State and Prospects of Outdoor Environment Research in TPU

Ryuichiro Yoshie

Tokyo Polytechnic University, 1583 Iiyama, Atsugi city, Kanagawa, Japan

ABSTRACT: The Global COE Program "New Frontier of Education and Research in Wind Engineering" of Tokyo Polytechnic University (TPU) will be completed at the end of March, 2013. In the five year period of the program, the team Project 3 has been carrying out researches on outdoor wind/thermal environment and air pollution. This paper outlines the framework of the entire research plan of the Project 3, and introduces some of the research results that we achieved remarkable progress. These study areas are taking important role in the framework of the entire research of the Project 3. This paper also shows future perspective of the Project3, and discusses the strategy and responsibility of our generation to maintain the activities of Wind Engineering Research Center of TPU.

KEYWORDS: Global COE program, Heat island phenomena, Air pollution, Urban ventilation, Urban planning, Atmospheric stability

1 INTRODUCTION

Winds have a great influence on the outdoor environment in urban areas. Problems they cause roughly be classified into strong wind and weak wind issues. Strong winds around high-rise buildings bring about unpleasant and in some cases dangerous situations for people in outdoor environment. Weak wind conditions can also cause problems. Air pollution and the heat island phenomena become more serious in weak-wind regions in urban street canyons. The importance of urban ventilation is now broadly recognized as a countermeasure to the urban heat island phenomena and air pollution problem, so it is becoming extremely important to ensure adequate air ventilation paths in urban spaces. The winds enhance natural ventilation in buildings which can reduce the energy consumption of mechanical ventilation fans and air conditioners for cooling. The moderate winds improve human thermal comfort for both indoor and outdoor environment in summer. The environmental wind engineering associated with the wind tunnel experiment, field measurement, and numerical analysis can contributes to the solutions of those issues.

In the Global COE program of Tokyo Polytechnic University, Project 3 covers research and education in the fields of outdoor wind environment and air pollution. The ultimate purpose of the project is proposal of guidelines for urban development. Fig.1 shows framework of the entire research of Project 3. Many research items direct toward this ultimate goal with some of them closely related to each other. In this article, achievement in some of the important study areas, namely: Reproduction of occurrence frequencies and vertical profiles of wind velocity and temperature by meso-scale simulation, Generalization of convective heat transfer from urban canopy surfaces, Effects of building arrangement on urban ventilation and their generalization, Effect of atmospheric stability on urban pollutant concentration and its generalization, Large Eddy Simulation of gas/thermal dispersion in non-isothermal boundary layer, are outlined and presented.



Figure 1 framework of the entire research of Project 3

2 RESEARCH RESULTS OF OUTDOOR ENVIRONMENT IN TPU

2.1 *Reproduction of occurrence frequencies and vertical profiles of wind velocity and temperature by meso-scale simulation*

To assess the pedestrian wind environment around tall buildings based on occurrence frequencies of wind velocities, we need reliable statistical wind observation data from near their construction sites. However, wind observatories are not always located near construction sites. Even if they do, the observation height is sometimes not high enough and the wind data are affected by surrounding buildings. Meso-scale simulation can be an alternative to direct observation. We aimed to use the WRF (The Weather Research and Forecasting Model), a meso-scale simulation model, in order to prepare standard wind data at high-altitude for the assessment of the pedestrian wind environment. We also aim to use WRF for research on urban heat island phenomena, which is becoming serious in large cities in Japan. One of the effective countermeasures against heat island phenomena is to lead cool air of sea breeze into urban canopies. This strategy strongly depends on the vertical profile of wind velocity and the temperature of the sea breeze. Before doing these investigations using WRF, it is necessary to confirm how WRF can correctly reproduce the occurrence frequencies and vertical profiles of wind velocities. For this validation, observation data measured by Doppler Sodar in the Minami Senju district in Tokyo (Miyashita et al. 2002) were used. In order to well regenerate the vertical profile of wind velocity by WRF, it is considered that an appropriate surface roughness should be given to the WRF calculation. However, the default setting of WRF based on USGS (United States Geological Survey) expresses urban areas as only by one category and gives a uniform roughness length regardless of building densities and heights.

Thus, we used GIS (Geographic Information System) data to appropriately classify urban landuse categories and to give roughness lengths to the WRF calculation. We conducted two cases of WRF calculations using a default setting and using GIS data, and the results were compared with the observation data.

Calculations were carried out for a period of six month from January 1 to June 30, 2000. To set initial and boundary conditions we used FNL (Final) Operational Global Analysis data from the NCEP (National Center for Environmental Prediction). The calculations were conducted using three-stage, two-way nesting grids. The calculation domains is shown in Fig. 2. The Minami Senju district, used for the comparison, is included in Domain 3.



Figure 2 Computational Domain

The default setting of WRF employs the USGS's 24 categories of land use and their corresponding ground-surface parameters such as roughness length, albedo, and so forth. However, in the USGS, urban area is expressed by only one category and its roughness length is uniformly 80cm regardless of building density and building height. Moreover, some areas that would be considered "urban" in reality are classified as pasture, grassland, and other categories in the USGS. Thus, the USGS does not sufficiently express the actual circumstances of Tokyo. For these reasons, we used GIS data published by the Ministry of Land, Infrastructure, Transport, and Tourism to appropriately classify land-use categories. Furthermore, we classified the urban area into three categories, "Low", "High", and "Commercial" (Table 1). We used roughness lengths of 70cm, 100cm, and 150cm for Low urban area, High urban area, and Commercial urban area, respectively. We adopted these values by referring to Grimmond and Oke (1999). Fig. 3 shows land-use categories based on the USGS and the GIS, which shows large differences between them.

