International Journal of High-Rise Buildings
June 2013, Vol 2, No 2, 115-121

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Air Pollutant Dispersion Phenomena at a Street under a Sky Train Station in Bangkok, Thailand

Kyosuke Hiyama[1†], Tomomi Hoshiko[2], Tassanee Prueksasit[3], Shinsuke Kato[4], and Makoto Koganei[1]

[1]*Faculty of Engineering, Yamaguchi University, Yamaguchi, Japan*
[2]*Department of Urban Engineering, Faculty of Engineering, The University of Tokyo, Tokyo, Japan*
[3]*Department of Environmental Science, Faculty of Science, Chulalongkorn University, Bangkok, Thailand*
[4]*Institute of Industrial Science, The University of Tokyo, Tokyo, Japan*

Abstract

The ventilation performance of a street in Bangkok, Thailand, was investigated by performing measurements and conducting a CFD analysis. We focused on a street that was covered by an elevated train station. It was shown that the ventilation efficiency varied drastically depending on the angle between the street and the wind direction. When the wind direction was parallel to the street, the elevated structure had a negative influence, which created higher pollutant concentrations than in locations without elevated structures. However, when the wind direction was perpendicular to the street, the pollutant concentrations in the two situations were similar. Using a CFD analysis and ventilation performance indexes, it was shown that the elevated structure directed the wind flow and enhanced the ventilation efficiency, which positively affected ventilation performance. These kinds of knowledge can lead us to optimize city planning including high-rise buildings with high ventilation efficiency.

Keywords:

---

1. Introduction

One option for reducing the density of toxic gases in the urban atmosphere, and thereby reducing health risks due to air pollution, is to limit the generation of toxic gases. Another option is to dilute the generated gas by mixing urban air with fresh air from higher altitudes. The ultimate objective of this study is to optimize a mechanism for diluting toxic gases in residential areas and enhance urban ventilation efficiency. In particular, this study aims to optimize the ventilation performance of streets in Asian cities, where air pollution due to automobile emissions continues to be a significant concern.

Although elevated structures, such as elevated highways and train stations, enrich the transportation system, they decrease the air quality below them because such structures are obstacles to ventilation (Charusombat, 1994). This tendency is significant if the elevated structures are surrounded by high-rise buildings. In this paper, we clarify the impact of an elevated structure on the air quality underneath the structure. First, we performed measurements to qualitatively study the actual situation on a street beneath an elevated structure in Bangkok, Thailand (Hiyama et al., 2011a). Then, we conducted CFD analyses to observe the wind and pollutant dilution characteristics and quantitatively evaluate the ventilation performance (Hiyama et al., 2011b, 2012). For the quantitative analysis, we used the purging flow rate (PFR) and the local air change rate (LACR). With the results of the measurements and CFD analysis, we analyzed the airflow phenomena in a street canyon with an elevated structure and the vertical ventilation performance.

2. Measurements

Concentrations of NO_2, which has a strong correlation with traffic volume, were measured on “Rama I Street” in Bangkok, Thailand (Hiyama et al., 2011a). This street is partially covered by the BTS railway and passes by the BTS “National Stadium Station”. We determined the effects of elevated structures from measurements taken at two different locations on the street. The first location (a) is a point that is not covered by an elevated structure, and the second, location (b), is a point where there is a BTS station and all lanes are covered by an elevated structure (Figure 1).

Figure 2 shows the wind directions measured approximately 1 km south of the street at the meteorological observation station at Chulalongkorn University. For wind direction, an angle of zero degrees represents a northerly wind. On the 27th of January, the wind was blowing from the northwest until approximately 7:00, when it shifted to a constant easterly wind. Because Rama I Street runs east to west, the day was characterized by wind blowing pa-

---

[†]Corresponding author: Kyosuke Hiyama
Tel: +81-836-85-9711
E-mail: hiyama@yamaguchi-u.ac.jp

Location (a): Normal street Location (b): Street covered by an elevated structure

Figure 1. Locations of measurements.

