# Field Measurement and CFD Analysis on Thermal Environment and Ventilation Efficiency in Street Canyons to Investigate the Influence of Roadside Trees and Moving Automobiles

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**Abstract**

This study aims to investigate and clarify the effects of roadside trees and moving automobiles on airflow distribution, turbulent diffusion of air pollutants, ventilation efficiency and thermal environment within street canyons. The detailed field measurements were carried out at two streets with different densities of roadside trees and traffic volume in the central part of Sendai city, Japan. Furthermore, a series of CFD analyses targeting at the same location as field measurements was carried out. The ventilation efficiencies within street canyons with different conditions of roadside trees and moving automobiles were respectively evaluated.

**Key words:** Field Measurement, CFD analysis, Street Canyon, Roadside Trees, Moving Automobiles

## 1. INTRODUCTION

Greening planting is the most popular strategy in environmental design for improving outdoor climate in urbanized areas. One of the common ways to increase the greenery is to plant roadside trees along the streets. Although investigations of airflow, turbulent diffusion of air pollutants and thermal environment in urban street canyons have been carried out individually by many researchers, there are only very few studies examined comprehensively the effects of roadside trees on these urban context problems. Furthermore, the influence of moving automobiles is also a significant factor affecting the real situation of environment in street canyons. This study aims to clarify the effects of roadside trees and moving automobiles on thermal comfort of pedestrians and ventilation efficiency within street canyons by means of the field measurements and CFD analyses.

## 2. FIELD MEASUREMENTS

Field measurements were carried out during the summer of 2006 (August $9^{th}$-$11^{th}$), at the central part of Sendai, Japan (Note1). Fig. 1 shows the locations for the field measurements. Table 1 summarizes the measurement details. Various measurements including traffic volume were undertaken at the two main streets, namely Hirose Street and Jozenji Street (Figs. 1) Axes of these two streets are east-west. In Hirose Street, maidenhair trees are planted along sidewalks and median strip (Photo 1(1)). On the other hand, zelkova trees are planted at Jozenji Street in four rows and the density of trees is much higher than that of Hirose Street. The upper region of the street canyon along Jozenji Street is covered with tree canopy, which forms a tunnel-like closed space (Photo 1(2)). The meteorological conditions can be found in our previous paper (Kikuchi et al. 2007).

Table 1. Measurement details

| Sampling Sites | | Measurement Items | Instruments | Number of Sites |
|---|---|---|---|---|
| Rooftops | $R_J$ (h=50m) | Wind Velocity, Turbulence Statistics | 3D Ultrasonic Anemometer | 1 |
| | | Concentrations of NO and $NO_2$ | Analyzed with Gas Analyzer | 1 |
| | | Air Temperature and Relative Humidity | Temperature / Humidity Sensor | 1 |
| | | Long-wave and Short-wave | Four - Component Radiometer | 1 |
| Streets | Area A (Hirose-street) | Wind Velocity, Turbulence Statistics | 3D Ultrasonic Anemometer | 2 |
| | | Concentrations of NO and $NO_2$ | Analyzed with Gas Analyzer | 5 |
| | | Air Temperature and Relative Humidity | Temperature / Humidity Sensor | 5 |
| | | Globe Temperature | Globe Thermometer | 2 |
| | | Surface Temperature | Thermal Imaging Camera | 5 |
| | | Traffic Volume | Observation | 2 |
| | Area B (Jozenji-street) | Wind Velocity, Turbulence Statistics | 3D Ultrasonic Anemometer | 4 |
| | | Concentrations of NO and $NO_2$ | Analyzed with Gas Analyzer | 5 |
| | | Air Temperature and Relative Humidity | Temperature / Humidity Sensor | 6 |
| | | Globe Temperature | Globe Thermometer | 3 |
| | | Surface Temperature | Thermal Imaging Camera | 6 |
| | | Long-wave and Short-wave | Four - Component Radiometer | 1 |
| | | Traffic Volume | Observation | 2 |

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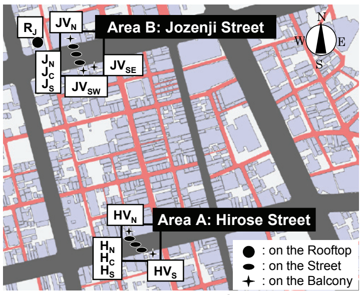



Fig. 1: Target areas of the field measurements

(1) Hirose Street (cf. Fig. 1, Area A) (2) Jozenji Street (cf. Fig. 1, Area B)

