STUDY ON THE APPROPRIATE SELECTION OF URBAN HEAT ISLAND MEASURE TECHNOLOGIES TO URBAN BLOCK PROPERTIES

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ABSTRACT

Toward the appropriate selection of urban heat island measures technology in the street canyon, the introduction effects of the technologies in the typical street canyon are analysed by the model calculation. It is appropriate to use street trees for the improvement of the thermal environment on the sidewalk and high reflectance paint or water-retentive pavement for the reduction of surface temperature on the roadway. Reduction of solar radiation gain to the sidewalk pavement surface is dependent on the location and area of the shadows by street tree. Shadows by street tree are likely to occur on the northern sidewalk of the east-west road than the eastern (or western) sidewalk of the north-south road. While the shadow by the street tree is occurred on the sidewalk, the area of the shadow is proportional to the square of the width of tree crown (the radius) and inversely proportional to the distance of each tree. It is necessary to be considered a priority according to the road orientation and time zone primarily used by pedestrian.

KEYWORDS

Urban Heat Island, Radiant Environment, Street Canyon, Properties of Urban Block

1 INTRODUCTION

Various urban heat island measure technologies have been proposed and the performance of each technology has been evaluated. Toward the appropriate selection of urban heat island measures technology, relationship between where the technology has been introduced and the effect by the introduction of technology must be studied. In order to understand where these technologies should be introduced, the relationships between the properties of urban canopy components and the radiant environment in an urban street canyon are examined in previous paper by the authors (Takebayashi and Moriyama, 2012). As a consequence, the top priorities for the implementation of urban heat island measures are the roofs, the north sides of east-west roads, and the center of north-south roads. From the view point of introduction of appropriate technique for each place, it is analysed the relationship between benefits by heat island measure technique and places it was introduced. Objective techniques are street tree, green wall, high reflectance paint and water-retentive pavement, which are pointed out benefits are relatively large in previous study (Takebayashi and Moriyama, 2012). Objective places are road and wall surface. The roof surface has the highest priority for urban heat island measure due to the highest solar radiation gain. However, surface temperature distribution is relatively small because the shading effects by the penthouse or surrounding buildings are not so remarkable. So, the benefits by the heat island measure technique are as similar as the results of previous study which has been carried out on the horizontal surface (Takebayashi and Moriyama, 2007). The evaluation index is surface temperature distribution on the road and wall. Surface heat budget and radiation transfer are calculated in the typical street canyon model. The parameters of the street canyon are orientation and width of the street.

2 RADIATION TRANSFER AND SURFACE HEAT BUDGET MODEL IN THE URBAN CANOPY

2.1 Outline of the calculation model

The urban canopy components—roofs, walls, and roads—are divided into grids, and for each surface, direct, diffuse, and reflected solar radiation and infrared radiation are calculated. Sky view factors from each surface and view factors between the surfaces are calculated by the Monte Carlo method. Mutual radiation between the surfaces is calculated using Gebhart's absorption factors. It is assumed that all surfaces are uniform diffuse reflectors and only one reflected radiation flux is included within the calculation. The objective condition is a sunny summer day, when the normal direct solar radiation is calculated by Bouguer's equation, the horizontal diffuse solar radiation is calculated by Nagata's equation, and the infrared radiation from the sky is calculated by Brunt's equation. The surface heat budget for each surface is calculated and the one-dimensional heat conduction equation is estimated for each wall, roof, and road.

Surface heat budget on each surface:

$$R_n = V + lE + A \tag{1}$$

where R_n is net radiation [Wm^{-2}], V is sensible heat flux [Wm^{-2}], lE is latent heat flux [Wm^{-2}], and A is conduction heat flux [Wm^{-2}].

One-dimensional heat conduction equation:

$$C_p\gamma \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} \tag{2}$$

where $C_p\gamma$ is heat capacity [Jm^{-3}K^{-1})]; λ is thermal conductivity [Wm^{-1}K^{-1}]; T is the temperature of the wall, roof, or road [K]; t is time [s]; and x is the distance to the wall, roof, or road [m].

