Journal of Civil Engineering and Architecture 11 (2017) 897-914
doi: 10.17265/1934-7359/2017.10.001

Optimization Design of Open Spaces Based on Wind Tunnel and CFD Simulation: Case Study of a Street Canyon in Northern China

Zhiming Guo[1], Tsuyoshi Setoguchi[1], Norihiro Watanabe[1] and Takuya Tsutsumi[2]

1. Faculty of Engineering, Graduate School of Engineering, Hokkaido University, Sapporo 0608628, Japan;

2. Northern Regional Building Research Institute, Hokkaido Research Organization, Asahikawa 0788801, Japan

Abstract: Airflow in open spaces can significantly affect spatial quality. Therefore, according to the type of building structures, the airflow also has different forms. Studies have been conducted on the relation between airflow and pedestrian comfort; however, only few of them have focused on comprehensive urban planning that considers different weather conditions and people's ability to adapt. This research focuses on the differences in wind conditions caused by different spatial forms in different seasons. On the basis of a field survey in both summer and winter in a public open space, evaluation standards developed from environmental meteorological data and public feedback were used to evaluate simulation results. Next, several assumptions about canyon orientation and building types were proposed. Wind tunnel and CFD (computational fluid dynamics) simulations were conducted to evaluate the assumptions. The results showed that the canyon orientation significantly affected overall wind conditions and different building structures affected airflow. This research also provides a method to evaluate urban areas that have complicated wind environments.

Key words: Urban form, outdoor comfort, open space, wind tunnel simulation, optimization design.

1. Introduction

Public open spaces are important in cities [1], the environmental characteristics of which are determined by the climatic conditions. Therefore, to ensure practicable and usable public open spaces, designs must be based on the climate in order to reduce climatic effects and improve and enhance comfort [2].

Research on open spaces in seasonal cities requires a consideration of the temperature differences between summer and winter. In particular, as cities in colder regions have longer winters and shorter summers, the people in these climates, such as Northern China, Russia, Sweden, and southern Argentina, are better able to cope with the cold than people from other temperate regions; consequently, the environmental evaluation standards need to be suited to the region under investigation.

Corresponding author: Zhiming Guo, Ph.D. Candidate; research fields: urban and regional research. E-mail: burningrain1988@eis.hokudai.ac.jp.

Most wind comfort environmental research to date has been based on discrete points rather than spatial dimensions [3]. On the basis of research by Verkaik, Willemsen and Wisse, NEN8100 and NPR 6097 were developed as standards and guidelines for measuring wind comfort [4-11]. From research into pedestrian wind comfort, standards were established for threshold values based on hourly average wind speed ($UTHR$ = 5 m/s). Isyumov and Davenport, Lawson, and Melbournealso designed wind comfort criteria on the basis of wind flow patterns [12-14]. However, these have generally referred to the mechanical effect of wind on pedestrian wind comfort and have seldom included spatial considerations [7]. Janssen compared the above four criteria types using a specific campus case and found that when used in complicated urban areas, there were large differences in the results, indicating that they were not useful as design guidelines [15]. Some qualitative research has focused on the wind effect on people or buildings; however, these did not consider other factors such as air temperature, relative humidity, solar radiation, individual differences [15], specific environmental, or climatic characteristics, or any spatial details.

Other applied research has focused on thermal comfort and urban forms [16-22]; however, few considered wind speed as a high priority factor for thermal comfort or focused specifically on cold regions or low temperature environments. From the characteristics of the outdoor environment, the main factors affecting people's comfort have been identified as air temperature, solar radiation, relative humidity, air velocity, activities, clothing, and individual differences [23]. In a man-made environment, the following factors can be used to control comfort: solar radiation, which is affected by building shade [24, 17], ventilation caused by the differences in spatial forms, and the adaptability and differences in the people using the public space [25].

According to a field survey in both summer and winter in a specific public open space as well as environmental meteorological data, this research focuses, in particular, on the environmental wind effects of different spatial forms. Evaluation standards developed from meteorological data and feedback analysis were used for the simulation research.

On the basis of the prevailing air velocity and directions in both summer and winter in this area, a wind tunnel simulation was conducted, the results from which informed a proposal for optimum street alignments and building types. By analyzing the results, the reasons for the wind changes in the area were found.

CFD (computational fluid dynamics) simulation was also used for the wind tunnel simulation to check the wind paths; however, as the reliability and accuracy of CFD simulation have been questioned [26], in this study, the CFD simulation was set with the same conditions as the wind tunnel simulation only to check the wind path as a reference for the wind tunnel simulation. Using the above research design, this paper developed design guidelines and research methods for public spaces in colder climates.

2. Methods and Materials

A field survey that analyzed the relation between air velocity and wind comfort level was conducted to determine the comfort air velocity threshold. Depending on the average annual air velocity and the prevailing wind directions during the survey period, a wind tunnel simulation was then conducted using different urban street alignments and building types with the aim of improving the wind environment. A CFD simulation was also used to check the details.

2.1 Area Description

The pedestrian street in this study was in the downtown area of Shenyang, China (41°48′01.11″ N, 123°27′49.33″ E), a winter city in northeastern China. The general climate in Shenyang is temperate monsoon, with four distinct seasons (2009-2004). Depending on the climate data from China Meteorological Administration, the annual average temperature change from 2009 to 2014 is about 60 °C. Because of these climatic characteristics, there are different wind conditions in summer and winter, with the prevailing wind direction and the annual average air velocity in summer being SSW and 2.5 m/s, and in winter being ENE and 2.0 m/s [27].

The research area, which is located between high, density commercial buildings, is one of the most popular public open spaces in the city center (Fig. 1). However, because of the complicated building structures, this area suffers from varying microclimates throughout the day. A target area model at a scale of 1:500, which included pedestrian streets and surrounding buildings, was developed for both the wind tunnel and the CFD simulations.

2.2 Field Survey

The field survey was carried out during extreme temperatures in summer and winter. The microclimate

Fig. 1 Target area and surrounding buildings.

situation and the corresponding CSV (comfort sensation votes), which were the integrated reactions of pedestrians to the microclimates [28] (see Table 1), were analyzed to determine the acceptable air velocity level and threshold.

Five years (2009-2014) of climate data were analyzed (Fig. 2) [29]; summer from July to September and winter from December to February, with Jul. 28-Aug. 9, 2015 (12 days in summer) and Jan. 15-29 (15 days in winter), 2016 being chosen as representative data periods for the hottest part of summer and coldest part of winter.

Table 1 Scale used by participants for subjective responses regarding comfort during field surveys.

Value	Comfort sensation vote
-3	Very uncomfortable
-2	Uncomfortable andunacceptable
-1	Uncomfortable, but acceptable
0	Neutral
1	Slightly comfortable
2	Comfortable
3	Very comfortable

