SIMULATION STUDY OF THE INFLUENCE OF DIFFERENT URBAN CANYONS ELEMENT TO THE CANYON THERMAL ENVIRONMENT

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ABSTRACT

Heat island is a big issue for large cities especially located in hot and moist climate in Asian countries. The phenomenon is severer in an urban canyon because of surrounding highrise buildings causing little ventilation and heat dissipation from traffic. The first purpose of this study is to investigate thermal environment of a main street in Osaka by intensive measurement in the summer of 2006. Osaka is the second largest city and suffers from the most severe heat island in Japan. The second purpose is to propose several fundamental renovations and a composite renovation for the improvement of thermal environment in the canyon and verify the efficiency of the measures by CFD simulation. It was found that modifications in the building height along the street and ground surface materials, and increase of quantity of green can improve thermal environment to the level of 2.0 K reduction in SET* in maximum.

KEYWORDS

heat island, CDF simulation, thermal environment, urban canyon, urban renovation

INTRODUCTION

In most large cities heat island effect is developing, (T.J.Williamson and E.Erell 2001) as the result, thermal environment in an urban canyon which is surrounded with wall-like buildings has become very severe in summer time due to man-made heat dissipation from buildings and traffic, paved ground surface and increase of building height. There are many reports which investigate the effect of the quantity of green, shapes of buildings and configuration of the urban canyon on its thermal environment (A.Toriyama 2001), however, most of them just compare the environment in different types of streets but very few try to investigate the environment difference formed by the quantity of green, the configuration of the canyon, etc. in a same street. In addition environment investigation for the streets running east-west can be found much but not much for running south-north streets. Although studies predicting thermal environment improvements by some countermeasures in urban canyons in a measurement basis can also be found, (E.Shaviv, A.Yezioro et al. 2001, K.Takahashi, H.Yoshida et al. 2003, S.Ito, H.Yoshida et al. 2005) only a few studies aimed to estimate the effectiveness by CFD simulation together with the validation of the simulation accuracy using measurement results in a real canyon. Therefore the purposes of this study are;

1) Evaluating the effect of quantity of green and configuration of a canyon on thermal environment in a real main-street in Osaka, Japan.
2) Carrying out CFD simulation for the real street and verifying the accuracy of the simulation results by comparing with the measurement results.
3) Proposing and evaluating measures to mitigate heat island effect by reducing man-made heat emission, increasing the quantity of green and modifying configuration of the canyon.

MEASUREMENT OF THERMAL ENVIRONMENT IN A REAL CANYON

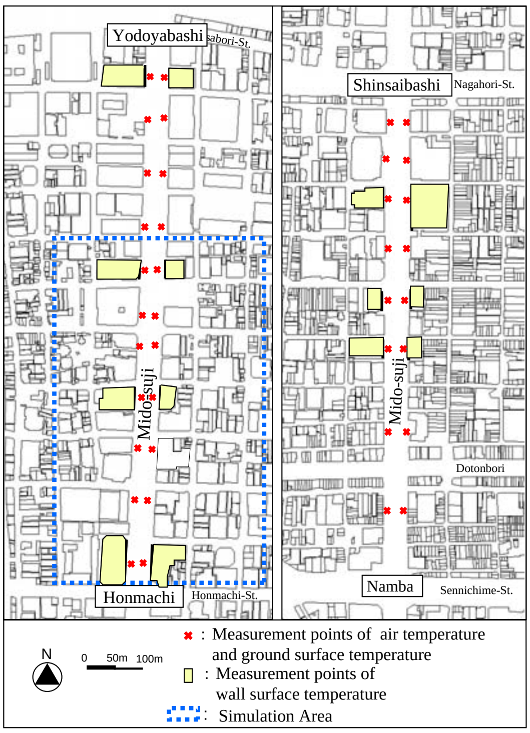

Figure 1 Measurement Points

Photograph 1 Mido-suji

Table 1 Canyon configuration

	Average height of east side buildings (m)	Average height of west side buildings (m)	Aspect ratio (H/W)
Yodoyabashi-site	28.2	23.2	0.58
Namba-site	30.6	44.4	0.85

Intensive measurement of thermal conditions, air temperatures, ground surface temperatures and wall surface temperatures, was carried out along the walkways of Mido-suiji, the main street of Osaka, in order to clarify the influence of quantity of green and configuration of the canyon on thermal environment.