No.	USGS/SIB Land-Use Category	GIS Land-Use Category	Urban Category	Surface Z0 [cm]	Albedo [%]	Soil Moisture [%]	Surface Emmisivity [%]
		House and	Low	70			
1	Urban Land	Dahlia Dadidia a	High	100	15	10	88
		Fablic Building	Commercial	150			
2	Dryland Cropland and Pasture	Farm	-	15	17	30	98.5
3	Irrigated Cropland and Pasture	Paddy Field	-	10	18	50	98.5
7	Grassland	Park and Grass	-	12	19	15	96
15	Mixed Forest	Forest	-	50	13	30	97
16	Water	Lake and Sea	-	0.01	8	100	98
19	Barren or Sparsely Vegetated	Soil Surface	-	1	25	2	90

 Table 1
 Land-use Categories and Surface Parameters



Figure 3 Land-use Categories in Domain 3

We carried out two kinds of calculations: one using the default setting of WRF with USGS (Case 1), and the other using the land-use categories and surface parameters based on GIS data. Fig. 4 and Fig. 5 compare wind rose and probabilities of exceedance of mean wind velocity (10 minutes averaging 300m high) between the results of WRF and observation data, respectively. Calculated wind roses by Case1 and Case2 agreed well with the observation data. The probability of exceedance of wind velocity calculated by Case 2 agreed very well with the observation data. The probability of exceedance calculated by Case 1 was higher than that of Case 2. However, the difference was not so large at this high altitude.



For the comparison of vertical profiles for mean wind velocity, we firstly extracted southerly wind (wind direction= $180^{\circ} \pm 33^{\circ}$ at 200m high) for both observation and calculation. Then the vertical profiles of wind velocity of the observation data were classified into eight clusters by cluster analysis. Corresponding clusters of calculated results were made so that each cluster at the same time of the observation data became the same cluster. Fig. 6 shows vertical profiles of wind velocities in representative four clusters. Averaged values $\pm 1 \sigma$ (standard deviation) at each height in each cluster are plotted in the figures. The percentage shown in the caption for each cluster is the occurrence frequency for that cluster. There is a pretty good match between observation and calculated results. In particular, Case 2 using GIS is remarkably close to the observation values. Case 1, using the default setting of USGS, generally show higher values than the observation data.



Figure 6 Vertical Profile of Mean Wind Speed

As mentioned above, it becomes clear that the WRF can well reproduce the wind rose and occurrence frequencies and vertical profiles of wind velocity if the roughness length is appropriately given. Although description about temperature was omitted in this manuscript, occurrence frequencies and vertical profiles of the temperature were also investigated. It was found that occurrence frequencies and vertical profiles of temperature calculated by the WRF agreed very well with the observation data except at lower altitude. Prediction accuracy of the temperature at lower altitude was improved by coupling an Urban Canopy Model with the WRF. Thus, we obtained a prospect that the WRF can be used for our purpose, i.e. preparation of standard high-altitudes wind data, extraction of representative vertical profiles of wind velocity and temperature, and analysis of urban heat island phenomena.

2.2 Generalization of convective heat transfer from urban canopy surfaces

The WRF coupled with an Urban Canopy Model is considered as an effective tool for the prediction of urban heat island phenomena. The Urban Canopy Model is responsible for predicting the heat transfer from the urban canopy to the overlaying atmosphere. In the Urban Canopy Model (Kusaka et al., 2001) adopted by the WRF, the local convective heat transfer from the urban canopy surfaces and its dependence on urban parameters such as building coverage ratio and building height variations are not explicitly modeled. In the model, the Convective Heat Transfer Coefficient (CHTC) from canopy surfaces is evaluated from Jurge's formula (1924). It is based on the CHTC of a heated copper square plate, which was oriented perpendicular to a uniform air flow in a wind tunnel. In this formula, the local convective heat transfer coefficient from building walls and ground depends only on the velocity inside the canopy. However, this cannot be justified since other urban parameters also contribute to the heat transfer coefficient. Moreover, this model cannot distinguish the difference between convective heat transfer coefficients on different wall surfaces, i.e., windward, leeward, side wall of the building and the ground, instead it expresses the CHTC generally as wall. Thus, we need to generalize the CHTC of the building canopy surfaces (ground, windward wall, leeward wall and side wall) more explicitly with respect to the urban parameters that affecting the CHTC of urban canopy surfaces.

For this purpose, wind tunnel experiments were firstly carried out to roughly grasp the dependence of urban parameters on bulk heat transfer from an urban canopy in a thermally stratified wind tunnel as shown in Fig. 7 and 8. Six experimental cases were carried out for different configurations of urban canopy (three cases with uniform-height blocks of 0.05m and the other three cases with 0.05m and 0.1m-height blocks arranged in a staggered manner). The mixed arrangement of 0.05m- and 0.1m-height blocks are referred to as non-uniform-height cases. The building coverage ratios (hereafter referred to as BCR) were varied as 6%, 11% and 25% for both the uniform- and the non-uniform-height cases.



Figure 7 Experimental setup

$ \begin{array}{c} \rightarrow & \text{Inlet X=0} \\ \rightarrow & 1.9 \text{ m/s} \\ 7.8 \text{ deg C} \\ \rightarrow & & & \\ \end{array} $						0.75m
1.85 m			6.925 m	Measurir	ng section (Outlet) 🥒	
WxDxH						
0.05 x 0.05 x 0.05						
All dimensions in m						
Build coverage ratio	25 %	11.125 %	6.25 %	25 %	11.125 %	6.25 %
Category	uniform height	unifrom height	uniform height	non-uniform height	non-uniform height	non-uniform height

Figure 8 Experimental setup and List of experimental cases

However, it is not an easy task in wind tunnel experiments to evaluate local CHTC, which vary on individual surfaces of building roof, wall and ground. Hence CFD simulation with a low-Reynolds-number k- ε model was conducted to predict the convective heat transfer on these surfaces. The two-equation heat-transfer low-Reynolds-number model proposed by Abe et al. (1994, 1995) was chosen for the present work. Abe et al. reported that this model quite successfully predicted turbulent heat transfer in a separating and reattaching flow. The computational domain was an exact replica of the wind tunnel in windward length and vertical height. Minimum width was selected by considering symmetry in the Y direction. Fig. 9 shows a top view of the computational domain and grid arrangement (for example: BCR-25% case). Structured mesh arrangement with very fine mesh near the wall surfaces (first mesh 0.2mm from wall surfaces). As a result, non-dimensional distances from the wall Y⁺ were below 1.0 for most of the fluid cells close to the wall surfaces. No- slip boundary conditions were applied for wall shear stress. For thermal boundary conditions, surface temperatures obtained from the experiments were prescribed and a heat conduction boundary condition (Fourier's Law) was applied for heat flux on the wall surfaces.



