

Characteristics of flow and temperature field along a heated street canyon in the multiple-fan turbulence wind tunnel

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ABSTRACT: Street canyon phenomenon, in which waste heat and exhaust gases stagnate in the space between multi-story buildings, is contributed for urban air quality deteriorating. The flow field, temperature field, and concentration field of a pollutant in a street canyon are complex. Much research has focused on the flow field, gas concentration field, and their numerical simulations. However, the temperature distribution of the flow field on the street surface has not been investigated experimentally. Therefore, the purpose of this study is to experimentally characterize the effects of building arrangements on the street surface temperature distribution and flow pattern along a heated street canyon. In addition, numerical simulation was used for comparing the experimental results. As a result of this research, contribution factors of cooling effect along the heated street canyon were become clear.

KEYWORDS: Street canyon, wind tunnel, numerical simulation, flow field, temperature field.

1 INTRODUCTION

In recent years, urban air quality has deteriorated due to an increase in the number and density of multi-story buildings. One contributing factor is the street canyon phenomenon, in which waste heat and exhaust gases stagnate in the space which is canopy, above the streets and between high-rise buildings. The flow field, temperature field, and concentration field of a pollutant in a street canyon are complex; highly reliable experimental data is required for the evaluation, prediction and improvement of each field. Much research has focused on the flow field¹, gas concentration field²⁻⁴, and their numerical simulations³⁻⁷. However, the temperature distribution of the flow field on the street surface has not been investigated experimentally. Therefore, the purpose of this study is to experimentally characterize the effects of building arrangements on the street surface temperature distribution and flow pattern along a heated street canyon. The experiments were performed by actively controlled multiple-fan wind tunnel in our campus; Oita National College of Technology (ONCT). In the ONCT wind tunnel, any kind of turbulent fluctuating flow was generated by actively controlled multiple-fans. This study was carried out under the collaborative work with Toyohashi University of Technology (TUT). TUT wind tunnel has different type of generating turbulence. Compared to our work with different types of turbulent wind properties, it is expected that new knowledge could be obtained. In this paper, as the first step, the effects of building arrangements on street surface temperature and flow patterns with using our multiple-fan wind tunnel are reported. In addition, numerical simulation was used for comparing the experimental results.

2 EXPERIMENTAL SETUP

2.1 Multiple-fan Wind Tunnel

The turbulence wind tunnel is an actively controlled multiple-fan-type generator with 66 small, independently computer controlled inlet fans. Each fan duct has separately channels the air from the inlet to the measurement section, at which point the air streams are mixed to create turbulent flow. Any natural turbulent wind condition can be generated by the actively controlled fans. The measurement section has a height of 1015 mm, a width of 1095 mm, and a length of 3600 mm. The wind tunnel apparatus is shown in Figure 1. To generate imitated natural wind in this tunnel, Kármán type spectrum⁸⁻⁹ was used. This spectrum was shown well the natural wind to set several parameters in the equation (1). To create a time series wind velocity fluctuating data for controlling fans of wind tunnel, inverse FFT method was used.

$$S_u(f) = 4I_u^2 L_u U \frac{1}{\{1 + 70.8(\frac{fL_u}{U})^2\}^{\frac{5}{6}}} \quad (1)$$

2.2 Experimental Method

The street canyon model was built comprising a heated street model and building models. To heat the street model, electrical current was impressed to a thin metal plate directly set in the bottom of the street floor. The building models were made of plastic blocks in three-dimensional configurations. Two normalized sizes were used: 1:1:1 and 2:1:1, where the model size is normalized to the street canyon width. The building models were arranged in several configurations along the heated street, as shown in Table 1. The building models had various combinations of upstream and downstream building heights in both linear and staggered arrangements. Thermography which is infrared imaging camera, was used to observe the temperature distribution of the heated street. In addition, the flow field in the canopy was observed using the smoke-wire method. The wind tunnel was used to test in steady flow and fluctuating turbulent flow.

