WIND TUNNEL EXPERIMENTAL STUDY OF AIRFLOW AND POLLUTION DISPERSION IN AREAWAY SPACE

Zhen BU*, Shinsuke KATO**, Takeo TAKAHASHI**, Hong HUANG**
*the University of Tokyo, Tokyo, Japan; ** Institute of Industrial Science, the University of Tokyo, Tokyo, Japan

Abstract

In residential house design, areaway space can play a great role in improving the living environment in the adjacent basement by wind-driven natural ventilation. However, little is known about this kind of ventilation phenomenon due to the complicated air exchange process. The air flow pattern in the areaway space is actually characterized with unsteady recirculation flows, which is similar to that in a street canyon. In order to gain more knowledge in this field, a wind tunnel experiment was carried out at the first stage of this research to investigate the characteristics of airflow and pollution dispersion in an idealized three-dimensional areaway model. The results reveal the behaviors of unsteady vortex movement in the areaway space and also indicate that the apect ratio and the above-ground building have significant influences on the local air flow patterns, pollution dispersion characteristics as well as ventilation performances.

Key words: areaway, basement, wind tunnel experiment, ventilation

1. INTRODUCTION

In recently years with the increasing demand for more land in urban areas, it becomes preferable to build a house with a basement as a space for living purpose, especially in some crowded metropolitan cities like Tokyo. However, some problems such as negative psychology, lack of fresh air, dampness, appear as a hindrance to the full use of basement. Most of these problems are related to air quality in the basement, which can be solved by use of mechanical ventilation, or most commonly by incorporation of natural ventilation. The utilization of wind-driven natural ventilation can be achieved by the construction of an areaway space in front of basement, which provides more advantages compared with the mechanical system. As shown in Figure 1, areaway is a sunken courtyard allowing access, air and light to a basement through openings; it may potentially help create a pleasant microclimate within basement by wind-driven natural ventilation through openings, such as window and doorway. According to the Japanese Building Code, areaway should be built in dwelling house having a basement for living purpose. Besides the utilization of areaway in contemporary buildings, the similar type of courtyard can also be found nowadays in some vernacular dwellings around the world. One example is the so called Yaodong in rural areas of West China as shown in Figure 2.

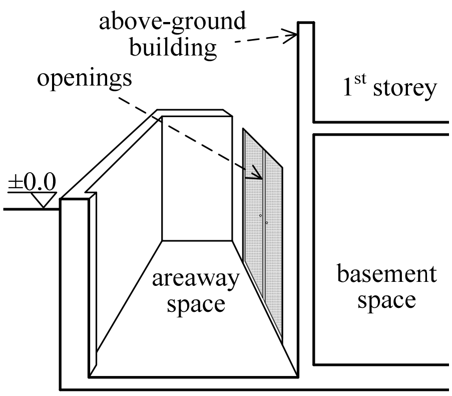


Figure 1. Schematic Diagram of Areaway

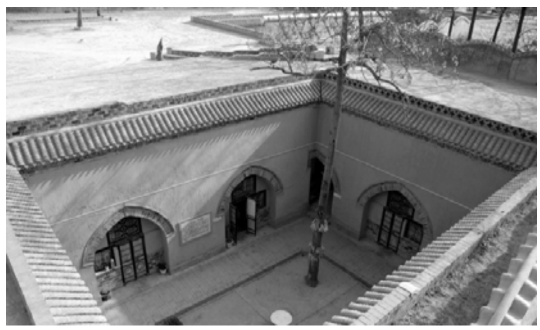


Figure 2. Vernacular sunken courtyard in Yaodong

There are some differences between areaway and other types of courtyard, for example, the existence of above-ground building and the size of areaway space. These differences (named as ventilation factors hereafter) may have significant effects on the ventilation performance, which have not been stuided yet. From the viewpoint of ventilation or air exchange process, the air flow in an areaway is similar to that happens in a street canyon but with a smaller scale. Since the width to height ratio (aspect ratio) of areaway is usually less than 1 in dwelling house in urban area, the air flow pattern within this space corresponds to the skimming flow regime according to Oke's classification of flow regimes in street canyon [Oke 1988], which is characterized by vortexes re-circulation within the canyon and a free shear layer across the top opening when the wind is perpendicular to the long axis.