Outline of measurement

The measurement was conducted from 8:00 to 20:00 on August 10, 2006 along the east and west walkway of Mido-suji (44m in width and 3km in length) located in Chuo-ku, Osaka city, Japan. This street is running north-south and noted for the main street which represents Osaka, namely the symbol of the city. The measurement points are shown in Fig. 1 and photograph-1 shows a typical view of the street. Temperatures, air humidity and surface temperatures of building walls and streets were recorded hourly.

Air temperatures and humidity were measured at the height of 1.5m and surface temperatures of building walls and streets were measured by handy infrared thermometers. It took about 40 minutes to perform a round of measurement and the measured data were corrected for the time difference. Sky and green view factors were estimated using fish-eye pictures taken at every site.

Sky and green view factors in Yodoyabashi and Hommachi area (called Yodoyabashi-site below) differ from those in Shinsaibashi and Namba (called Namba-site below). The values are shown in Fig. 2 and the canyon configurations of both sites are given in Table 1.

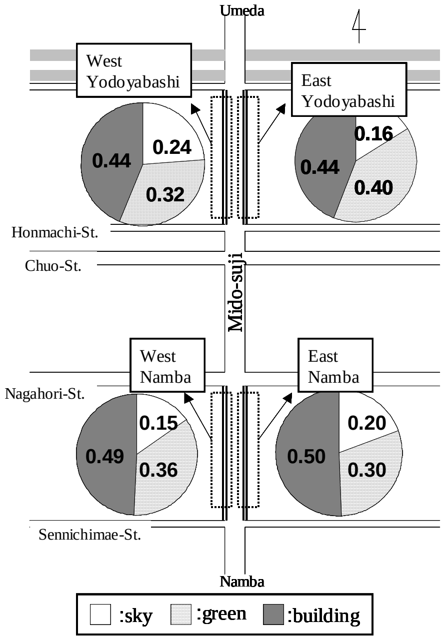

Figure 2 View Factors

Measurement results

Surface temperatures on walkways

The surface temperatures on walkways in Yodoyabashi-site and Namba-site are shown in Fig. 3. The surface temperatures of the streets were obtained as an area weighed mean of sunny and shaded area temperatures. On the east walkway little difference (within 2K) were observed in both sites. The reason of this little difference in spite of less green and larger sky view factors in the east walkway of Namba-site compared to those of Yodoyabashi-site would be less solar radiation due to the deeper canyon formed by the higher buildings along west side in Namba-site compared to those of Yodoyabashi-site.

The surface temperatures of the west walkway of Yodoyabashi-site are about 3-9 K higher than those of Namba-site in the morning. The reason should be receiving more solar radiation because of less green in Yodoyabashi-site.

Surface temperatures of building façade

The temperature variations with time for the east and west building façade in both sites are shown in Fig. 4. The temperatures were calculated as the area weighted average of those measured at the height of 5m, 15m and 30m of buildings.

East façade temperatures in Namba-site are about 3-6 K higher than those of Yodoyabashi-site except between the hours of 15:00 and 17:00. This is because that higher sky view factors due to less green in Namba-site cause more solar radiation on the east façade.