Figure 9 Top view of part of computational domain (For example: BCR-25% case)

Figure 10(a) and (b) compares the bulk heat transferred from the urban canopy by the experiments and the CFD simulations for uniform- and non-uniform-height cases, respectively. The CFD results showed good agreement with the experimental results. The velocity and temperature profiles of the CFD results also corresponded well with the experimental results for all cases (Pillai et al., 2010). Thus, we judged that the CFD simulations were valid.



After this validation, the local CHTC for a particular wall surface was investigated from the CFD results. The heat flux q (W/m²) on the floor and block surfaces were obtained from CFD results and surface integrated for each surface area. The local CHTCs for individual canyon surfaces were obtained from equation (1)

$$CHTC = \frac{\sum_{j=1}^{m} q_j A_j}{S \cdot (T_s - T_R)}$$
(1)

where *CHTC* - convective heat transfer coefficient (W/m²°C), q_j = surface heat flux on individual cells on floor and block surfaces (W/m²), A_j =area of individual cells on surfaces, m = number of cells on floor and block surfaces, S = area of individual canyon surfaces like windward wall, leeward wall, ground wall and side wall (m²), T_s = area-weighted average temperature of ground and block surfaces (°C), T_R = reference temperature (°C).

Fig. 11 and Fig. 12 (for example) shows the local CHTC of canyon surfaces with horizontal distance in the flow direction for roof, windward wall, leeward wall and ground The CHTC decreases with the horizontal distance in the windward direction due to higher air temperature in the downstream direction. Moreover, the CHTC increases with decrease in building coverage ratio. The CHTC is higher for roof and windward wall than the other surfaces like leeward wall and ground. Thus, the effect of building coverage ratio and building height variation of an urban canopy should be considered in evaluating the CHTC of canopy surfaces. Also, the CHTC should be modeled for individual building surfaces and not in general as CHTC for walls.



Figure 12 CHTC profile in horizontal distance in the flow direction for individual canopy surfaces for 25% BCR.

Although these results were obtained from a CFD simulation at wind-tunnel-model scale, it would be applicable to real-scale heat transfer phenomena if there were a valid similarity between the scales. We checked the similarity by performing CFD simulation for 10 times and 100 times the wind tunnel model scale. It was confirmed by the relationship between Rex (local Reynolds number) and Nux (local Nusselt number). As shown in Fig. 13, the relationships between Rex and Nux obtained from different scale simulations could be expressed by one function regardless of scale and wind velocity. Thus the local CHTCs from model scale can be converted to those of real scale.



Figure 13 Relationship between local Reynolds number and local Nusselt number.

After this confirmation, parametric CFD simulations more than 30 cases changing urban configuration parameters were conducted in order to generalize the CHTC from the urban canopy surfaces to the atmosphere. Tentative equations for evaluating local CHTC from urban parameters and atmospheric parameters were proposed based on the results of the parametric CFD simulation. Fig. 14 compares the local Nusselt number (Nux) obtained from the proposed equation and CFD simulations. The proposed equation well expresses the Nux obtained from the CFD simulations. But we need more parametric studies to increase generality. The generalized equations will be incorporated into the Urban Canopy Model in WRF which can be used for urban planning for mitigating urban heat island phenomena.



Figure 14 Comparison between local Nusselt number obtained from CFD simulation and proposed equation

2.3 Effects of building arrangement on urban ventilation and their generalization

With rapid urbanization, urban air pollution and urban heat island effects have become more and more serious. Urban ventilation efficiency should be taken into account since it affects the dispersion and dilution of pollutant and heat in urban areas. It is worth systematically investigating the effects of urban building arrangement (such as building coverage ratio, building array, and building height variation) on urban ventilation efficiency in order to practically guide urban ventilation design in these areas.

To investigate the effect of building arrangement on urban ventilation efficiency, we firstly chose a dense city in Hong Kong for a representative urban area. Hong Kong, where population is concentrated on a small land and high-rise buildings are densely packed, is facing serious problems of the heat-island phenomena and the accumulation of pollutants because of the poor ventilation in cities and the rapid increase in energy consumption. In order to tackle these problems, the City Planning Bureau of the Hong Kong government aims to establish the "Air Ventilation Assessment System (AVAS)." The consultant team for the AVAS has started the investigation on the city planning guidelines for improving air ventilation and assessment methods for the air ventilation, under the slogan of "The more air ventilation, the better." The most adopted measure for improving air ventilation in a city is to lead the horizontal wind to the inside of the city, that is, to secure "horizontal ventilation paths" just above the ground. Actually, there have been some reports (Kubota et al. 2000, Kubota et al. 2002) that urban air ventilation can be improved by lowering gross building coverage ratio, and so reducing building coverage ratio by enlarging street width and open space is extremely effective as a measure for mitigating the heat island phenomena. However, we consider that in the urban area densely packed with high-rise buildings, such as Hong Kong, it is difficult to reduce considerably building coverage ratio. Therefore, it is important to lead the upper breeze to the inside of the urban canopy by modifying the configuration of buildings, that is, to secure "vertical ventilation paths." With the purpose of providing fundamental information for the AVAS establishment, we investigated the influences of the configuration of buildings in terms of floor area ratio, building coverage ratio, and variation of building heights on the wind velocity at the pedestrian level.