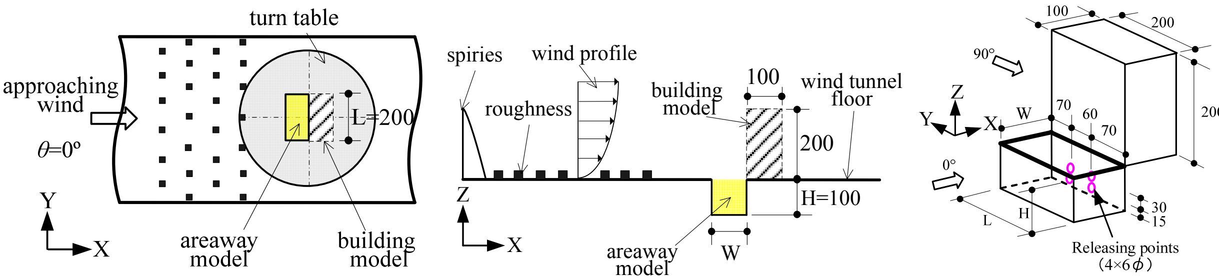
*Corresponding author's address: 4-6-1-CW403, Komaba, Meguro-ku, Tokyo;
Email: *buzhen@iis.u-tokyo.ac.jp*

Although there are many researches about flow and transport problems in street canyon in the past, the air flow problem in the areaway space in three-dimensional geometry with turbulent upstream boundary-layer flow and the pollutant dispersion problem with pollutant released from side wall have not so far been studied. Moreover, the understanding of these characteristics in areaway space is of great practical importance for the application of areaway in residential dwelling design.

In order to obtain reliable information concerning the airflow and dispersion characteristics in areaway space, a wind tunnel experiment was performed on a small-scale mdel of a dwelling building with areaway space, since wind tunnel can allow easier and more accurate control of wind speed and wind direction as well as the study of other factors, when compared with on-site measurement or full-scale experiment. As a preliminary study, this present paper shows our results of wind tunnel experiment with an aim to have an in-depth understanding of airflow and dispersion characteristics in areaway space and to investigate the influences of ventilation factors on ventilation performance.

2. DETAILS OF WIND TUNNEL EXPERIMENT

2.1. Experimental set-up



(a) Plan elevation (b) Vertical elevation (c) concentration experimental model

Figure 3. Experimental arrangement and the areaway model (unit: mm)

The experiment was performed under neutral atmospheric conditions in the boundary layer wind tunnel at Institute of Industrial Science, the University of Tokyo, which offers a working section of 16.5m long by 2.2m wide and 1.8m high. A thick boundary layer was generated at the measurement position using the combination of spires and 3 types of roughness elements.

As shown in Figure 3(a) and (b), a blank box made of clear cast acrylic was used to model the areaway space with an approximate 1/30 scale, which was mounted under the wind tunnel floor. In addition, a detached building model was also used and mounted on the wind tunnel floor to investigate the influence of above-ground obstacle on the flow pattern within the areaway space. Here, the width of the areaway (W) model is adjustable to allow the change of W/H aspect ratio. Here the height of building model was chosen as the reference height H_R (200mm), and the corresponding stream-wise velocity in the approaching wind was used as reference velocity U_R. In the velocity measurement, U_R=5.7m/s and in the flow visualization and concentration measurement, U_R=1.3m/s. In the concentration measurement, mixtures of ethylene (1.19%) and air were used as the tracer gas with a total releasing rate of 4cc/s and the concentration was sampled at a rate of 0.8cc/s. Trace gas was released from four 6mm diameter holes drilled on one side wall of areaway as shown in Figure 3(c) to simulate the generation of pollutant from the adjacent basement. The flow visulaization experiment was also performed, where the tracer smoke was injected continuously from the upstream of the model.