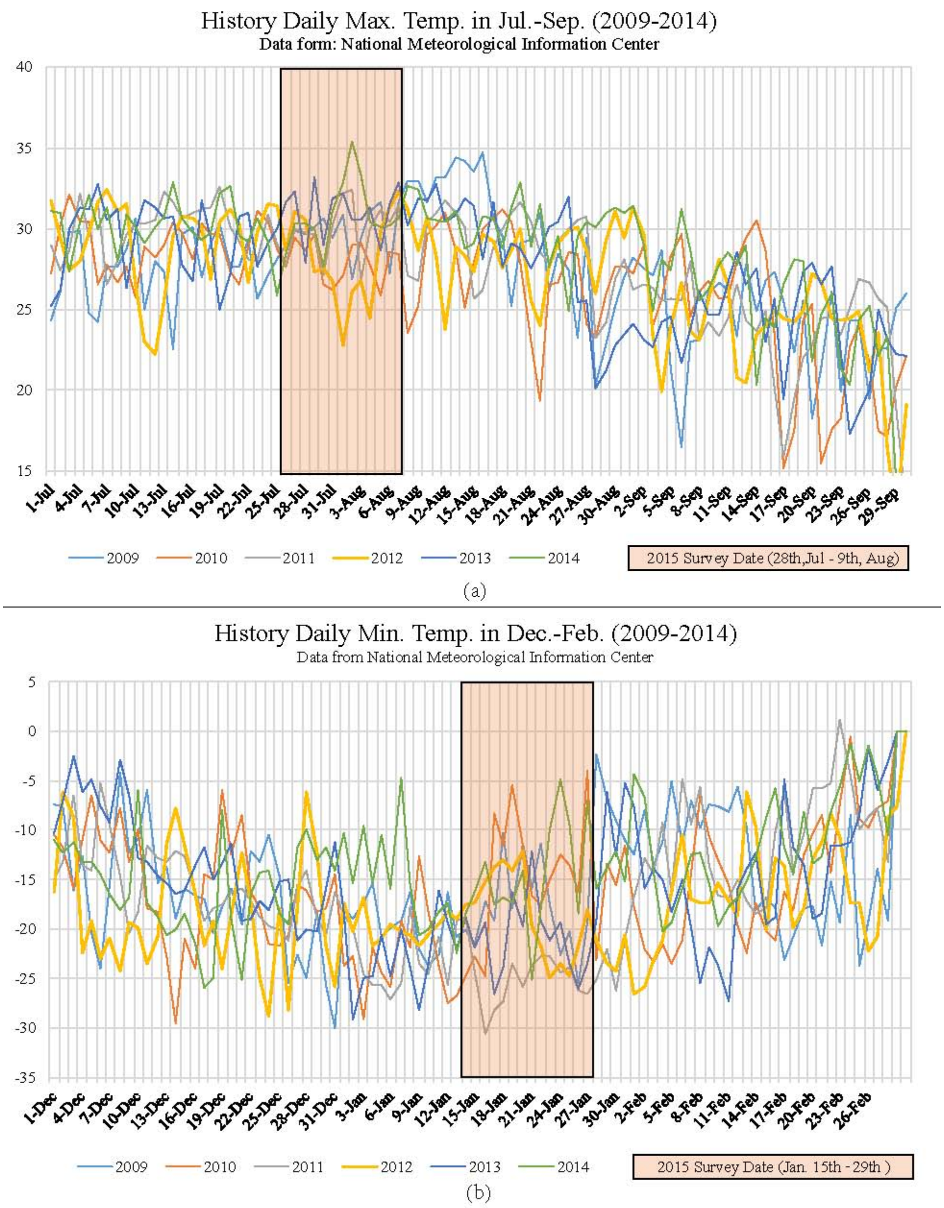

Fig. 2 Historical daily maximum and minimum temperatures from: (a) July to September (summer); and (b) December to February (winter) 2009-2014.

Note: Weather station No. 54342 Coordinates: 41°44 N, 123°31 E, altitude = 49 m.

On the basis of position and space, 15 sampling points were chosen for the collection of microclimate and comfort data every 15 minutes from 9:30 to 20:00 on the survey days (see Fig. 3). The microclimate data included ambient temperature (*Ta*) and air velocity (*v*). (see Table 2).

2.3 Wind Tunnel Simulation

Wind tunnel simulations were conducted several times for the original case and the redesigned cases for both summer and winter. The research area model and its surrounding buildings were built of Styrofoam at a scale of 1 to 500. The research area comprised a circle with a diameter of 900 m (Fig. 4). An atmospheric boundary layer wind tunnelwith a 1.8 m by 1.8 m cross section and a 20 m/s maximum air velocity was used for this research, as shown in Fig. 5.

Depending on the relations between the positions, 93 measurement points were determined, as shown in Fig. 3, at which 93 thermistor anemometers (Kanomax Climomaster model 0965-03) were set at the height of 3 mm on the model to measure the air velocity every second, which was calculated at 1.5 m, which was determined as the average head height of Chinese in a real situation [30]. A reference anemometer (Kanomax Climomaster model 0965-21) (Fig. 4) was set in front of the model at the height of 0.4 m, which was equal to 200 m, so as not to affect the surrounding buildings, to calculate the real air velocity from the vertical air velocity profiles, which could be calculated using the power-law at an exponent of 0.27 [31] (Fig. 6). Depending on the annual mean air velocity, the air velocity at each measurement points was calculated, as follows [32]:

$$\frac{V_w}{V_r} = \left(\frac{H_w}{H_R}\right)^{\alpha} \quad (1)$$

where:

V_w = air velocity in wind tunnel at the height of the weather station;

V_R = air velocity at the height of the reference anemometer;

H_w = height of the weather station (No. 54342 41°44′ N, 123°27′ E, H_w = 44.7 m [27]);

H_R = height of the reference anemometer (200 m);

α = exponential coefficient (0.27).

$$\frac{V_{1.5}}{V_w} = \frac{V_{r1.5}}{V_{rw}} \quad (2)$$

where:

$V_{1.5}$ = air velocity at a height of 1.5 m in the wind tunnel;

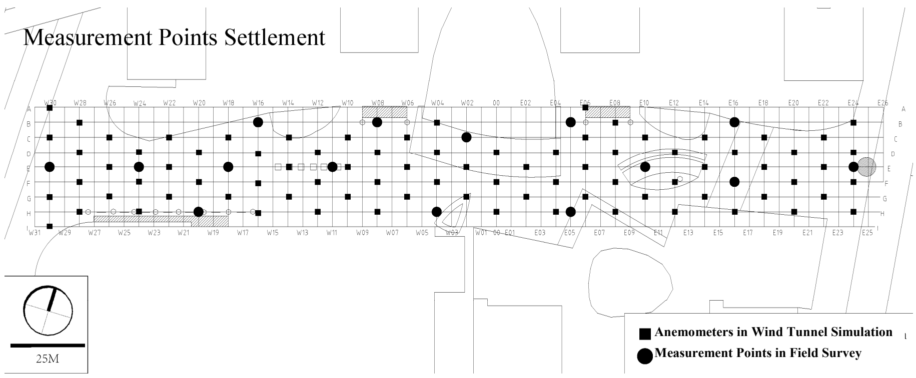

Fig. 3 Anemometers in wind tunnel and measurement points in field survey.

Table 2 Measurement factors for micrometeorological parameters, Shenyang, Northern China.

Parameter	Accuracy	Resolution	Range	Setting place
Air velocity (*v*)	Larger than 3% of reading, least significant digit	0.1 m/s	0.6-40.0 m/s	1.5 m as the average height of the head
Ambient temperature (*Ta*)	0.5 °C	0.1 °C	(-)29.0-70.0 °C	

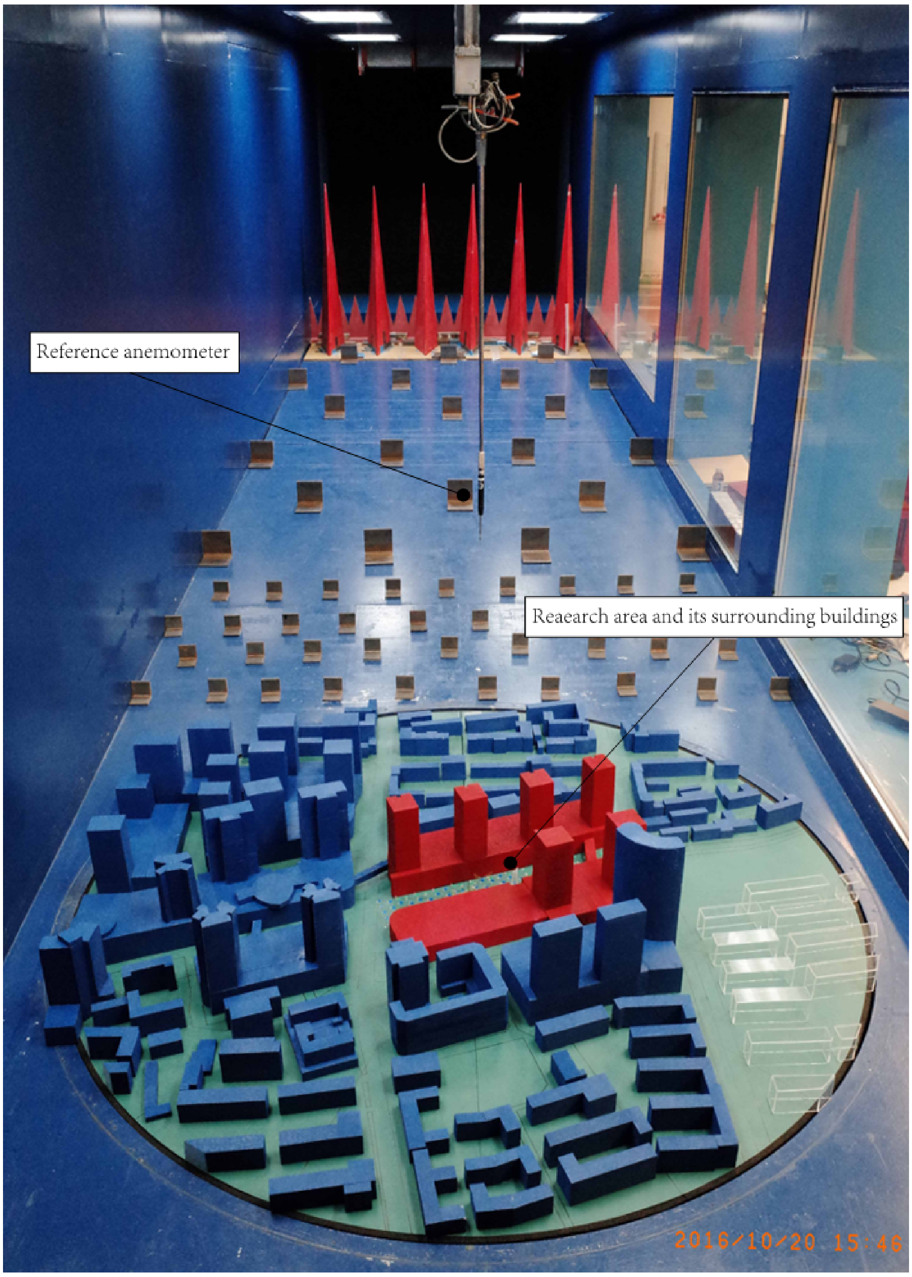

Fig. 4 Research model in the wind tunnel.

