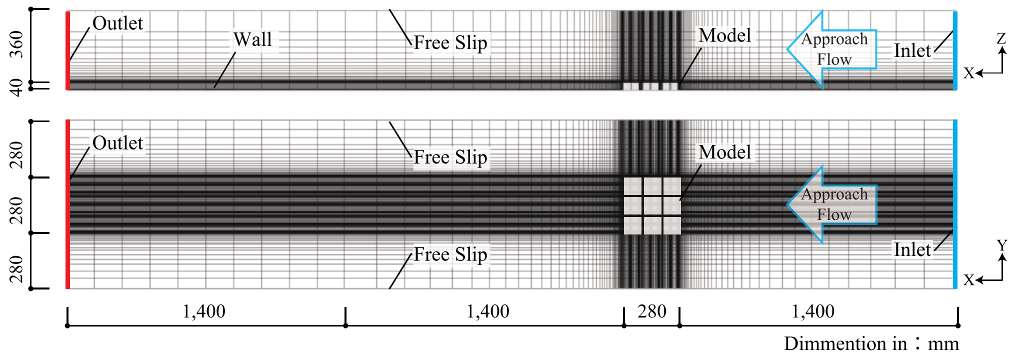


Figure 9: Mesh layout of analysis area in CFD (LES)

Mesh layout is shown in Figure 10. As an approach flow, measured profiles of wind velocity, turbulent intensity and turbulent length scale were reproduced as an inflow boundary condition using spectral synthesizer in Fluent. In Figure 10, the layout of the models was shown. Only nine blocks were used and the All the size of gaps are set at 4mm. This size is the same as the gap size of Case 2 of wind tunnel test, but the gaps of surrounding blocks are different from those of blocks for wind tunnel test. This difference is intended to make an safer conditions in CFD analysis.

The calculation was unsteady and k-ε model was used for the first 1000 time steps to make a initial situation for LES calculation. Figure 11 shows monitored points of wind velocity fluctuation of three components.

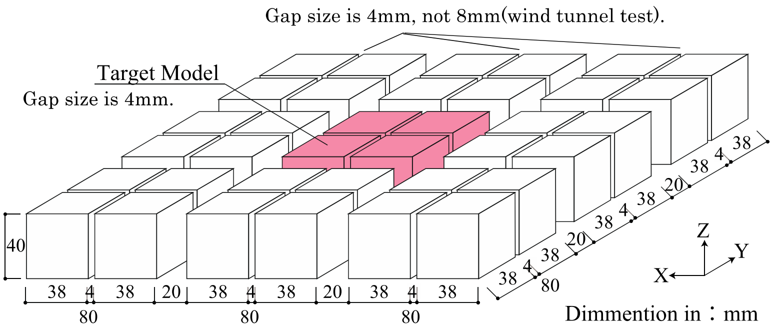


Figure 10: Size and layout of nine blocks including target blocks with the same gap of 4mm (not 8mm in the case of wind tunnel test)

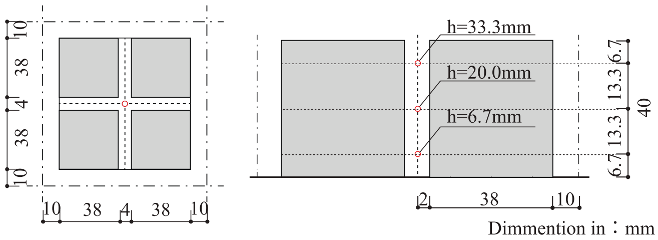
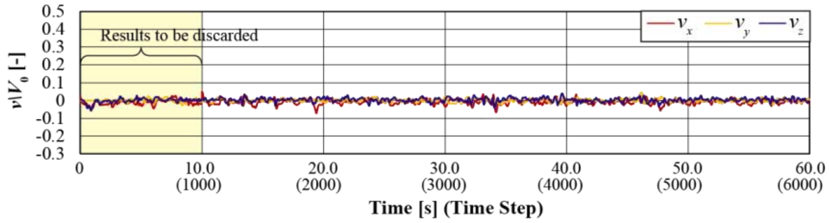


