Influence of Building Envelope's Solar Reflectivity, Wind Speed and Building Coverage Ratio on Urban Heat Environment

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ABSTRACT

In recent years, especially, the climate change (CC) and urban heat island (UHI) effects are becoming serious problems, affecting people's life and health, especially in hot summer. For large cities such as Tokyo or Osaka in Japan, the UHI effect is particularly intense. It is known that about 40% of urban anthropogenic heat comes from buildings in large cities. To reduce the anthropogenic heat from buildings is an important countermeasure to this problem.

Strategies for UHI mitigation include urban ventilation, urban greening, green roof, highly reflective (HR) roads, and HR building envelopes, etc. In order to mitigate the urban heat island phenomenon and reduce the building cooling heat load, it has been common to apply the building envelopes because it is easy to apply and free of maintenance.

However, the effect of HR coating materials on urban outdoor thermal environment have not been thoroughly studied. In addition to the HR coatings, it is considered that the outdoor airflow and building coverage ratio possibly affect the outdoor thermal environment. This study aims to use Computational Fluid Dynamics (CFD) analysis method to predict the outdoor thermal environment, including three thermal sensation index: 1) outdoor temperature, 2) wet bulb globe temperature (WBGT), and 3) new standard effective temperature with consideration of outdoor solar radiation (hereinafter abbreviated as OUT_SET*) by varying the parameters of solar reflectivity, wind speed and building coverage ratio, and the results are reported in this study.

KEYWORDS

CFD simulation, Outdoor thermal environment, Outdoor temperature, WBGT, OUT_SET*

1 INTRODUCTION

The urban heat island (UHI) effect is a well-known climate change phenomenon in recent years and is becoming very serious, especially in summer, due to the rapid increase of urban anthropogenic heat [1]. While it has a profound effect on the cooling energy consumption of the building, the strength of UHI in hot climates can raise the temperature by as much as 10ºC, which can increase discomfort and have a major impact on human lives [2]. It is reported that there is much research has focused on defining the relationship between rising temperatures and various elements of the city to reduce the impact of UHI. A reviewed paper indicated that there are mitigation strategies such as: HR and radioactive light colored materials, cool colored materials, phase-change materials (PCM), dynamic cool materials used for building roofs or facades, urban albedo increase, and green roofs etc [3]. Furthermore, other studies have focused on the microscale, which shows the impact of urban design on climate [4]. A study showed that increasing the percentage of urban green cover and urban albedo can lower the temperature of the city, reduce the energy consumption of the building, and improve the outdoor thermal comfort [5]. HR coatings are widely studied in a strategy to reduce the UHI effect. The higher the total solar reflectivity, the lower the painted surface temperature, thus indicating that it can be used to reduce the cooling load of buildings, directly related to energy conservation in buildings.

However, since the influence of the HR building envelope on the outdoor environment temperature has not been widely discussed in Japan, this study aims to evaluate the effect of solar reflectivity of building envelopes on the outdoor thermal environment which includes air temperature, wet bulb globe temperature (WBGT), and new standard effective temperature with consideration of outdoor solar radiation (hereinafter abbreviated as OUT_SET*) with ~~in~~ consideration of the variation of the solar radiation reflectivity of the building envelope. In addition to the solar reflectivity, the other factors such as wind speed and building coverage ratio of the city are also used to evaluate the outdoor thermal environment by using computational fluid dynamics (CFD) analysis method.

2 MATERIALS AND METHODOLOGY

2.1 Analysis Target

The analysis target is assumed to be the architectural blocks located in Chuo Ward, Osaka City of Japan (34.4 ºN, 135.31 ºE). As shown in **Fig.1**, the dimension of one block model with a rectangular shape is set to a variable size of 75 m, 80 m and 85 m in east-west direction, a variable size of 75 m, 80 m and 85 m in north-south direction, and a constant size of 40 m in height direction, and a total of nine such blocks are in the CFD simulation. As shown in **Fig.2**, the analysis area is set to be 4800 m × 900 m × 400 m.

