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Outdoor Micro-Climate Analysis of Green Buildings on Environmental Affects Using PALM Software

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Abstract: This paper aims to analyses the effect of green buildings on the environment, which is currently affected by climate change. PALM or parallelized large-eddy simulation model was applied in order to simulate the urban vegetation on the outdoor thermal environment. The model solved the non-hydrostatic incompressible Navier-Stokes equation. There were 9 cases in total with 3 different design categories; 3 cases are for Conventional Building (non-vegetation building), 3 cases are for Green Rooftop, and the other 3 cases are Green Floor (no building). All cases had same characteristic of grids which are cubes with 1.0 m of all sides. As an initial condition, wind flows 5 m/s from left to right and a pressure gradient of 0.004 Pa/m were assigned to keep the speed of the wind. Boundary conditions were periodic boundary conditions in both x and y directions. In z-direction, the condition of the bottom was set as a no-slip condition while on the upper part was set as slip condition. This study divided the cases into 2 assessment groups with potential temperature as the main parameter; i) comparisons between normal building and Green Rooftop. ii) The comparisons between Green Rooftop and Green Floor. Almost all cases of Green Rooftop obtained the lowest result compared to the other potential temperature result. It explained that Green Rooftop indeed can have a good impact for the environment. But, among all of the 3 different types of the Green Rooftop with vegetation on the top of the building, case 2 had the lowest potential temperature (300.06˚K). Height/Width (H/W) ratio of case 2 was 0.3 while the effective H/W ratio was around 0.4 – 0.6. It showed that case 2 is approaching the minimum limit on the effective H/W ratio. It had the best performance for potential temperature because of the balance condition between H/W ratio and solar radiation towards the area.

Keywords: Green roof, potential temperature, H/W ratio, U-Value, PALM

1. Introduction

There are several problems happened in the world such as the rise of the sea level, expansion of subtropical deserts, extinction of various animals, the erratic weather changes, climate change, pollution, global warming, flood, and etc. All

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*Corresponding author: intan.supraba@ugm.ac.id problems happened because there are a lot of material usages (manufacture, transportation, delivery, and installation) that potentially produce kind of waste which can harm the environment. The design of the building (exterior and interior) can affect the environment too, such as water conservation factor, appropriate site development factor, and the comfort of the environment and human life. About 25% of world emissions of the greenhouse gas CO_2 came from the Asia-Pacific region. If this trend continues, the projected contribution from this region may go up to 36% in 2025 and over 50% by the end of the 21st century [1]. Other data from the World Resources Institute shows that the global carbon project estimated a total emission of 37.1 gigatonnes of CO_2 in 2018 [2]. The greenhouse effect causes global warming which is known to affect the environment and human health. Besides the greenhouse effect, material usage (manufacture, transportation, delivery, and installation) produces waste which can harm the environment. The design of a building (exterior and interior) can also affect the environment, such as water conservation, relevant site development and the comfort of the environment and human life. According to the experiment conducted by Budhyowati, there are 2 factors that might cause the heat; external factors (solar radiation) and internal factors (human) [3]. The arrangement of the building affects the amount of solar radiation transfer to the building. It occurs because the building elongated facade orientation inclines to block the sun path. Heat radiating through walls and entering the window easily can also occur due to the absence of exterior shading. Not only for the arrangement of the building that affected heat on the environment but also the material type. Material has Albedo Value as the ratio to determine the estimated heat delivered by the material. Albedo originates from the Latin word strata that defines the replication of incoming solar radiation from a convinced surface and can be calculated as the ratio of radiosity. Radiosity is the radiant flux from a surface). The term contained in high albedo materials is solar reflectance which also considered as an indicator of albedo [4]. The effectiveness of high albedo/highly reflective materials in mitigating Urban Heat Island (UHI) is due to the reflection of solar radiation that does not make high temperature effect on urban surfaces. It means that low reflective and low albedo materials are responsible of higher surface and air temperatures because they absorb the solar radiation [5]. Fig. 1 portrays the various urban environment albedos according to OKE [6] and for the calculation of Albedo's ratio is presented in Eq. (1).

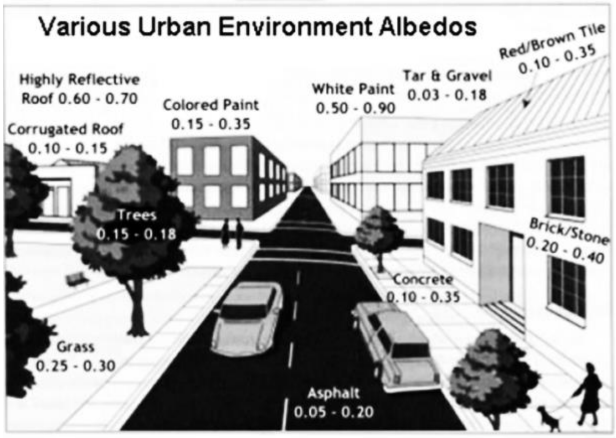

Fig. 1 - Various Urban Environment Albedos [6]

$$Albedo\ Value = \frac{\sum(A_n \times L_n)}{\sum L_n} = \frac{[(A_1 \times L_1) + (A_2 \times L_2) + \cdots + (A_n \times L_n)]}{L_1 + L_2 + \cdots + L_n} \tag{1}$$

where: A_n = Albedo value of material, L_n = Roof area. According to GBCI; When the Albedo's ratio is low, the material's ability to reflect solar radiation will be better [7]. Therefore, the minimum value of Albedo is 0.3. Albedo values can be calculated using the formula in Eq. (1).