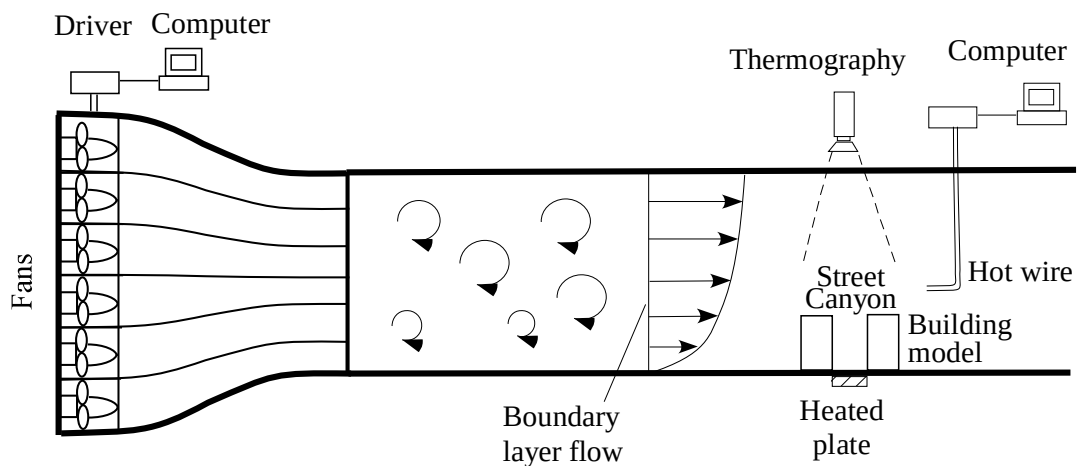


Figure 1. Wind tunnel experimental setup.

Table 1. Configurations of three-dimensional models.

Case	Upstream model	Downstream model	Arrangement
Case 1	1:1:1	1:1:1	Linear
Case 2	2:1:1	2:1:1	Linear
Case 3	1:1:1	2:1:1	Linear
Case 4	2:1:1	1:1:1	Linear
Case 5	Alternating (Symmetrical)		Linear
Case 6	Alternating (Asymmetrical)		Linear
Case 7	1:1:1	1:1:1	Staggered
Case 8	2:1:1	2:1:1	Staggered
Case 9	1:1:1	2:1:1	Staggered
Case 10	2:1:1	1:1:1	Staggered
Case 11	Alternating (Left diagonal)		Staggered
Case 12	Alternating (Right diagonal)		Staggered

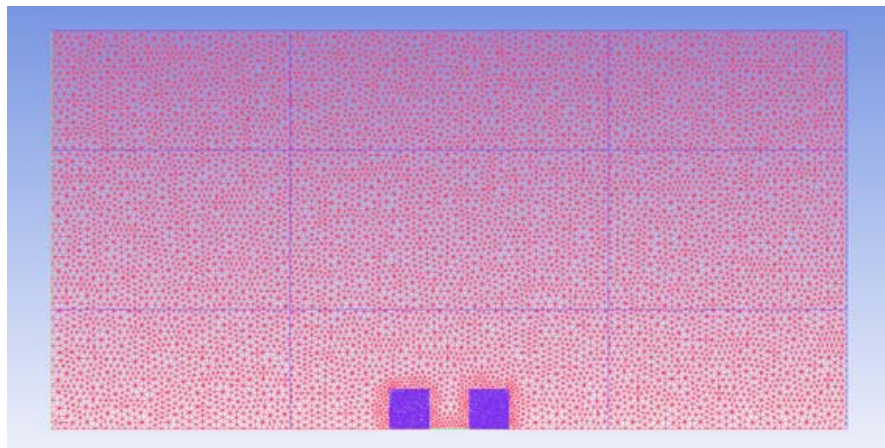


Figure 2. Mesh setup for numerical simulation.

2.3 Numerical simulation setup

To comparing the numerical results with the experimental results of temperature field and flow field of wind tunnel experiments, the validity of the numerical analysis methods and results of numerical analysis has been verified. It seems to be able to establish a quantitative approach by creating of numerical calculation of heated street canyon phenomenon. In this study, to investigate for the numerical analysis of temperature field and flow field in the street canyon, general-purpose thermal and fluid analysis software; ANSYS CFX ver.13, was used for steady state flow condition. This software consist of three steps individual software, CFX-Pre which is to set the boundary conditions, CFX-Solver which is to perform the analytical calculations and CFX-Post which is to display the analysis results. Computational domain was set 0.15m for Y-axis, 0.5m for Z-axis, 1m for Z-axis in the direction of the rectangular parallelepiped, which was placed two pitch sizes of imitated buildings toward the street for the original position. Type of mesh was automatically created by Tetra Mixed as shown in Figure 2, which is commonly used in fluid analysis. Mesh points of the analysis model is about 1.6 million. The solver was set by standard k- ϵ model for turbulent condition.