A typical sunny summer day, August 4, 2011, was set for the weather conditions. It was selected from hot days Japan meteorological agency issued a warning. The criteria is more than 35°C in daily maximum air temperature. Observation data that were recorded at the Kobe meteorological observatory (34°41.8′ N, 135°12.7′ E) were used. Local distribution of wind velocity in the urban canyon was not considered and the convective heat transfer coefficient was assumed to be a constant with a value of 12.5 Wm^{-2}K^{-1}. It can be discussed mainly the impact of radiation heat exchange in the street canyon. Initial surface and inner temperatures of each component were set at 27°C, and the calculations were repeated twice on the same day to consider the effects of heat storage.

The walls and roofs were assumed to be 0.3 mm thick concrete and the roads were assumed to have 0.2 mm thick asphalt and 0.35 mm thick soil. Parameters regarding heat conduction are set based on previous study results by the authors (Takebayashi and Moriyama, 2012); solar reflectance, emissivity, thermal conductivity, heat capacity of concrete are 0.2, 0.95, 1.64 Wm^{-1}K^{-1}, 1.93 MJm^{-3}K^{-1}, and solar reflectance, emissivity, thermal conductivity, heat capacity of asphalt are 0.1, 1.0, 0.74 Wm^{-1}K^{-1}, 2.1 MJm^{-3}K^{-1}, and thermal conductivity, heat capacity of soil are 0.62 Wm^{-1}K^{-1}, 1.58 MJm^{-3}K^{-1}.

2.2 Outline of the urban canopy model and heat island measure techniques

From the results of the previous study, the characteristics of road surface temperature in the street canyon can be explained by the typical two-dimensional street canyon model represented by the building height and road width. It is necessary to distinguish east-west road and north-south road, and thermal characteristics of both roads are overlaid on the intersection. In this paper, north-south road and east-west road whose width is 20 m (narrow), 30 m (middle), 50 m (wide) are selected to the objective road, with constant building height 30 m, by referring to the typical urban block of Kobe city. They are treated as a two-dimensional street canyon model. However, because the street trees are assumed to be planted continuously along the road in the two-dimensional street canyon model, the examination of changing the arrangement interval of the street tree is carried out in the next chapter. Outline of street canyon model with street tree and green wall is shown in figure 1. Both side buildings with 30 m height are located by 1 m set back from the road, and the sidewalk with 3 m width is in the front of them. Street tree with 2 m width is located between the roadway and sidewalk. The widths of the roadway are 10 m, 20 m, 40 m and it is equally divided to three for analysis. Mesh interval for calculation is 0.5 m constant in both horizontal and vertical directions.

Objective heat island measure techniques are street tree, green wall, high reflectance paint and water-retentive pavement. The height of street tree, the height under the tree crown, solar radiation shielding factor of leaves, evaporative efficiency of leaves are 10 m, 2.5 m, 0.8, 0.3, respectively. The height of green wall is 5 m which is 0.5 m away from the wall. Solar radiation shielding factor of leaves, evaporative efficiency of leaves are 0.8, 0.3, respectively. The reflectance of high reflectance paint is 0.4 which is painted on asphalt road surface. The evaporative efficiency of water-retentive pavement is 0.3 which is changed from asphalt road surface. It is continuous water supply type pavement with the irrigation equipment.

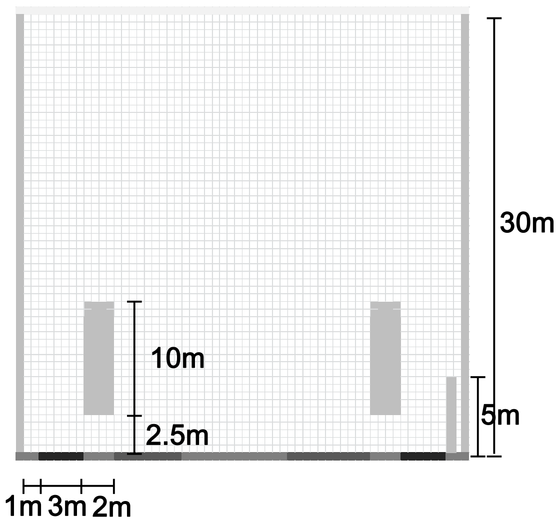

Figure 1: Outline of street canyon model with street tree and green wall

2.3 Calculation results

The daily mean surface temperature is averaged along each side sidewalk, each side roadway and center of roadway, from the calculation results of introducing the countermeasure technology. And, the daily mean wall surface temperature is used for the green wall examination. Benefit of each technology is occurred at different time depending on the introducing location. Some technologies influence on night temperature by the thermal storage of road and wall materials. In this study, it is assumed that the daily mean surface temperature represents not only the thermal environment during the day, but also heat storage effect during the night. For example, the benefit by high reflectance paint is about 7 K during the day and about 0.5 K during the night on the center of the north-south road, then it is about 1 K on daily average.