Based on the problems mentioned above, researchers have come up with innovative green construction ideas such as: i) On Earth Day, April 21, 1993, President Clinton announced plans to make the Presidential mansion "a model for efficiency and waste reduction" and ii) On Earth Day 1998, the then-chair of AIA/COTE, Gail Lindsey, announced the first "Top 10 Green Projects," to call attention to successful green design, a program that has continued to the present [8]. Green construction refers to green rooftops or green buildings which can benefit the environment. Green construction, especially green rooftops, uses energy resources, water, materials and land more efficiently and more effectively than traditional construction. The aim of green construction is to specifically plan and execute construction processes to minimize its negative impacts on the environment to achieve a balance between the environment and human needs for the present and future generations [9]. Thermal reduction can also occur due to sufficient green space in the building, the temperature increases by 0.4 – 1.8˚C while for every addition of 50% of green open space, the air temperature decreases by 0.2 – 0.5˚C. Green open space simultaneously reduces radiation to heat the air up due to the transpiration process, so the presence of green open space brings a sense of comfort in terms of lower air temperatures, also oxygen supply for living things around green open space [10]

Referring to the previous explanation, this paper shows the analysis of green construction by modeling a green floor and green rooftop to define environmental impacts of the building. Application of green rooftop as energy conservation must have significant energy-saving potential for a humid climate [11]. Green rooftop was found to provide heating and cooling load reductions over the heating and cooling seasons. The green roof was installed with enhanced insulation performance by increased soil depth. By increasing the soil depth, green roofs were found to be more effective in reducing heat loss during the heating season. When the characteristics of the soil layer and vegetation in the green roof were taken into account, the installation of green roofs in existing buildings with low insulation levels was found to improve energy performance and conform to the last insulation requirements [12]. Building arrangements will be provided to prove that building arrangement is also needed to reduce heat in an environment. The height (H) of buildings and the width (W) of building arrangement should be balanced [13]. When the H/W ratio increases, the wakes are prone to disruption, resulting in the creation of a wake intervention flow. With an increase in the H/W ratio, the street canyon becomes isolated from the circulated airflow in the urban boundary layer. As a result, a stable circulatory vortex is created inside the canyon. This continuous circulatory vortex produces the skimming flow regime that transpires more often in urban areas [14]. Fig. 2 visualizes flow patterns in a street canyon.

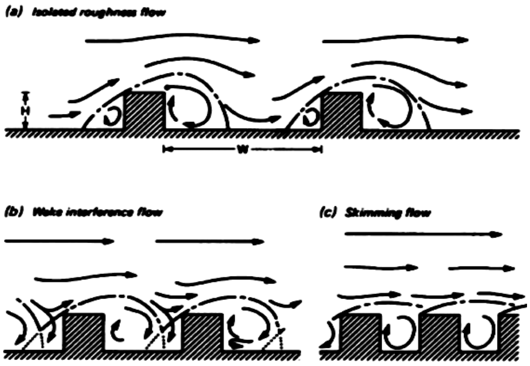

Fig. 2 - Flow Patterns in a Street Canyon [13]

2. Research Methods

Nine cases with three different design categories were investigated in this study; three cases involved conventional buildings (CB), three cases involved green rooftops (GR) while three other cases involved green floors with vegetation 1 m above the ground and without building (GF). Each category had three different design types; four buildings in an area, sixteen buildings in an area and a hundred buildings in an area. The number of buildings was calculated based on the green rooftop category. The category of the green rooftops has 25% of green areas out of the total area, which is 40000 m^2. Fig. 3 shows the design layout of the model while Figure 4 shows the characteristics of each building. Red refers to the buildings.

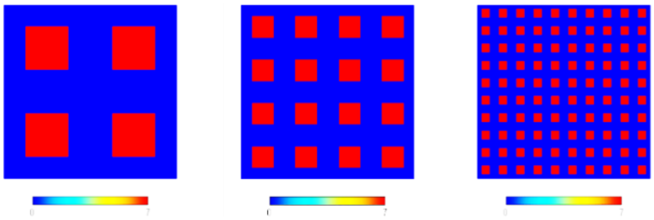

Fig. 3 – Design layout

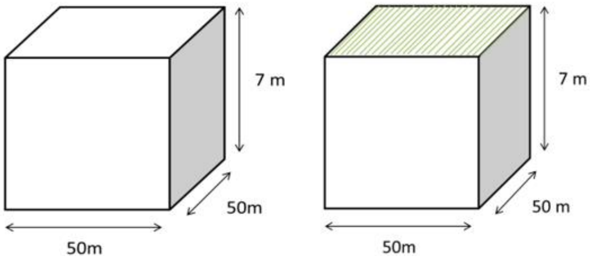

Fig. 4 - (a) Normal building; (b) Green rooftop

In this study, the height of all the buildings is 7 m, but the length and width of each variety are explained in Table 1. The classification of urban vegetation distribution is explained in detail in Table 2.