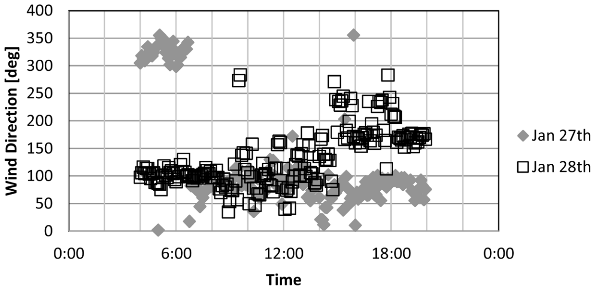


Figure 2. Measured wind direction.

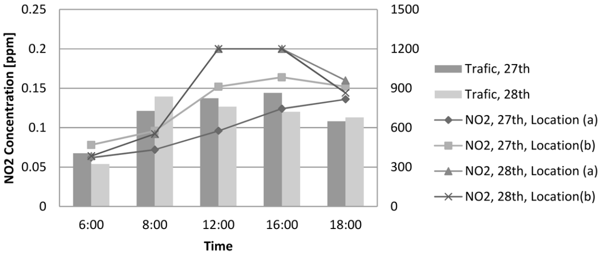


Figure 3. Traffic and NO_2 concentrations.

rallel to the street. However, unlike on the 27th, the wind direction was not constant throughout the day on January 28th. The wind shifted from easterly in the morning to westerly in the evening. The day was characterized by the wind direction shifting throughout the day.

Figure 3 shows the relationship between traffic volume and NO_2 concentration. The concentrations were higher at location (b) relative to location (a) on the 27th, when the wind was blowing parallel to the street. This difference is an indication of a reduction in ventilating efficiency due to the elevated structures that cover the road area. In contrast, the concentrations at the two locations were similar on the 28th, when the wind direction shifted throughout the day. This similarity is an indication of the absence of a correlation between the elevated structure covering the road area and the ventilating efficiency. Uehara et al. showed that the lid effect from an elevated road does not significantly increase ground-level concentrations when the wind direction is perpendicular to the road (Uehara et al., 2003). Thus, the lid effect was not prominent on January 28th. The results also show that the concentrations on the 28th were higher than those on the 27th, even though the traffic volumes were almost the same. This finding indicates that the ventilation efficiency can be strongly influenced by the wind direction.

3. CFD Analysis

3.1. Subjects of the CFD analysis

In the measurements, the sky train station only had an obvious impact on the air quality when the wind direction was parallel to the street. To determine the cause of this phenomenon, we conducted a CFD analysis. Figure 4 shows an outline of the calculation target. We used two models, Model 1 and Model 2, for the comparison. Model 1 contains a cavity that represents a street canyon, such as a roadway surrounded by buildings. Model 2 contains a cavity that represents a street canyon with an elevated structure, such as a sky train station in Bangkok. To generalize the problem, we used simplified models. The height of the cavity was 17.5 m, which corresponds to the height of a building with five floors. The width of the cavity was 25 m, which corresponds to the width of a 5-lane roadway with sidewalks. The length of the cavity was 200 m. In Model 2, an object corresponding to a sky train station was installed above the cavity. The bottom surface of the elevated structure was located 7 m above the bottom surface of the cavity. The height of the object was 7 m, which corresponds to the height of a sky train station with 2 floors. Its width was 20 m, and its length was 100 m. We used these models to analyze the wind and pollutant dilution characteristics for two cases. The first case has a wind direction parallel to the street canyon, and the other case has a wind direction perpendicular to the street canyon. In this case studies, we assume that sea breeze is blowing over the models and keep the air clean.

3.2. Calculation conditions

Table 1 shows the calculation conditions of the inflow. The outflow condition was solved by applying a no gradient condition to the normal line. The lateral faces were treated as symmetrical boundaries, and the top face was treated as a free-slip boundary; the surface wall equation was solved by applying the generalized logarithm law. The standard k-ε model was employed for the turbulence