With reference to the about-600-m range of the urban area in Mong-Kok, which is one of the urban areas most densely packed with high-rise buildings in Hong Kong, we produced a model district with a scale ratio of 1/600 as shown in the perspective diagram in Table 2. The reason why such a simple model was adopted instead of reproducing the buildings in Mong-Kok accurately is that the purpose of this experiment is not a special case study targeted at Mong-Kok but the acquisition of general knowledge regarding the effects of the configuration of buildings on the air ventilation characteristics of the district. Table 2 shows the features of the models used in the wind-tunnel experiments. As the reference case, we prepared Case 0, in which model buildings with the same height (assumed height: 45 m) are placed so that its street width, building coverage ratio, and floor area ratio correspond to those in Mong-Kok. As for Cases 1 and 2, the horizontal configuration (gross building coverage ratio) of the district was not changed, while the gross floor area ratios of Cases 1 and 2 were set at 3/2 and 2/3 times that of Case 0, respectively (that is, the building heights of Cases 1 and 2 were set at 3/2 and 2/3 times that of Case 0). As for Cases 3 and 4, their gross building coverage ratios were set at 2/3 and 1/2 times that of Case 0, respectively, by enlarging street width. Meanwhile, their building heights were set at 3/2 and 2 times that of Case 0, so that their gross floor area ratios become equal to that of Case 0. The building height of each of Cases 1 to 4 is homogeneous. On the other hand, as for Cases 5 and 6, there are two heights (60 m and 30 m) and three heights (60 m, 45 m, and 30 m), respectively. Meanwhile, their horizontal configuration, the gross building coverage ratio, and the gross floor area ratio are equal to those of Case 0. As for Case 7, towers with the same horizontal configuration as Case 4 (gross building coverage ra-tio: 32%; height: 60 m) was placed on the upper layer of the podiums with

the same horizontal configuration as Case 0 (gross building coverage ratio: 63%; height: 15m). This configuration is often seen at building complexes in Hong Kong. As shown in Fig. 15, measurement points are placed at 1.5 m (in real scale) above the ground within the range of 380 m (in real scale) of these models, and then scalar wind velocity were measured.

Case No. Case 0 (Standard case)		Case 1 (Floor area ratio 3/2-fold)	Case 2 (Floor area ratio 2/3-fold)	Case 3 (Building cov- erage ratio 2/3-fold)	
Perspective of model ar- rangements	Wind Wind	Wind	Wind Wind	Wind	
Floor area ratio	954 %	1272 %	636 %	954 %	
Building coverage ratio	63 %	63 %	63 %	42 %	
Real building height	45m (homogeneous)	60m (homogeneous)	30m (homogeneous)	72m (homogeneous)	
Case No.	Case 4 (Building cov- erage ratio 1/2-fold)	Case 5 (2 level of building height)	Case 6 (3 level of building height)	Case 7 (with Podiums)	
Case No. Perspective of model arrange- ments	Case 4 (Building cov- erage ratio 1/2-fold)	Case 5 (2 level of building height)	Case 6 (3 level of building height)	Case 7 (with Podiums)	
Case No. Perspective of model arrange- ments Floor area ratio	Case 4 (Building coverage ratio 1/2-fold)	Case 5 (2 level of building height)	Case 6 (3 level of building height)	Case 7 (with Podiums)	
Case No. Perspective of model arrange- ments Floor area ratio Building coverage ratio	Case 4 (Building coverage ratio 1/2-fold) Wind Wind 954 % 32 %	Case 5 (2 level of building height)	Case 6 (3 level of building height)	Case 7 (with Podiums)	

Table 2 Configuration of buildings in each experimental case



Figure 15 Layout of buildings and measurement points

The findings from this experiment can be summarized as follows:

1) It was found that the air ventilation in the cases reflecting the current situation of the urban area densely packed with high-rise buildings in Hong Kong is much poorer than that in Japanese districts with medium to high-rise buildings.

2) When the building height is uniform, the spatial average of the wind velocity ratios at the pedestrian level does not depend on floor area ratio, but depends on building coverage ratio.

3) When building heights are not uniform, the air ventilation especially behind buildings improved. It is necessary to consider not only the gross building coverage ratio at the pedestrian level but also the configuration of buildings at higher level. Thus we proposed "vertically averaged gross building coverage ratio" defined by Eq. (2) to express the urban ventilation efficiency.

$$\lambda_{ac} = \frac{1}{h_{max}} \int_0^{h_{max}} \lambda(z) dz \qquad (2)$$

where λ_{ac} : vertically averaged gross building coverage ratio, h_{max} : highest building level in the district, $\lambda(z)$: ratio of the horizontal cross-section area of buildings at an altitude of z to the total area of the district

Fig. 16 shows the relation between the "vertically averaged gross building coverage ratio" and the spatial average of the wind velocity ratios for each case. The spatial average of the wind velocity ratios of all cases can be almost plotted on a single line. Even if the configuration of buildings significantly varies with height, it may be possible to universally evaluate the average air ventilation at the pedestrian level by using the "vertically averaged gross building coverage ratio", which is useful for designing basic schemes for urban developments.



Figure 16 Relation between vertically averaged gross building coverage ratio and spatial average of wind velocity ratios

4) When building heights are not uniform, the air temperature is considerably improved. This is because cool air above buildings is transported to the ground level and hot air in the street canyons is exhausted to the upper atmosphere effectively. This result indicates that it is important to take into account the "vertical ventilation paths" to cope with the heat island phenomena. Secondary, a typical residential area in Shanghai (Fig. 17) was chosen to investigate the effect of building arrangement on urban ventilation efficiency. It was chosen because similar urban arrangements can be seen in many regions in China. The ventilation efficiency was investigated by CFD simulation with a standard k- ε model. For the CFD simulation, a simplified reference urban model (Fig. 18) was designed according to a typical residential area. Fig. 19c shows an enlarged view of a center block in Fig. 18. This block comprised a total of 72 residential buildings (48m (L) ×12m (W) ×18m (H)) with 6 stories. The building coverage ratio (BCR), which represents the ratio of ground floor area to lot area, was 40% and the floor area ratio (FAR), which represents the ratio of total floor area to lot area, was 240%. To compare the ventilation efficiency of different urban patterns, other BCRs and arrays (Layouts 2-18) were considered, as shown in Fig. 19. The BCR was changed by increasing the building height while keeping the FAR constant. The lengths (L) and widths (W) of buildings were not changed. The passage widths D1 and D2 between adjacent buildings changed with BCR and building array. The main road width in these models was 20m for all cases, as shown in Fig. 18.