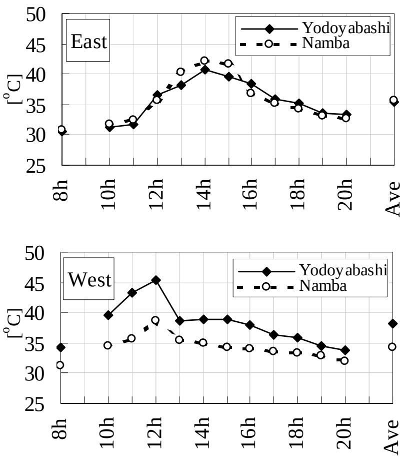

Figure 3 Surface temperatures on walkway

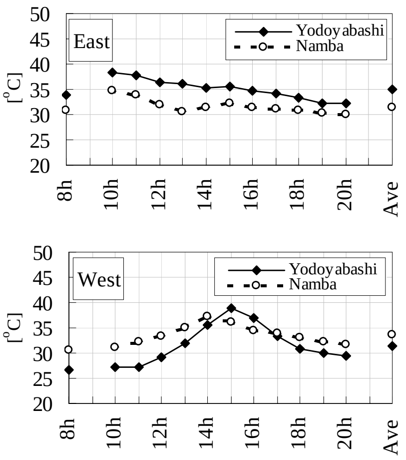

Figure 4 Surface temperatures of building walls

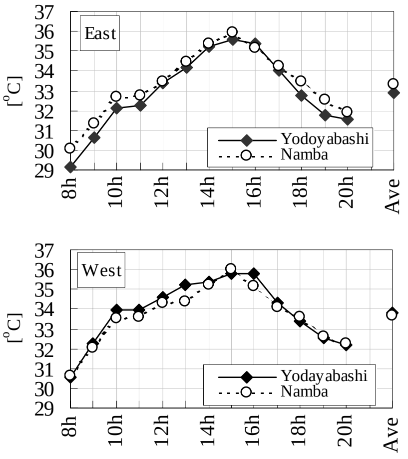

Figure 6-1 Air temperatures of east and west walkway

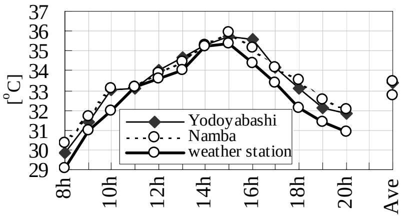

Figure 5 Air temperatures of streets and weather station

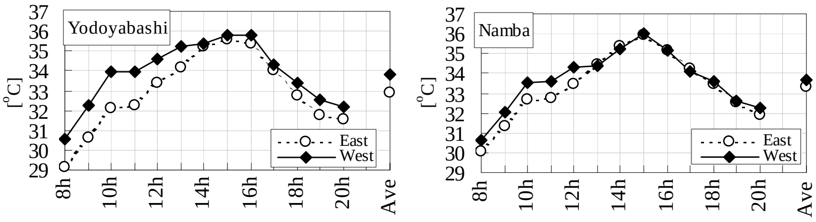

Figure 6-2 Air temperatures of Yodoyabashi-site and Namba-site

The temperatures of the west façade in Yodoyabashi-site are about 2-7 K higher than those in Namba-site. Similar reason as above can be found in Yodoyabashi-site.

Air temperatures

Air temperature variations with time in Yodoyabashi-site, Namba-site and of the weather station of Osaka are shown in Fig. 5. The temperatures at the two sites are about 1 K higher than those of the weather station of Osaka between the hours of 8:00 and 10:00, and 16:00 and 20:00. These three are almost equal between the hours of 11:00 and 15:00. Therefore it is presumed that cool wind from the Osaka Castle Park, which is located north-east of the weather station and has a large green area, would reach the wether station and made the temperature decrease as wind directions stayed in-between north and east from 8:00 to 10:00. Air temperatures at both sites are higher than those of weather station between the hours of 16:00 and 20:00. This is the typical heat island effect to be intrinsic in urban canyon.

The air temperature differences in Yodayabashi-site and Namba-site are shown in Fig. 6-1. In the east walkway of Namba-site air temperatures are about 0.5-1.0 K higher than that of Yodoyabashi-site between the hours of 8:00 and 11:00, and 18:00 and 20:00. This should be because the temperatures of east building façade in Namba-site are higher than those of Yodoyabashi-site regardless that the surface temperatures of the walkways of Namba-site and Yodoyabashi-site are almost equal. The air temperatures in Yodoyabashi-site are about 0.5-1.0K higher than those of Namba-site between the hours of 10:00 and 13:00. This would be because the surface temperatures of the walkways and the east façade of Yodoyabashi-site are higher than those of Namba-site.

The air temperature variations in the east and west walkways are shown in Fig. 6-2. The air temperatures of the west side are about up to 2.0 K higher than those of the east side in Yodoyabashi-site and about 1.0 K higher in Namba-site in the morning. In the afternoon temperatures of the west side are still higher. This would be due to traffic heat conveyed by the circular wind formed in the urban canyon coupled with heat stored in canyon structures in the morning.

THERMAL ENVIRONMENT ESTIMATION OF WALKWAYS BY CFD SIMULATION

Calculation method

For CFD simulation the κ - ε three-dimensional turbulent flow model improved by Launder and Kato is used. (B.E.Launder and M.Kato 1993).

$$\rho = const. \quad (1)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (2)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho \overline{u_j u_i}}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\mu\frac{\partial u_i}{\partial x_j} - \rho g_i (T - T_o) \quad (3)$$

$$\frac{\partial \rho C_p T}{\partial t} + \frac{\partial u_i C_p T}{\partial x_j} = \frac{\partial}{\partial x_j} K \frac{\partial T}{\partial x_j} + \dot{q} \quad (4)$$

We assume the fluid to be incompressible (equation-1), and solve the simultaneous equations of conservation laws of mass (equation-2), momentum (equation-3), and energy (equation-4). Pressure correction is done using the SIMPLE method.