Table 1 - Building classification of this study

Case	Building Number	Building Dimension (m)	Building Gap (m)	H/W Ratio
1	4	50 x 50 x 7	50	0.1
2	16	25 x 25 x 7	50	0.3
3	100	10 x 10 x 7	50	0.7

Table 2 - Green rooftop case classification

Case	Area (m^2)	Green Rooftop		Building with Green Rooftops
		Percentage (%)	Area (m^2)	Dimension
1	40000	25	10000	50 x 50 x 7
2	40000	25	10000	25 x 25 x 7
3	40000	25	10000	10 x 10 x 7

All areas have the same grid characteristics, with a measurement of 1.0 m on all sides. As an initial condition, a wind flow of 5 m/s from west to east and a pressure gradient of 0.004 Pa/m are provided to maintain wind speed. In Indonesia, the main wind direction in the rainy season varies from Southwest to Northwest, while in the dry season is dominated southwest to west. The similarity, both in the dry season and in the rainy season the wind direction from the West remains significant. Data that presents a combined distribution wind speed and direction for 20 years shows that the direction of the wind is dominant is from Southwest to Northwest. But, the most direct wind direction is from the West [15]. International Standards suggest that the effectiveness of a windshield is generally effective up to 5 m/s [16]. Boundary conditions are periodic boundary conditions in both x and y directions. In z-direction, the condition of the bottom is set as a no-slip condition while the upper part is set as a slip condition. The parameter that differentiates each area is the vegetation field. Fig. 5 shows the area of the model simulated in Parallelized Large-Eddy Simulation Model (PALM) Software.

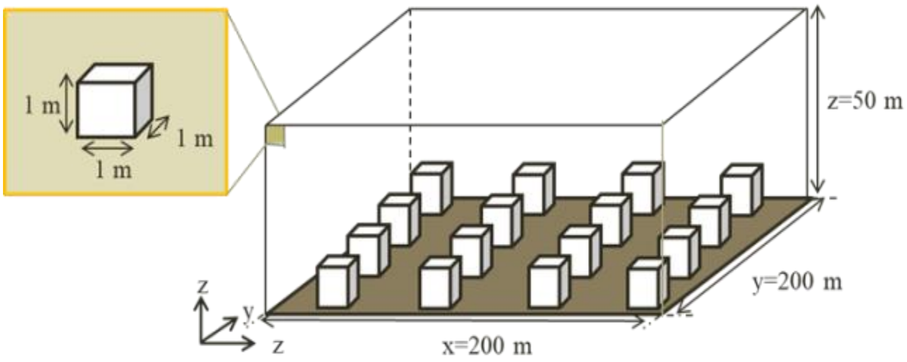

Fig. 5 - Building area model

3. Results and Discussion

3.1 A Comparison between Conventional Building (CB) and Green Rooftops (GR)

It can be seen from Fig. 6, Fig. 7 and Fig. 8 that the potential temperature situated 1 m above the ground of a GR is lower than that of CB. This figure shows the movement of potential temperature from a height of 1 – 50 m above ground. The next part focuses on the area around the building. Table 3 shows the potential temperature from a height of 1 – 10 m above ground.