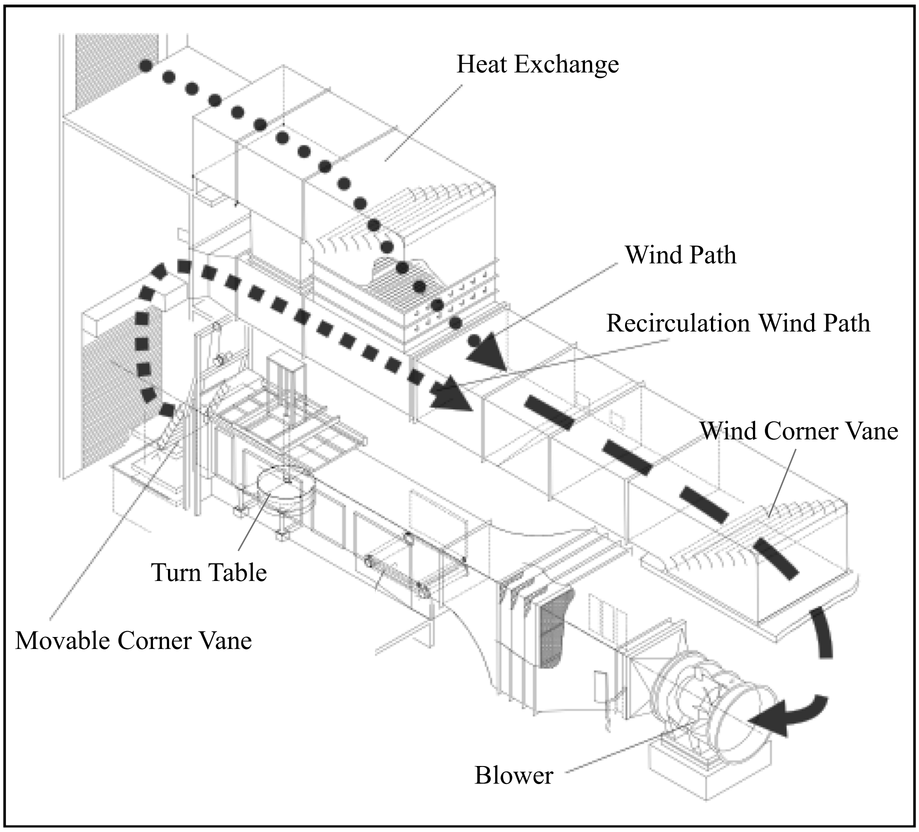

Fig. 5 Environmental wind tunnel used in this research [33].

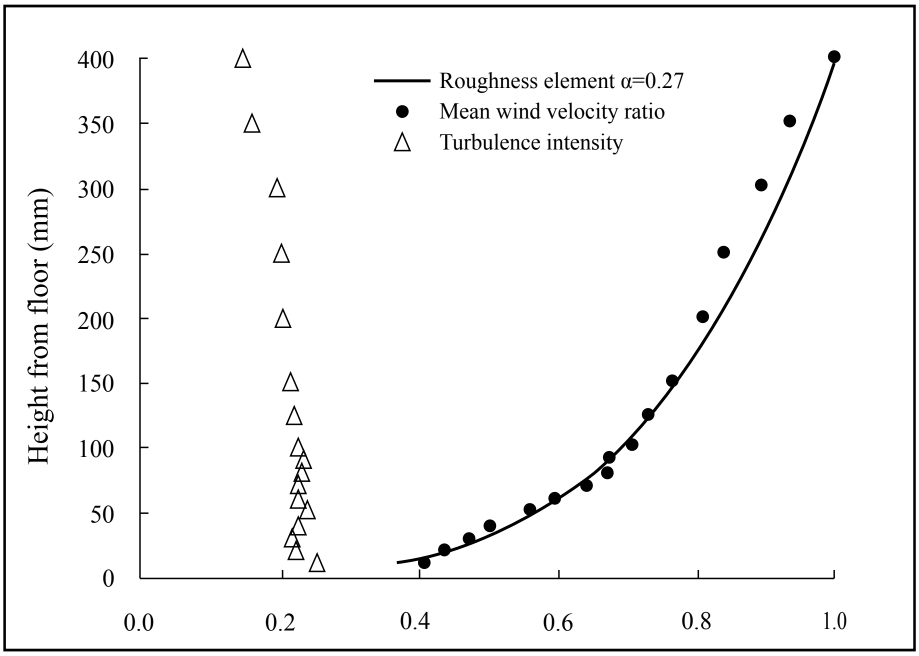

Fig. 6 Vertical air velocity profiles [34].

V_w = air velocity at the height of the weather station in the wind tunnel;

$V_{r1.5}$ = air velocity at a height of 1.5 m in the real situation;

V_{rw} = annual average air velocity from the weather station (summer 2.5 m/s SSW, winter 2.0 m/s ENE)

[27].

2.4 CFD Simulation

The CFD simulation was conducted using the software PHOENICS developed by Cham Ltd. to simulate the airflow under the same situations with the wind tunnel. Using the CFD simulation, the detailed wind pressure and air flow path distributions were detected.

A Cartesian grid system across the whole zone was used to divide the research area and surrounding area in consideration of the research area boundaries. The dimensions 900 (x) × 900 (y) × 900 (z) m were adopted with 233 (x-direction) × 225 (y-direction) × 250 (z-direction) cells at each axis. The grids were changed gradually from fine close the central area to coarse nearer the outer boundary. A 1.2 expansion rate was maintained for the grid adjustment. The standard k-ɜ turbulent model with 5,000 iterations were applied for the CFD simulation.

3. Results

3.1 Wind Comfort in Summer and Winter

The field survey results gave general information for the measured ambient temperature and air velocity, as shown in Table 3; the temperature range was 24.4-35.9 °C (summer) and (-)21.6-2.2 °C (winter), and the air velocity range was 0-7.1 m/s (summer) and 0-4.8 m/s (winter).

Acceptable airflow and thresholds were analyzed by calculating the mean CSV of pedestrians for every 0.1 unit of air velocity. During the survey days in summer and winter, more than 2,500 groups of effective data were recorded. As Fig. 7 shows, the CSV increased with an increasing air velocity in summer and decreased with an increasing air velocity in winter. Linear regression was conducted as follows:

Summer:

$$y = 0.2459x - 0.275 \quad (R^2 = 0.67066) \tag{3}$$

Winter:

$$y = -0.1346x - 1.7746 \quad (R^2 = 0.37224) \tag{4}$$

The regression coefficients were 0.2459 in summer and -0.1346 in winter that indicated that the residents in Shenyang were more sensitive to the summer wind. With the scale for subjective responses about comfort sensation in Table 1, the neutral air velocity in summer is 1.12m/s; however, in winter, all CSVs were below -1, indicating that the microclimate air velocity was unable to satisfy the neutral level. When the air velocity was higher than 1.67 m/s, it was found to be unacceptable.

The above results indicated that a higher air velocity in summer and taking shelter from the wind in winter would improve comfort levels.