3 RESULTS AND DISCUSSION

3.1 *Wind tunnel experimental results*

The temperature distributions in low-turbulence steady flow are shown in Figure 3. The Case 1 configuration, per Table 1 (i.e., $WS/H_b=1$ with 1:1:1 upstream and downstream building models in a linear arrangement), in which the areas in the middle of the street and in front of the downstream buildings were well cooled due to the frontal eddy generated at separation flow reattachment, is shown in Figure 3 (a). The Case 2 configuration, (i.e., 2:1:1 upstream and downstream building models in a linear arrangement), in which the street areas in line with the building gaps were remarkably cooled due to flow acceleration, are shown in Figure 3 (b). However, the areas just behind the upstream buildings were not well cooled due to flow stagnation. Cavity flow was also observed in the street by flow visualization.

The temperature distributions of the Case 3 and Case 4 models are shown in Figure 4. Per Table 1, the Case 3 configuration has taller downstream buildings, whereas the Case 4 configuration has taller upstream buildings. Horseshoe vortices formed in the gaps between the upstream buildings in both configurations. In Case 3, the separation flow from the upstream buildings collided with the downstream buildings and formed a frontal eddy, resulting in effective cooling of the street surface in front of the downstream buildings. Because the upstream buildings in Case 4 are taller, the air flowing between the buildings was accelerated and a lee eddy was formed over the street.

The temperature distributions of the Case 5 and Case 6 model configurations, both of which feature a linear arrangement of alternating building heights, are shown in Figure 5. The Case 5 model is arranged symmetrically, where both upstream and downstream buildings have the same height. The Case 6 model is arranged asymmetrically, where the upstream and downstream buildings have different heights. In Case 5, the street areas in line with the building gaps were well cooled, however, the areas just behind the upstream buildings were not well cooled due to flow stagnation, and the separation flow from the upstream model skimmed over the downstream model. Case 6 exhibited a considerable cooling effect over the street in front of the downstream model, specifically when the air flow collided with the taller downstream buildings and formed a frontal eddy.

The temperature distributions of the Case 4 and Case 10 model configurations are shown in Figure 6. Both configurations feature taller upstream buildings, but Case 4 features a linear arrangement whereas Case 10 features a staggered arrangement. The areas behind the upstream buildings nearest to the gaps were well cooled by the trailing vortices that were generated from the upstream side walls. In Case 10, the trailing vortices collided with the downstream buildings and formed a horizontal frontal eddy. Therefore, the cooling effect of the Case 10 model configuration is slightly higher than that of Case 4. However, if the upstream model were taller than the downstream model, it is clear that the cooling effect would decrease due to flow stagnation behind the upstream model.

The data in Figures 3 through 6 reveal a significant correlation between the formation of an eddy and the cooling effect on the street; how the eddy forms on the street surface determines the cooling effect.