Photo 1: View of measurement areas

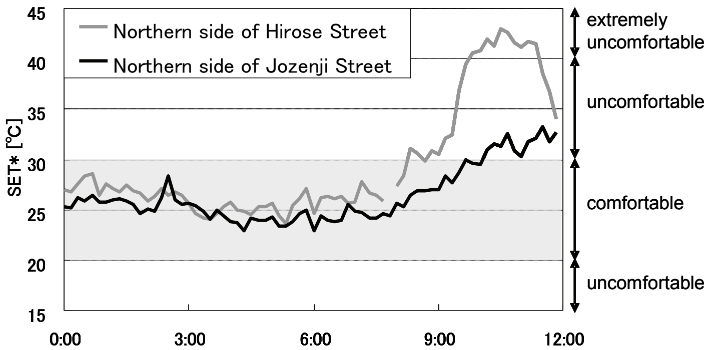
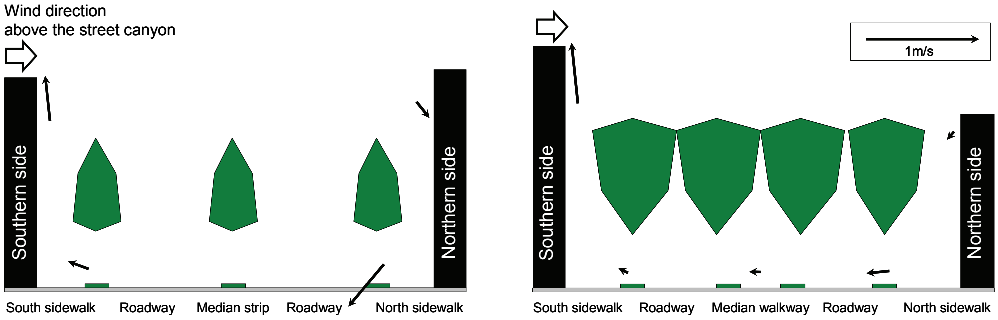
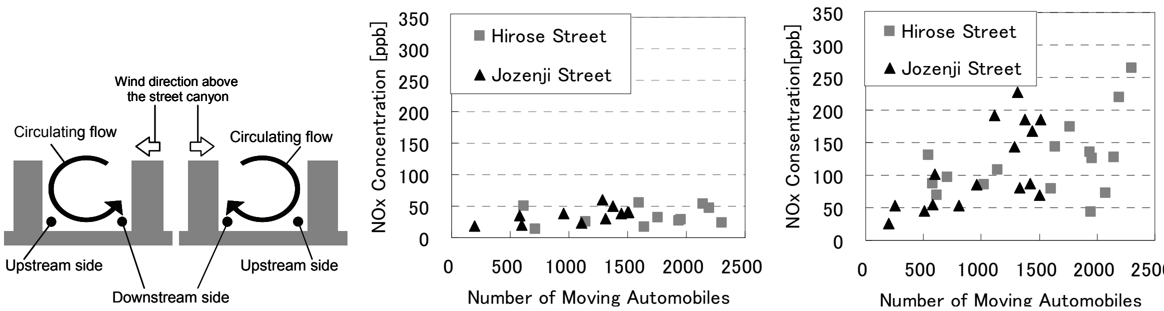



Fig. 2: SET* (h=1.2m, August 11)




(1) Hirose Street (2) Jozenji Street

Fig. 3: Vertical distributions of wind velocity vectors (9:00 on August 11th)




(1)Definitions of upstream and downstream sides (2) Upstream side (3) Downstream side

Fig.4: Relation between $NO_X$ concentration and number of moving automobiles

Fig. 2 shows the comparison of time variation of Standard Effective Temperature (SET*) over a 12-hour period (Note 2). The SET* at Jozenji Street was significantly lower than that of Hirose Street during daytime due to the shading effects of trees. The vertical distributions of wind velocity vectors within street canyons are illustrated in Fig. 3. In both street canyons, flow circulations were observed. The results presented here were classified into two groups, namely, upstream and downstream measuring points. The upstream measuring points mean the measuring points located at the upstream of the roadway, considering the wind direction near the ground surface in the circulating flow within the street canyons,while the downstream measuring points are the measuring points located at the downstream of the roadway (cf. Fig. 4(1)). The relationships between $NO_X$ concentration and the number of moving automobiles on the both stream sides are illustrated in Figs. 4(2) and (3). At the pedestrian level, $NO_X$ concentration on the upstream side of the circulating flow was not affected by the number of moving automobiles (Fig. 4(2)). On the other hand, $NO_X$ concentration was increased on the downstream side due to the increased number of moving automobiles (Fig. 4(3)). Fig. 5 illustrates the vertical distributions of normalized $NO_X$ concentration $c^{**}$ [$m^3$/automobile] (Note 3) at the same time as that shown in Fig. 3. It is clearly shown that the $c^{**}$ values in Jozenji Street were higher than those of Hirose Street. In the both streets and $c^{**}$ on the southern side at the downstream of the circulating flow was higher than that of northern side located in the upstream side.