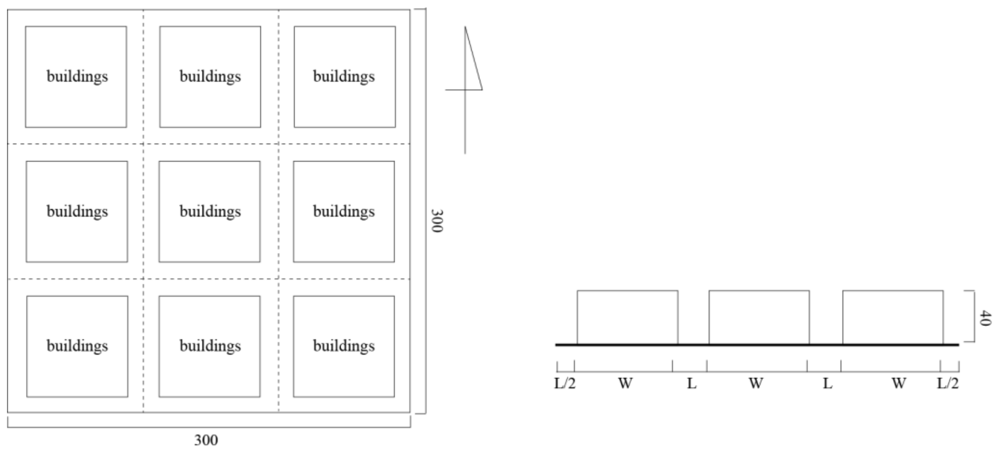

Fig. 1 Plane and Elevation of Target Area

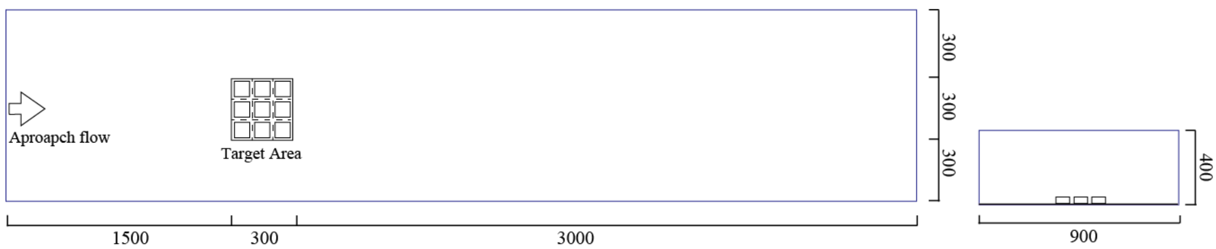

Fig. 2 Plane and Elevation of Analysis Area

2.2 Analysis Condition

The same as ANSYS Fluent, the software STREAM [7] often used in Japan is adopted to evaluate the outdoor thermal environment. The condition of CFD analysis is shown in **Table 1**. The room temperature of the block model is set to a fixed value of 24°C. According to NEDO database [6], the initial outdoor temperature is set to a daily average value of 30.6°C on July 31st, the solar radiation (direct and diffuse) is set to the value at culmination time of July 31st, and the wind direction is set to west. For the thermal boundary condition, the convective heat transfer coefficients between air and solids (ground and building surface) are given by the generalized power law.

Table 1 Analysis Condition

CFD code		STREAM V14(RC2)
Turbulence model		Standard k-ε model
Algorithm		SIMPLER
Discretization scheme		QUICK
Area of CFD analysis		X(4800m)×Y(900m)×Z(400m)
Boundary condition	Xmin	Fixed temperature, Power law (Exponent recipracal(n)=4)
	Xmax	Natural outflow boundary
	Ymin	Fixed temperature, Free slip
	Ymax	Fixed temperature, Free slip
	Zmin	Fixed temperature, Free slip
	Zmax	Fixed temperature, Free slip
	Fluid-Solid	Temperature power law, No slip
Weather condition		June 21st ,12:00, in Osaka Sunny Day
Solar condition	Solar position	Altitude:79.04°, Azimuth:0.00°
	Direct solar radiation	658W/m^2
	Diffuse solar radiation	236W/m^2
Indoor preset temperature		24°C
Outdoor temperature		30.6°C
Wind direction		West