3.2 Wind Situation for the Original Survey Area from the Wind Tunnel Simulation

The wind tunnel simulation results are shown in Fig. 8, from which it can be seen that the distribution of air velocity in both summer and winter were roughly the same. Airflow in the western area was lower than in the central and eastern areas. In summer, there was a dark red area in the center and an orange area in the west. The CSV analysis showed that the comfort level in this area was higher than in the green and blue areas in which the air velocity was lower than 1.12 m/s. In winter, there were three parts showing orange, which were considered to be unacceptable areas. The green and blue areas were better than the yellow and orange

Table 3 General information for the microclimate data in the central open space, Shenyang, Northern China

Season	Data		Avg.	Max.	Min.
Summer	Jul.-Aug., 2015	*Ta* (°C)	29	35.9	24.7
	(*n* = 2,520)	*V* (m/s)	1.2	7.1	0
Winter	Jan., 2016	*Ta* (°C)	–21.6	2.2	–21.6
	(*n* = 2,520)	*V* (m/s)	1	4.8	0

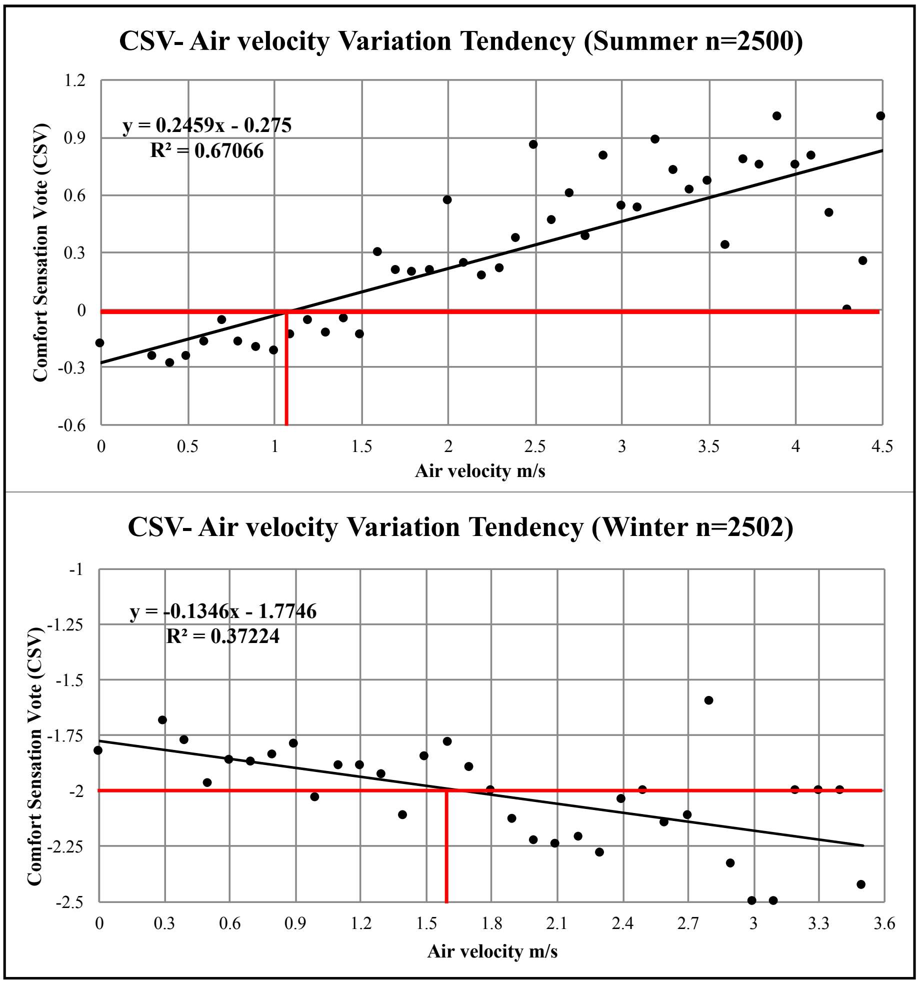

Fig. 7 CSV—air velocity variation tendency.

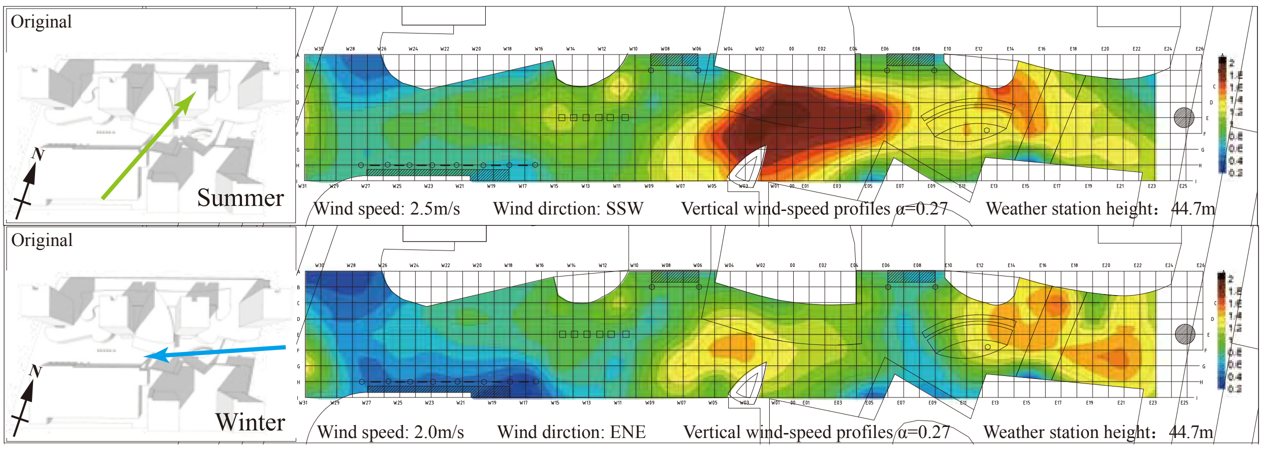

Fig. 8 Wind situation of the original survey area by wind tunnel simulation.

area for people outside.

3.3 Wind Situation Affected by Canyon Orientation

Previous research has found that the wind attenuation of an individual space is affected by canyon aspect ratios and orientations [35]. Fig. 9 shows that when the airflow was parallel, the attenuation factors for the four cases with different aspect ratios were higher than when the airflow was perpendicular.

As the prevailing wind directions were different between summer and winter, there were also fixed angles between the wind direction and the street alignment. Two assumptions are proposed for changing the canyon orientation to satisfy the following situations:

Streets aligned parallel to the summer wind direction have a higher air velocity in summer.

Streets aligned perpendicular to the winter wind direction have less strong wind in winter.

As shown in Fig. 10, rotating the street counterclockwise (CCW) 22.5° would make the summer wind parallel to the street. Rotating the street clockwise 90° would make the winter wind perpendicular to the street.

As Fig. 11 shows, the wind in the rotated streets changed significantly. This illustrates that changing the angles between the streets and the prevailing wind direction can radically change the wind situation. However, the CCW 22.5° could decrease the air velocity area in summer and increase the air velocity in the central and western areas in the winter, which, based on the results, would not meet the requirements for a comfortable wind environment.

In Fig. 12, when the street was rotated clockwise (CW) 90°, the wind situation in both summer and winter obviously changed. The street had higher air velocity in summer and lower air velocity in winter, thereby satisfying the requirements for a comfortable wind environment in both seasons; however, for a northern city such as Shenyang, because of its extreme winter temperatures, reducing the wind in winter would be more important than increasing the air velocity in summer. Therefore, prioritizing the long winter period by making the winter wind direction perpendicular to the main street would significantly improve wind comfort.

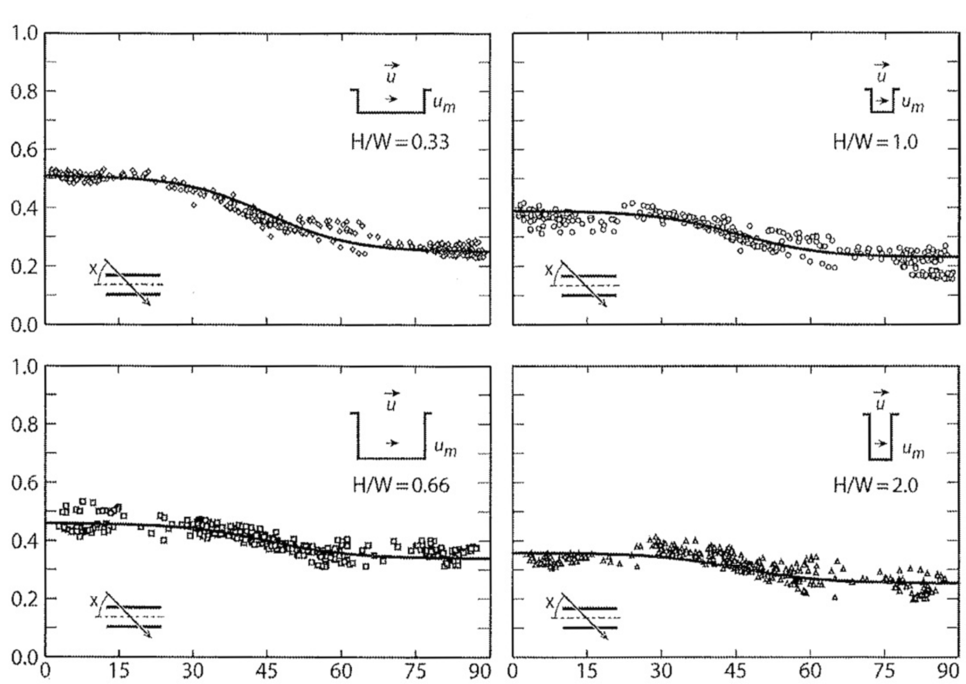

Fig. 9 Correlation between wind attenuation and angle of attack for street canyons of varying aspect ratios [35].