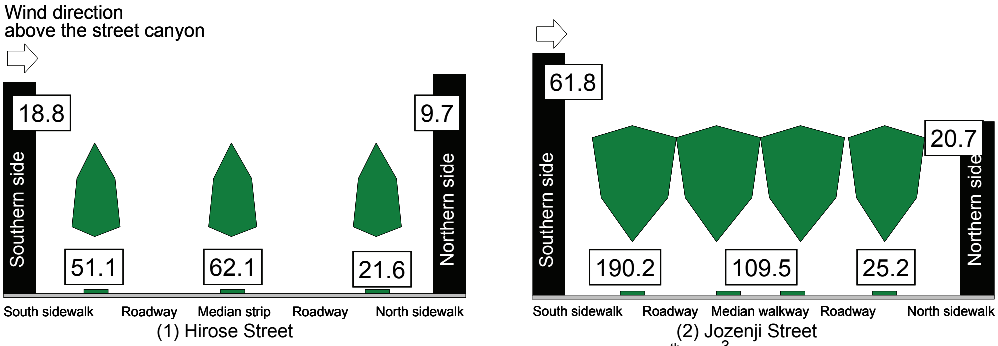



Fig. 5: Normalized $NO_X$ concentration (9:00 on August 11th) [$m^3$/ automobile]

## 3. CFD ANALYSES

In this study, two-stage nested grid technique was adopted (cf. Fig. 6). Fig. 7 shows the test cases. Case 2 considers the current situations of trees, while the roadside trees at northern and southern sides are pruned to increase the ventilation rate from the upside of street canyon in Case 3. For a comparison, the situation without the trees is also simulated in Case 1. By using the tree and vehicle canopy models proposed by the present authors (Mochida et al. 2008, Konno et al. 2009), the effects of roadside trees and moving automobiles on the turbulent flowfields within street canyons (cf. Photo 1(2)) were incorporated in all cases. Ventilation efficiencies within street canyons with different conditions of roadside trees were evaluated by using SVE3 (Scale for Ventilation Efficiency 3) proposed for evaluating the ventilation effectiveness in a room (Kato and Murakami 1988). SVE3 corresponds to the mean traveling time required by the supply air mass to reach the point concerned. In this study, SVE3 is applied to evaluate the ventilation efficiency within street canyon (Note 4).

Table 2 indicates the incoming and outgoing flow rates at the upside of the evaluation domain. In Case 2 where the actual tree planted condition is reproduced, both of the incoming and outgoing flow rates are decreased compared to the case without trees (Case 1). It is shown that the flow rates at the upside of the evaluation domain were increased in Case 3 compared to Case 2 by pruning the roadside trees. Fig. 8 shows the vertical distributions of wind velocity vectors and SVE3. In Case 3, down draft is generated between the building and trees at the upstream side (A' side). As a result, the SVE3 values in this case became lower than those of Cases 1 and 2 (Fig. 8).