Daily average surface temperature reduction by street tree is shown in figure 2. The benefit on the northern sidewalk of the east-west road is greater than the others. The benefit on the eastern and western sidewalk of the north-south road is greater than the others. It means that the improvement of thermal environment on the pedestrian space is remarkable.

Daily average surface temperature reduction by green wall is shown in figure 3. The benefit of the east-west road on the north side wall is larger than the south side wall. And the difference due to the road width is not sure. The difference of the benefit of the north-south road between the west and east side wall is small. And, the benefit on large road width is larger than the others. The benefit on the wall which is received large solar radiation is greater than the others.

Daily average surface temperature reduction by high reflectance paint and water-retentive pavement are shown in figures 4 and 5. The benefits by both high reflectance paint and water-retentive pavement are larger on the center of north-south road and from the center to northern side of east-west road where the solar radiation gain is large. The difference of benefits by between water-retentive pavement and high reflectance paint is depending on the evaporation efficiency of water-retentive pavement, solar reflectance of high reflectance paint and weather condition.

Daily average surface temperature reduction by street tree, high reflectance paint and water-retentive pavement are shown in figure 6. As described above, the benefit by both high reflectance paint and water-retentive pavement appears mainly on the roadway. On the other hand, the benefit by street tree is concentrated mainly on the sidewalk. Since the benefit by street tree is caused by solar radiation shielding by the tree crown, the shadows by canopy occur mainly on the sidewalk. Therefore, it can be said that the introduction of water-retentive pavement and high reflectance paint on the roadway is more appropriate for the road surface temperature reduction and the introduction of roadside tree is more appropriate for the thermal environment improvement on the sidewalk. Technology by solar radiation shielding on the wall such as green wall is suitable to the wall surface temperature reduction.

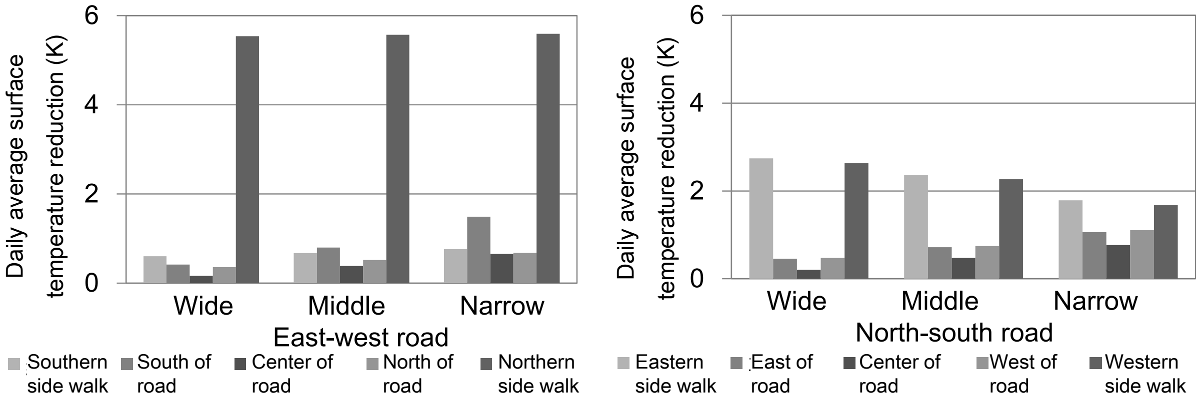

Figure 2: Daily average surface temperature reduction by street tree

(Left: east-west road, Right: north-south road)