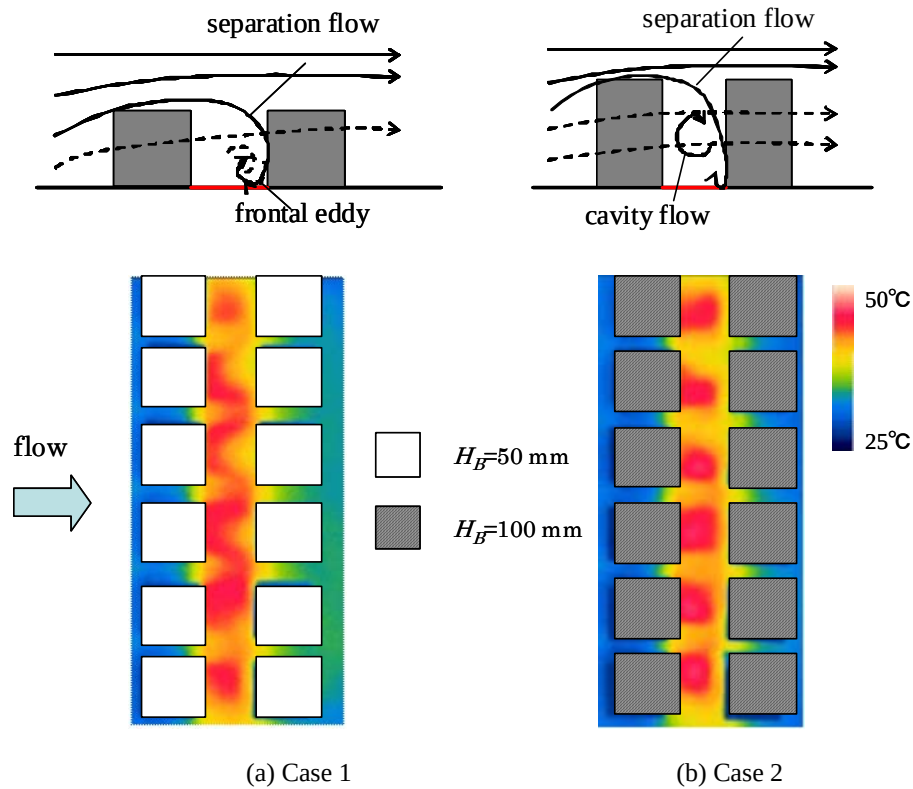


Figure 3. Temperature distributions of Case 1 and Case 2 models.

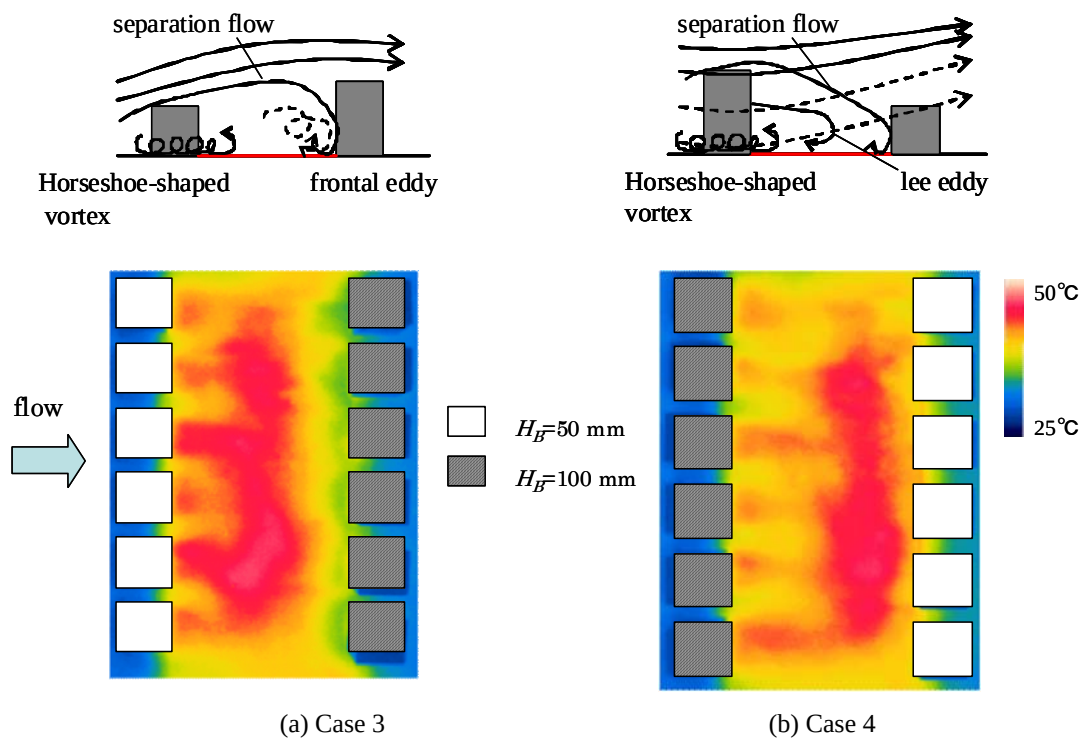


Figure 4. Temperature distributions of Case 3 and Case 4 models.