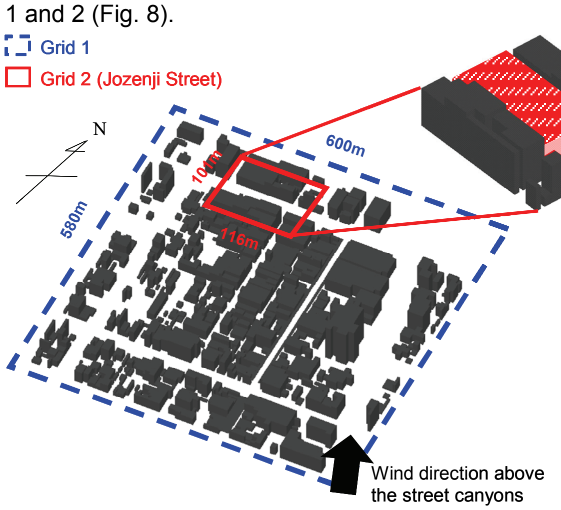



Fig. 6. Computational Domain

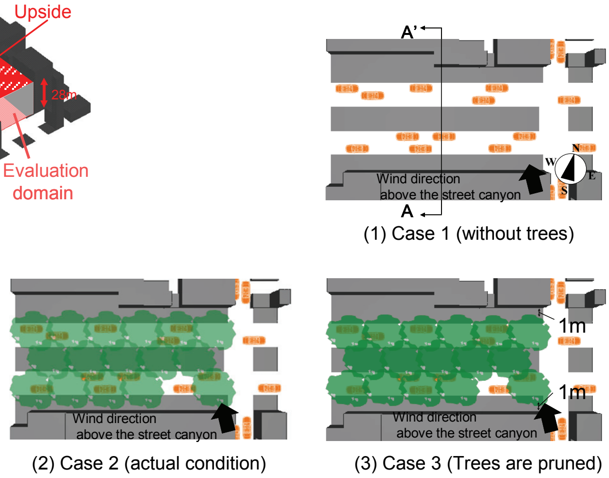



Fig. 7. Test Cases (Grid 2 (cf. Fig 6))

Table 2. Incoming and outgoing flow rates at the upside of the evaluation domain [$m^3$/s]

| | Case1 | Case2 | Case3 |
|---|---|---|---|
| Incoming Flow rate | 258 | 209 | 218 |
| Outgoing Flow rate | 1122 | 841 | 868 |

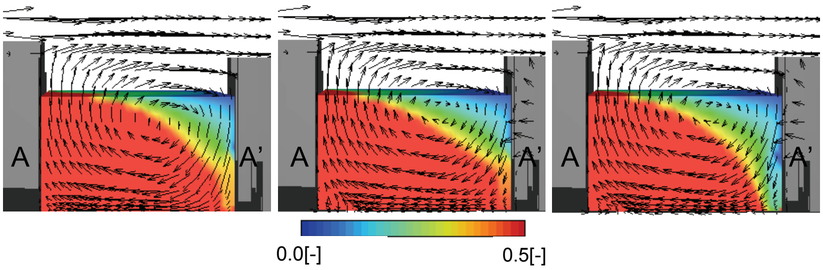



Fig. 8. Vertical distributions of wind velocity vectors and SVE3 (12:00 on August 11$^{th}$)

## 4. CONCLUSIONS

The field measurements were carried out at two streets with different densities of roadside trees and traffic volume in the central part of Sendai city, Japan. It was shown that the high density roadside trees decreased the flow rate from the upside of street canyon and increased the contaminant concentration near the ground level. To investigate the ways to improve this situation, the ventilation efficiencies within street canyons with different conditions of roadside trees were evaluated based on the results of CFD analyses. In the case where the roadside trees near the building walls were pruned, the flow rate from the upside was increased and thus the ventilation efficiency was improved.

**Notes**

1. Sendai is located at the northeastern region of Honshu, Japan, facing the Pacific Ocean and has over one million populations.
2. SET* is an indicator that gives an overall evaluation of thermal comfort considering the effects of wind velocity, air temperature, humidity, MRT, clothing and metabolism (Gagge 1977). Here, wind velocity, air temperature, humidity and MRT were given from the results of field measurements. In this study, MRT was evaluated following the relation given in ASHRAE Handbook 2001.Clothing insulation and metabolic heat generation are assumed to be 0.6[clo] and 1.4[met] respectively.
3. In this paper, $NO_X$ concentration is normalized as;

$$c^{**} = \frac{c}{\left(\frac{n}{\langle u_c \rangle WH}\right)} \quad [\mathrm{m^3/\ automobile}] \quad \cdots (1)$$

where, $c$ : $NO_X$ concentration [-], $<u_c>$ : average of wind velocity above street canyon [m/s]
$W$ : width of street [m], $H$ : average building height [m]
$n$ : number of moving automobiles per unit time [number/s]

4. SVE3 can be calculated, based on the concentration at each point in the case of uniform contaminant generated through the evaluation domain shown in Fig. 6 and fresh air is assumed to enter the domain from upstream side. It is defined by the follwing equations;

$$SVE3(x) = \frac{C'_x(x)}{C_s} \quad [-] \quad (2) \qquad C_s = \frac{q}{Q} \quad [-] \quad (3)$$

where, $SVE3(x,y,z)$[-] : Scale for Ventilation Efficiency 3 at position $(x,y,z)$
$C(x,y,z)$[-] : The contaminant concentration in case of uniform contaminant generation throughout the enaluation domain.
$C_S$[-] : the perfect mixing concentration, $q$[$m^3$/s] : the contaminant generation rate, $Q$[$m^3$/s] : airflow rate

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