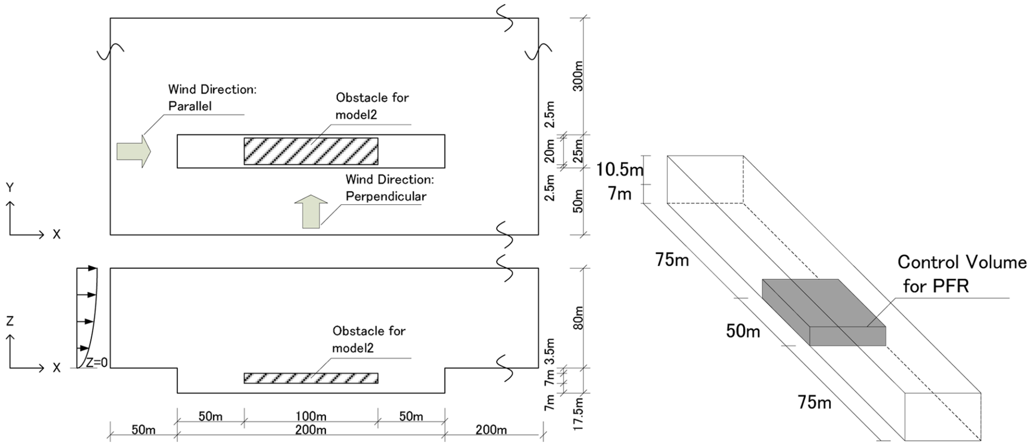


Figure 4. Calculation mode and control volume for concentration generation.

Table 1. CFD calculation conditions

Inflow condition	$U = U_0 \times (Z/Z_0)^{1/4}$, $k = 1.5 \times (I \times U)^2$, $I = 0.1$, $\varepsilon = C_\mu \times k^{3/2}/l$, $l = 4(C_\mu \times k)^{1/2} Z_0^{1/4} Z^{3/4}/U_0$

Z_0: referential height 10.0 m, U_0: referential velocity 1.0 m/s, U: wind velocity, Z: vertical coordinate [m], k: turbulent energy [m^2/s^2], ε: energy dissipation [m^2/s^3], I: turbulent intensity, l: turbulence length [m]

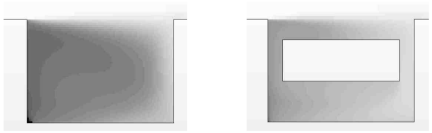
model. The first-order upwind differential scheme was used for the advection term, and the second-order upwind differential scheme was used for the concentration. According to the concentration transport calculation, once the flow field was calculated, the scalar equation was solved as a passive contaminant. The concentration field was analyzed when the contaminant was uniformly discharged from the control volume in the cavity. This parameter was used because there is a massive amount of clean air flowing in the atmosphere above cities, and the ventilation efficiency can be evaluated by approximating the airflow intake into the cavity from higher altitudes. Figure 4 shows the control volume. The control volume was determined at the center of the cavity. The source rate was 1 kg/m^{3}s. The calculation area was divided into a mesh of approximately 1,000,000 elements. The mesh size in the cavity under the elevated structure was 0.5 m × 0.5 m × 0.5 m. The mesh size increased as it grew outward from the cavity. The maximum size was 5.0 m × 5.0 m × 5.0 m.

3.3. Calculation results

Table 2 shows the results of the average source concentrations source in the control volume, as shown in Figure 5. The concentration in Case 3, where the wind direction was parallel to the street and the elevated structure was present, is obviously higher than that in Case 1, without the elevated structure. When the wind direction was parallel to the street, an obvious impact of the elevated structure was observed. In contrast, the concentrations in Case 2 and Case 4 have no such obvious differences. The results show the same tendencies that were observed in the experimental measurements. Figure 6 shows the velocity fields in the cavity for Case 2 and Case 4 for a cross section in the Y direction. In Case 2, a vortex was observed in the cavity. The pollutant concentration was transported by the vortex and diluted by the wind passing above the cavity.

a) Case 1

b) Case 3

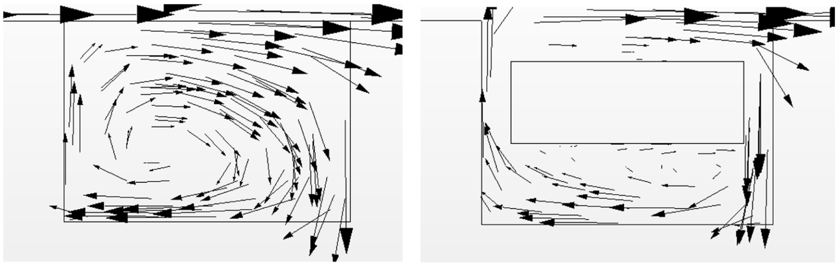


a) Case 2 b) Case 4

Figure 5. Scalar field; cross sections at the center of street in the X-direction for Case 1 and Case 3 and in the Y-direction for Case 2 and Case 3. The unit of the scalar concentration is kg/m^3.