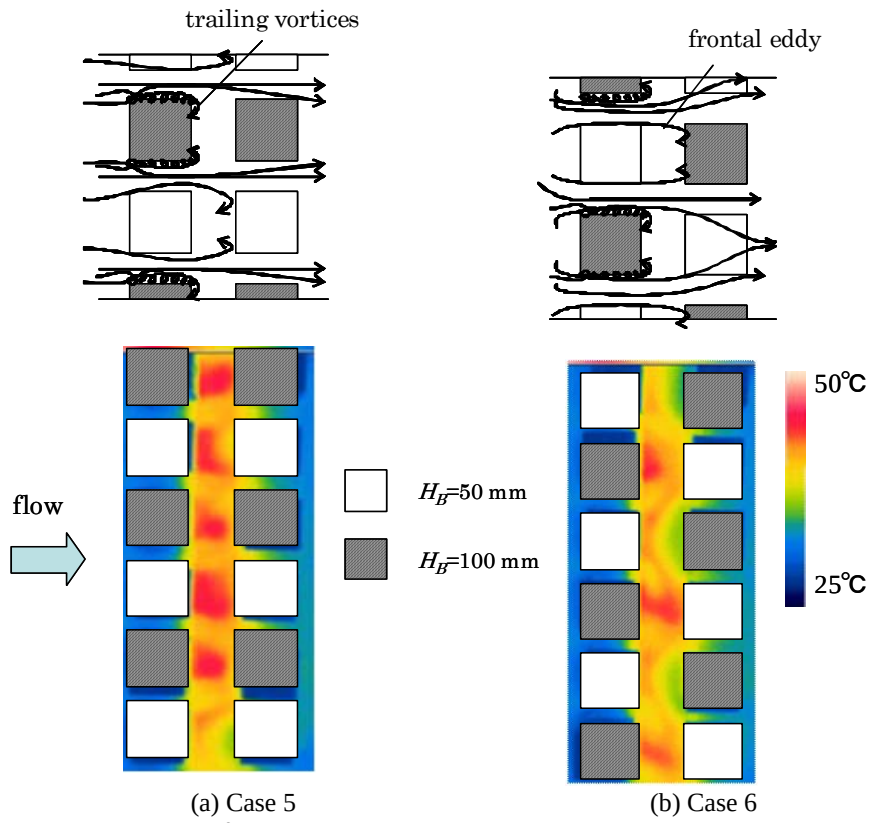


Figure 5. Temperature distributions of Case 5 and Case 6 models.

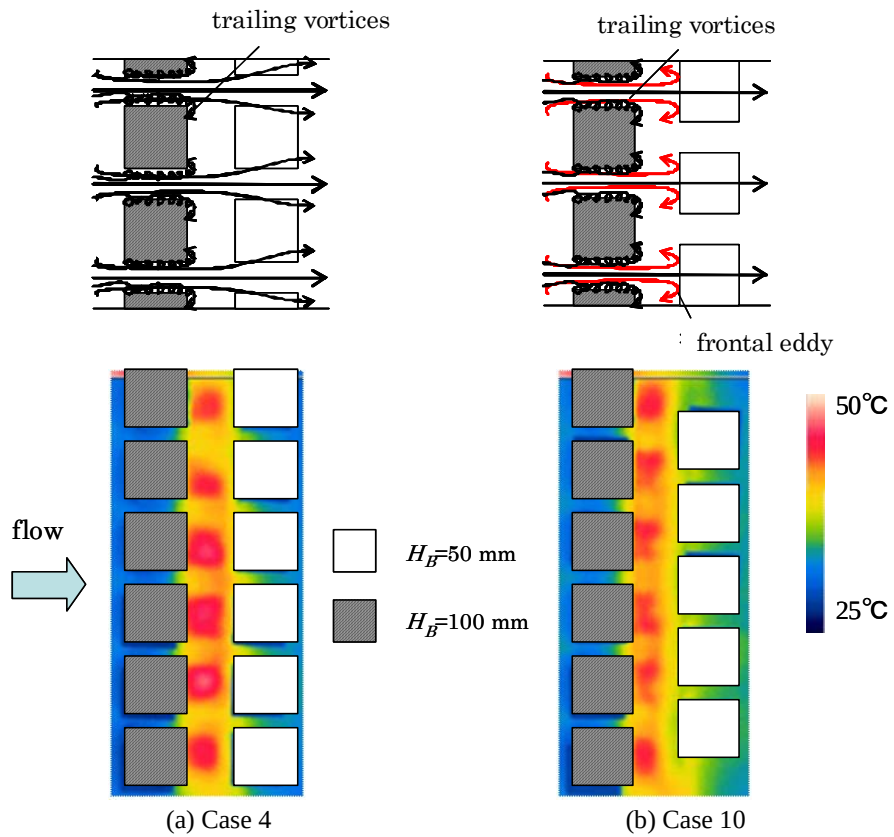


Figure 6. Temperature distributions of Case 4 and Case 10 models.

3.2 Numerical simulation results

Results of numerical analysis are described below in different configurations of building models located in a uniform steady flow as shown in Figure 7. For each case, these figures show the temperature distribution and stream lines.