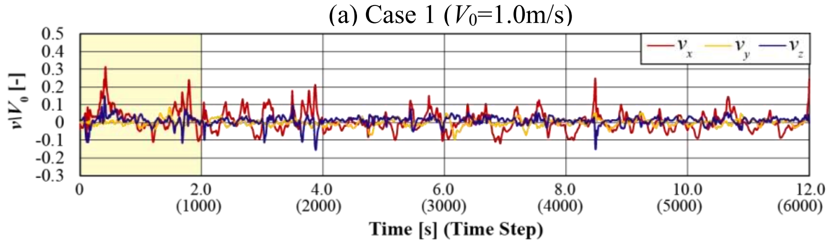
Figure 11: Monitored points of wind velocity in CFD

3.2 Results and Discussions

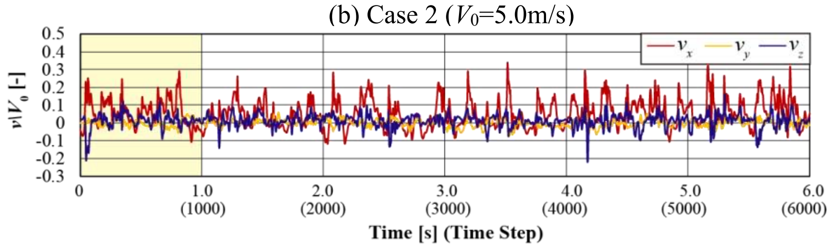
In Figure 12, the variations of wind velocity components at the monitored point with the height of 20 mm (Figure 11) in time series were shown as for each case. From these figures, in Case 1 and 2, the fluctuation of velocity is smaller than the other three cases, and the fluctuation magnitude in Case 3 (V_0=10m/s) is almost close to the fluctuation of velocity in Case 4 and 5. There can be, however, the dependence on the upper wind velocity of the amplitude of fluctuation of the wind velocity in the gap of buildings.



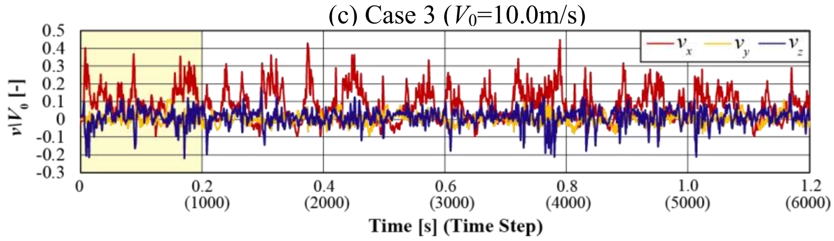
(a) Case 1 (V_0=1.0m/s)



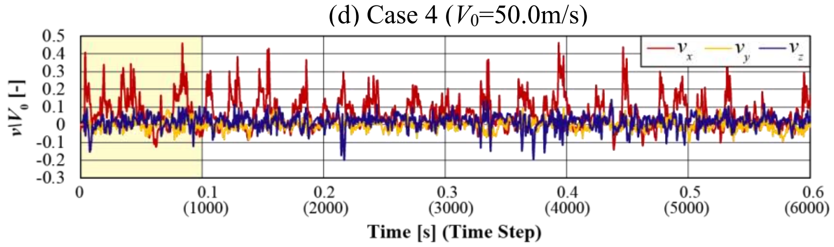
(b) Case 2 (V_0=5.0m/s)



(c) Case 3 (V_0=10.0m/s)



(d) Case 4 (V_0=50.0m/s)



(e) Case 5 (V_0=100.0m/s)

Figure 12: Variation of each component of wind velocity at point with the height of 20mm (see Figure 11)

In Figure 13, the distributions of wind pressure coefficient are shown. The standard dynamic pressure is that of the wind velocity of approach flow at the height of buildings (40mm), and the standard static pressure is that of at the top of analysis area, 140mm leeward of inlet boundary. From these figures, it is clear that the distribution of wind pressure is dependent on upper wind velocity. It has to be said that 10 m/s of upper wind velocity is not enough for the prediction of wind pressure coefficient on the walls in gaps.