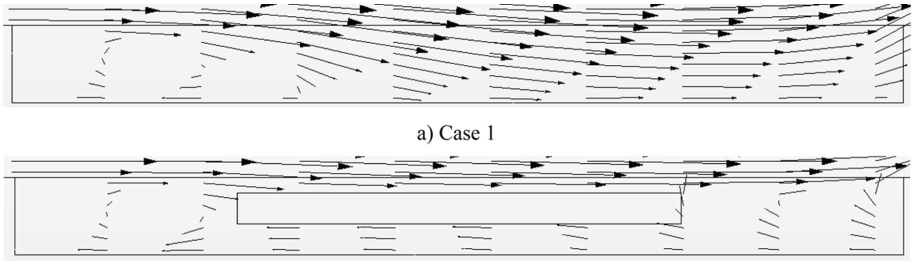
Table 2. Average concentrations in the control volume

Case No.	Case 1	Case 2	Case 3	Case 4
Existence of elevated structure	No	No	Yes	Yes
Wind direction to street	Parallel	Perpendicular	Parallel	Perpendicular
Concentration [kg/m^3]	68	430	400	360



a) Case 2 b) Case 4

Figure 6. Velocity field; cross sections at the center of street in the Y-direction.



a) Case 1

b) Case 3

Figure 7. Velocity field; cross sections at the center of street in the X-direction (length scale of vectors is different from that in Figure 6).

In this case, even when an obstacle was present at the center of the cavity, it did not have an obvious influence on the flow field created by the vortex. Furthermore, the obstacle could play a role in arranging the flow made by the vortex and enhancing airflow in the cavity. As a result, the concentration in Case 4 became lower than the concentration in Case 2. In contrast, the obstacle played a different role when the wind direction was parallel to the street. Figure 7 shows the velocity fields in the cavity for Case 1 and Case 3 for a cross section in the X direction. In Case 1, the airflow passing above the cavity blew down into the cavity and diluted the pollutant concentration generated in the control volume. In contrast, the airflow passing above the cavity in Case 3 becomes part of the airflow circulating around the obstacle and also contributes to the phenomenon observed in Case 4. Furthermore, the wind direction at the bottom of the cavity in Case 3 is opposite the direction observed in Case 1. In these contexts, the characteristics of the concentration dilution are dramatically changed by the existence of the elevated structure. While the values of the concentrations in Cases 2, 3 and 4, in which circulation flow fields such as vortexes are observed, are the same, the concentration in Case 1 is 10% less than the other cases. In other words, the efficiency of the ventilation in Case 1 is more than ten times greater than the other cases.

4. Discussions

4.1. Quantitative evaluation using PFR

From the results of the CFD analyses, we evaluated the ventilation efficiency on each measurement date. The amount of pollutant generated had a large influence on the observed concentration. To study the ventilation efficiency, we excluded the pollutant emission rate. Then, we used *PFR* and *LACR* as generalized indexes to evaluate the ventilation efficiency.

PFR was originally defined as the effective airflow rate required to remove or purge the local pollutants. Eq. (1) shows the definition of *PFR*. In this paper, we use m^3/h as the unit of *PFR*:

$$PFR = q/c \tag{1}$$

where q is the spatially uniform generation rate of the pollutant source [kg/h] and c is the average concentration over the entire target domain [kg/m^3].

PFR can also be defined by Eq. (2):

$$PFR = V/(VF \times T) \tag{2}$$

where V is the volume of the area [m^3], VF is the visitation frequency [-] and T is the average length of time the pollutant remains in the area [h].