2.3 Analysis Case

In this research, as shown in **Table 2**, a total of nine analysis cases were analyzed. The solar reflectivity is varied from 0.3 to 0.7 with the interval of 0.1, the wind speed is varied from 1m/s to 5m/s with the interval of 2m/s, and the building coverage ratio is varied from 0.56 to 0.72 with the interval of 0.08. The basic case is set as the condition that the solar reflectivity of ~~on~~ the block (building) surface is 0.5, the wind speed is 3 m/s, and the building coverage ratio is 0.64. According to the database of Japan Meteorological Agency (JMA) [8], the external wind speed at the height of 24 m from the ground surface is set in this study. In addition, the solar reflectivity of the ground surface is set to a constant value of 0.75 [9], and the long wavelength emissivity of the building exterior and the ground surface is set to a constant value of 0.9.

Table 2 Analysis Case

Analysis parameter	**Solar reflectance[-]**	0.3	0.4	0.5	0.6	0.7
	Wind speed[m/s]	1		3	5	
	Coverage ratio[-]	0.56 (L=25,W=75)		0.64 (L=20,W=80)	0.72 (L=15,W=85)	

2.4 Thermal sensation index

In this study, three thermal sensation index which includes outdoor temperature, WBGT and OUT_SET*, are evaluated by CFD under nine cases (see **Table 2**).

The WBGT is an index developed for the purpose of heatstroke prevention in field military training, and it is considered to be dangerous when it exceeds 31°C. In this study, the relative humidity is fixed at constant value of 68%. The WBGT can be calculated using equation (1).

$$WBGT = 0.7T_{nwb} + 0.2T_g + 0.1T_a \tag{1}$$

As for MRT, long wavelength radiation is considered only when used indoors, but solar radiation must be considered when used for outdoor thermal environment evaluation. The spatial distribution of global solar radiation (GSLR) and the long wavelength radiation temperature (MRT) can be calculated from the analysis software. GSLR is the amount of solar radiation received in the upward horizontal plane, taking direct, diffuse and scattered solar radiation into consideration. The distribution of GSLR at 1.5m above the ground is shown in **Fig. 3**. In this study, OUT_MRT is calculated by separating direct solar radiation and diffuse (scattered) solar radiation. The separation of them was done by calculating the cases separately in the case of the sunshine and the sunshade.

The case of sunshade is judged as the condition that GSLR is more than $S\downarrow_{input}$. Thus, the case of sunshade can be expressed as equation (2),

$Case\ of\ the\ sunshine$:

$$S\downarrow = \frac{S\downarrow_{input}}{sin\beta},\ D\downarrow = GSLR - S\downarrow_{input} \tag{2}$$

The case of sunshade is judged as the condition that GSLR is less than $S\downarrow_{input}$. Thus, the case of sunshade can be expressed as equation (3),

$Case\ of\ the\ sunshade$:

$$S\downarrow = 0, \qquad D\downarrow = GSLR \tag{3}$$

OUT_MRT is calculated by equation (4),

$$OUT\_MRT = \left[\frac{f_p(1-\alpha_{cl})S\downarrow}{F_{eff}\sigma} + \frac{(1-\alpha_{cl})\{D\downarrow + (D\downarrow + S\downarrow)\alpha_{GND}\}}{\sigma} + T_{MRT,L}^4\right]^{0.25} \tag{4}$$

The albedo of clothes (α_{cl}) is 0.4, the effective radiation area ratio (F_{eff}) is 0.75, and the projected area ratio of the human body to direct solar radiation is calculated by equation (5) [10],

$$f_p = 0.42cos\beta + 0.43sin\beta \tag{5}$$

OUT_SET* was calculated by using OUT_MRT in the calculation of SET* proposed by Gagge et al [11]. The calculation conditions for SET* are assumed to be a human body with a height of 1.77 m, a weight of 81.7 kg, a surface area of 2.0 m^2, the amount of clothes of 1 clo, and the amount of metabolism ~~is~~ of 1.5 met for the real environment.