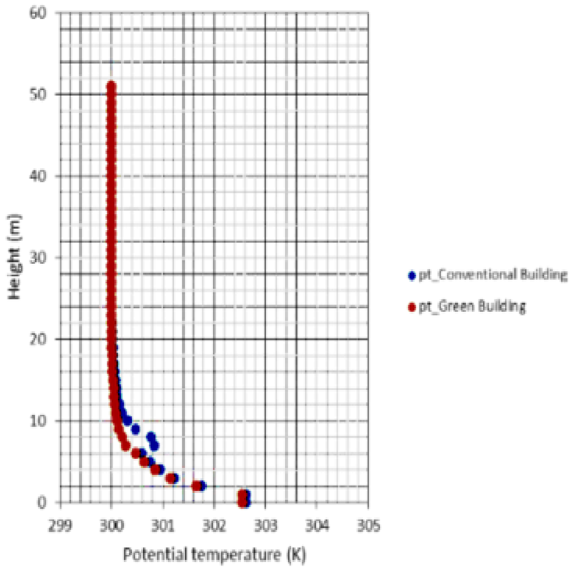

Fig. 6 - Potential temperature of CB and GR in case 1

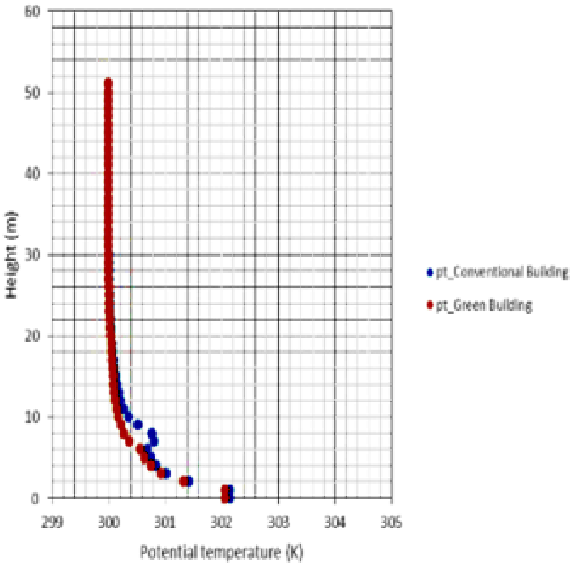

Fig. 7 - Potential temperature of CB and GR in case 2

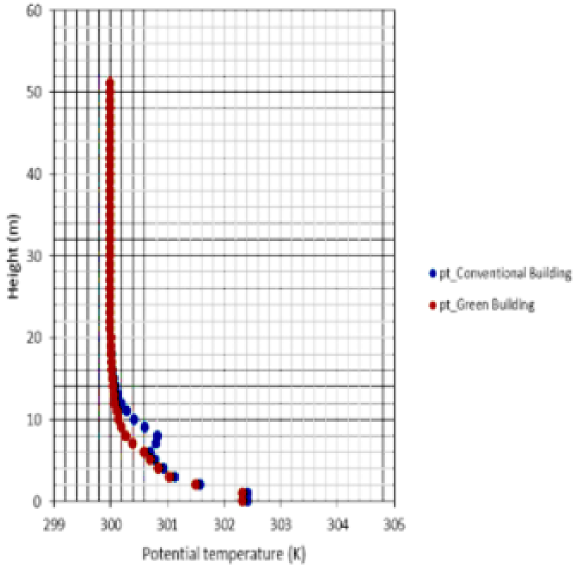

Fig. 8 - Potential temperature of CB and GR in case 3

Table 3 - Comparison of potential temperature between CB and GR in all cases

Height of Building	Case 1		Case 2		Case 3	
	Conventional Building (K)	Green Rooftop (K)	Conventional Building (K)	Green Rooftop (K)	Conventional Building (K)	Green Rooftop (K)
1	302.64	302.54	302.16	302.06	302.43	302.33
2	301.76	301.67	301.43	301.33	301.59	301.50
3	301.24	301.15	301.02	300.93	301.13	301.05
4	300.96	300.86	300.86	300.75	300.94	300.85
5	300.75	300.65	300.76	300.64	300.80	300.70
6	300.60	300.48	300.70	300.56	300.70	300.59
7	300.84	300.29	300.81	300.38	300.81	300.40
8	300.77	300.21	300.77	300.29	300.83	300.28
9	300.49	300.16	300.52	300.22	300.61	300.20
10	300.32	300.12	300.37	300.18	300.43	300.15

Fig. 9 shows the results of the comparison between CB and GR, which indicated that a building with a GR has a lower temperature compared to that of a CB. Focusing on the point 1m above ground, it shows that case 2 has the lowest potential temperature compared to other cases. At 7m above ground (rooftop), case 1 recorded the lowest temperature among all cases. This result is influenced by building design, where case 1 has a larger GR which makes the temperature on the rooftop lower than the rooftop temperatures of other cases. Meanwhile, the distance between buildings is large enough that thermal radiation can flow freely to the ground without being blocked by any other building. In case 2, the size of the building as well as the distance between buildings is average. This situation makes the temperature on the rooftop higher than the rooftop temperature in case 1. Furthermore, the building distance is relatively narrow, causing thermal radiation from the sun to be blocked by other buildings. Case 3 has the smallest buildings amongst all cases, indicating high potential temperature on the rooftop. The building's distance is also too narrow, thus causing an increase in heat produced by wind patterns forming turbulence airflow. Even though radiation does not have a massive impact on the building, the walls and the asphalt road still absorb and resist small amounts of radiation. This affects the potential temperature of the building. Additionally, that small distance causes the air particles around the building to rub against each other and generate heat.

GR always have lower temperature compared to conventional buildings. This indicates that GR has better effects on the environment. Furthermore, from Table 5, it can be seen that at a height of 6m above ground, the GR in case 1 has the lowest temperature among all cases. Figure 10 provides a comparison of the potential temperature between CB and GR 7m above the ground.