2.2. Measurement techniques

The mean velocity and longitudinal turbulence intensity profile for the undisturbed boundary layer is shown in Figure 4. The mean approaching wind profile followed a power law distribution with and exponent close to 0.25 and the turbulence level near flow was about 30%, which represents the approaching wind conditions in residential suburbs [ASCE 1999]. The flow field was investigated using split-fiber probes (SFP; 55R55; DANTEC) designed for measuring flows with a high turbulence and separation. In this current study, three velocity components were measured in order to provide details of mean flow and turbulence statistics in the areaway model. The sampling rate was 1 KHz and 32,768 samples were taken at each point. The average concentration measurements were carried out using a total hydrocarbon meter with flame ionization detector (FID). The flow field in the areaway model was visualized by the laser sheet method.

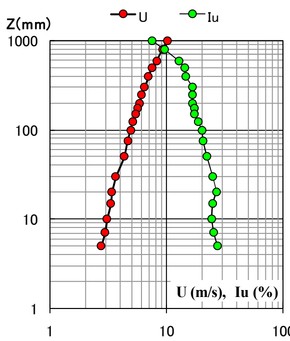


Figure 4. Velocity and turbulence profiles

3. RESULTS OF AIRFLOW IN AREAWAY

3.1. Aspect ratio (W/H)

The results presented here concern flow visualizations and flow patterns of four W/H aspect ratios: 1.0, 0.7, 0.5 and 0.3, in Figure 5 and 6 respectively. The areaway model is in three-dimensional geometry, without the above-ground building. During the measurements, the approaching wind was normal to the length direction of the areaway model and all the four cases studied indicated the skimming flow regime.

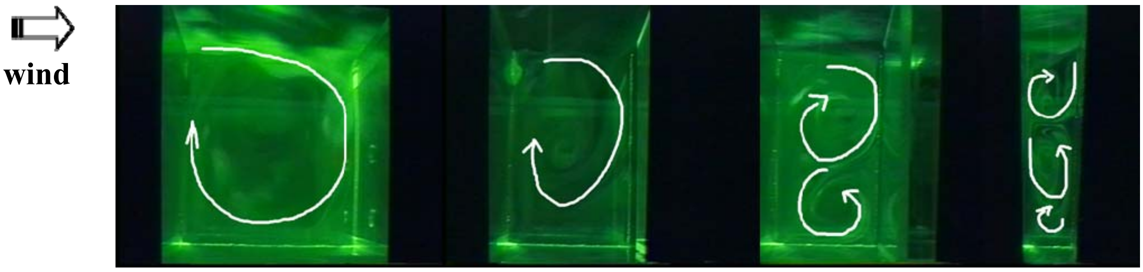


Figure 5. Flow visualizations in the central vertical plane

As shown in the instantaneous flow fields in Figure 5 and 6, the different recirculation patterns are found in the areaway model. For W/H=1, one main vortex is found rotating around the center of the areaway in a clockwise direction and for W/H=0.7, besides the main vortex, another small vortex can be observed in the downstream near the ground corner. For a reduced aspect ratio of 0.5, the main vortex still remains but the position of its center becomes higher. Another weaker vortex can be intermittently observed in the lower part of the areaway, although it cannot be explicitly plotted in the mean velocity field due to the low magnitude of velocity. The same features are found for W/H=0.3, where Figure 6 shows almost zero velocities in the lower part of areaway, indicating that the boudnary layer aloft can hardly penetrate to the deep bottom, giving poor ventilation. It should be noted that the re-circulation flow is unstable in nature, especially near the top of the areaway, which shows strong intermittent characteristics. This fluctuation might be due to the high turbulence in the approaching flow above the areaway and the Kelvin-Helmholtz instability in the shear layer which is originated from the upstream corner.