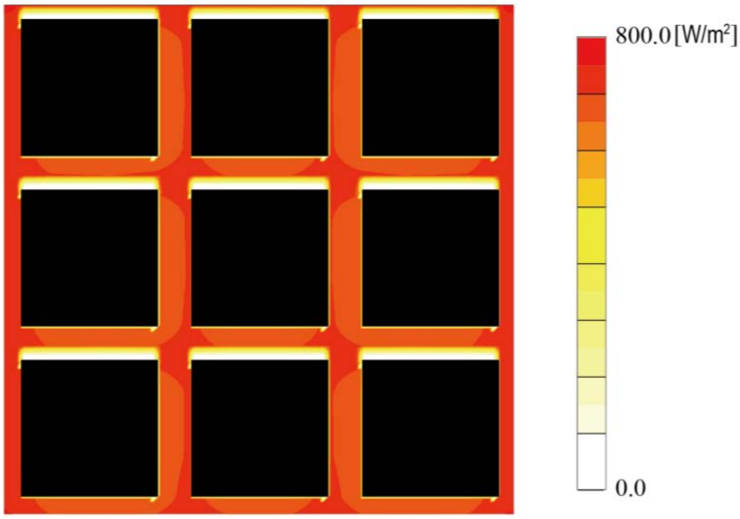

Fig. 3 Horizontal distribution of GSLR at height of 1.5m above the ground under solar reflectivity of 0.5

3 RESULTS AND DISCUSSION

The horizontal distribution for ~~of~~ each index shows a relatively similar distribution under either condition, thus as a representative, the wind speed and thermal sensation index (outdoor temperature, WBGT and OUT_SET*) distributions of horizontal section at height of 1.5 m above the ground under the basic case set as solar reflectivity of 0.5, wind speed of 3 m/s, and building coverage ratio of 0.64 are shown in Figs.4-7.

3.1 Wind speed distribution

The distribution of wind speed contour and vector at a height of 1.5 m above the ground under the basic case is shown in **Fig. 4**. It is shown that the wind speed is slower on the windward side of the building and faster on the leeside of the building.

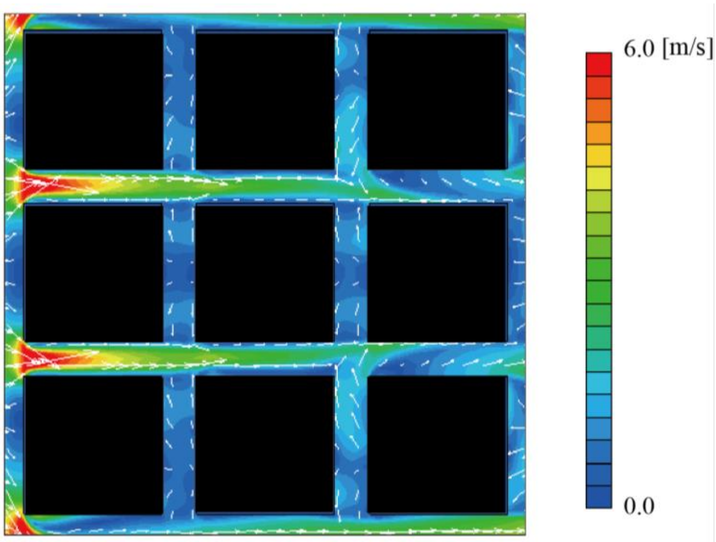

Fig. 4 Wind speed distribution of horizontal section at height of 1.5m above the ground under wind speed of 3 m/s

3.2 Outdoor thermal sensation index

The distribution of outdoor temperature at a height of 1.5m above the ground under the basic case is shown in **Fig. 5**. The horizontal distribution of outdoor temperature is almost the same as that of wind speed. It is shown that the stronger the wind (see **Fig.4**), the lower the outdoor temperature. In addition, since the temperature does not decrease in the shaded area, it may be said that the effect of solar radiation on the outdoor temperature is small.