$$-\eta C_d a u_i^2 / 2 \quad (5)$$

$$\frac{\varepsilon}{\kappa} 2\eta C_d a \left(u_i^2\right)^{\frac{3}{2}} \quad (6)$$

$$E_s = \beta \alpha_w \left(f_a - f_s \right) \quad (7)$$

$$lE = L \beta \alpha_w \left(f_a - f_s \right) \quad (8)$$

The term given by formula (5) is the aerodynamic resistance by a tree and it is added on the right-hand member of the momentum equation (3). The term (6) is the dissipation ratio in turbulent flow by the tree. This is also added to the equation of turbulent dissipation, which is not shown. Evapotranspiration from a tree is modeled by the equation (7) and heat absorption given by the equation (8) is incorporated in CFD modeling.

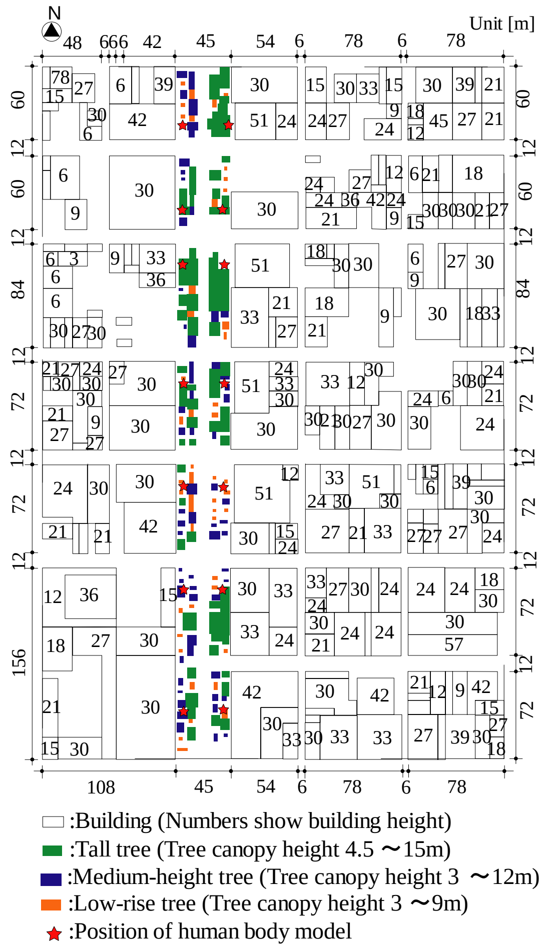

Figure 7 Plan of Basic Model

Boundary Conditions

Boundary conditions in the inlet section were determined by pre-simulations performed as follows.

Firstly an urban model for preliminary simulation is built so as to have the roughness which represents typical building configurations in Osaka city. The vertical distribution of mean horizontal wind is given by the logarithmic law and that of turbulent energy is given based on the standards of building load calculation (AIJ 2004). The dissipation ratio of turbulence is obtained assuming that generation and dissipation of turbulence are balanced in the inlet boundary section. Boundary conditions of stress on the surfaces of solid bodies are based on logarithmic law and heat transfer coefficient on the surfaces is set to be 11.6 W/m^2 .The boundary condition of the upper section and the side sections of the analytical region is assumed to be free-slip. The air temperature in the upper section was set to be the temperature measured at the weather station of Osaka. The side surfaces are assumed to be thermally insulated.

Secondly CFD simulation is carried out multiple times by replacing the inlet conditions with the outlet conditions obtained by the previous calculation in each time. Simulations are carried out until the conditions converge.

Thirdly the CFD simulation of the relevant space is carried out using the final inlet conditions obtained by the above process. The surface temperatures of solid body such as buildings and walkways are set as the measured.

Simulation model

Simulation was carried out hourly between the hours of 10:00 and 15:00 on August 10, 2006 for the Yodayabashi-site. The plan of the simulation model is shown in Fig. 7. Heat dissipated from traffic is calculated based on the number of traveling cars measured at the site and the types of cars recorded. Car speed was estimated by visual observation. Heat dissipation rate for each car is taken from National Institute for Land and Infrastructure Management (equation 9).