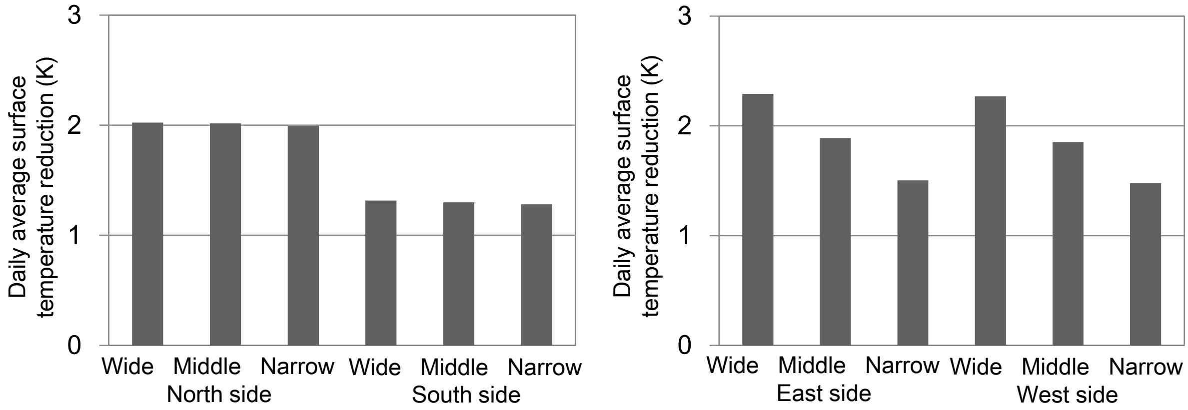

Figure 3: Daily average surface temperature reduction by green wall

(Left: east-west road, Right: north-south road)

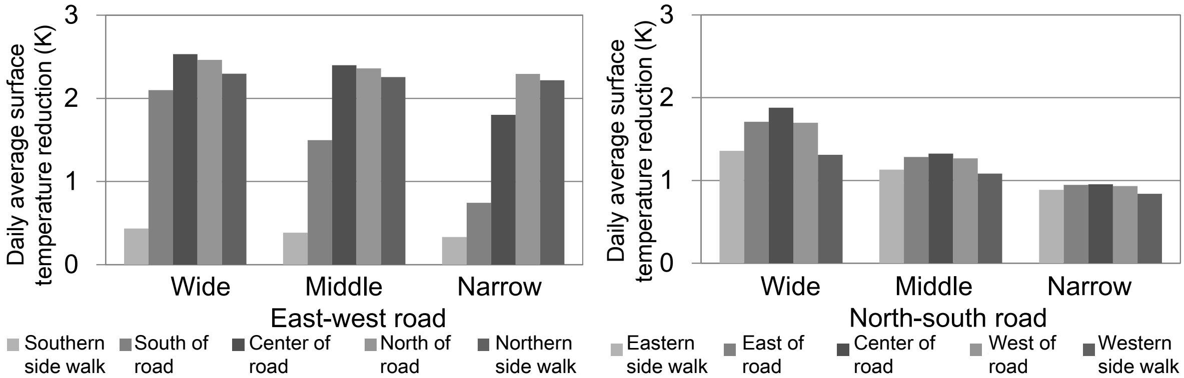

Figure 4: Daily average surface temperature reduction by high reflectance paint

(Left: east-west road, Right: north-south road)