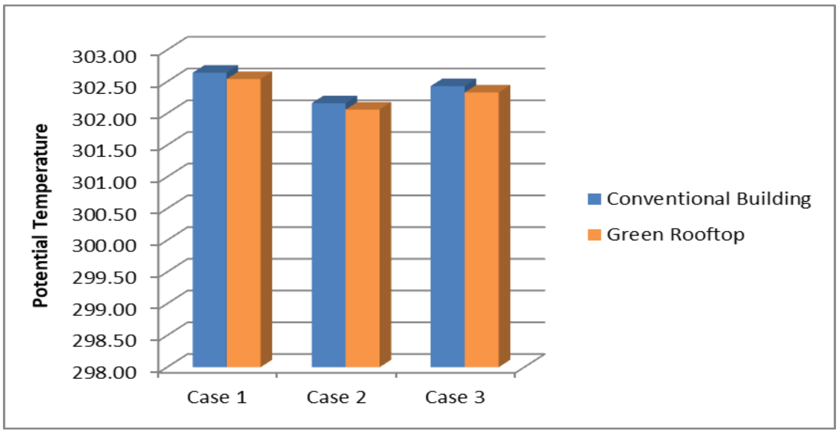

Fig. 9 - Comparisons of potential temperature 1 m above the ground

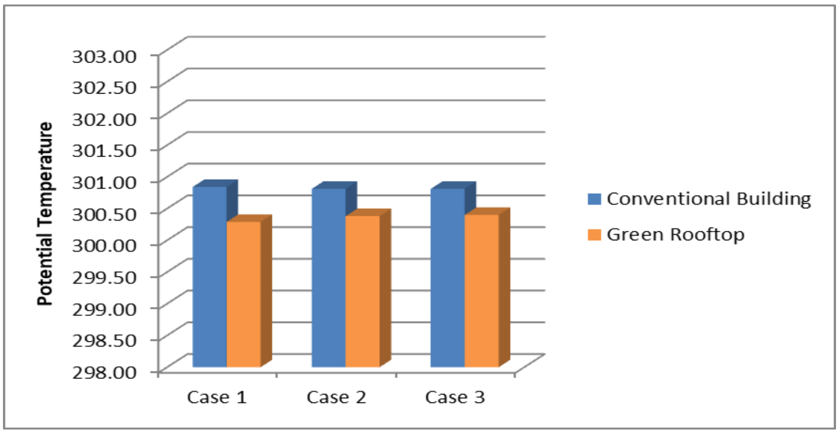

Fig. 10 - Comparisons of potential temperature 7 m above the ground

3.2 Wind Flow Pattern

Wind flow pattern gives more explanation about the results of the data. By analyzing the movement of the wind direction, the data will be understood easily.

3.2.1 Conventional Building

The wind pattern in case 1 can be seen in Fig. 11 that shows wind pattern of the area from the front, represented by the blue color on the building's front Air circulation at a wider distance between buildings will affect the temperature around the building. Air particles will easily flow without being blocked by the building, prompting the temperature to decrease. Meanwhile, solar radiation is the main factor of heat increasing in case 1. Fig. 12 illustrates the wind pattern found in case 2. It shows wind pattern in case 2 from the front side. However, because the buildings are blocking the solar radiation, the temperature around buildings in case 2 remains relatively low.

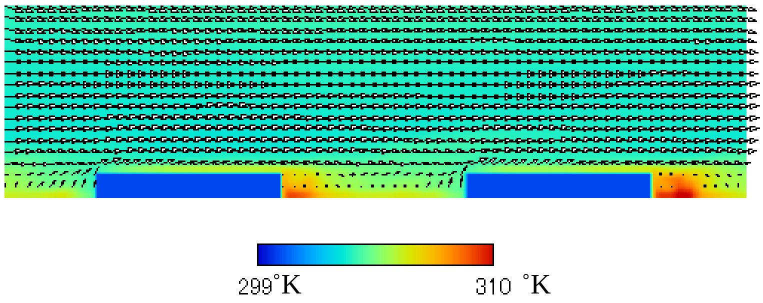

Fig. 11 - Wind flow pattern of CB in case 1 in vertical cross section

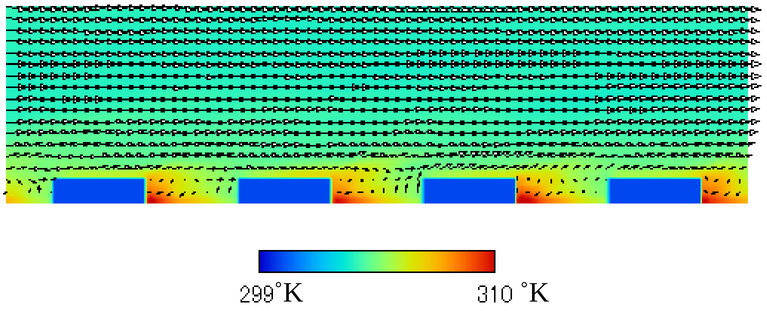

Fig. 12 - Wind flow pattern of CB in case 2 in vertical cross section

Fig. 13 shows the wind pattern around the building in case 3. Its visualized wind pattern and thermal color in case 3 around the buildings. It can be seen that the wind pattern in case 3 is more irregular. It makes a circle around the buildings and it causes heat as a result of the air particles that rub against each other. The heat was also produced because the walls are too close from each other. There is no air circulation in the gap of the building and the heat transfer from the walls and asphalt road produces a higher potential temperature.

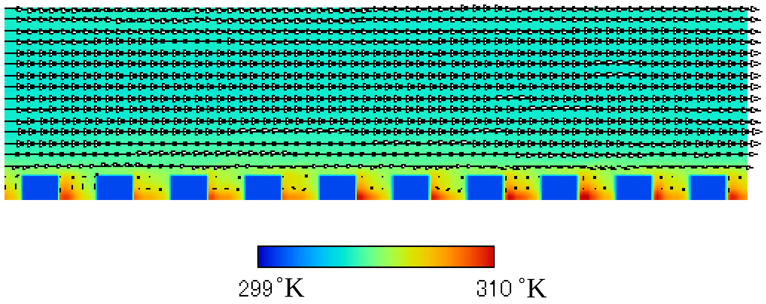

Fig. 13 - Wind flow pattern of CB in case 3 in vertical cross section

Fig. 11, Fig. 12 and Fig.13 visualize the wind flow pattern in cases 1, 2 and 3 of the CB using a horizontal cross section view. The figures indicate that the weather behind the building is warmer than the other areas. It can be seen from the figures that the right side of the building is warmer than the left side. That is because the wind flows from left side of the building to right. Wind that comes from the left side is blocked by the building, so that the right side gets less wind-flow compared to the left. Air pressure moves from a high place to the low place. This theory is proven by the temperature condition at 1 m above the ground which is lower than the upper side. Fig. 15 and Fig. 16 portray the wind flow pattern in the horizontal cross section of the CB in cases 2 and 3.

