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Building Configuration of Low-Cost Apartments in Bandung—Its Contribution to the Microclimate and Outdoor Thermal Comfort

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Abstract: This paper aims to find the microclimate aspect within the building form and configuration of five low-cost apartments (henceforth *rusun*) in Bandung, Indonesia. There are parallel, square, and interspersed plots investigated with specific discussion on the microclimate aspects that gain human perception of outdoor thermal comfort. The microclimate prognostic model, i.e., ENVI-met, was used to determine the mean radiant temperature (Tmrt), which was then used to describe the living quality of outdoor thermal comfort, i.e., PET (physiologically equivalent temperature) in a hot-humid climate context. A parallel plot with building orientation toward north-south was found as the most beneficial building form and configuration. Somehow, the parallel plot toward the west-east orientation did not provide similar performance. Nevertheless, the square plot provided uncomfortable perception as there was an absence of building shade within the wide open space and ground cover to absorb the insolation. The interspersed plot can be considered for the building configuration because it generates more wind among other plots. The building form and configuration of *rusun* with passive design seems to not be able to achieve outdoor thermal comfort. The highest PET value of Model D with the square plot had PET = 41 °C (hot) while the lowest PET in Model A with the parallel plot (N-S) had PET = 34.2 °C (slightly warm).

Keywords: hot-humid climate; building form and configuration; microclimate; *rusun* in Bandung

1. Introduction

The handling of densely populated settlements has become a concern of the government since 2007 when it launched the 1000 Towers program, the affordable flats, or *rusun* (*Rusun* is the Indonesian name forlow-cost apartment. Local governments with a population of more than 10,000 persons/ha are obliged to provide land to build *rusun* with incentives from the ministry of Public Works and Housing.). This program is aimed at revitalizing overcrowded areas, especially in cities with population densities of more than 10,000 people/km^2. According to the Ministry of PUPR, the target for 2019, 500 units of *rusun*, will be completed in Indonesia from 2015–2019, although backlog is still around 0.8% [1]. It is most likely that the program will carry on in the following years and shows the importance of rusun's existence. Thus, the presence of *rusun* is not only shaping the country's image but is also having a significant influence on the urban living quality.

The hot-humid climate region lies near the equator which influenced by the amount of insolation. This incoming solar radiation potentially induces the heat. Therefore, this sun is the most significant aspect of dealing with the outdoor condition. Nevertheless, there is no extreme temperature, since the gap in temperature, either in daytime or nighttime, monthly or yearly has no significant difference. Building geometry and its configuration has proven to contribute to the atmospheric condition and substantial impact to the urban microclimate [2,3]. The variant of building height and space between them are able to reduce solar gain and enhance wind speed at the pedestrian level [4,5]. Those different combinations will give the configuration and variety of different built forms. Later, the measurement of built forms is stated primarily in building coverage ratio (BCR), floor area ratio (FAR), canyon (H/W) also green coverage ratio (GCR) and surface area (SA) will be investigated as the main contributors to the microclimate.

Despite few studies regarding *rusun* and its correlation with outdoor thermal comfort in Indonesia, Karyono [6] has mentioned the adaptive model in Bandung, stating that "neutral temperature (Tn) is defined as a temperature in which respondents' mean votes were equal to zero, while comfort range (Tcr) is a range of temperature in which respondents' mean votes were between −0.5 and +0.5." Futher, the result of Karyono's study showed that neutral temperature (Tn) in Bandung is 24.7 °C in terms of air temperature (Ta) while Tcr is 23–26.5 °C Ta.

The linear relationship which Humphreys derived between comfort temperature and mean outdoor temperature for free-running buildings [7,8] known as:

$$\text{Tcr} = 0.534\ \text{Tod} + 12.9 \quad (1)$$

In a tropical country, the range of acceptable temperature seems wide, at more than 26.1 °C. Hence, we may assume that neutral temperature is equal to comfort temperature. As stated by the Bandung climate agency [9], the average air temperature in Bandung is 23.40 °C, which means outdoor temperature in Bandung is possible to achieve the thermal comfort requirement. Based on Equation (1), the mean outdoor temperature for thermal comfort requirement is 25.4 °C.