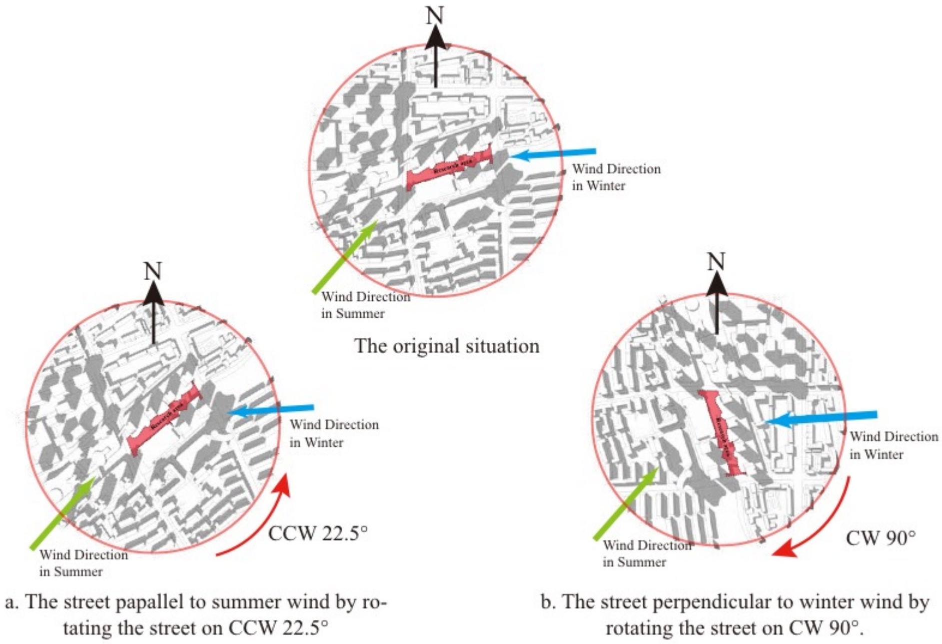

Fig. 10 Changing the canyon orientation.

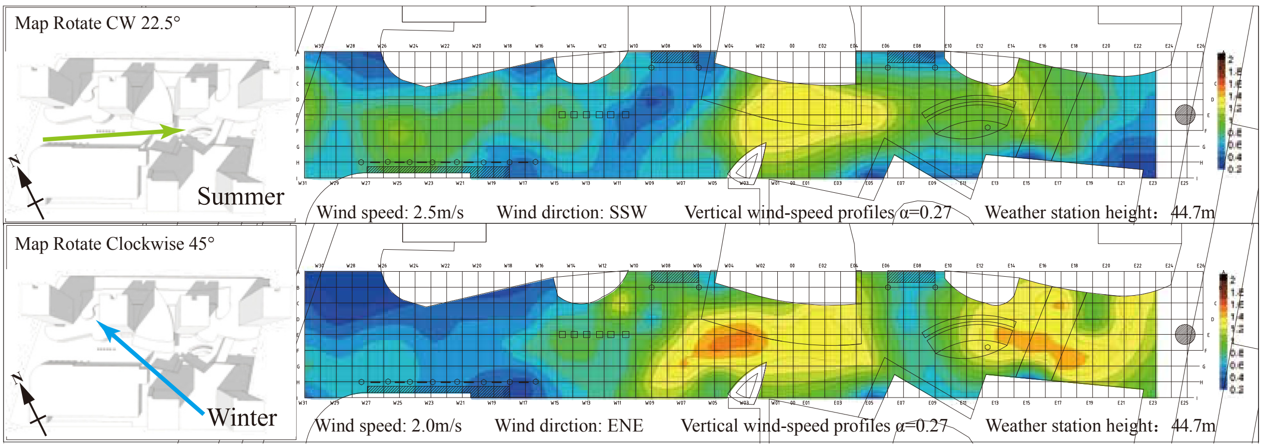

Fig. 11 Wind situation of the survey area by rotating CCW 22.5°.

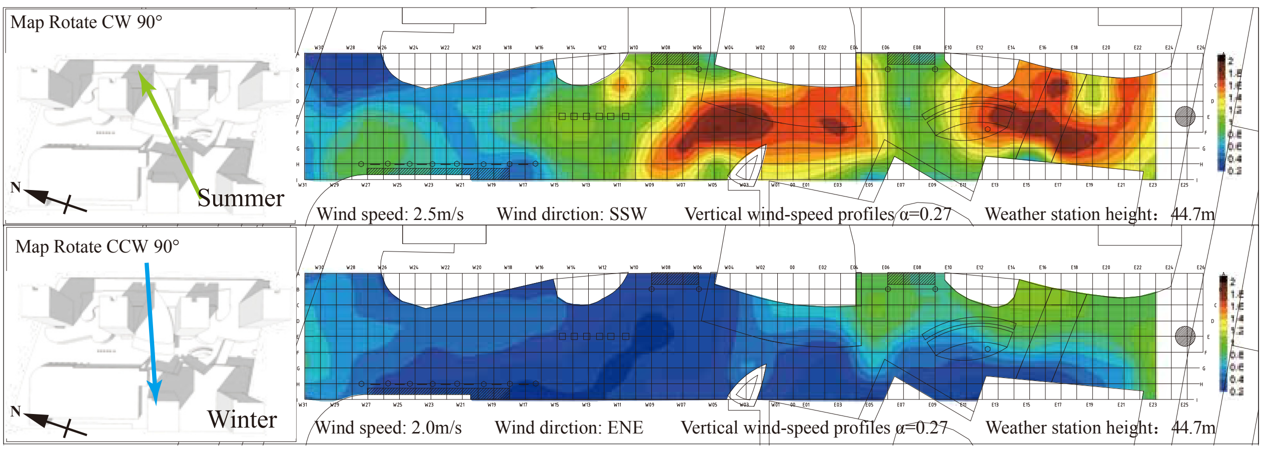

Fig. 12 Wind situation in the survey area by rotating CW 90°.

3.3 Wind Situation by Changing Building Types

On the basis of the simulation results from the original street, several hypotheses were made for the different building types without changing the building floor area ratio. Wind tunnel simulations were conducted on these cases to determine the impact of building type change on wind flow.

As shown in Fig. 13, high-rise buildings, podium buildings, and building details' propositions were considered. A1-3 were for high-rise buildings: in A1, two high-rise buildings were set back to determine the impact of the high-rise building position on wind flow; in A2, the high-rise buildings were changed to a plate type to determine the impact of building shape on wind flow; and in A3, the high-rise buildings were shortened and compacted while meeting the same sunshine conditions to determine the impact of building density on wind flow at the pedestrian level.

B1 and B2 were used for podium buildings to determine whether special building shapes or building structures affected wind flow: in B1, the skyway connecting the two main podium buildings was removed to determine whether the skyway affected the wind flow at the street entrance; and in B2, two-side street entrances were broadened by smoothing the irregular building edges, and the alleyway on the south side between the two main buildings was closed off, from which B2-1 was proposed, in which all irregular podium buildings were smoothed and the two podium buildings on the south side were set at the same height. As Fig. 14 shows, comparisons of wind tunnel simulation results between the original situation and each proposed building type were conducted.

In summer, the general wind flow distributions in A1-3, B1, and B2 did not change from the original layout. However, in B2-1, a high air velocity area was found in the central and eastern areas and at the same time, there was a higher air velocity on the west side. Therefore, it was concluded that regular building edges force the wind to blow rapidly and consistently. In detail, in A3, the eastern area had lower air velocity and the central area had higher air velocity than the original. In B1, when the skyway was removed, the high wind area in the east was smaller and more separated.