Wind conditions at pedestrian level in an urban area play an important role in the dispersion of vehicle pollutants, diffusion of heat, and ventilation of buildings, as well as the comfort and safety of pedestrians. Therefore, it is necessary to understand the pedestrian wind environment around buildings 0-2m (z) and to take them into account in urban design. A uniform pollutant source assumed to be a passive scalar was generated throughout the 0-2m (z) volume of the center block, as shown in Fig. 20, to simulate pollution from residence areas and vehicles. The pollutant source volume (PSV) was 326m (LB) \times 326m (LB) \times 2m (h) (except the building part).



Figure 17 Typical residential area in Shanghai



Figure 18 Reference urban block model



Figure 19 Building arrangements

Тор

Back

 $L_{\rm B}$

Right

.efí

Front A

×

wind

Take layout 4 (BCR=10%, Aligned array) as an example: **Pollutant Source Volume (PSV)** *Location*:0-2m (z) volume of center block

Size:326m (L_B) \Box 326m (L_B) \Box 2m (h) (Note: except building part)

Five surfaces of PSV

a. Front (Windward surface)b. Back (Leeward surface)c. Left, Right (side surfaces)d. Top (upper surface)

Figure 20 Pollutant source volume (PSV)

Fig. 20 shows grid arrangement of the CFD simulation for the reference case. The computational domain contained 8 blocks surrounding the central one. All 9 blocks had the same arrangement. For the reference case, the domain size was $1378m (x) \times 1378m (y) \times 198m (z)$ and a structured grid of 2,337,984 cells was made.



Figure 21 Computational domain and grid arrangement

From the CFD simulation results, ventilation efficiency indices (spatially-averaged wind speed ratio, VRw (Ng, 2009) and normalized pollutant concentration, C*, and visitation frequency, VF (Bady et al, 2008) was obtained, and their relationships were investigated. The results are shown in Fig. 22. In general, Both "VRw - C*" and "VRw - VF" are negatively correlated (C* and VF decreases as VRw increases), and "VF - C*" are positively correlated (C* increases as VF increases).



righte 22 Relationships among ventuation enterency indices

One of the most important purposes of this study was to propose a practical design parameter for evaluating urban ventilation efficiency. We proposed a practical design parameter, Passage Ratio, PR (Hu and Yoshie, 2013) for evaluating urban ventilation efficiency. As shown in Fig. 23, stronger relationships between PR and ventilation efficiency indices were found compared to other existing practical parameters. With increase in PR, VRw increased while C* and VF decreased. The PR can be obtained from urban configurations, and it is possible to roughly estimate the ventilation efficiency indices from the PR. It is useful for designing basic schemes of urban developments.





2.4 Effect of atmospheric stability on urban pollutant concentration and its generalization

For environmental impact assessment of air pollution, a Gaussian plume model is usually used in Japan. This model is applicable for pollutant dispersion from a high chimney (Fig. 24a), but it is obvious not appropriate for pollutant dispersion within an urban area (Fig. 24b). Even so, it is used for this situation. One of the reasons why wind tunnel experiments (WT) or CFD simulations are not commonly used for environmental impact assessment for air pollution is that too many cases of wind tunnel experiments or CFD simulations would be required because various classes of atmospheric stability would have to be considered. (Eg. 16 wind directions ×10 stability classes = 160 cases). Another reason is that few institutes have a thermally stratified wind tunnel. If a general function independent of wind direction, urban shape, and location expressing the effect of atmospheric stability on pollutant concentration could be proposed, it would become possible to conduct WT/CFD for only neutral conditions and convert the results (pollutant concentrations under neutral condition) into those in other atmospheric stability conditions by using the proposed general function.



(a) from high chimney

(b) within urban area

Figure 24 Dispersion of pollutant

We firstly attempted to find the general function that expresses the effect of atmospheric stability on NOx concentration from observation data at air pollution monitoring stations of the Tokyo Metropolitan Government (TMG). Observation data in this study consisted of two parts. One was hourly averaged NO_x concentration data observed at 25 general air pollution monitoring stations in Tokyo 23 ward area. The other part was meteorological data including wind speed and direction, solar radiation and cloud cover of Japan Meteorological Agency (JMA). Procedure of data analysis is as follows.

- Step 1. Define hourly atmospheric stability classes from 3:00 to 21:00 based on the modified Pasquill–Gifford stability table (Table 3) using above meteorological data. The data from 22:00 to 2:00 were omitted because there are no cloud cover data to evaluate atmospheric stability classes during that time zone.
- Step 2. For each station normalize hourly NO_x concentration value by the formulation below. $C^* = CUH^2/Q$ (2) where C^* is non-dimensional normalized NO_x concentration; *C* is observed NO_x concen-

tration (ppb); U is wind speed (m/s); H is the representation, C is observed NO_x concentration, Q is used to be encoded and NO_x concentration, U is observed NO_x concentration, Q is a subserved NO_x concentration, Q concentrating Q concentration, Q concentrat

- Step 3. For each station, classify the C^* by 133 groups based on day and hour (7 days and 19 hours from 3:00 to 21:00). We assume that the NO_x pollutant emission rate Q is the same if the day and hour is the same.
- Step 4. For each station, divide the above 133 groups into 2128 groups (133*16) based on 16 wind directions

- Step 5. For each station, divide the above 2128 groups into 10640 groups (2128*5) based on 5 wind speed (U) ranges (0.5<U<2m/s; 2≤U<3m/s; 3m/s≤U<4m/s; 4m/s≤U<6m/s; 6 m/s≤U). The first range 0.5<U<2m/s is different from the first range in table 3 (U<2m/s). We omit wind speed data less than 0.5m/s because the wind direction under very weak wind condition is not stable and always changing.
- Step 6. For each station, select C^* under neutral conditions " C_n^* " on each day, hour, wind direction and wind speed range.
- Step 7. For each station, average the selected C_n^* to obtain the 5 years averaged $C_{n,ave}^*$ values for each day, hour, wind direction and wind speed range.
- Step 8. For each station, divide all C^* data by $C^*_{n,ave}$ to get the ratio that expresses the stability effect for each day, hour, wind direction and wind speed range. (*Q* and *H* are eliminated in this step because the same *Q* and *H* exist in both denominator and numerator. As described in step 3, we assumed that *Q* is the same if the day and hour is the same.) Thus, Stability Effect Ratio = $C^*/C^*_{n,ave}$ (3)