On the contrary, even if the outdoor temperature is compliant with achieving building thermal comfort, this does not seem to occur in the context of the microclimate. A previous study on high-dense settlements in Bandung has shown that building density significantly contributes to heat trapped on the urban surface [10]. The characteristic of urban morphology with low floor area ratio (FAR), high building coverage ratio (BCR), and areas with no green open space leads to environmental heat intensity. The study on *rusun* in Bandung also reveals the increase of insolation within the built environment. Somehow, *rusun* has not offered outdoor thermal comfort as a living space [11]. Building performance has not been comprehensively filled with the mandatory design and build process. Units are merely constructed based on the needs of some of the user units. Another study about *rusun* in Surabaya also mentions that hot conditions have been caused by building orientation, insufficient shading devices, and building materials [12]. The phenomenon above could be as a result of the lack of specific building planning and design standards that refer to the building form and configuration for *rusun.* Legal aspect review and prototype assessment of *rusun* have been completed, where most were inappropriate for outdoor thermal comfort [13]. The legal aspect of *rusun* referred to in 05/PRT/M/2007 somehow has not been mandatory in the design process. Plots that are built for *rusun* only because of land availability have not been built considering the potential effects, especially in the microclimate. Generally, there are three kinds of plot types for *rusun* in Indonesia, which are the parallel, interspersed, and square plot.

The idea of bringing the urban building configuration, such as building coverage, floor area ratio, building canyon, the green ratio, as well as surface area, is to provide a suitable microclimate. It is also possible to explore the passive design strategies of building group in a tropical region where, throughout the year, there is no extreme temperature to face. This passive design strategy is then able to contribute to the outdoor thermal comfort. Thus, the aim of this study is to describe the specific building geometry and configuration to meet meteorological conditions in hot, humid regions and assess outdoor thermal comfort through the heat budget, i.e., PET (physiologically equivalent temperature).

2. Case Study

The case study is located in Bandung, Indonesia 6°55′ S and 107°37′ E, at 768 m. Seven *rusuns* have been built in Bandung from 1981 to 2012, and eleven new *rusuns* are planned by the government. Five samples of the building group study area were chosen based on various types of *rusun* with different building plots and configuration, which were grouped as follows (Figure 1):

a. Parallel plot, which includes *Rusun* PTDI (PTDI stands for Perseroan Terbatas Dirgantara Indonesia (Indonesian Aerospace Limited Liability Company). It is a low-cost apartment for PTDI employees), as Model A and *Rusun* UPI (UPI stands for Universitas Pendidikan Indonesia (Indonesia University of Education). It is a university dormitory for UPI students.) as Model B
b. Interspersed plot, which includes *Rusun* Cigugur (Model C)
c. Square plot, which comprises *Rusun* Cingised (Model D) and *Rusun* Pharmindo (Model E)

The building form and configuration were determined, as seen in Figure 1a for the parallel plot; Figure 1b for the square plot and Figure 1c for the interspersed plot.

The five forms of *rusun* considered in the study discussed were derived from a previous study that emphasized that building plot and configuration play a major role in setting the urban microclimate [11]. This article then seeks the contribution of microclimate to the outdoor thermal comfort, which is stated as PET indices.