In winter, the general distributions for the wind in A1, A3, B1, and B2 did not change from the original. In B2-1, as with summer, the air velocity in all areas was higher; however, the highest air velocity was lower

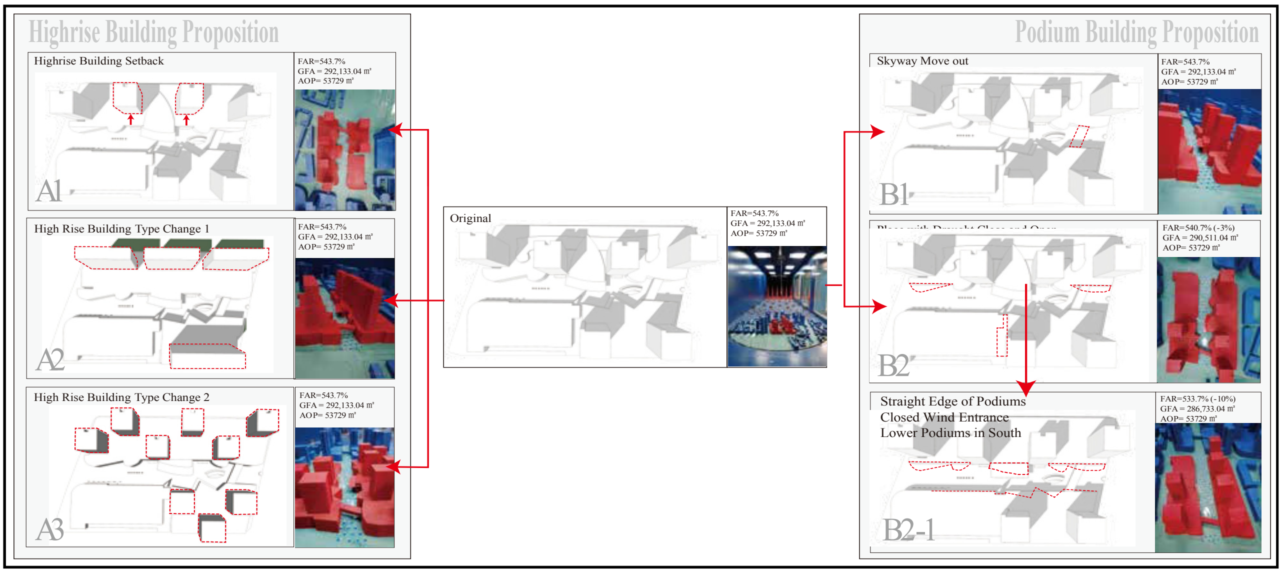

Fig. 13 Building type propositions.

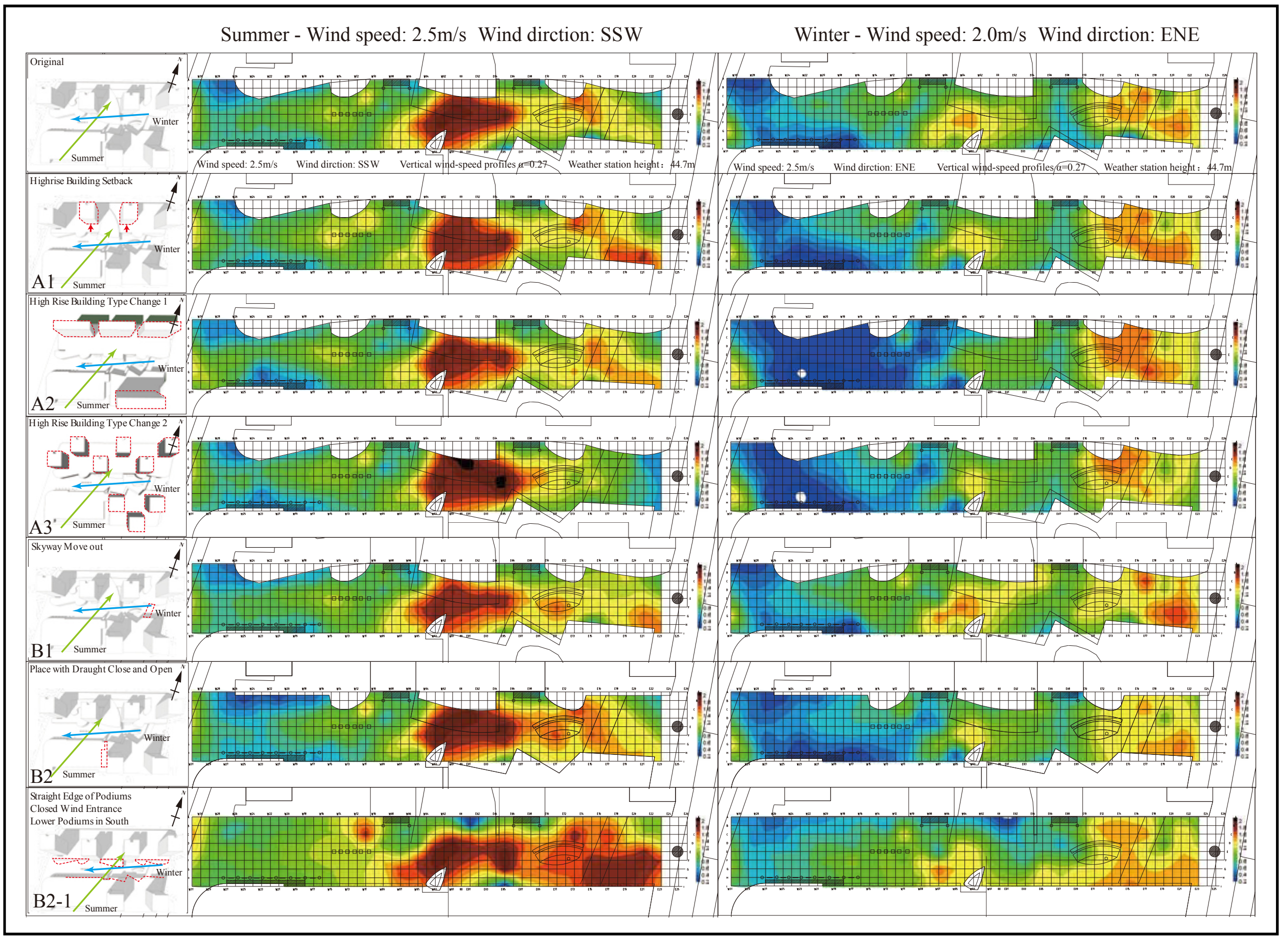

Fig. 14 Wind flow at the survey area when changing building types.

than in other cases. In A-2, there was no higher air velocity in the central area and the western area had a lower air velocity than the original. In detail, in B-2, the eastern area had a lower air velocity than the original case and in A-3, the air velocity in the central and western areas were lower than the original.

In summary, it was concluded that changing the building type affected wind flows. For lower air velocity in winter and higher air velocity in summer, A2 and B2-1 proved to be the most effective.

3.4 Wind Situation by Changing Building Type and Rotating the Urban Street

Further hypotheses were proposed to clarify the optimal case. By rotating A2 and B2-1 CW 90°, wind tunnel simulations were again conducted.

As shown in Fig. 15, in summer, for A2, the high air velocity areas on the eastern and western sides increased. The high air velocity area on the eastern side was larger than in the original case and the highest air velocity area was also larger; however, the central area air velocity was lower than in the original case. In B2-1, the air velocity distribution was almost the same as the original case and the overall air velocity was higher than the original case. The highest air velocity area in both the central and eastern areas increased.

In winter, the wind flow distribution in A2 was similar to the original case, but the air velocity in the eastern and western entrances to the square significantly increased. In B2-1, the low air velocity area was larger than in the original case, but there was no high air velocity area. In summary, by changing the building types and rotating the urban street, B2-1 achieved an optimum result.

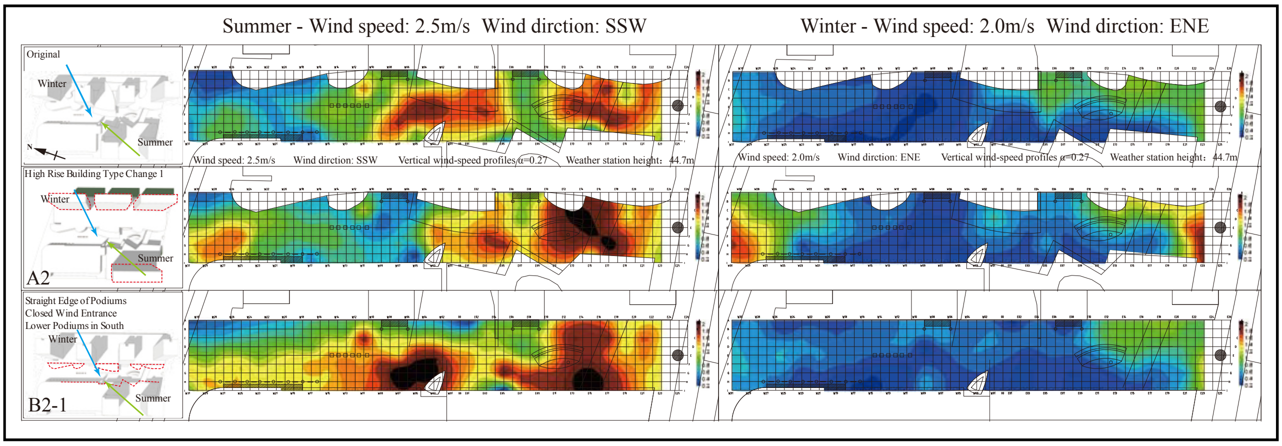

Fig. 15 Wind situation by changing the building types and changing the canyon orientation.