Surface wind speed at	Daytime Solar radiation (T) (kW/m ²) Nighttime cloud co						
10m above ground (<i>U</i>) (m/s)	T ≥ 0.6	0.6 > T ≥ 0.3	0.3> T ≥ 0.15	T <0.15	8~10	5~7	0~4
U < 2	А	A-B	В	D	D	G	G
2≤ <i>U</i> <3	A-B	В	С	D	D	E	F
3≤ <i>U</i> <4	В	B-C	С	D	D	D	Е
4≤ <i>U</i> <6	С	C-D	D	D	D	D	D
$6 \leq U$	С	D	D	D	D	D	D

 Table 3
 Modified Pasquill-Gifford stability classes

Note: The nighttime refers to the period when there is no solar radiation

Solar radiation data are used during daytime and cloud cover data are used during nighttime.

The first and last hour of nighttime should be defined as neutral condition "D" regardless of cloud cover.

Stability class	А	A-B	В	B-C	С	C-D	D	Е	F	G
Definition	Very unstable		Unstable		Slightly unstable		Neutral	Slightly stable	Stable	Very stable
Corresponding number	1	1.5	2	2.5	3	3.5	4	5	6	7

Table 4 Atmospheric stability classes

Fig. 25 shows the example of $C_{n,ave}^*$ at station No.104 for NE wind direction at each hours. 5 years averaged value of $C_{n,ave}^*$ and $\pm 1\sigma$ (standard deviation) are plotted in the figure. The vertical dotted lines correspond to 00:00 (midnight). The daily variation of $C_{n,ave}^*$ in hour is regular from Mondays to Sundays. $C_{n,ave}^*$ increases from the minimum value at 3am to the maximum value at 9:00, because 9:00 is the rush hour.



Figure 25 C_n in NE wind direction (station No.104)

We attempted to integrate all the monitoring stations data to find a general relationship between atmospheric stability and NO_x concentration. The index "Stability Effect Ratio" was proposed for this purpose. It is the ratio between C^* and $C^*_{n,ave}$ at each hour, each day and each wind direction for each station. All averaged values of the "Stability Effect Ratio $\pm 1\sigma$ " (all stations, days, hours, wind directions, and wind speed ranges) are plotted against stability classes in Fig. 26a. The numbers in horizontal axis express the atmospheric stability classes shown in table 4. Data numbers of each class are written in the figure. The stability effect ratio is less than 1 under unstable atmospheric conditions, nearly 1 under neutral atmospheric conditions and larger than 1 under stable atmospheric conditions. However the standard deviations are very large probably due to the variability (uncertainty) of atmospheric condition and pollutant emission rate. In order to check whether the "Stability Effect Ratio" in Fig. 26a is independent of urban shape and location, two additional figures are added: values of the "Stability Effect Ratio $\pm 1\sigma$ " (all days, hours, wind directions, and wind speed ranges) at Station No. 104 (in Shinjuku-ku) and station No. 138 (in Edogawa-ku) were displayed in Fig. 26b and c. The tendencies of Fig. 26b-c are similar to Fig. 26a. Not only these two stations but also all the stations have the similar tendency (figures are omitted). Thus, there is a possibility that the "Stability Effect Ratio" is independent of urban shape and location. In addition, in order to check whether the "Stability Effect Ratio" in Fig. 26a is independent of wind direction, three additional figures are added (Fig. 26d-f). Values of the "stability effect ratio $\pm 1\sigma$ " at Station No. 138 (in Edogawa-ku) under N, NE and S wind directions were shown in figures 26d-f respectively. Some differences were found. However data number is small. So we cannot judge whether the atmospheric stability ratio is independent of wind direction from these data.



As mentioned above, it was found there is a possibility that the Stability Effect Ratio was independent of wind speed, urban shape and location, and wind direction. But the deviation of the ratio was large probably due to variability (uncertainty) of atmospheric condition and pollutant emission rate. Thus in order to reduce the variability (uncertainty) of atmospheric condition and

pollutant emission rate, wind tunnel experiments and CFD simulations were conducted under nonneutral (weakly unstable, unstable, weakly stable and stable) and neural conditions.

The experiments were conducted in a thermally stratified wind tunnel at Tokyo Polytechnic University (TPU). Fig. 27 shows the experimental setup. The unstable and stable turbulent boundary layers were generated by 26 very thin roughness elements which were made of aluminum angles in the upstream. They create a long, rough upwind fetch to generate a turbulent boundary layer.



Figure 27 Experimental setup (units: mm)

Total 9×14=126 cubic blocks were put in an unstable and a stable turbulent boundary layer in a downstream (Fig. 28) to represent building blocks. Each building block has the same configuration: L (60mm) × W (60mm) × D (60mm). The city blocks were spaced 60mm apart in the x direction and 60mm apart in the Y direction. The overview of the building block arrangement was shown in Fig. 28. Tracer gas ethylene (C₂H₄) was released from a plane of the floor. Fig. 29 shows measuring points. The locations of the measuring points were selected so that various flow patterns (reverse flow, upward flow, downward flow in the street canyons and flow on the roads) were included.



Figure 28 Arrangement of building blocks



Table 5 summarizes the atmospheric stability conditions. Totally 5 cases were conducted. The reference height was 0.32m, and the velocity at this height of inflow boundary was set as reference velocity (U_R) . The atmospheric stability was characterized by Bulk Richardson's number (Ri_b) . Bulk Richardson number can be expressed as the following.

$$Ri_{b} = \frac{gH_{R} \times (T_{R} - T_{s})}{(T_{0} + 273) \times U_{R}^{2}}$$

Where g is the acceleration due to gravity (m/s2); H_R is the reference height (m); T_R is the temperature at reference height (°C); T_S is the ground surface temperature (°C); T_0 is the average inflow temperature (°C); U_R is the velocity at reference height (m/s). Ri_b for 5 inflow profiles were summarized in the last row of Table 5. Values of Ri_b ranged from -0.23 (unstable) to 0.29 (stable).