Heat generated from air-conditioning systems in buildings is estimated based on building types, floor area, which are determined as the equation 10 from the census report by Department of Urban Planning of Osaka, and unit heat generation rates for each building type, which are obtained from the reference

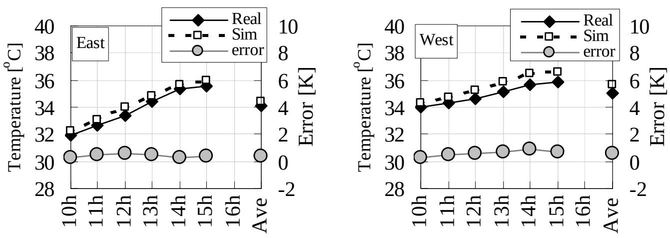

Figure 8 Measured and simulated values and errors

(Kinki Branch of The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan 1997). The positions of heat exhaust from buildings were identified using air photographs.

$$Q_c = \sum_i N_i \; q_{ci} / L \qquad (9)$$

$$Q_b = q_b \; S_b / S \qquad (10).$$

Simulation results

The results of the simulation and the measurement regarding air temperatures at a height of 1.5 m on the east and west walkways and the differences or errors are shown in Fig. 8. The errors of the east walkway fall within 0.3-0.5 K and in average 0.4 K. For the west they fall within 0.3-0.8 K and in average 0.6 K. The variation of the simulation results with time is similar to the measurement. The results, therefore, convince us that simulation can be used to predict thermal environment after renovation of an urban canyon. This model is defined as "Basic Model" in this paper.

THERMAL ENVIRONMENT IMPROVEMENT OF THE WALKWAYS BY URBAN CANYON RENOVATIONS AND EFFECT VERIFICATION BY CFD

We propose fundamental renovations to improve the thermal environment of the urban canyon and carry out CFD simulation to quantify the effect of the measures by comparing with the results of the Basic Model. All simulations were carried out for Yodayabashi-site at 15:00 on August 10, 2006 when the highest air temperature was observed. The improvement effect is principally evaluated by SET*. The positions of human models are shown in Fig. 7. The SET* is calculated using air temperature, relative humidity, wind speed and MRT which are estimated in simulation. In addition it is assumed that the insulation value of clothing is 0.6 clo and metabolic rate is 1.4 met based on summer wear and stand up posture conditions.

Basic renovation models and results

Six renovations to improve thermal environment such as increasing evapotranspiration of green and modification of building shape and configuration were considered to reduce man-made heat. The renovation measures are summarized in Table 2. The sections of the renovated canyon are shown in Fig. 10. In Table 3 the results are given with differences between those of the renovations and the Basic Model.

Traffic closure in side-roads (case 1)

Simulation Case-1 intends to decrease heat dissipation from traffic by about 38% by closing the side-roads. As a result air temperature decreases about 0.2 K and SET* decreases 0.1 K in the west walkway, although not much improvement is not made in the east walkway.

Installation of arcades (case 2)

Case-2 aims to moderate radiation environment by installing arcades with 5.5 m wide at the height of 6 m above the walkways. Wind velocity decreases by 0.5-0.9 m/s and SET* rises by 0.5-0.8 K even though MRT decreases by 0.6-1.1 K. This means that arcades do not give good effect if solar radiation is cut by buildings itself.

Increasing amount of trees (case 3)

At present the amount or the size of trees in the street is not plenty at many locations, therefore, Case-3 intends to increase all the trees to the maximum size. Eventually solar radiation becomes to be cut off considerably and MRT decreases by 0.5-1.8 K and air temperature also decreases by 0.2-0.4 K due to increased evapotranspiration. As a result SET* decrease by 0.2-0.5 K.

Increasing building height along east walkway (case 4)

Case-4 aims to increase wind velocity in the canyon by creating a vortex wind in the canyon and bringing downward cool breeze. The phenomenon would be realized by increasing the buildings height along the east walkway: in precise increasing the height from the present 50 m to 75 m. The result shows that wind speed increases by 0.5-0.7 m/s resulting SET* decrease by 0.3-0.5K.

Corner-cut of buildings (case 5)

Case-5 intends to enhance cross breeze by modifying building shapes. We thought that corner-cut of buildings may provide good effect, however, the result shows that wind velocity falls by 0.1-0.3 m/s resulting SET* increase by 0.1-0.3 K.

Constructing water streams (case 6)

Case-6 aims to reduce air temperature by water evaporation and long wave radiation by cool water surface. For this purpose we considered to construct water streams nearby the two walkways. The temperature of the water was set to be 30 ℃ which is the average temperature of a typical hottest summer day in Osaka. The result shows that air temperature along the west sidewalk decreases by 1.2 K and MRT by 0.3-0.4 K and SET* by 0.2-0.5 K accordingly.