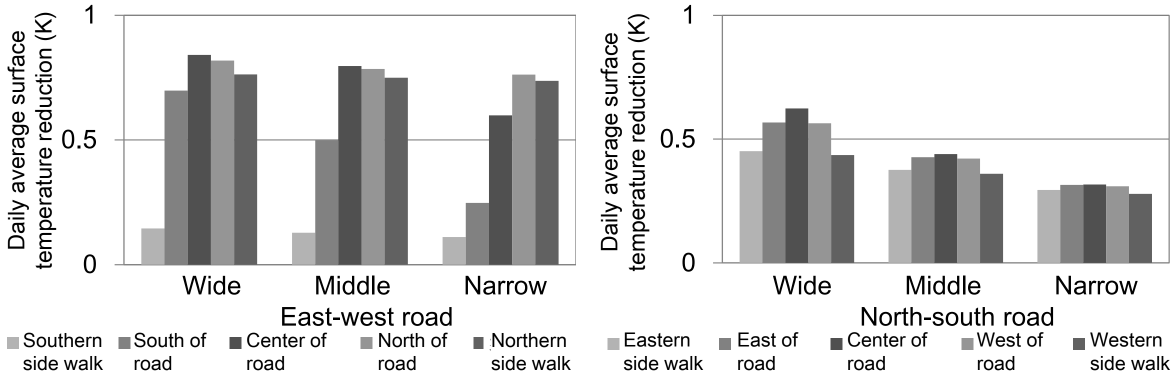

Figure 5: Daily average surface temperature reduction by water-retentive pavement

(Left: east-west road, Right: north-south road)

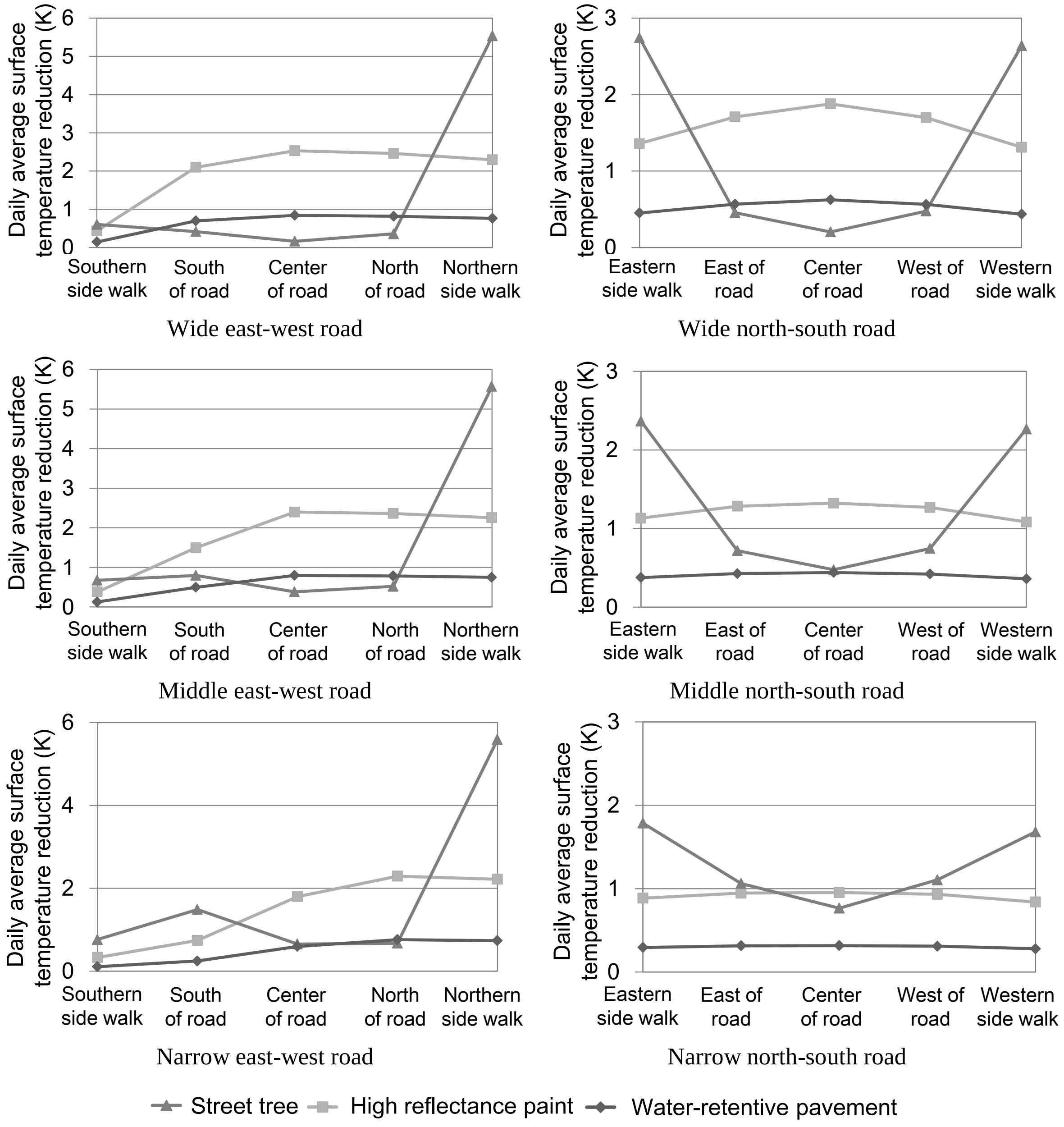

Figure 6: Daily average surface temperature reduction by street tree, high reflectance paint and water-retentive pavement