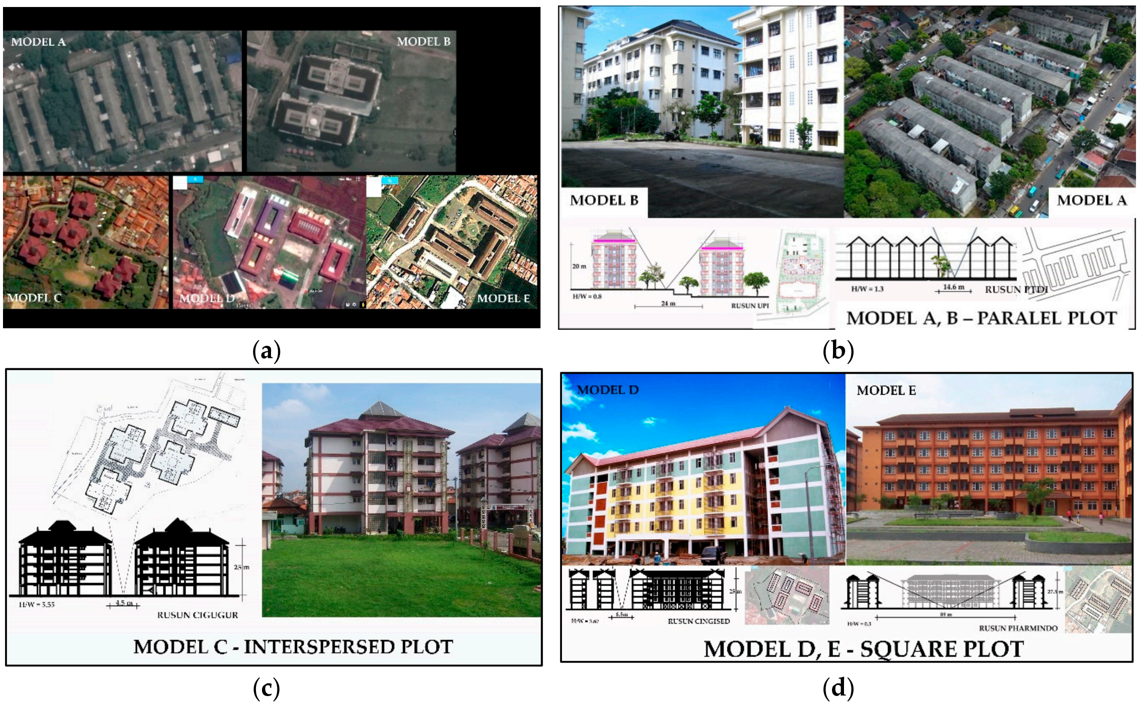

Figure 1. Rusun as case study in Bandung, there are: (**a**) satellite imagery from google earth; (**b**) parallel plot which are Model A and B; (**c**) interspersed plot: Model C; (**d**) Square Plot: Model D and E.

3. Methods and Instruments

This study is based on a micrometeorological measurement and prognostic model to assess thermal perception. Regardless of the diversity of urban sites, which impact microclimate, the WMO Guide to Meteorological Instruments and Methods of Observation suggests a simplified classification of urban forms with respect to roughness length, aspect ratio (height-to-width) of urban canyons, and percentage of built/hard surfaces [14].

Micrometeorological measurement was conducted on 5, 9 and 13 June 2012 from 06:00–19:00 with two hourly interval data using LM-800, which was calibrated using Davis Vantage Pro2. The initial data from those measurements including Ta (air temperature), v (wind speed), and RH (relative humidity) will define the mean radiant temperature (Tmrt) generated by ENVI-met. The thermal perception will then be generated from RayMan 1.2 to find the PET indices.

The building geometry and configuration of the five models have been remodeled using AutoCAD and Sketch-up to determine the building coverage ratio (BCR), floor area ratio (FAR), green coverage ratio (GCR), canyon (H/W), and surface area (SA).

There are three spot measurements, which are open area (O), shading area, (S) and terrace (T). Three different building configurations, such as parallel plot, interspersed plot, and square plot will compare their microclimate and outdoor thermal comfort indices. The method used is described in Figure 2.