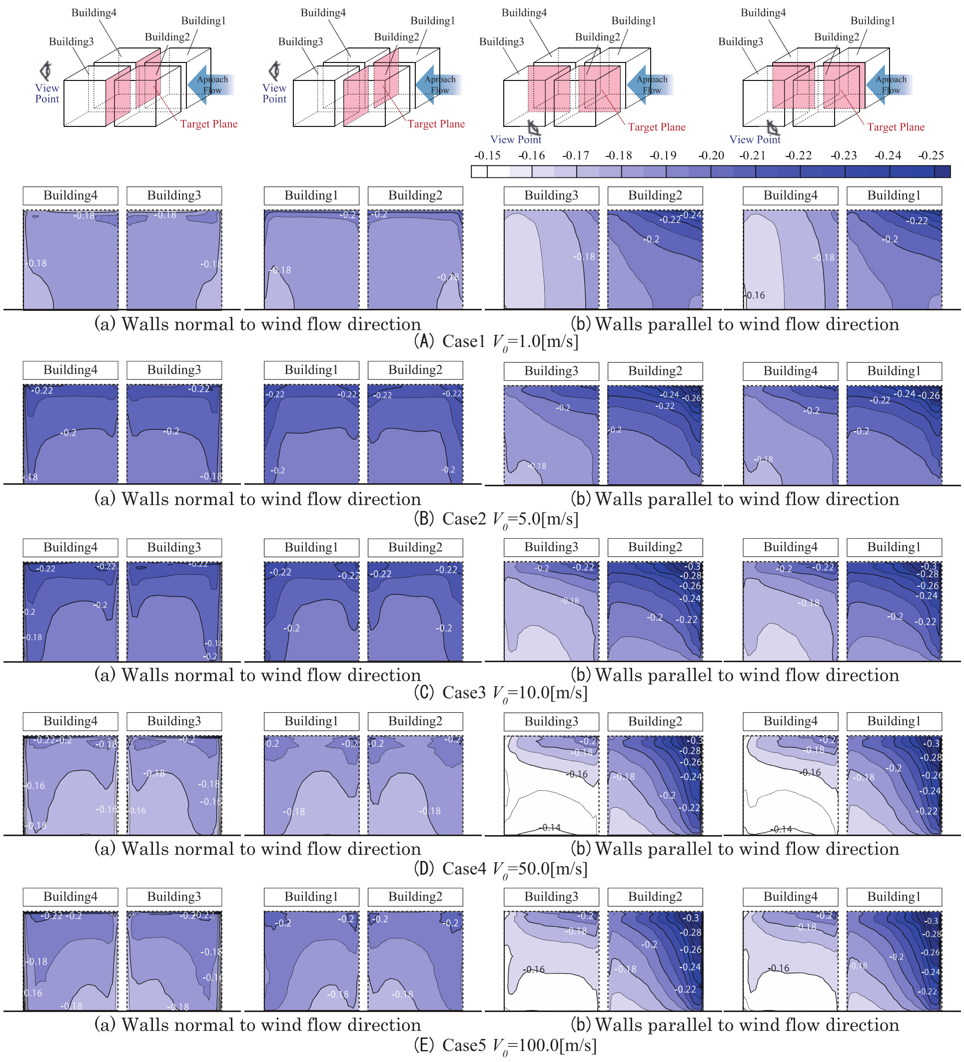


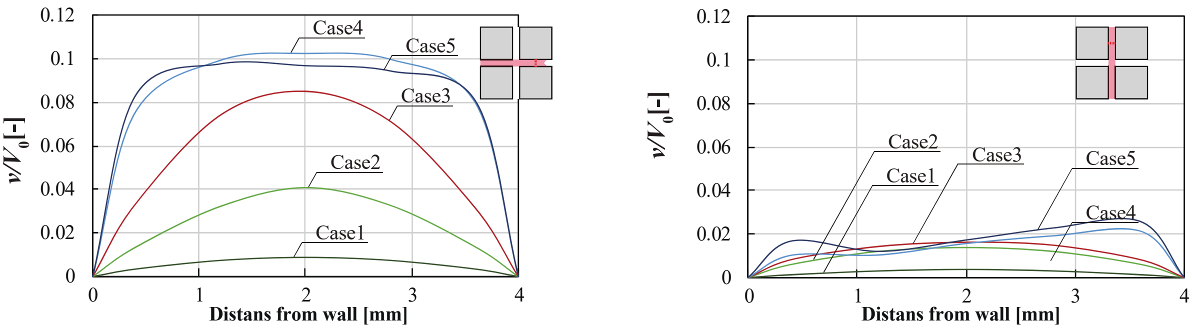
Figure 13: Distribution of wind pressure coefficient on the walls facing building gaps in each case

In Figure 14, the distribution of wind velocity in the gaps are shown. As for the velocity in the gap parallel to the wind flow, the distribution of velocity is depending on the upper wind velocity, but wind velocity in Case 4 and 5 are almost the same. It is clear that 10 m/s of upper wind velocity is not enough to predict the wind velocity in the gaps. However, the gap length of surround blocks is 4mm, which is narrower than the gap length in wind tunnel test, so this tendency might not be true of the results of wind tunnel test. The investigation, therefore, based on Reynolds number of the flow in the gap will be needed.
From Figure 15 through Figure 18, the normalized variables such as wind velocity, turbulent length scale, turbulent energy and turbulent dissipation rate were showed as a function of Reynolds number in the gap. The averaged wind velocity of three points at the center of gaps (Figure 11) were used for the calculation of Reynolds number. From Figure 15, when Reynolds number is larger than 1000, wind velocity is rather stable. In Figure 16, turbulent length scale shows a peak value at the Reynolds number of 1000. It seems to be difficult to