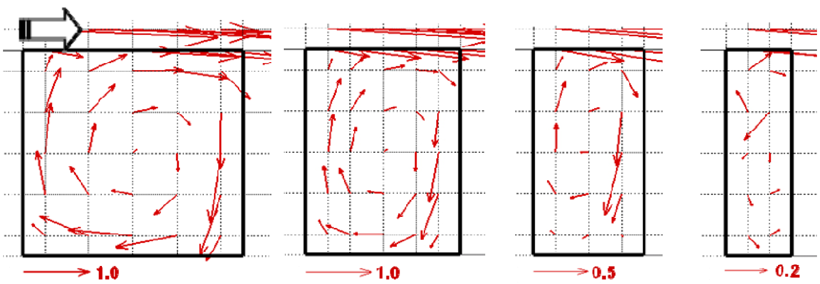


Figure 6. Mean velocity vectors in the central vertical plane

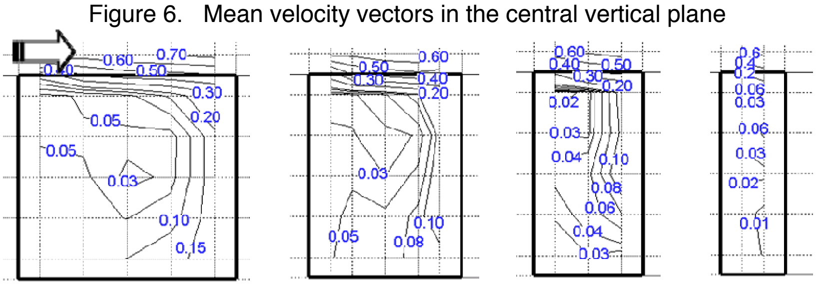


Figure 7. Turbulent kinetic energy fields in the central vertical plane

Figure 7 depicts the turbulent kinetic energy (TKE) contours in the same planes calculated from the measured three fluctuating velocity components. As indicated in these plots, high value of TKE can be found near the top level and downwind region of the areaway space, while low value of TKE is near vortex center. It indicates that high TKE near the top level is advected or transported into areaway space mainly in the downwind region.

3.2. The influences of building model

Figure 8 shows the mean velocity vectors in three vertical planes of the areaway with the existence of building model. Two cases were investigated for wind direction 0° and 180° respectively; the first case is when the building is on the leeward side of areaway with the aspect ratio of 1.0, while the other one is on the windward side. For the leeward building case, a strong clockwise vortex can be detected in the areaway space. In the central vertical plane, the 2D flow pattern is formed which is similar to that shown in Figure 6. In other two planes, 3D flow pattern is formed due to the influence of the above-ground building. Since there is a strong downwash effect of the approaching wind against the building below the stagnation point, the advection of momentum and turbulent transport are stronger than those in the case without the building model. For the windward building case, as indicated in the right figure, a counter-clockwise vortex can be found in the areaway space due to a large clockwise vertex generated at the wake region of building model (not shown). Both cases show similar properties with respect to the flow patterns in the areaway space. Nevertheless compared to the leeward case, the wind speed and TKE level are decreased to about 50% in the windward building case.

4. RESULTS OF CONCENTRATION FIELD

The following concentration measurements are presented in terms of the ratio $\mathbf{K=CU_RH_R^2/q_s}$, where C is the actual concentration [ppm], q_s denotes releasing rate of ethylene [cc/s].

Figure 9 shows the corresponding concentration fields of the cases in section 3.1 without the building model. Tracer gas was released on the windward side wall, with the four releasing points marked in pink color (the detail is shown in Figure 3(c)). In another case, tracer gas was released on the leeward side wall to investigate the influence of releasing position on local pollutant dispersion.

For W/H=1.0, the higher concentration appears in the left region of the space irrespective of releasing position. When the releasing points are on the leeward side the average K decreases by about 30%. Figure 9 also shows a generally increasing concentration with decreasing aspect ratio. For a deep areaway, the concentration on the windward side is much higher than on the leeward side at the lower part. On the contrary, the concentration on the leeward side is higher than on the windward side at the top part of the areaway. This is mainly due to the different recirculating directions of the vortexes inside this space, which also indicates that the concentration of pollutant inside the areaway has a direct correlation with the velocity field.