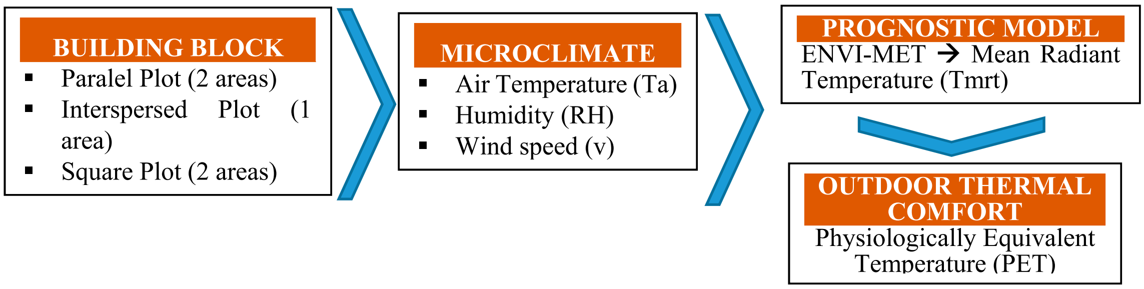

Figure 2. Research Method.

4. Dependence of Urban Microclimate on Building Configuration

4.1. Urban Canopy Layer in a High Density Area

Owing to being situated on the Tropic of Cancer at 23.5° north and 23.5° south, the tropical region faces prolonged isolation, which means the incoming solar radiation potentially induces the heat because the solar radiation occurs longer than that of other climatic regions [15]. As a fast-growing metropolitan city in Indonesia, the trends of urbanization in Bandung impact on urban developments in both land-use and housing densities. The urban roughness is governed by the city's morphology, such us building configuration, open space, and the surface coverage. The urban canopy layer (UCL), which refers to the area between rooftops and the ground, is influenced by the urban roughness impact on the street canyon flow, ducting and trapping of airflow, and multiple reflections of radiation [3,16,17].

The complexity of materials and morphology of the urban surface, which contribute to the urban microclimate and are influenced by sensible heat-flux to the urban area are the fundamental matters that are missed by urban designers and architects. Whereas this micro-scale of urban structure defined by the sky view factor (SVF) has a significant effect on the outdoor thermal comfort at the pedestrian level [16]. Thus, urban designers and architects can contribute to the adaptation of the urban microclimate by making modifications toward the urban surface. Figure 3 describes the significance of building density and surface coverage, which contribute to the atmospheric urban canopy layer [18].

Further, there are six factors that significantly define human's perception of their thermal environment, which describes the sensation of heat comfort. These are dry-bulb temperature (the air temperature Ta which is equivalent with operative temperature (To)), black globe temperature (Tg to know Tmrt), wind velocity (v), and wet-bulb temperature (Tw to find RH and VP). The other is a behavioral factor that is the metabolic rate (M), clothing insulation (clo), and moisture permeability (im) [19,20].