COMPOSITE MODEL

Finally we investigated a composite renovation model which is shown in Fig. 11, 12 and 13. This model is based on a realistic urban plan proposed by a group of city planners who collaborated with the urban environment engineers in order to mitigate heat island phenomenon in Osaka. The composite model incorporates permeable pavement for bicycle road and reflection pavement for the vehicle road in addition to Case 1, 3, 4 and 6 measures. In Table 4 incorporated measures are given.

Table 2 Proposals

Approach	Improvement measure	Case
Reduction of man-made heat release	Traffic closure in side-roads	1
Shielding of solar insolation	Installation of arcades	2
	Increasing amount of trees	3
Increase of wind velocity	Raising building height along east walkway	4
	Corner-cut of buildings	5
Increase of evapotranspiration	Increasing amount of trees	3
	Constructing water streams	6

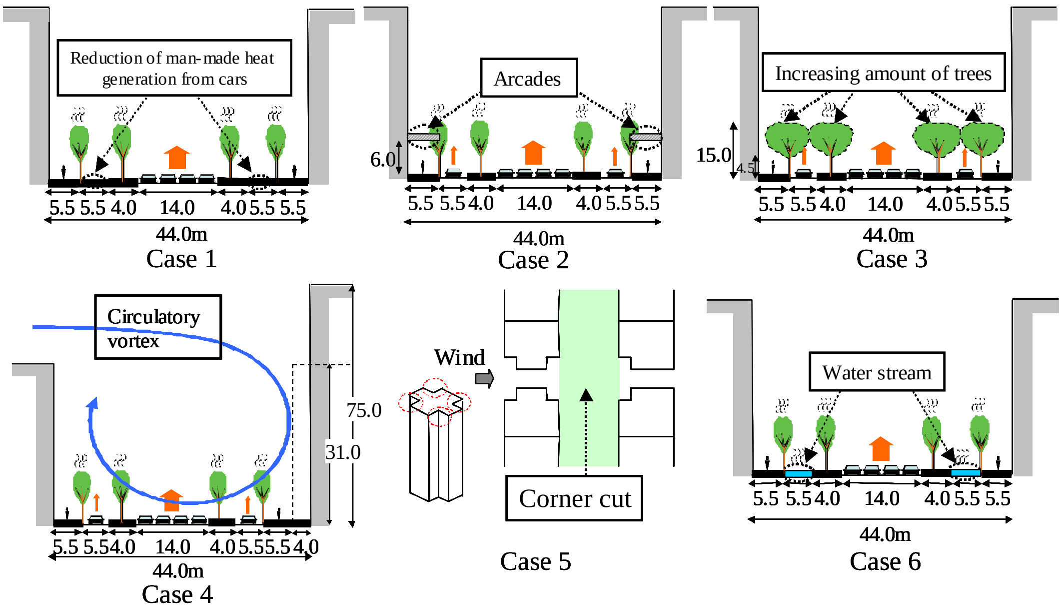

Figure 9 Section of case 1-6

Table 3 Results of simulation of proposals to improve thermal environment

	Ideas to improve thermal environment	West sidewalk				East sidewalk			
		Air temperature [°C]	MRT [°C]	Wind velocity [m/s]	**SET* [°C]**	Air temperature [°C]	MRT [°C]	Wind velocity [m/s]	**SET* [°C]**
-	Basic Model	36.5	34.2	1.3	**32.2**	35.9	35.7	1.7	**32**
Case 1	Traffic closure in side-roads	-0.2	-0.1	0	**-0.1**	-0.1	-0.6	0	**0**
Case 2	Installation of arcades	0.1	-0.6	-0.5	**0.5**	0	-1.1	-0.9	**0.8**
Case 3	Increasing amount of trees	-0.4	-0.5	-0.1	**-0.2**	-0.2	-1.8	0	**-0.5**
Case 4	Raising building height along east walkway	-0.2	0.1	0.7	**-0.5**	-0.1	0	0.5	**-0.3**
Case 5	Corner-cut of buildings	0	0	-0.3	**0.3**	0	0.1	-0.1	**0.1**
Case 6	Constructing water streams	-1.2	-0.4	0	**-0.5**	-0.1	-0.3	0.1	**-0.2**

Simulation Results of Composite Model

The simulation results are summarized in Table 5. Air temperatures along the east walkway decrease by 0.1-0.6 K from Basic-Model case and along the west by 0.9-1.8 K. This would be due to the effect of evaporation from water surface and evapotranspiration from the trees, and the surface temperature drop on the vehicle road by permeable pavement and heat reflection pavement.