The idea of *PFR* includes the idea of *VF*. The *VF* describes the average frequency with which pollutants generated in the local domain return to the local domain after being transported outside it (Bu et al., 2009). Therefore, the *PFR* indicates the airflow rate itself, which works to effectively dilute the air pollution in the targeted domain. The airflow that returns to the local domain after being transported outside once is excluded from the *PFR*. Furthermore, the *LACR* in the investigated area is calculated by dividing the *LACR* by the volume of area *V*. This process is shown in Eq. (3).

$$LACR = PFR/V \quad (3)$$

Sandberg (1983) first proposed the idea of the *PFR*. It has been widely used as an index to evaluate ventilation performance and air quality in indoor airflow problems (Peng and Davidson, 1997). At present, its usage has been expanded to include the evaluation of ventilation performance in outdoor airflow problems (Bu et al., 2009, 2010, 2011; Bady et al., 2011).

Table 3 shows the *PFR* and the *LACR* for each case. In Case 1 and Case 3, the indexes were recalculated with a wind velocity of 1.7 m/s at a height of 18 m, assuming the average wind velocity on January 27th, when the measurement was performed. In Case 2 and Case 4, the indexes were recalculated with a wind velocity of 1.3 m/s, assuming the average wind velocity on January 28th, when the measurement was performed. Kato (2010) noted that the *LACR* outdoors should be satisfied over 60 times to reduce the health risk to residents in the buildings along a street. We should note that the area with the sky train station on Rama I Street did not satisfy this criterion on January 27th, while the area without any elevated structure did satisfy this criterion. However, there were no obvious effects from the sky train station on January 28th, when the wind direction was perpendicular to the street. In contrast, the CFD results reveal the possibility that the sky train station enhances ventilation by effectively diluting the pollutants. Therefore, we cannot simply conclude that the sky train station dramatically reduces the air quality under it. Kato (2010) also noted that the ventilation efficiency must be evaluated with year-round hours of probable exceedance. Using the full-year wind profile and an exceedance probability analysis using the indexes, we can optimize the locations of elevated structures. The optimization can minimize the impacts of elevated structures on the air quality beneath them, for example, by preventing structures from being built above streets parallel to the main wind direction of the target city. Furthermore, it could possibly enhance the ventilation efficiency, for example, by positioning the elevated structure above the street perpendicular to the main wind direction and, thus, enhancing the creation of wind vortexes, as shown in the CFD analysis. With the accumulation of these devices, we expect that optimized city planning can be achieved by satisfying the exceedance probability is satisfied and minimizing the health risks to pedestrians.

4.2. Qualitative evaluation

To understand the concentration dilution phenomenon and reduce health risks to pedestrians, we need to understand the idea of ventilation paths. There are two types of ventilation path: a horizontal ventilation path and a vertical ventilation path. The vertical ventilation paths have an especially important role in dense urban areas (Kato and Hiyama, 2012). Vertical ventilation is defined as vertical introduction to wind, as outlined in Figure 8. In coastal cities such as Bangkok, thick, cool layers of air are produced over the sea. Vertical ventilation paths enable the introduction of the cool air to the urban area by redirecting the wind from the skies above the city. To understand vertical ventilation, knowledge of the airflow in a street canyon is necessary. The airflow and diffusion properties in a street canyon are determined by its shape and the condition of the wind above it. The building-height-to-street-width aspect ratio (H/W) is used to express the shape of a street canyon. H is the building height, and W is the street width. Oke (1988) determined three flow regimes for wind perpendicular to the street axis in neutral stratification. Figure 9 shows the outlines of these regimes. When the distance between buildings is relatively long ($H/W < 0.3$), the airflows around buildings do not interact. The recirculation created in front of the building and the wake behind the building occur continuously, and the wind above the buildings flows into the street between the buildings. This flow regime is called "isolated roughness flow". Meanwhile, when the distances between buildings become shorter ($0.3 < H/W < 0.7$), the wake behind the upwind building is disturbed by the recirculation flow generated by the buildings in front of it. This flow regime is called "wake interference flow". When the buildings are much closer ($0.7 < H/W$), the recirculation flow becomes stable. In this situation, the interaction between the airflow above buildings and the wind inflow into the street becomes smaller. This flow regime is called "skimming flow". Generally, street canyons tend to create skimming flow. The case studies in this paper can be divided into two regimes. In Case 2 and Case 4, the H/W in the wind direction perpendicular to the street is greater than 0.7. In these cases, the flow regime is skimming flow, and the concentration in the street canyon is advected by the recirculation flow. Because recirculation flows are not influenced by the obstacle, there are no large differences in the concentrations between Case 2 and Case 4. Mean-