The results of all figures show that case 3 has irregular heat distribution in the area. Because of the amount of the building that is distributed throughout the area, the heat is also distributed irregularly. Solar radiation at some part is not blocked by the building. Instead, some of them are scattered based on the wind direction that is influenced by the number of the buildings. This is due to the amount of solar radiation that is successfully spread along the walls and the air particles that move in a circular motion around the area.

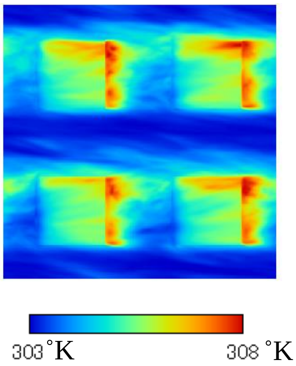

Fig. 14 - Wind flow pattern of CB in case 1 in horizontal cross section

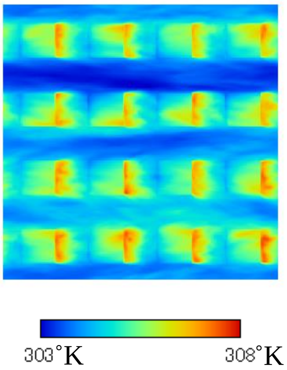

Fig. 15 - Wind flow pattern of CB in case 2 in horizontal cross section

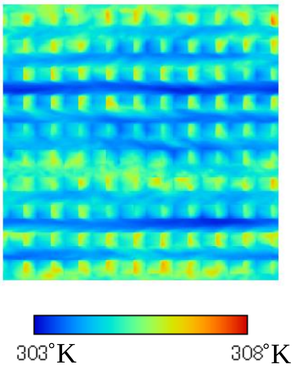

Fig. 16 - Wind flow pattern of CB in case 3 in horizontal cross section

3.2.2 Green Rooftop

Fig. 17 describe the wind flow pattern through the vertical cross section of the Green Rooftop in case 1. Similar to the case 1 of CB, case 1 of GR also has the same theory brought about by the air particles and solar radiation. The difference is in the presence of the Green Rooftop that makes the potential temperature lower than that of the CB. Fig.18 shows the wind flow pattern of the vertical cross section of the GR in case 2. It can be noting that the GR in case 2 also has irregular pattern around the building caused by the distance between the buildings. It makes the temperature rise even though the amount of solar radiation that successfully reaches the buildings are less than the amount of solar radiation found in case 1. Nonetheless, the amount of green roof is large enough to make an impact on the potential temperature surrounding the building.

Fig. 19 shows the wind flow pattern in the vertical cross section of the GR in case 3. The GR in case 3 were initially estimated to produce lower results compared to cases 1 and 2 because of the type of vegetation that is spread along the area. Furthermore, the narrow distance from this building to other buildings can block the solar radiation. However, the fact is that case 3 has higher result than case 2. It can be seen that the green rooftop in case 3 has irregular motion around the building as an effect of the distance between buildings. Close distance makes the temperature of the place is warner. The narrow distance prevents the flow of air circulation around the building. The wind is blocked by the building, prompting the air particles to rub against each other. The heat on the walls and asphalt road will transfer heat to the building's surroundings. It subsequently causes the temperature to rise.