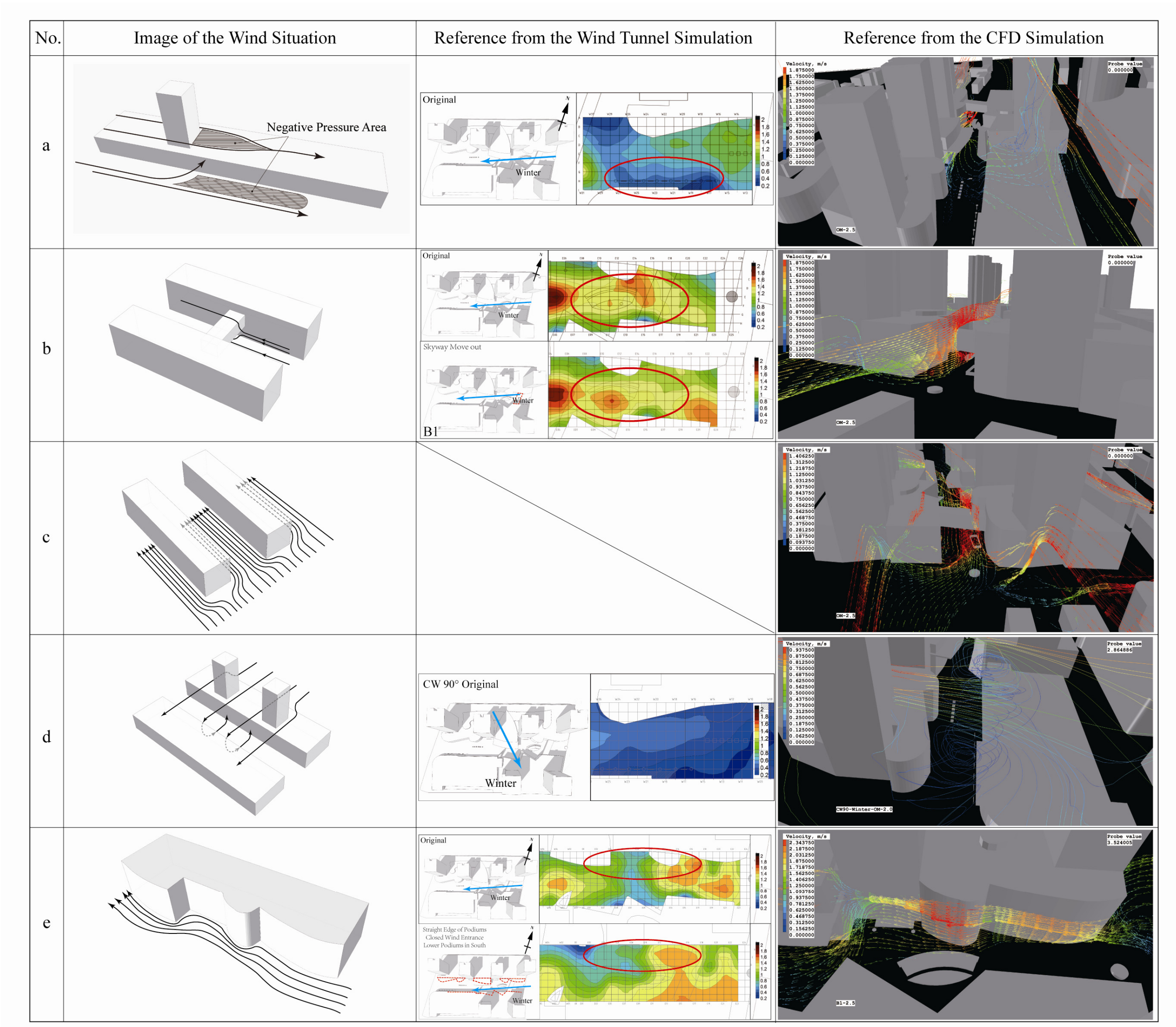

Fig. 16 Schematic of wind flow.

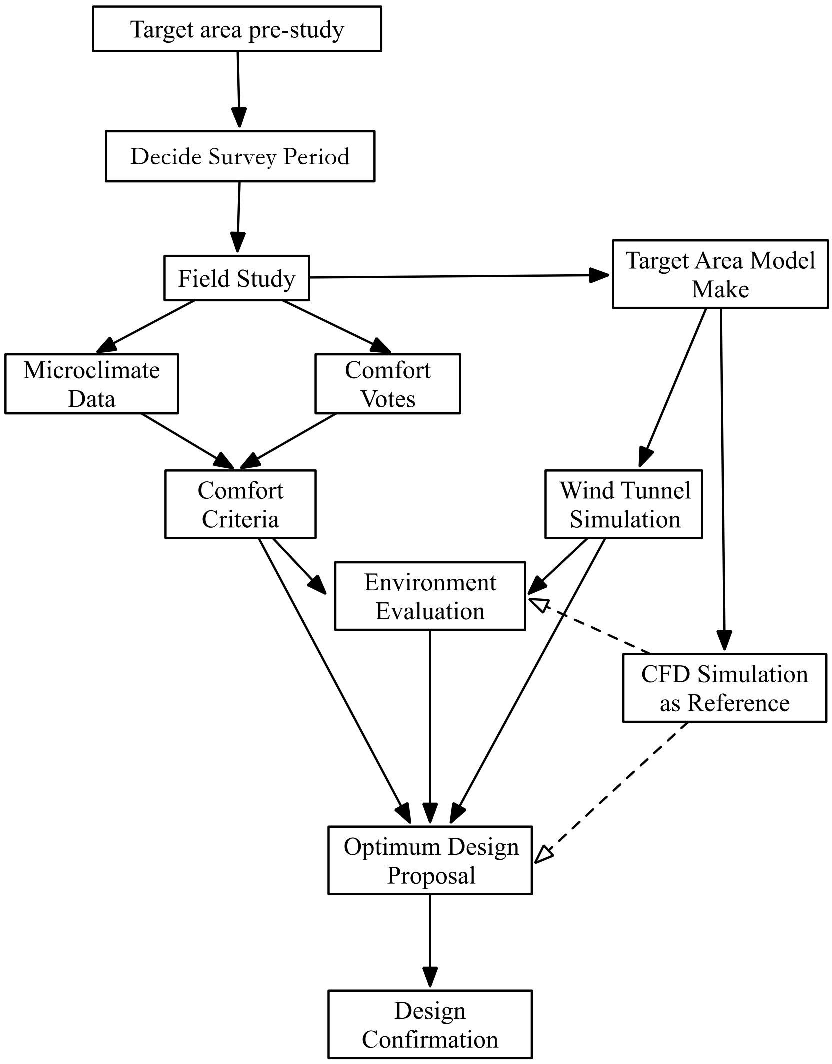

Fig. 17 Schematic representation for the optimization of public open space design.

3.5 Aerodynamic Flow Effect

From the above simulation results, several conclusions were made. Fig. 16 gives the schematics from the results of the wind tunnel and CFD simulations.

Fig. 16a shows that the wind shadow area formed a native pressure zone. The pedestrian-level wind in the lower position moved to a higher native pressure zone, which caused lower air velocity at the pedestrian-level. This principle can be used to create a low air velocity area.

Fig. 16b shows that the skyway acted as a wind diverter. The wind passing through the skyway was separated into two parts and the air area was decreased by the skyway; however, the air volume per unit area increased, which caused the air velocity under the skyway to increase.

As Fig. 16c shows, the wind flow went through the air duct formed by the urban canyon and the air velocity increased because of the increase in air volume per unit area. This is called a funnel effect, which occurs when narrow building structures cause accelerated air velocity [36].

As Fig. 16d shows, the airflow coming from the back side of the building crossed the podium from the roof. Parts of the airflow were obstructed by the podium opposite, and went down in a reverse direction, causing a lower pedestrian-level wind.

As Fig. 16e shows, streamlining the building edges also changed the air duct area, causing a higher airflow at the narrow section.

4. Conclusion

In this case study, by collecting microclimate and corresponding comfort data for summer and winter, wind comfort criteria were developed to be used as standards for a wind simulation, the results from which were applied to improve wind comfort. While these research methods cannot provide a uniform approach for wind comfort, they give guidance on dealing with wind in special urban areas that have complicated wind environments and individual differences.

A higher air velocity in summer and taking shelter from the wind in winter would improve comfort levels. The residents in Shenyang were more sensation to the wind in summer. The air velocity of 1.12 m/s in summer is the threshold of neutral air velocity. When the air velocity was higher than 1.67 m/s in winter, it was found to be unacceptable.

The prevailing wind directions during hot and cold periods in a monsoon climate city should be used to decide on urban layout as suitable street orientation can control wind attenuation.