Figure 10 shows the concentration fields with the above-ground building in leeward side or in windward side. In both cases, the mean concentration level decrease by 75% and 45% respectively, compared to the corresponding case without the above-ground building. It indicates the strong influence of building on local ventilation performances due to a strong vortex formed in the areaway space, which is capable of dispersing the pollutant from interior to free stream more efficiently.

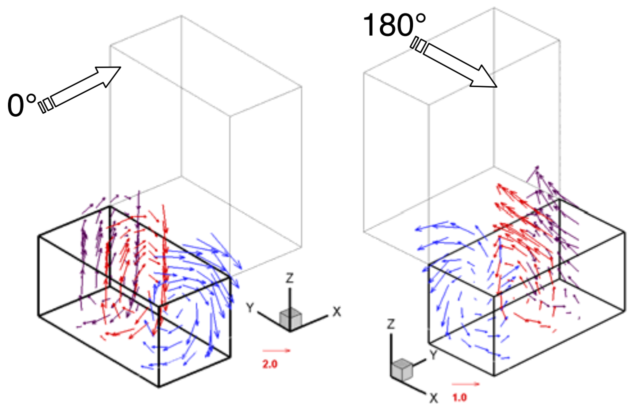


Figure 8. Mean velocity vectors in the three vertical planes

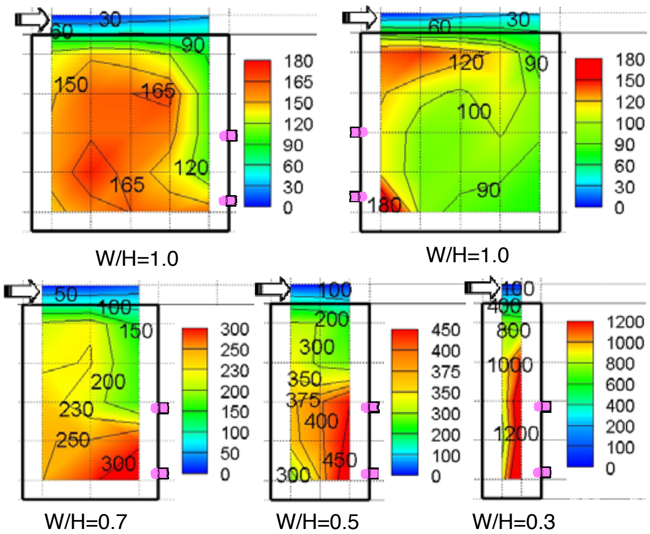


Figure 9. Mean concentration fields in the central plane

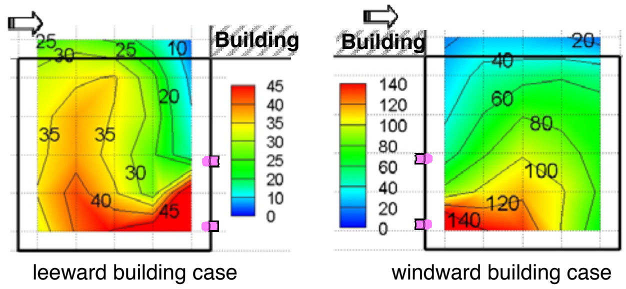


Figure 10. Mean concentration fields with building model

5. CONCLUSIONS

The wind tunnel experiment was carried out to investigate local flow patterns and dispersion properties in the areaway space. The results reveal that the geometry of areaway space, especially the W/H aspect ratio and the layout of building have significant effects on the local flow field and concentration field which mainly depend on the local vortex structures. In addition, there is a strong relation between the local concentration level and fluctuating velocity. The releasing position of pollutant also has an important influence on the concentration level. It was also found that the vortex movements in the areaway space were very unsteady and showed intermittent behaviors which were very critical for the pollutant dispersion.

References

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