explain the reason of this peak at present. As for turbulent energy and turbulence dissipation rate, these values become quite large at high Reynolds number over 1000. That respects the transition from laminar airflow to turbulent airflow. It can be said that Reynolds number of over thousands could be necessary to predict the turbulent property by CFD and also wind tunnel test.

From the data obtained by wind tunnel test in Chapter 2, Reynolds number in the gaps between buildings are at most less than 500, which is not enough for the prediction of even wind velocity. As the wind pressure is affected by wind velocity along the wall in gaps, this Reynolds number is not enough for the prediction of wind pressure, too. Of course, it is true of turbulent energy and turbulence dissipation rate.

It is concluded that the scale of 1/1000 and small gap length such as 4, 8 and 16mm was rather out of required range of Reynolds number. In fact, there is a limitation of Reynolds number, so the CFD is more accurate method to examine the airflow and wind pressure in urban building arrays.



(a) Building gap parallel to wind flow (b) Building gap perpendicular to wind flow

Figure 14: Distribution of normalized wind velocity in gaps between buildings in each case

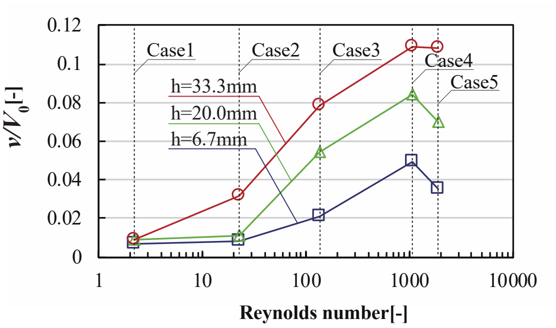


Figure 15: Relationship between Reynolds number and normalized wind velocity in the gap