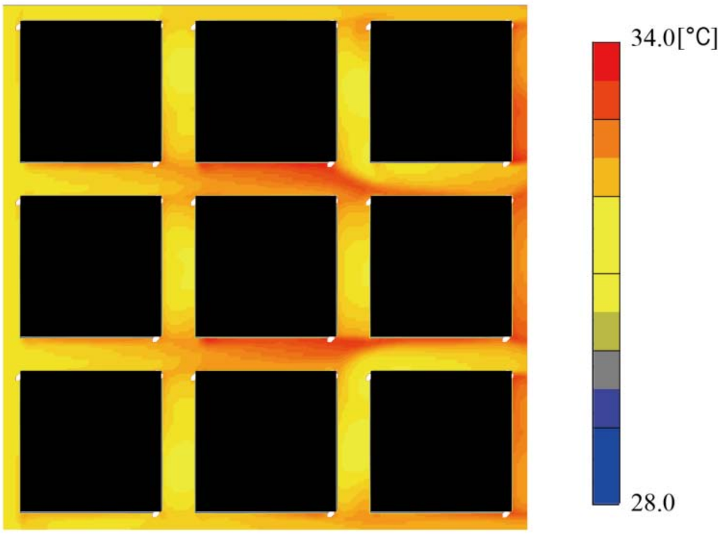

Fig. 5 Outdoor temperature of horizontal section at height of 1.5m above the ground under the basic case

The distribution of WBGT at height of 1.5m above the ground under the basic case is shown in **Fig. 6**. The result showed that the WBGT is higher while the wind speed is weaker. Unlike distribution of outdoor temperature, the WBGT of the shaded area is decreasing, thus it may be considered that the effect of solar radiation on WBGT is more significant, compared with outdoor temperature. In the shadow area, the WBGT is between 28-30ºC, thus the shadow area is considered to be a thermal comfort zone. However, in the sunshine area, the WBGT is exceeding 31ºC or more, thus the sunshine area is considered to be a dangerous area for the human body.

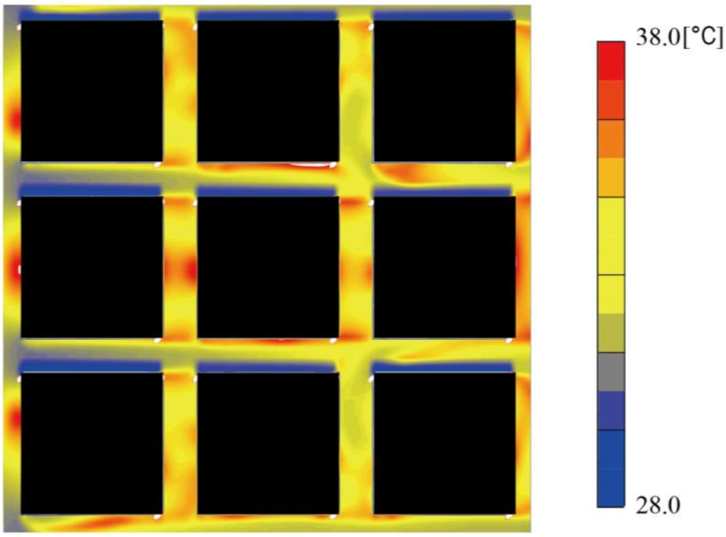

Fig. 6 WBGT of horizontal section at height of 1.5m above the ground under the basic case

The distribution of OUT_SET* at height of 1.5m above the ground under the basic case is shown in **Fig.7**. It is shown that the horizontal distribution of OUT_SET* is almost the same as that of WBGT. However, it also indicated that the range of OUT_SET* is about 6 ºC higher than WBGT.

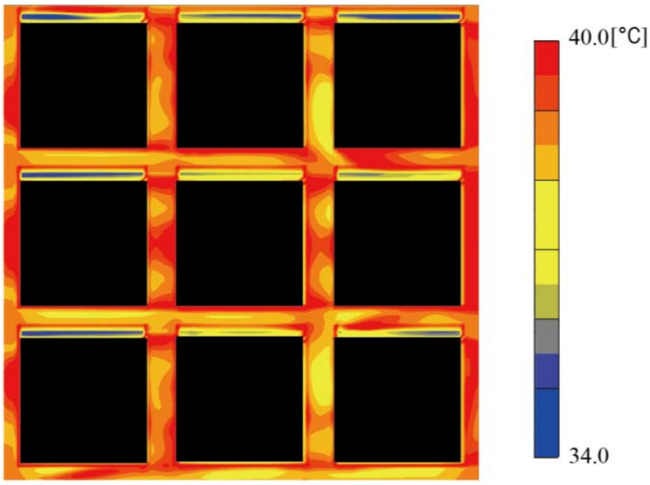

Fig. 7 OUT_SET* of horizontal section at height of 1.5m above the ground under the basic case

3.3 Correlation between thermal sensation index and analysis parameters

In order to investigate the influence of analysis parameters (solar reflectivity, wind speed and building coverage ratio) on three thermal sensation index (outdoor temperature, WBGT and OUT_SET*) in more detail, the change in the three thermal sensation index under each analysis condition (detailed in **Table 2**) are shown in Figs.8-10.