The temperature distributions and stream lines of the Case 1 model configuration are shown in Figure 7 (a). Some part of airflow at the top of the model which separated the upstream side was reattached to the downstream model on the front surface, and the heated street canyon was cooled by the airflow as the downdraft. In addition, the downdraft would be part of the circulating flow of the entire street, to excite the circulation.

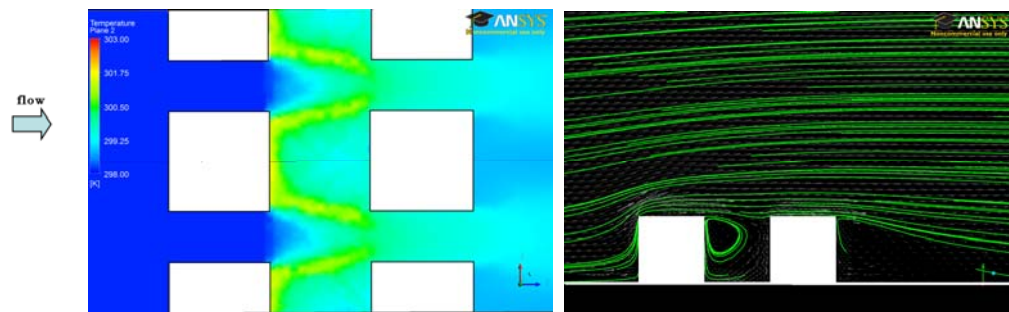
The temperature distributions and stream lines of the Case 2 model configuration are shown in Figure 7 (b). Airflow separated on the leading edge of the front model was increased speed in the gap between the buildings, and the street of the gap between the models surface was cooled well. Circulating flow which was stable in street canyon has been formed, and the separated flow from the upstream model was difficult to approach in the street canyon. It became clear that the cooling range for the backward of the upstream model was narrow compared with the Case 1 configuration.

The temperature distributions and stream lines of the Case 3 model configuration are shown in Figure 7 (c). The most of the separated flow from the upstream side model reattached to the front surface of the downstream side as a downdraft. The downdraft become part of the circulating flow of circulating whole street canyon, and the flow which were passing through above the street made the circulating flow excite furthermore. Therefore, the airflow which reattached to the downstream side model is easy to influx from the top, a large amount of cold air flowed into street, the entire street has been efficiently cooled.

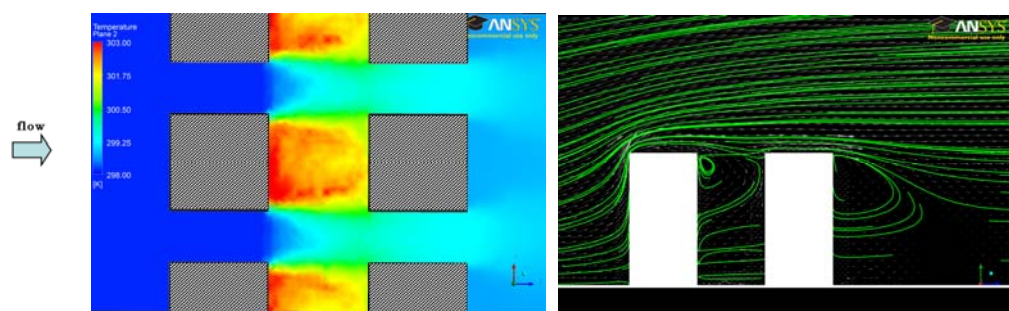
The temperature distributions and stream lines of the Case 4 model configuration are shown in Figure 7 (d). As with Case2, airflow separating on the leading edge of the front model was increased speed in the gap between the buildings, and the street of the gap between the models surface was cooled well. Airflow which separated from the top of the upstream side were passed through downward without reattach on the downstream model, the airflow is difficult to approach from the top to the street surface, stable circulating flow was formed above the street.

Figure 8 shows the temperature distribution and wind velocity vectors of the street surface for the Case1 configuration. Central part of the upstream side behind the model is cooled well by a cold downdraft from the top. Airflow which flows to the rear of the model was reattached to the street surface, high-temperature part formed arched shape. This is because cold air which has flowed into the street from the top, with exchanging heat on the street, spread radially with weakening the cooling capacity. Even though the street surface of the gap between the models were easily cooling, arched shaped high-temperature part were distributed on the street surface. This is because the airflow of the cooling capacity was weakened by heat exchange along the high-temperature part on the street surface.