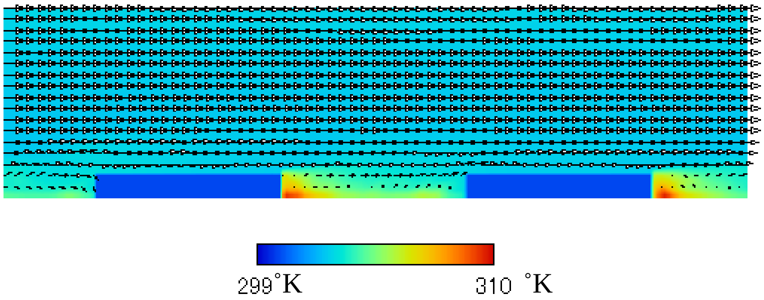

Fig. 17 - Wind flow pattern of GR in case 1 in vertical cross section

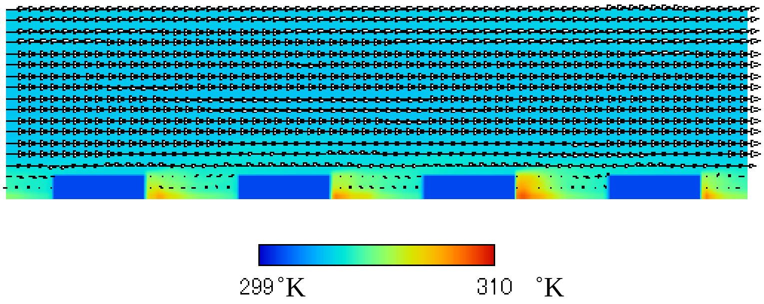

Fig. 18 - Wind flow pattern of GR in case 2 in vertical cross section

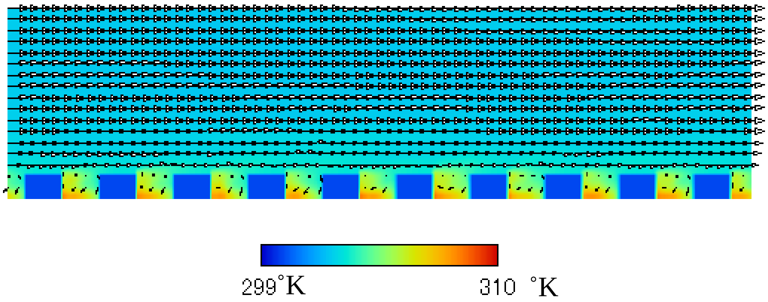

Fig. 19 - Wind flow pattern of GR in case 3 in vertical cross section

Compared to the figure of the CB, the figure of the GR reveals cooler colors. This proves that the temperature in the GR area is lower than in the conventional building area. Fig. 20, Fig. 21 and Fig. 22 show the wind flow pattern found in the horizontal cross section of the GR in cases 1, 2, and 3, respectively. The figures show that the weather of the GR area in case 1, case 2 and case 3 is cooler than the area of the CB. This proves that the presence of a GR has a good effect on the area.

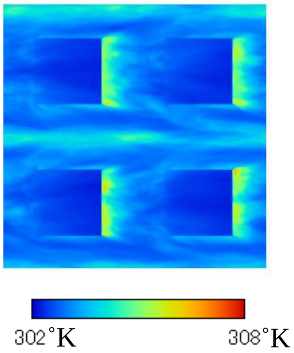

Fig. 20 - Wind flow pattern of GR in case 1 in horizontal cross section

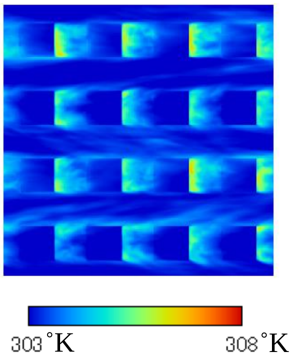

Fig. 21 - Wind flow pattern of GR in case 2 in horizontal cross section

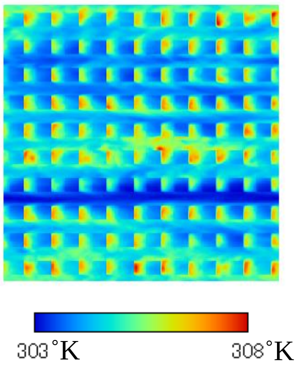

Fig. 22 - Wind flow pattern of GR in case 3 in horizontal cross section

3.3 Comparison between Vegetation on Green Floors (GF) and Green Rooftops (GR)

Fig. 23, Fig. 24 and Fig. 25 show the result of the potential temperature (measured in Kelvin) of GR with an added vegetation area on the top of the building (7 m) and a vegetation area 1m above ground (Green Floor). From the figure, it can be observed that the movement of potential temperature starts to become similar starting at a height of 20 m above the ground. It verifies that the location of vegetation also affects the temperature in the environment.