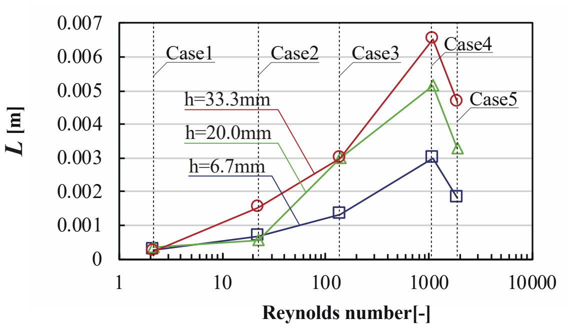


Figure 16: Relationship between Reynolds number and turbulent length scale in the gap

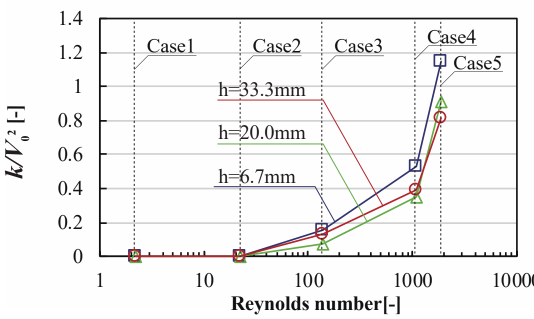


Figure 17: Relationship between Reynolds number and normalized turbulent energy in the gap

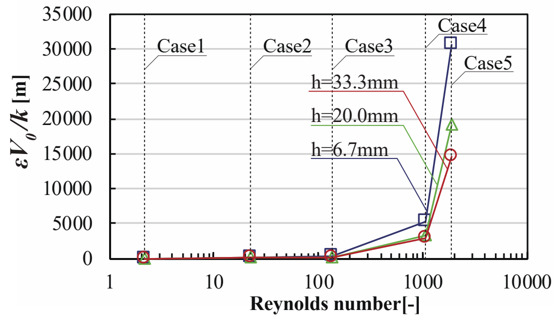


Figure 18: Relationship between Reynolds number and normalized turbulence dissipation rate in the gap

4 CONCLUSIONS

In this study, wind tunnel test and CFD analysis were conducted to investigate the wind pressure coefficient on the walls facing the building gaps and wind velocity in the gaps of buildings in high density block of metropolis such as Osaka in Japan. As a result, concluding remarks are as follows.

From wind tunnel test:

- The wind pressure coefficient on the wall in the gap has a negative correlation with the gap length of buildings.
- The wind velocity in the gap has a positive correlation with the gap length of buildings.
- The total pressure tends to increases along the gap in the flow direction, and this can be considered to be caused by the inflow of momentum of outer airflow over the blocks.
- At the entrance of airflow into the gap, the wind pressure of the wall of one large building without gaps at the location of the gap seems to be the total pressure of the airflow, which can be used to judge the direction of airflow.

From CFD analysis by LES (Large Eddy Simulation):

- The amplitude fluctuation is large at the upper wind velocity of high speed. This phenomenon is considered to mean the airflow in the gap becomes turbulent as the increase of wind velocity in the gap.
- It is clear that the distribution of wind pressure on the wall is dependent on upper wind velocity. It has to be said that 10 m/s of upper wind velocity is not enough for the prediction of wind pressure coefficient on the walls in gaps.
- The distribution of wind velocity in the section of gap reflect the turbulent state of airflow, which is caused by Reynolds number of airflow in the gap. The case of 50 m/s and 100 m/s of upper wind velocity are enough for state of turbulence, but 10 m/s is not enough.
- From the view point of the effect of Reynolds number, 1000 of Reynolds number seems to be needed for the prediction of wind velocity and turbulent length scale, and Reynolds number of more than 2000 will be needed to predict the turbulent energy and turbulence dissipation rate of the airflow in the gap.

5 ACKNOWLEDGEMENTS

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