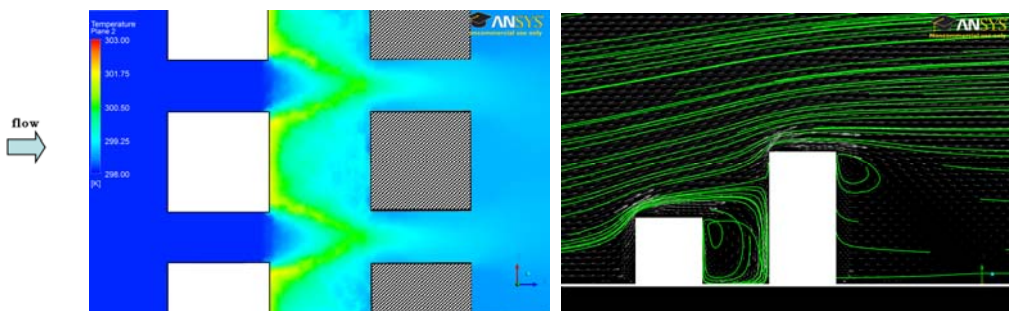
The data in Figures 7 through 8 reveal a correlation between the temperature distribution and stream structure for the cooling effect on the street; how the downdraft forms in the street for the circulating flow determines the excitation of the cooling.



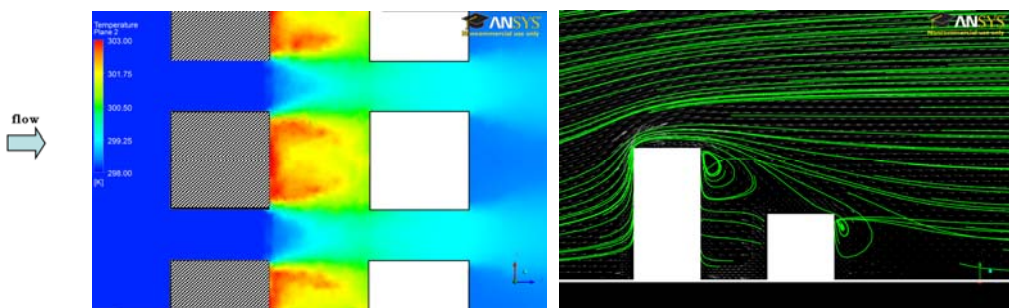
(a) Case 1



(b) Case 2



(c) Case 3



(d) Case 4

Figure 7. Temperature distribution and stream line.

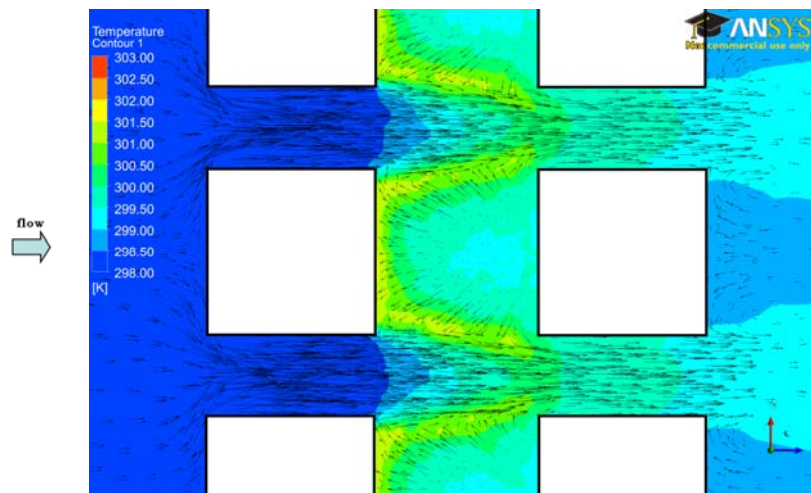


Figure 8. Temperature distribution and flow vector of Case 1.