Airflow in open spaces can affect spatial quality, and building structures can affect airflow. Building structures were found to cause five types of airflow found in this research, knowledge that can be used to improve pedestrian comfort.

5. Discussion

This research provided a method to evaluate special urban areas with complicated wind environments and individual differences.

As Fig. 17 shows, first, pre-research such as basic geographic information and historical climate information is needed on the target area, from which periods of extreme weather that significantly affect human comfort are identified.

Second, field surveys are conducted during the extreme weather periods to collect sufficient microclimate and comfort data. By analyzing the relation between the microclimate data and average comfort, the comfort variation trends corresponding to the microclimate can be identified and threshold comfort values estimated.

Third, using wind tunnel and CFD simulations to evaluate the current environmental situation, the disadvantages of the current situation can be identified.

Fourth, new designs or reconstruction designs can be proposed to improve wind comfort. The wind tunnel and CFD simulations are conducted again to check the new area and evaluate the new environment.

The fourth step is conducted several times until an optimum design is determined.

For new projects, a neighboring urban area or a space with similar functions not far away from the target area should be chosen to conduct the same work.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number JP25249082. The first author is supported by the Chinese Scholarship Council (CSC) scholarship (File No. 201406080003). The authors would like to express their appreciation to the Hokkaido Research Organization, Building Research Department, Northern Regional Building Research Institute for the wind tunnel simulation experiment.

References

[1] Mohit, M. A. 2013. "Quality of Life in Natural and Built Environment—An Introductory Analysis." *Procedia-Social and Behavioral Sciences* 101: 33-43.

[2] Gehl, J. 2011. *Life between Buildings: Using Public Space.* Washington, DC: Island Press.

[3] Zhu, Y., Shen, Y., Li, Y., and Shi, X. 2014. "A Comprehensive Pedestrian Wind Environment Assessment System for High Density Cities." Presented at the 9th International Symposium on City Planning and Environment Management in Asian Country, Oita, 2014: 171-6.

[4] Verkaik, J. W. 2000. “Evaluation of Two Gustiness Models for Exposure Correction Calculations.” *J Appl Meteorol.* 39 (9): 1613-26.

[5] Verkaik, J. W. 2007. “On Wind and Roughness over Land.” Ph.D. thesis, Wageningen University. The Netherlands. P.123.

[6] Willemsen, E., and Wisse, J. A. 2002. “Accuracy of Assessment of Wind Speed in the Built Environment.” *J Wind Eng Ind Aerodyn.* 90: 1183-90.

[7] Willemsen E, and Wisse, J. A. 2007. “Design for Wind Comfort in The Netherlands: Procedures, Criteria and Open Research Issues.” *J Wind Eng Ind Aerodyn.* 95 (9-11): 1541-50.

[8] Wisse, J. A., and Willemsen, E. 2003. “Standardization of Wind Comfort Evaluation in the Netherlands.” Presented at 11th Int. Conf. Wind Eng. (11ICWE), Lubbock, Texas.

[9] Wisse, J. A., Verkaik, J. W., and Willemsen, E. 2007. “Climatology Aspects of a Wind Comfort Code.” Presented at 12th Int. Conf. Wind Eng. (12ICWE), Cairns, Australia.

[10] NEN (Nederlands Normalisatie Instituut). 2006. *Wind Comfort and Wind Danger in the Built Environment.* NEN 8100 Dutch standard. (in Dutch)

[11] NEN. 2006. *Application of Mean Hourly Wind Speed Statistics for the Netherlands.* NPR 6097:2006 (in Dutch). Dutch practice guideline.

[12] Isyumov, N., and Davenport, A. G. 1975. “The Ground Level Wind Environment in Built-up Areas.” In *Proceedings of fourth international conference on wind effects on buildings and structures,* Heathrow, UK: Cambridge University Press, 403-22.

[13] Lawson, T. V. 1978. “The Wind Content of the Built Environment.” *J Ind Aerodyn.* 3: 93-105.

[14] Melbourne, W. H. 1978. “Criteria for Environmental Wind Conditions.” *J Ind Aerodyn.* 3: 241-9.

[15] Janssen, W. D., Blocken, B., and Van Hooff, T. 2013. “Pedestrian Wind Comfort around Buildings: Comparison of Wind Comfort Criteria Based on Whole-Flow Field Data for a Complex Case Study.” *Building and Environment* 59: 547-62.

[16] Ali-Toudert, F., and Mayer, H. 2006. “Numerical Study on the Effects of Aspect Ratio and Orientation of an Urban Street Canyon on Outdoor Thermal Comfort in Hot and Dry Climate.” *Building and Environment* 41 (2): 94-108.

[17] Lin, T. P., Matzarakis, A., and Hwang, R. L. 2010. “Shading Effect on Long-Term Outdoor Thermal Comfort.” *Building and Environment* 45 (1): 213-21.

[18] Johansson, E., and Emmanuel, R. 2006. “The Influence of Urban Design on Outdoor Thermal Comfort in the Hot, Humid City of Colombo, Sri Lanka.” *International journal of biometeorology* 51 (2): 119-33.

[19] Thorsson, S., Honjo, T., Lindberg, F., Eliasson, I., and Lim, E. M. 2007. “Thermal Comfort and Outdoor Activity in Japanese Urban Public Places.” *Environment and Behavior* 39 (5): 660-84.

[20] Nikolopoulou, M., and Steemers, K. 2003. “Thermal Comfort and Psychological Adaptation as a Guide for Designing Urban Spaces.” *Energy and Building* 35 (1): 95-101.

[21] Nikolopoulou, M., and Lykoudis, S. 2006. “Thermal Comfort in Outdoor Urban Spaces: Analysis across Different European Countries.” *Building and Environment* 41 (11): 1455-70.

[22] Ahmed, K. S. 2003. “Comfort in Urban Spaces: Defining the Boundaries of Outdoor Thermal Comfort for the Tropical Urban Environments.” *Energy and Buildings* 35 (1): 103-10.

[23] Höppe, P. 1984. *Die Energiebilanz des Menschen.* Vol. 49. Munchen: Universitat Munchen, Meteorologisches Institut. (in German)

[24] Fazia, A., and Helmut, M. 2006. “Numerical Study on the Effects of Aspect Ratio and Orientation of an Urban Street Canyon on Outdoor Thermal Comfort in Hot and Dry Climate.” *Int. J Building and Environment* 41: 94-108.

[25] Brown, R., and Gillespie, T. 1986. “Estimating Outdoor Thermal Comfort Using a Cylindrical Radiation: The Mometer and an Energy Budget Model.” *Int. J Biometeor.* 30: 43-52.

[26] Blocken, B. J. E., Stathopoulos, T., and Van Beeck, J. P. A. J. 2016. “Pedestrian-Level Wind Conditions around Buildings.” *Building and Environment* 100 (1): 50-81.

[27] China Meteorological Bureau, Climate Information Center, Climate Data Office and Tsinghua University, Department of Building Technology. 2005. *China Standard Weather Data for Analyzing Building Thermal Conditions.* China Building Publishing House, China.

[28] Tanabe, S. I. 1988. *Thermal Comfort Requirements in Japan.* Doctoral dissertation, Waseda University, Tokyo, Japan.

[29] China Meteorological Administration, National Meteorological Information Center. n.d. “The Database of Climate Standard Daily Value in Chinese International Ground Switching Center.” Beijing (China): China Meteorological Administration, National Meteorological Information Center, Website of Chinese Meteorological Data. Accessed August 4, 2012. http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0.html. (in Chinese)

[30] General Administration of Sport of China. 2014. “Communiqué of Nationals’ Physique.” Accessed November 25, 2015. http://www.sport.gov.cn/n16/n1077/n1422/7331093.html. (in Chinese)

[31] Kaltschmitt, M., Streicher, W., and Wiese, A., eds. 2007. *Renewable Energy: Technology, Economics and*

Environment. New York: Springer Science & Business Media.

[32] Heier, S. 2005. *Grid Integration of Wind Energy Conversion Systems*. Chichester: John Wiley & Sons. p. 45. ISBN: 0-470-86899-6.

[33] Tsutsumi, T. 2009. "Snowdrift Wind Tunnel." *Wind Engineers* 34 (1): 36-41.

[34] Meng, X. W., and Setoguchi, T. 2010. "Development of Urban Design Guidelines with Wind Tunnel Simulations for Downtown Districts in Winter Cities." *Journal of Asian Architecture and Building Engineering* 9 (2): 355-62.

[35] Erell, E., Pearlmutter, D., and Williamson, T. 2012. *Urban Microclimate: Designing the Spaces between Buildings*. New York: Routledge.

[36] Wu, H. 1994. "Pedestrian-Level Wind Environment around Buildings." Doctoral dissertation, Concordia University.