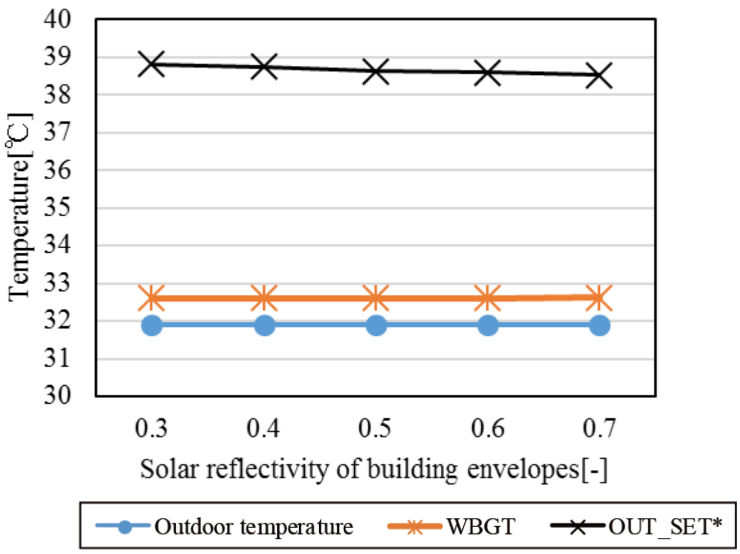

Fig. 8 Correlation between thermal sensation index and solar reflectivity

Correlation between thermal sensation index and solar reflectivity of building envelopes is shown in **Fig. 8**. The results show little effect of solar reflectivity on both outdoor temperature and WBGT. However, it is shown that the change in solar reflectivity has relatively larger effect on the OUT_SET*, compared to other two thermal sensation index. The OUT_SET* is slightly decreasing by about 0.5°C when increasing the solar reflectivity of building envelopes from 0.3 to 0.7.

Therefore, it is concluded that the HR building envelope may give an effective impact on the OUT_SET*. However, the effect is relatively small and further study such as more detailed CFD analysis and field experiment is necessary.

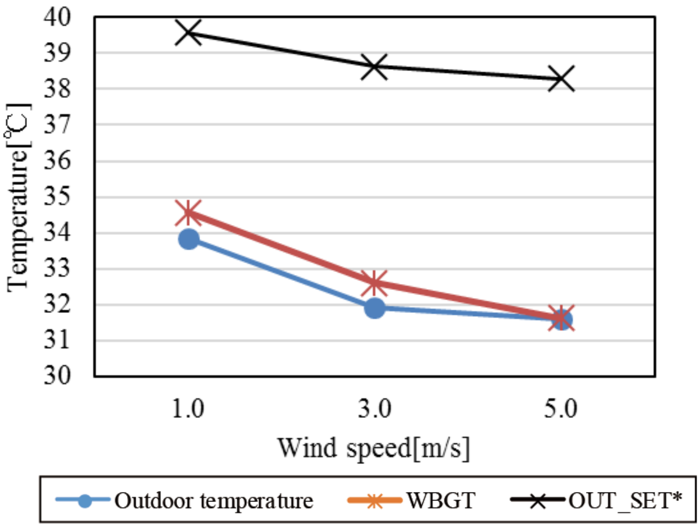

Fig. 9 Correlation between thermal sensation index and wind speed

Correlation between thermal sensation index and wind speed is shown in **Fig. 9**. It was found that as the wind speed became stronger, all of thermal sensation index substantially decreased. When the wind speed is varied from 1m/s to 5m/s, the outside temperature and WBGT decreased by about 3°C respectively, and OUT_SET* decreased by about 1.5°C. Therefore, it is concluded that the wind speed has a great influence on the thermal environment around the building.