Wind velocity on the east walkway rises by 0.7-2.9 m/s in all spots except the spot E2. On the other hand it decreases by 0.3-0.8 m/s in W1, W2 and W3 and rises in W4 and W5 by 1.5-1.7 m/s along west sidewalk. From the CFD results it was found that the horizontal wind directions are quite diverse over the site and the heights and locations of the buildings intricately influences wind flow pattern and velocity. This means that precise and specific CFD analysis reflecting canyon configuration is necessary in a composite model. MRT decrease by 1.3-2.9 K along the east walkway and by 0.8-0.3 K along the west. Although SET* in E2 and W2 rises due to wind velocity reduction, those in other spots decreases by 2.0 K as maximum.

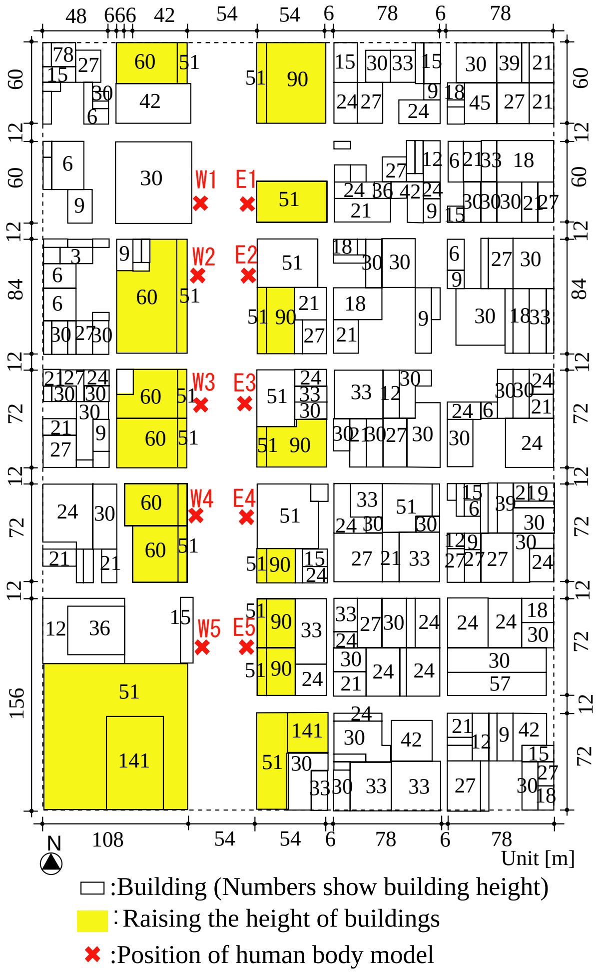

Figure 10 Plan of Composite model

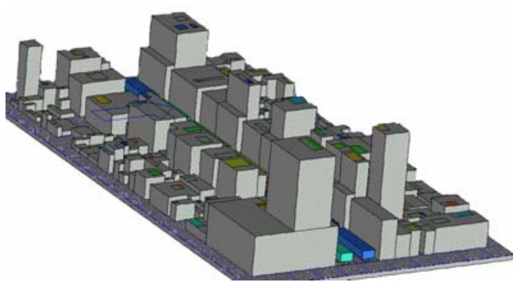

Figure 11 Bird's-eye view of composite model

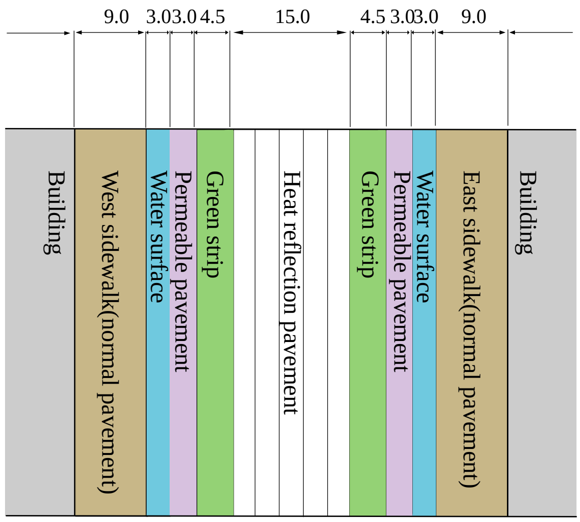

Figure 12 Road surface finishing

Table 4 Renovation measures of Composite model

Approach	Improvement measure
Reduction of man-made heat release	Traffic closure in side-roads
Shielding of solar insolation	Increasing amount of trees
Increase of wind velosity	Raising building height along east walkway
Increase of evapotranspiration	Increasing amount of trees
	Constructing water streams