	Unstable	Weakly unstable	Neutral	Weakly stable	Stable
$U_{\rm R}$ (m/s)	1.4	1.8	1.8	1.5	1.2
$T_{\rm R}$ (°C)	9	10	11	48	55
$T_{\rm S}$ (°C)	49	41	11	16	14
ΔT (°C)	40	31	0	32	41
<i>T</i> ₀ (°C)	13	14	11	48	55
Ri _b	-0.23	-0.1	0	0.13	0.29

Table 5 Atmospheric stability conditions ($H_R = 0.32m$)

CFD simulations with the standard k- ϵ model were also conducted. Fig. 30 shows the grid arrangement.





Figure 30 Grid arrangement for CFD simulation

All the measured concentration data (measurement positions see Fig. 29) in the wind tunnel tests were included for investigating the effect of atmospheric stability on gas concentration. There were totally 92 measuring points for each case. As shown in Figure 29, those measuring positions located in different places. Some were in the street while some were in the canyon between blocks. Moreover, four heights in vertical direction were included. Concentration values at the measuring points calculated by CFD simulations were also investigated.

The correlations for normalized non-dimensional concentration C^* between neutral condition and non-neutral conditions were investigated and shown in Fig. 31 and 32 As shown in the figures, data were plotted almost on a single straight line for both experiment and CFD simulation. Thus the ratio between C^* under non-neutral conditions and neutral condition were independent of the measurement locations (the flow filed around the measuring positions). C^* under unstable condition were smaller than C^* under neutral condition, and C^* under stable condition were larger than C^* under neutral condition.



Figure 31 Correlations of C^* (Neutral-Unstable)



Figure 32 Correlations of C^* (Neutral-Stable)

Fig. 33 shows the ratio between C^* under un-neutral condition and C_n^* under neutral condition obtained from experiment and CFD results. This is the Stability Effect Ratio (SER) on pollutant concentration (SER= C^*/C_n^*). Averaged SER $\pm \sigma$ (the standard deviation) of all the measuring points are plotted in the figures. As shown in the figures, with the increase of Ri_b , the SER increases. Since the standard deviation is relatively small, the SER is almost independent of the locations or flow fields. But we need further case studies to confirm the generality of the SER. If the function of the SER is universal one, we can predict pollutant concentration under un-neutral condition from experimental or CFD results under neutral condition by using the function. It will bring about a drastic change in the environmental impact assessment of air pollution in Japan.



Figure 33 Stability Effect Ratio (SER) = Ratio between C^* under un-neutral condition and C_n^* under neutral condition

2.5 Large Eddy Simulation of gas/thermal dispersion in non-isothermal boundary layer

Urban heat island phenomena and air pollution become serious problems in weak wind regions such as behind buildings and within street canyons, where buoyancy effect cannot be neglected. In order to apply CFD techniques to estimation of ventilation and thermal/pollutant dispersion in urban areas, it is important to assess the performance of turbulence models adopted to simulate these phenomena. When simulating the turbulent atmospheric boundary layers using Large Eddy Simulation, a crucial issue is how to impose physically correct fluctuating inflow data. In a nonisothermal field, not only inflow velocity fluctuation but also temperature fluctuation is necessary. In this research, two inflow turbulence generation techniques (precursor method and recycling method) were investigated first. Then the generated turbulent inflow data were used for large eddy simulation of gas/thermal dispersion behind a high-rise building and within a street canyon in an unstable turbulent boundary layer

Firstly, we introduced a precursor method. In our wind tunnel experiment, the unstable turbulent boundary layer was generated by 26 very thin aluminum plates. In this precursor simulation, the whole wind tunnel (6.5 meters long) and all the aluminum plates (shown in Fig. 34) were reproduced by LES using a buoyant solver. The plates were treated as having zero thickness in the simulation. The wind velocity and temperature distribution at the inlet of the wind tunnel were spatially uniform and turbulent intensity was very small (less than 1%), so a uniform velocity U=1.43 m/s and a uniform temperature Θ =9.4°C without turbulence were given to the inflow boundary of the pre-simulation. A zero gradient condition was used for the outlet boundary condition. A no-slip boundary condition was applied to the wall shear stress on the floor. As thermal boundary conditions, the surface temperature was 45.3°C and a heat conduction boundary condition (Fourier's Law) was applied for the heat flux on the floor surface. The total mesh number used in the pre-simulation was $1042 \times 120 \times 79 = 9,878,160$. A unique time step Δ t=0.001sec was used to make sure that the maximum courant number was less than 1 in all positions of the domain. The sampling plane to obtain fluctuating velocity and temperature data was set at 0.1m (11 times the aluminum plate height) downstream of the last aluminum plate.



Figure 34 Inflow turbulence generation method (1) : precursor simulation

Another method for generating inflow turbulence in a non-isothermal boundary layer using a recycling procedure was also investigated here (Fig.35). Tamura et al. (2003) proposed a method for dealing with the thermally stratified effect. In the driver region, velocity fluctuation was generated using Lund's method (Lund et al., 1998) for a rough wall, while temperature was treated as a passive scalar, and a mean temperature profile was given to the inflow condition of the driver region. The same concept was adopted here, but the velocity fluctuation was generated using Kataoka's

method (Kataoka and Mizuno, 2002) with the roughness ground arrangement described by Nozawa and Tamura (2002). The roughness elements were exactly the same as those used in the wind tunnel experiment, but a short domain was adopted here. A mean velocity profile that came from the experimental measurement was prescribed for the inflow condition, and only the fluctuating part was recycled between outlet station and inlet station. The following damping function (Kataoka, 2008) was used to restrain development of the velocity fluctuation:

$$\phi(\eta) = \frac{1}{2} \{1 - \tanh[\frac{8.0(\eta - 1.0)}{-0.4\eta + 0.82}] / \tanh(8.0)\}$$
(1)

where, $\eta = z/\delta$. δ is the boundary layer thickness (0.25m). Only a neutral boundary layer (NBL) was simulated in the driver region, the temperature was treated as a passive scalar, a mean temperature profile of the experiment was prescribed at the inflow boundary of the driver section, and we tried to use the fluctuating velocity field to generate a fluctuating temperature field. The computational arrangement for the recycling method is shown in Fig. 1(b).