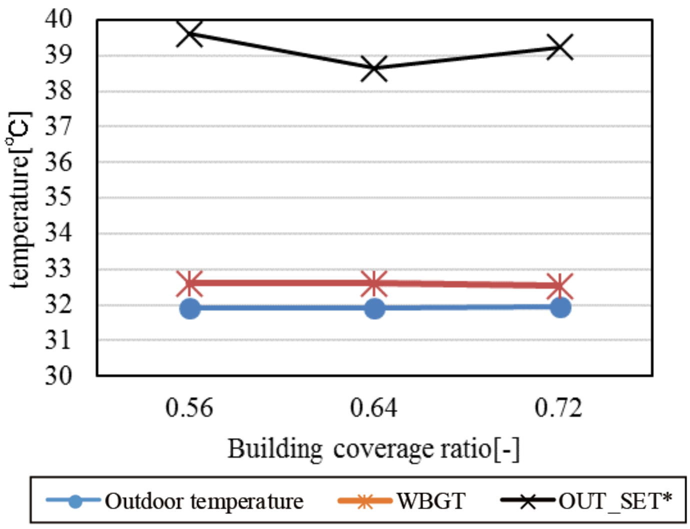

Fig. 10 Correlation between thermal sensation index and building coverage ratio

Correlation between thermal sensation index and building coverage ratio is shown in Fig. 10. Results showed that both outdoor temperature and WBGT are constant for changes in building coverage. The effect of building coverage ratio on the OUT_SET* showed that the OUT_SET* decreased by about 0.9oC when the coverage ratio is varied from 0.56 to 0.64, however it increased by about 0.4oC when the coverage ratio is varied from 0.64 to 0.72.

The reason for such change is considered to be the result of the interaction of short-wavelength and long-wavelength radiations. It is considered that short-wavelength radiation of solar plays a leading role when the building coverage ratio is small, and long-wavelength radiation of building envelopes plays a leading role when coverage ratio is large. Thus, we can see a decreasing trend in OUT_SET* when the coverage ratio is varied from 0.56 to 0.64, and an increasing trend in OUT_SET* when the coverage ratio is varied from 0.64 to 0.72.

4 CONCLUSION

This paper used CFD analysis method to evaluate the effect of solar reflectivity, wind speed and building coverage ratio on the outdoor thermal sensation index (outdoor temperature, WBGT and OUT_SET*).

The knowledge are obtained and summarized as following,

- Except for the effect of sunshade, the horizontal distributions of outdoor temperature, WBGT and OUT_SET* show the similar contours with that of wind speed.
- It is indicated that the WBGT and OUT_SET * are largely affected by the effect of sunshade.
- It is found that HR building envelopes are effective for hot environment mitigation by this CFD analysis, however the effect is small.
- It is concluded that the wind speed has a great influence on the thermal environment around the building.

For the future work, the research will be focused on comparison between CFD analysis and field measurement. In addition, the future work is also aimed at implementing the research on the reflective directional characteristic of building envelope materials and evaluating the effect of reflective directional envelope (i.e., retro-reflective glass film [12]) on the outdoor thermal environment by using CFD analysis method.

Nomenclature

$D \downarrow$	Diffuse solar radiation [W/m^2]
F_{eff}	Effective radiation area factor [-]
$S \downarrow$	Direct solar radiation [W/m^2]
$S \downarrow_{input}$	Input value of direct solar radiation [W/m^2]
$T_{MRT,L}$	Mean radiant temperature [K]
T_a	Outdoor temperature [°C]
T_g	Globe temperature [°C]
T_{nwb}	Wet-bulb temperature [°C]
OUT_MRT	Mean radiant temperature considering short wavelength radiation of the sun [-]
α_{cl}	Albedo of the clothed body surface [-]
α_{GND}	Ground albedo [-]
f_p	Projected area ratio of the human body to direct solar radiation [-]
β	Solar altitude [°]
σ	Stefan-Boltzmann constant (=5.67 x 10^{-8}) [W/ (m^{2}K^4)]

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