Table 5 Results of Composite model

		E1	E2	E3	E4	E5	W1	W2	W3	W4	W5	Average
Air temperature [°C]	Basic Model	35.9	35.8	35.9	36.0	36.1	36.4	36.0	36.2	36.8	37.3	36.2
	Composite Model	35.8	35.7	35.6	35.7	35.5	35.5	35.0	34.5	35.4	35.5	35.4
	difference	-0.1	-0.1	-0.3	-0.3	-0.6	-0.9	-1.0	-1.7	-1.4	-1.8	-0.8
wind velocity [m/s]	Basic Model	2.1	2.0	2.1	1.9	0.9	1.6	1.6	1.5	1.0	0.9	1.6
	Composite Model	2.8	1.4	2.9	4.8	3.8	1.3	0.9	0.7	2.7	2.4	2.4
	difference	0.7	-0.6	0.8	2.9	2.9	-0.3	-0.7	-0.8	1.7	1.5	0.8
MRT [°C]	Basic Model	36.6	35.2	35.1	36.6	35.0	33.8	34.1	34.1	34.0	34.5	34.9
	Composite Model	33.7	33.6	33.7	33.7	33.7	33.0	33.1	33.1	3.2	33.2	30.4
	difference	-2.9	-1.6	-1.4	-2.9	-1.3	-0.8	-1.0	-1.0	-0.8	-1.3	-1.5
SET* [°C]	Basic Model	31.9	31.6	31.6	32.0	32.5	31.8	31.7	31.8	32.5	32.9	32.0
	Composite Model	31.0	31.6	30.9	30.6	30.6	31.5	31.9	32.1	30.8	30.9	31.2
	difference	-0.9	0.0	-0.7	-1.4	-1.9	-0.3	0.2	0.3	-1.7	-2.0	-0.8

CONCLUSION

We investigated heat island phenomenon by intensive measurement of the urban canyon of the main street in Osaka, Japan. In addition we performed CFD simulation to validate the effect of six renovations to mitigate thermal environment, and then investigated the environmental improvement of a composite model which was proposed for the future renovation of the urban canyon. The followings are obtained findings.

1) About 2 K temperature differences were found along the same street. The differences are a result of combined effect of wind velocity, sky view factor, amount of green, solar radiation, building height and surface temperatures. Due to this complexity the rational explanation about the difference is too difficult to explain just based on measured data. Therefore investigation of urban environment by CFD simulation is very important.

2) Comparing errors between the measured data and the simulation results it was found that simulation can predict air temperatures within the accuracy of 0.4-0.6 K by which we can conclude that simulation is enough accurate to be used to predict the effect of renovations of urban environment.

3) Six fundamental renovations are proposed for the remedy of heat island and are verified by CFD simulation. Although reduction in SET* by 0.1-0.5 K can be achieved, it was found that some measures worsen SET* by 0.1-0.8 K.

4) A composite renovation model is proposed and verified. It was found that air temperatures and SET* can be decreased by 0.8 K in average (max. 1.8 K) and 0.8(max. 2.0 K) respectively.

NOMENCLATURE

a : Density of leaf area [m^2/m^3](=0.4)

C_d : Coefficient of resistance [-](=0.5)

C_p : Specific heat of air [J/kgK]

E_s : Transpiration rate [kg/m^{2}s]

f_a : Partial pressure of water vapor [kPa]

f_s : Partial pressure of saturated water vapor [kPa]

g_i : Acceleration [m/s^2]

K : Coefficient of heat conduction [J/msK]

lE : Absorption of heat [W/m^2]

L : Road width [m]

N_i : Traffic rate [number of cars/s]

P : Air pressure [N/m^2]

q_b : Specific heat generation of a building type[W/m^2]

q_{ci} : Heat dissipation rate for car types [J/m]

Q_b : Heat generation from a building [W/m^2]

Q_c : Heat release from traffic [W/m^2]

S_b : Total floor area of a building [m^2]

S : Area of heat exhaust [m^2]

t : Time [sec]

T : Air temperature [K]

u_i : Velocity [m/s]

x_i : Space co-ordinate [m]

α_w : Water vapor transfer coefficient conductivity [kg/m^{2}skPa]

β : Evaporation efficiency [-]

η : Ratio of green coverage [-]

μ : Coefficient of viscosity [kg/ms]

ρ : Density of air [kg/m^3](=1.176)

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