Figure 35 Inflow turbulence generation method (2) : Recycling method

Fig.34 shows the inflow characteristics generated by both the precursor method and the recycling method in the sampling position. The mean wind velocity, mean temperature, turbulent kinetic energy, and the r.m.s. value of temperature fluctuation agreed well with those of the experiment. Both methods can be used to generate turbulent inflow data for LES in a non-isothermal boundary layer.



Fig. 36 Inflow characteristics generated by precursor and recycling methods

The generated inflow turbulence data were saved in a Hard disk and used for an inflow boundary condition of Large Eddy Simulation for gas/thermal dispersion behind a single building (Fig. 37) and within street canyons (Fig. 38). Wind tunnel experiments were also conducted in the thermally

stratified wind tunnel of TPU. The floor surface temperature and the flow temperature were about 45° C and 10° C respectively to generate unstable turbulent boundary layer for both cases.



Firstly, for single building case, mean stream wise velocities $\langle u_1 \rangle$ of the experiment and the calculations are shown in Fig. 39. The results from the RANS model (two-equation heat-transfer model (Nagano and Kim 1988)) show overestimation of the recirculation size behind the building, and the calculated downward flow in the region around X₁/H= 0.7-1.5 is weaker than the experimental one. The calculated reverse flow near the ground and the rising flow along the rear surface of the building are stronger than those of the experiment. On the other hand, the recirculation size by the LES is narrower and the reverse flow near the ground and the rising flow along the rear surface of the building are weaker than those of the RANS model, which is closer to the experimental results.



Fig. 40 illustrates distributions of mean temperature. Although the vertical distribution of mean temperature far behind the building by the RANS model is similar to that of the experiment, the calculated temperature along the rear surface of the building is higher and the contour lines are predominantly vertical. This is because the strong rising flow along the rear surface of the building transported the hot air near the ground up along the rear surface. The vertical distribution behind the building in LES is similar to the experimental one.



Fig. 41 and Fig. 42 show the distributions of mean gas concentration. In the RANS calculation result, the high concentration area near the ground does not spread downwind of the gas emission point (marked as a 'black triangle'). Like the temperature distributions shown previously, calculated gas concentration along the rear surface of the building was higher due to the rising flow from the ground. The calculation does not reproduce the periodic fluctuations due to vortex shedding, and as a result, dispersion in the X2 direction (lateral direction) is inhibited (Fig. 42). For LES, the distribution pattern is much closer to that of the experiment than of the RANS model, especially regarding the lateral width of gas dispersion.



Secondary, street canyon model: Measuring points are illustrated in Fig. 43. Fig. 44 shows the distributions of mean stream-wise velocity, mean temperature, and mean concentration near the floor (z=H/6, H is building height). The LES results agreed well with the experimental data especially for the mean concentration. RANS model (with standard k- ε model) overestimate the concentration by about 200%. This is because the intermittent air exchanging between street canyon and upper atmosphere cannot be reproduced in RANS, while it is well captured by LES. Fig. 45 shows the correlations of mean concentration between experiment and LES results. Around 100 points shown in Fig. 43) were used to obtain these correlations. The LES results were very close to the experimental data.







Figure 45 Correlation between measured concentration and calculated concentration by LES

3 CONCLUDING REMARKS AND FUTURE PROSPECTS

In this manuscript, some of the research results obtained by the Project 3 : wind environment and air pollution group were introduced. Five of the most important study areas, namely: ① Reproduction of occurrence frequencies and vertical profiles of wind velocity and temperature by meso-scale simulation, ②Generalization of Heat transfer from urban canopy surfaces, ③Effects of building arrangement on urban ventilation and their generalization, ④Effect of atmospheric stability on urban pollutant concentration and its generalization, ⑤Large Eddy Simulation of gas/thermal dispersion in non-isothermal boundary layer, were outlined and presented. These study areas are taking very important role in the framework of the entire research of Project 3 as shown in the Fig 46. Unfortunately, we have not achieved the final goal yet. But fortunately the goal and the strategy are quite clear, and the research progresses that move toward the final goal have been steadily built. The research items that we made remarkable progress are shaded in the Fig. 46. We will continue our efforts to achieve the final goal in several years.



Figure 46 framework of the entire research of Project 3

If I am asked what the best thing was in the Global COE program, I would say that it is the human resources. I am very happy to work with various excellent postdoctoral researchers, PhD students and master students not only from Japan but also from abroad. I could never have achieved the results only by myself. All I did were just to give them clear and aggressive targets, and to advise them, give some ideas sometimes. It is my great pleasure that they left TPU to become company/university researchers after gaining remarkable knowledge and skill during their stay in TPU though they were unconfident when they started as a member of the project.

We have to secure excellent human resources and maintain our research activities at the Wind Engineering Research Center of TPU. In order to execute this, the following factors are very important;

• Securing research funds

• Improving the quality of undergraduate students for graduate school by reforming education

- Taking excellent graduate students from locally and internationally.
- Continuing to publish first-class research results in world-class journals.

The above factors are mutually related and we cannot say which is the most important (which comes first the chicken or the egg?). Thus we have to carry them out comprehensively. This is the primary responsibility of our generation who follow the great leader, Professor Yukio Tamura.

Finally, I would like to quote few words from Prof. Hajime Okamura, a Professor Emeritus at the University of Tokyo (The former president of Japan Society of Civil Engineers. When he was an under graduate student, as a pitcher of the baseball team of the University of Tokyo, he won 17 games in his career in the TOKYO BIG6 BASEBALL LEAGUE. It is the best record in the 100-year history of the baseball team of the University of Tokyo.)

"I found something from this experiment." \rightarrow Even junior high-school students can do that.

- Make hypothesis from a preliminary experiment and create a model or a theory, then carry out experiments to confirm.
- · Generalize or universalize research results. Otherwise, they cannot be used for engineering.

These quotes are what he said to us 15 years ago. I was strongly impressed by the words and I have been keeping them in my mind to carry out researches. I also have been saying the same words to my students. These quotes are truly strong foundation of my life as a researcher and for my students as well.

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