3 CALCULATION IN THE CASE OF CHANGING STREET TREE LAYOUT

The relationship between street tree layout and the thermal environmental improvement is analysed for the appropriate introduction policy of roadside trees. The calculation results of MRT at 12:00, 15:00, 17:00 on typical sunny day in summer are used for the examination.

3.1 Calculation method of the solar radiation shielding by roadside tree

The shape and solar transmittance of the tree crown are calculated from the survey results of street trees in Kobe city. Street tree model and objective urban block are shown in figure 7. It is assumed that street crown is floating in the air, the solar transmittance uniform in the entire crown with no change by the time. The building height is 18 m. The ArcGIS tool is used for the solar radiation shielding calculation on the road surface. At first, the visible area of the upper hemisphere is calculated considering the influence of surrounding buildings or street trees at the object road surface, then the direct solar radiation is calculated by the overlay of the solar orbit chart and the visible area, and the diffuse solar radiation is calculated by the overlay of the whole sky divided chart and the visible area. The reflected solar radiation is not taken into account.

Parameter of street tree layout is shown in table 1 and location of street trees is shown in figure 8. The diameter of the cylinder of the street tree model is the tree crown width (A) and the distance between each cylinder is tree interval (B). As a result of pre-calculation of the solar radiation gain as parameters as the tree crown width, the height of the tree and the solar radiation transmittance, the tree crown width is most sensitive to the solar radiation gain on the road surface, and the height of the tree is next. In this paper, we focus on the street trees layout mainly, but also on the tree crown width. And, we focus on the direct effect by solar radiation and ignore the mutual radiation exchange.

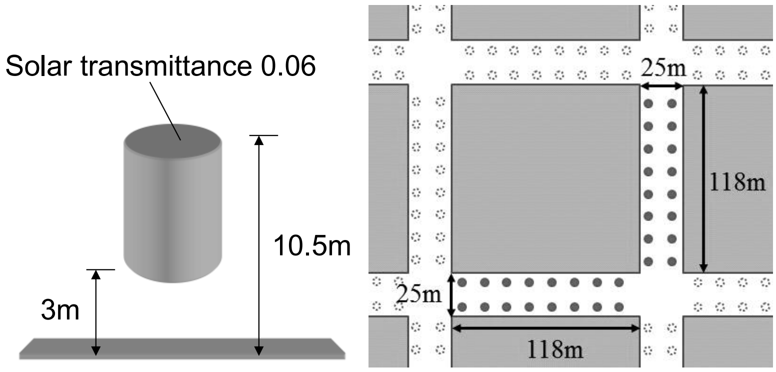

Figure 7: Street tree model and objective urban block (building height is 18 m)

Table 1: Parameter of street tree layout

Tree crown width (A)	Tree interval (B)
4 m	6, 8, 10, 12 m
6 m	8, 10, 12 m

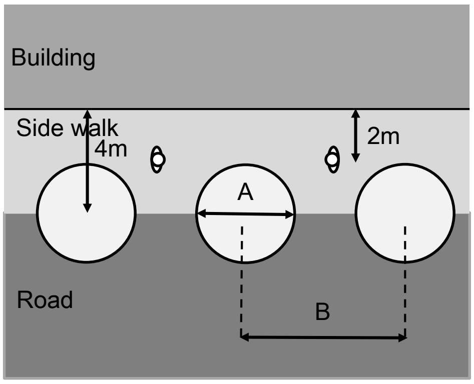

Figure 8: Location of street trees (A: crown width, B: tree interval)

3.2 Calculation results of solar radiation gain

Solar radiation gain averaged along the street at 12:00 in several tree interval cases is shown in figure 9. Solar radiation gain from 11:30 to 12:30 is averaged along the sidewalk. In the case of large tree crown width and small tree interval, solar radiation gain is small due to large proportion of the shaded area. The reduction of solar radiation gain on the northern sidewalk of the east-west road is greater than that on the eastern sidewalk of the north-south road, because half of the shadow by the roadside tree occurs on the driveway at the eastern sidewalk of the north-south road.