Table 3. *PFR* and *LCAR*

Case No.	Case 1	Case 2	Case 3	Case 4
PFR [m^3/h]	680000	82000	120000	98000
LACR [1/h]	78	9.4	13	11

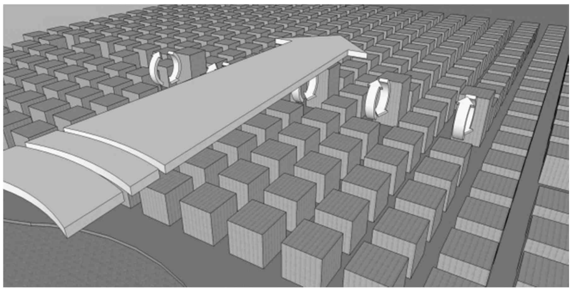
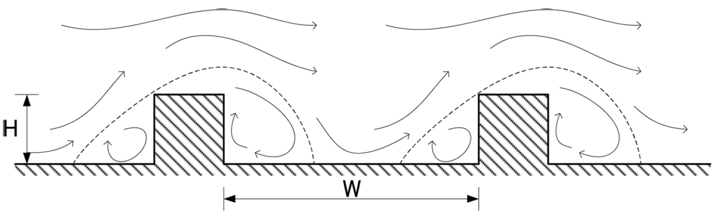
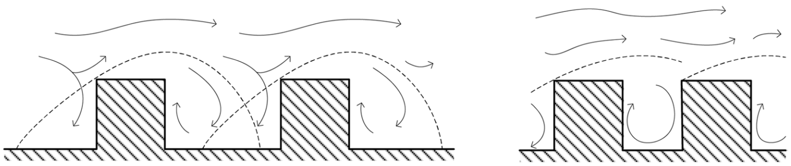


Figure 8. Image of vertical ventilation (Kato and Hiyama, 2012).



a) Isolated roughness flow (H/W < 0.3)



b) Wake interference flow (0.3 < H/W < 0.7) c) Skimming flow (H/W > 0.7)

Figure 9. Three flow regimes associated with air flow over building arrays with increasing H/W (Li et al., 2006).

while, in Case 1 and Case 3, the spacing of the buildings in the wind direction parallel to the street is much larger. H/W is less than 0.3. In these cases, the flow regime is isolated roughness flow. The airflow known as backward-facing step flow is induced in the street over the wake (Spazzini et al., 2001). In these cases, the obstacle blocks the inducing flow and reduces the ventilation performance. In this context, the concentration in Case 3 becomes much higher than in Case 1.

5. Conclusions

To reduce health risks in urban environments, it is necessary to reduce outdoor pollutant concentrations. To accomplish this reduction, using urban ventilation to efficiently dilute the pollutants generated in city areas has attracted a great deal of attention, in addition to using source control to reduce the actual release of pollutants. Especially the idea of urban ventilation is important for the city planning with mass of high-rise buildings. To address these issues, we performed measurements in Bangkok, Thailand, and conducted a CFD analysis to evaluate the ventilation efficiency. In this paper, we focused on the impact of an elevated structure on the ventilation efficiency. In the experimental measurements, a phenomenon was observed in which the ventilation efficiency in an area with an elevated structure obviously declined when the wind direction was parallel to the street. In contrast, there were no obvious impacts from the elevated structure when the wind direction was perpendicular to the street. Through CFD analysis, we analyzed the wind and pollutant dilution characteristics. When the wind direction was parallel to the street in cases without an elevated structure, the wind pushed the pollutants and removed them from the street. In the case including an elevated structure, the pollutants were removed by wind circulation along the elevated structure. When the wind direction was parallel to the street, the existence of the elevated structure had an obvious influence and decreased the efficiency by almost one tenth. However, there were no obvious influences when the wind direction was perpendicular to the street. In contrast, the elevated structure directed the wind flow and enhanced the ventilation efficiency. To exclude the effect of the amount of pollutant emissions and focus on the ventilation efficiency itself, we used *PFR* and *LACR* as generalized indexes. With the year-round exceedance analysis using the indexes and the full-year wind profile, we can plan for optimized elevated structures. The results reveal the possibility that the optimization of elevated structure locations could not only contribute to minimizing the impact of the structures on the ventilation efficiency but could also increase the ventilation efficiency by directing the circulation flow in street canyons.