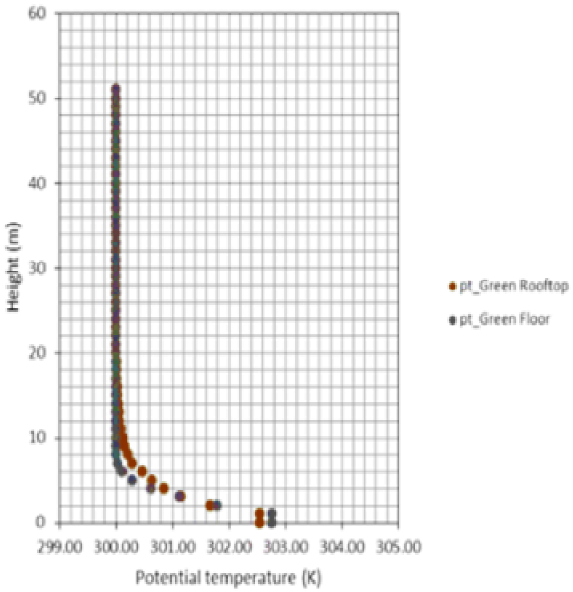

Fig. 23 - Potential temperature of GR and GF in case 1

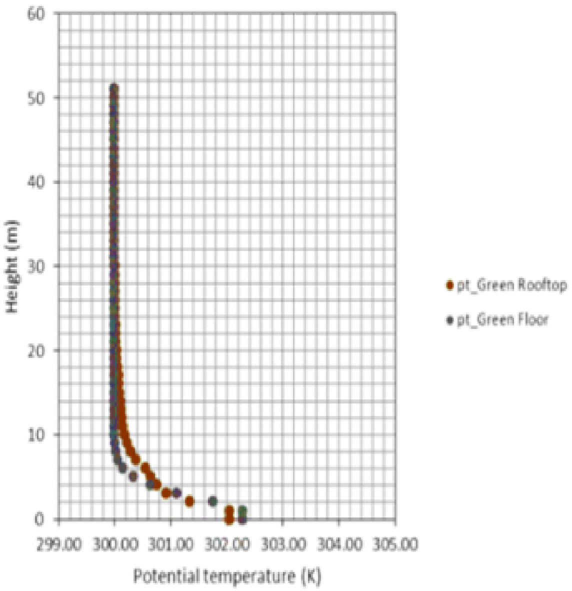

Fig. 24 - Potential temperature of GR and GF in case 2

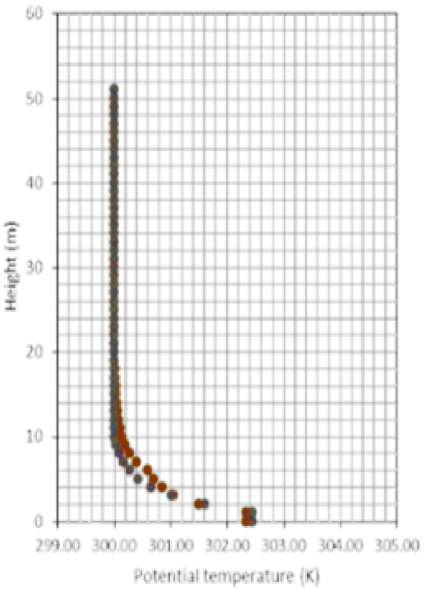

Fig. 25 - Potential temperature of GR and GF in case 3

Table 4 - Comparison of potential temperature between GR and GF in all cases

Height of Building	Case 1		Case 2		Case 3	
	Green Rooftop (K)	Green Floor (K)	Green Rooftop (K)	Green Floor (K)	Green Rooftop (K)	Green Floor (K)
1	302.54	302.76	302.06	302.28	302.33	302.45
2	301.67	301.80	301.33	301.76	301.50	301.61
3	301.15	301.13	300.93	301.11	301.05	301.02
4	300.86	300.63	300.75	300.64	300.85	300.65
5	300.65	300.29	300.64	300.33	300.70	300.43
6	300.48	300.11	300.56	300.15	300.59	300.28
7	300.29	300.04	300.38	300.06	300.40	300.18
8	300.21	300.01	300.29	300.02	300.28	300.09
9	300.16	300.00	300.22	300.00	300.20	300.04
10	300.12	300.00	300.18	300.00	300.15	300.01

Fig. 26 shows the comparison between cases 1, 2, and 3 of GR and GF at 1 m above the ground. The figure indicates that there is little difference between GR and GF. The presence of GF shows that even though the temperatures recorded are higher than those of green rooftops, it is still capable of reducing the urban heat of the area. Therefore, an area with only 25% of vegetation is able to reduce urban heat in a particular area.

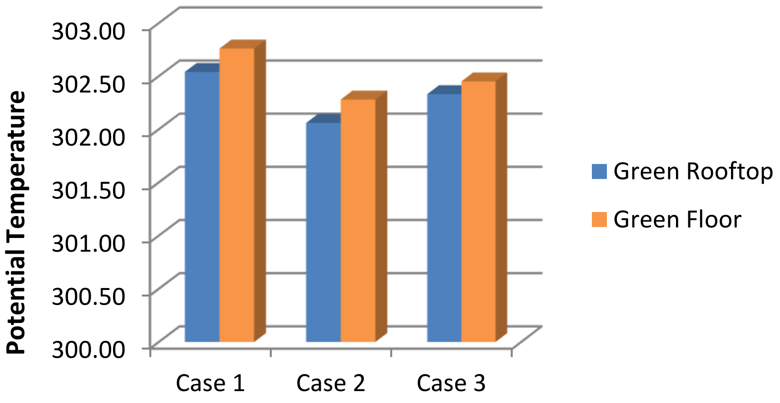

Fig. 26 - Comparisons of potential temperature at GR and GF

4. Conclusions

The results show that buildings with green rooftops have better results than conventional buildings. The potential temperature of green rooftop buildings is reduced by around 0.22˚C compared to conventional buildings. 25% of vegetation area reduces the temperature from around 0.22 to 0.34. It proves Effendy's theory that for every addition of 50% of green open space, the air temperature decreases by 0.2 – 0.5˚C.

Excessive distance affects the potential temperature around a building by causing the solar radiation from the building to point directly to the building, thereby trapping air particles around the building (no circulation). The cause of rising potential temperature does not only originate from the distance between buildings, but also the type of material, especially its capacity to absorb and resist heat. In this study, case 3 recorded a higher potential temperature because of the close distance while case 1 recorded a higher temperature due to the greater distance.

The following shows the comparisons of potential temperature between a green rooftop with vegetation on the top of the building and a vegetation area situated 1m above the ground. Compared to green floors, green rooftops have fewer effective results. The lowest potential temperature for vegetation 1m above the ground was found in case 2 which has 16 buildings. However, the results between green rooftops and green floors are not significantly different. This proves that green floors also have the potential to reduce urban heat in the area. If a minimum of 25% of an existing piece of empty land were to be covered by vegetation, the urban heat around the building area could be reduced.

The best mitigation design amongst all cases is case 2. It is due to the proper distance between buildings of an area. It mentioned above that an effective H/W ratio is around 0.4 – 0.6. The results show that case 1 has a height of 7 m and a width of 50 m. Therefore, the H/W ratio of case 1 is 0.1. Case 2 has the same height as case 1 and a width of 25 m which makes the H/W ratio 0.3. Case 3 has the same height as other cases and the width is 0.7.

From the explanation above, it is clear that case 2 is approaching the minimum limit on effective H/W ratio while case 3 is approaching the maximum limit of the H/W ratio. That is why case 2 and case 3 have the closest potential temperature results. However, case 2 has a better potential temperature result than case 3 because of other factors; narrower distance that results in no air circulation between buildings and the U-value effect of material that produces heat around the building. Meanwhile, case 1 has the worst design because of radiation that points directly to the walls and the ground even though the distance is wide enough to enable air circulation between buildings.

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