Solar radiation gain averaged along the street at 15:00 in several tree interval cases is shown in figure 10. Since solar radiation is less than 12:00, the reducing of solar radiation gain due to the change of street tree layout is also small, but the trend of the reduction of solar radiation gain is as same as 12:00. The reduction of solar radiation gain on the northern sidewalk of the east-west road is greater than the eastern sidewalk of the north-south road as well as 12:00, because many part of shadow occurs on the northern sidewalk of the east-west road than on the eastern sidewalk of the north-south road.

The reduction of the solar radiation gain on the sidewalk depends on the area and the position of the shadow by street trees. The shadow tends to occur on the northern sidewalk of the east-west road than the eastern sidewalk of the north-south road, because the shadow on the eastern side of the north-south road is on the wall and roadway as compared to the northern side of the east-west road.

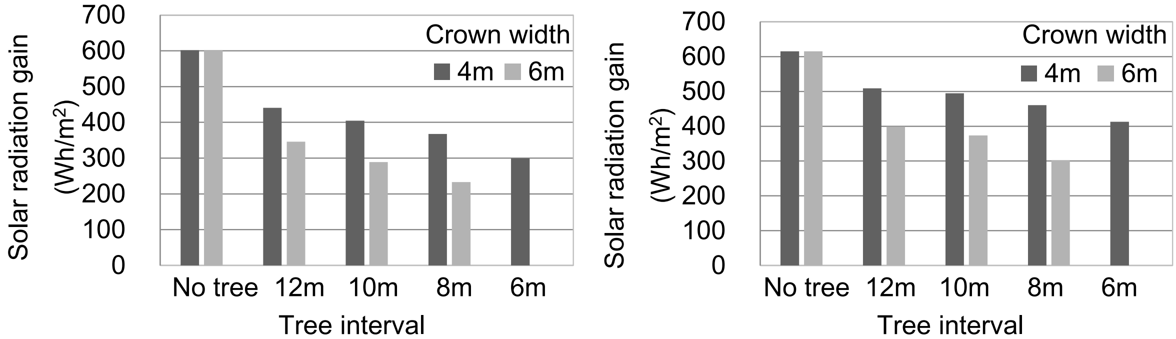

Figure 9: Solar radiation gain averaged along the street at 12:00 in several tree interval cases

(Left: northern sidewalk of east-west road, Right: eastern sidewalk of north-south road)

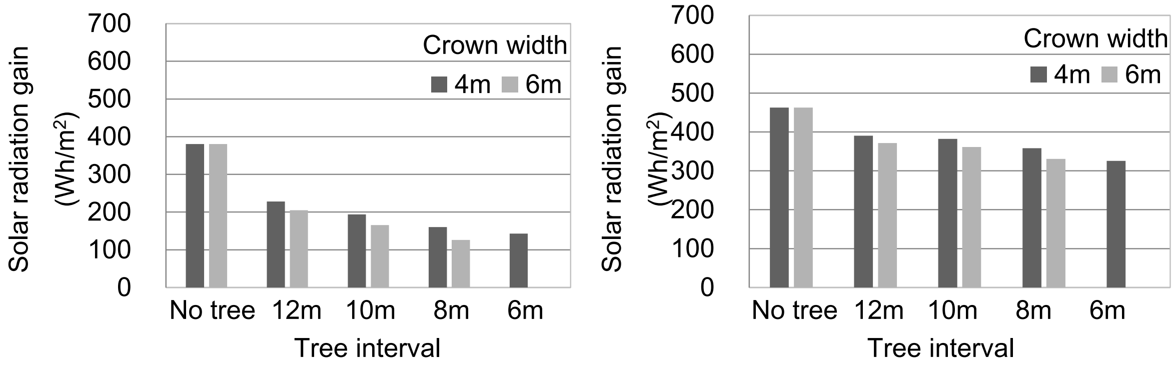

Figure 10: Solar radiation gain averaged along the street at 15:00 in several tree interval cases