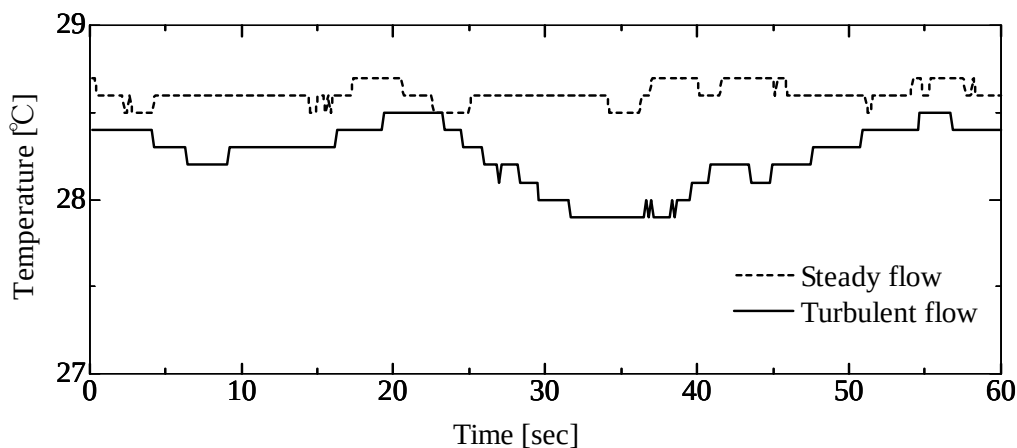


Figure 9. Temperature fluctuation in turbulent flow.

3.3 Turbulent effects

The temperature fluctuation in turbulent flow produced by actively controlled multiple-fan is shown in Figure 9. It is clear that the cooling effect of the turbulent flow is greater than steady flow; how well the street is cooled depends on the fluctuation of the turbulence and the downdraft. It is also evident that a turbulent eddy contributes to the cooling of a heated street surface. The average temperature is significantly low in the turbulence flow compared to the steady flow. The maximum and minimum temperature is fluctuating in the turbulent flow depends on the wind velocity. Because a significant velocity fluctuation exists when the actively controlled multiple-fans, the street temperature varies to the steady flow and the temperature distribution never reaches steady-state.

4 CONCLUSIONS

In this research, building models were arranged at the upstream and downstream sides of a heated street canyon, and the temperature distributions of the street were investigated. Several results were observed:

- (1) For the wind tunnel experimental results, temperature distribution and flow visualization reveal a significant correlation between the formation of an eddy and the cooling effect on the street; how the eddy forms on the street surface determines the cooling effect.
- (2) The numerical simulation results reveal a correlation between the temperature distribution and stream structure for the cooling effect on the street; how the downdraft forms in the street for the circulating flow determines the excitation of cooling.
- (3) For the turbulent effects, a significant temperature fluctuation exists when the actively controlled multiple-fans; how the velocity fluctuation varies the street temperature and the temperature distribution never reaches steady-state.

For future work, a database will be created for heated street canyons based on additional experiments in simulated natural wind flow using different types of turbulent wind tunnels.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

- 1 e.g., Oke, T.R., Street design and urban canopy layer climate, *Energy and Buildings* 11, 1988, pp.103-113.
- 2 Uehara, K., Yamao, Y., Oikawa S., Mochida, A., Wind-tunnel Experiments on Improving the Natural Ventilation of a Street-Canyon, *J. of Jpn. Soc. Atmos. Environ.*, 42(5), 2007, pp.301-309.[in Japanese]
- 3 Gromke, C., Ruck, B., Influence of trees on the dispersion of pollutants in an urban street canyon-Experimental investigation of the flow and concentration field, *Atmos. Environ.* 41, 2007, pp.3278-3302.
- 4 Khan, I.M., Simons, R.R., Grass, A.J., Upstream Turbulence Effect on Pollution Dispersion, *Environ. Fluid Mech.* 5, 2005, pp.393-413.
- 5 Kim, J.J., Baik, J.J., Urban street-canyon flows with bottom heating, *Atmos. Environ.* 35, 2001, pp.2295-3404.
- 6 Li, X.X., Liu, C.H., Leung, Y.C., Development of a $k-\varepsilon$ model for the determination of air exchange rates for street canyons, *Atmos. Environ.* 39, 2005, pp.7285-7296.
- 7 Walton, A., Cheng, A.Y.S., Large-eddy simulation of pollution dispersion in an urban street canyon-Part 2: idealized canyon simulation, *Atmos. Environ.* 36, 2002, pp.3615-3627.
- 8 Von Kármán : Progress in the Statistical Theory of Turbulence, *Proc. Nat. Acad. Sci.*, Washington D.C., 1948, pp.530-539.
- 9 Simiu, E., Scanlan, R.H. : Wind Effects on Structures, Second edition, John Wiley & Sons, 1986, pp.48-65.