Note

This paper is an edited version of previous literature (Hiyama et al., 2011a, 2011b and 2012).

Acknowledgements

This research is granted by the Center for Sustainable Urban Regeneration (cSUR), The University of Tokyo.

References

Bady, M., Kato, S., Ishida, Y., Huang, H. and Takahashi, T. (2011). “Application of exceedance probability based on wind kinetic energy to evaluate the pedestrian level wind in dense urban areas.” *Building and Environment*, 46(9), pp. 1817~1826.

Bu, Z., Kato, S., Ishida, Y. and Huang, H. (2009). “New criteria for assessing local wind environment at pedestrian level based on exceedance probability analysis.” *Building and Environment*, 44(7), pp. 1501~1508.

Bu, Z., Kato, S. and Takahashi, T. (2010). “Wind tunnel experiments on wind-induced natural ventilation rate in residential basements with areaway space." *Building and Environment*, 45(10), pp. 2263~2272.

Bu, Z. and Kato, S. (2011). "Wind-induced ventilation performances and airflow characteristics in an areaway-attached basement with a single-sided opening." *Building and Environment*, 46(4), pp. 911~921.

Charusombat, U. (1994). "Air pollution distribution under an elevated train station (A case study of silom station in downtown Bangkok)." Thesis submitted to the Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Master of Science in Environmental Engineering.

Hiyama, K., Hoshiko, T., Abe, S., Kato, S. and Prueksasit, T. (2011a). "Field measurement to assess the correlation between wind ventilation performance of and wind structure inside a street with an elevated structure in Bangkok, Thailand." *Procedia Environmental Sciences*, 4, pp. 239~244, Urban Environmental Pollution 2010.

Hiyama, K., Hoshiko, T., Kato, S. and Prueksasit, T. (2011b). "Study on air pollutant dispersion under a sky train station in bangko" International Workshop on Physical Modelling of Flow and Dispersion Phenomena, PHYSMOD-2011, pp. 296~303

Hiyama, K., Hoshiko, T. and Kato, S. (2012). "Vertical ventilation path and its impact on reduction of pollutant in street canyon." International conference on "Industrial Waste management and Process Efficiency", November 13-15, 2012. 11, Dhaka, Bangladesh, pp. 15~24.

Kato, S. (2010). "Urban wind environment and it's impact on indoor environment: Acceptable wind features of void space." in Proceedings of the 7th International Conference on Indoor Air Quality Ventilation and Energy Conservation in Buildings, Syracuse, New York, USA.

Kato, S. and Hiyama, K. (2012). Ventilating cities - Air-flow criteria for healthy and comfortable urban living, Springer, pp. 135~150.

Li, X.-X., Liu, C.-H., Leung, D. Y. C., Lam, K. M. (2006). "Recent progress in CFD modelling of wind field and pollutant transport in street canyons." *Atmospheric Environment*, 40, pp. 5640~5658.

Oke, T. R. (1988). "Street design and urban canopy layer climate." *Energy and Buildings*, 11, pp. 103~113.

Peng, S. H. and Davidson, L. (1997). "Towards the determination of regional purging flow rate." *Building and Environment*, 32, pp. 513~525.

Sandberg, M. and Sjoberg, M. (1983). "The use of moments for assessing air quality in ventilated rooms." *Building and Environment*, 18, pp. 181~197.

Spazzini, P. G., Iuso, G., Onorato, M., Zurlo, N. and Di Cicca, G. M. (2001). "Unsteady behavior of back-facing step flow." *Experiments in Fluids*, 30, pp. 551~561.

Uehara, K., et al. (2003). "Wind tunnel experiments on roadside air pollution around an actual major road in an urban area: Lid effect of an elevated road and prediction of concentrations within the street canyon." *Journal of Japan Society for Atmospheric Environment*, 38(6), pp. 358~376.