(Left: northern sidewalk of east-west road, Right: eastern sidewalk of north-south road)

3.3 Calculation results of MRT

MRT averaged along the street at 15:00 in several tree interval cases is shown in figure 11. The tree crown width is 4m. The calculation results by considering only the influence of the long wave radiation and those with the short wave radiation are separately shown. It is assumed that human body is cube, the weighting factor for upper and lower surface is 0.024 and that for side surface is 0.238 concerning for solar radiation gain area, the solar absorptance of the human body is 0.5, the human body walks on the center of the sidewalk, and MRT is averaged along the sidewalk.

The influence by the reduction of short wave radiation gain is significant for MRT. The influence by the difference of the street tree layout is mainly due to the difference of the short wave radiation on the human body. The reduction of MRT is greater on the northern sidewalk of the east-west road than on the eastern sidewalk of the north-south road. Because shadow of the roadside trees occurs on the perpendicular direction to the eastern sidewalk of the north-south road and on the parallel direction to the northern sidewalk of the east-west road, the area where the human body enters under the influence of shadow is large on the northern sidewalk of the east-west road.

The reduction of MRT on the sidewalk depends on the area where the human body enters under the influence of shadow. The shadow tends to occur on the perpendicular direction to the eastern sidewalk of the north-south road and on the parallel direction to the northern sidewalk of the east-west road. So, the shadow area on the northern sidewalk of the east-west road is larger than on the eastern (western) sidewalk of the north-south road.

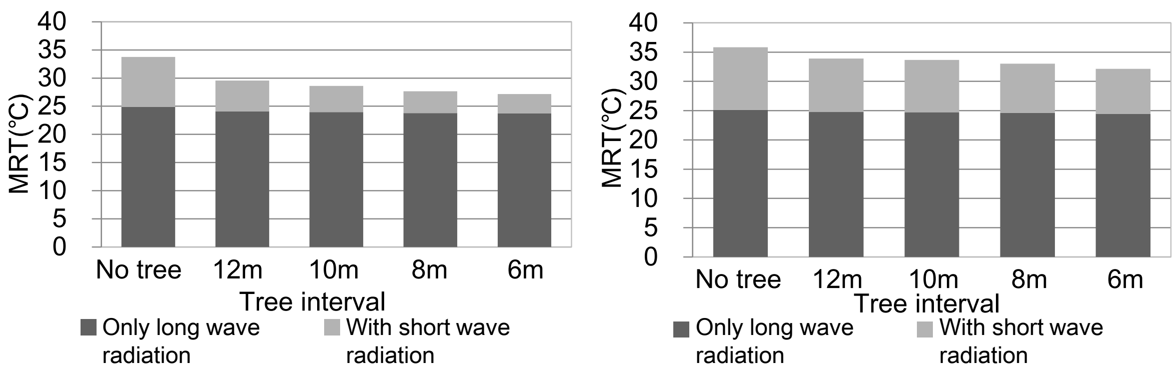

Figure 11: MRT averaged along the street at 15:00 in several tree interval cases (crown width is 4 m)

(Left: northern sidewalk of east-west road, Right: eastern sidewalk of north-south road)

4 CONCLUSIONS

From the view point of introduction of appropriate technique for each place, it is analysed the relationship between benefits by heat island measure technique and places it was introduced. Findings are as follows.

- The benefit by street tree is expected mainly for the sidewalk.
- The benefit by green wall is expected mainly for the wall surface.
- The benefit by high reflectance paint and water-retentive pavement is expected mainly for the roadway. The difference between high reflectance paint and water-retentive pavement depends on solar reflectance, evaporative efficiency and weather condition.
- The shadow by street tree is more significant to the thermal environment on the sidewalk. In the case of large tree crown or small tree interval, shadow is large and thermal environment is improved. Shadow tends to occur on the northern sidewalk than the eastern (western) sidewalk.

In conclusion, from the viewpoint of thermal environmental improvement, street tree is suitable for the sidewalk and high reflectance paint and water-retentive pavement is suitable for the roadway.

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