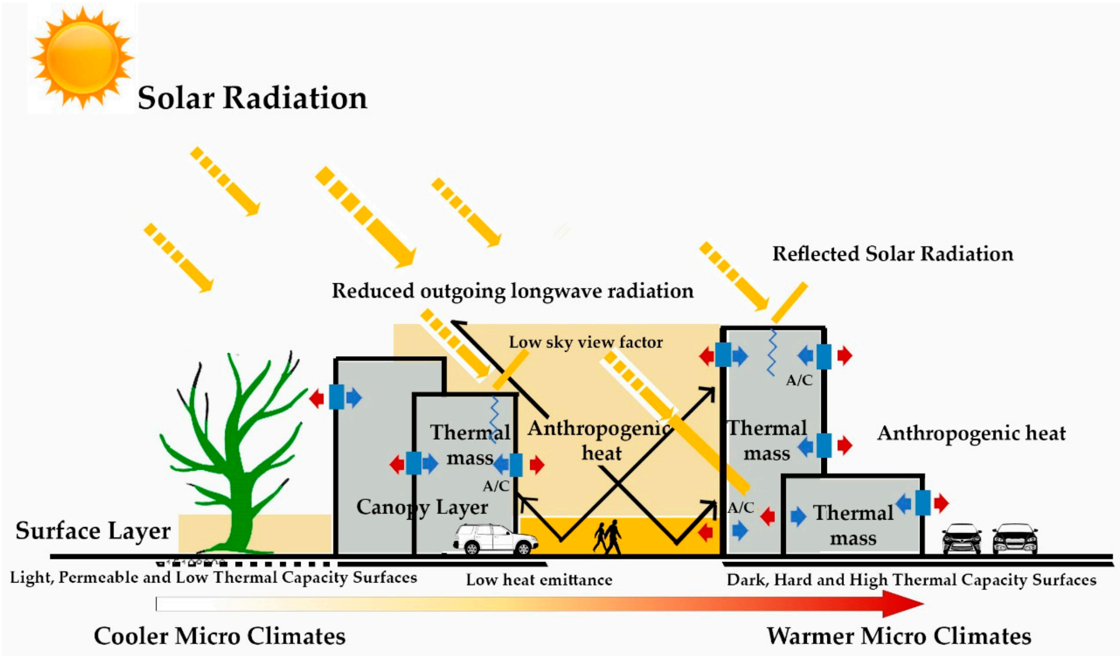

Figure 3. Urban Canopy Layer influenced by the building density and surface coverage. Source: A. Soltani and E. Sharifi, 2017.

4.2. Building Geometry and Configuration to Gain Outdoor Thermal Comfort

As mentioned above, the street canyon has a direct impact to the insolation towards the urban built environment in a tropical region, as clear skies may dominate low-latitude climates. The complexity of building spacing and continuity, building shape and height are connected to the surface reflectivity. Thus Brown and De Kay [21] suggested a building group strategies in the low latitude (0–8° N/S) required daylight factor 1.0 and the canyon (H/W) with spacing angle Tg $\alpha = 1.7–2.0$. Further, to reduce the solar insolation, the green open space must be considered. A study in Dhaka found that maximum air temperature decreases with increased H/W ratios. Furthermore, deeper H/W reduces air temperature but increases Tmrt, thus presenting a conflicting design option to achieve thermal comfort [22,23]. A study on urban canyons in Malaysia found that the best street orientation is north/south, northeast/southwest, then northwest/southeast and the urban canyon with height/width ratio of 3:1 represents the optimum shading and surface temperature [24]. Another study in Colombo, Sri Lanka shows a difference of maximum daily temperature up to 7 K as the different H/W ratio [25]. Meanwhile, in Indonesia, the study about building geometry had no direct contribution to induce wind speed to gain outdoor thermal comfort. It was also found that building configuration and mean radiant temperature had no direct correlation. Vegetation was found as more significant in reducing radiation [26].

The reciprocal correlation between building geometry and configuration as mentioned above has proven the possibility to create a microclimate to achieve outdoor thermal comfort. The urban canyon has a significant role toward direct or indirect insolation within the urban area, where this mean radiant temperature gives the contribution to outdoor thermal comfort.

4.3. Microclimate Prognostic Model

The prognostic model is based on fluid and thermodynamics using ENVI-met [27,28]. The PMV indices used in ENVI-met are a special adaptation to outdoor conditions, based on heat exchange. The energy balance describes heat exchange between the human body and the thermal environment [29].

In Brazil, ENVI-met is used to predict wind speed at two locations in Curitiba with R^2 = 0.7 and R^2 = 0.8 [30]. Meanwhile, in the Netherlands, within five different urban forms, ENVI-met is proven as a satisfied prognostic tool, where the RMSE value is between 2–4 as a result of the absence of the evapotranspiration condition [10,31,32]. Another study in Kuala Lumpur gives the design parameter for building height ratio and the amount of vegetation in the courtyard, which can achieve an acceptable level of thermal comfort in a tropical area [33].

4.4. Outdoor Thermal Comfort in a Hot and Humid Climatic Region

Studies about outdoor thermal comfort are considered a new subject compared to building (indoor) thermal comfort. The characteristic of outdoor temperature has a linear correlation with indoor thermal comfort especially for free-running buildings, as mentioned by Humphrey [7]. Comfort temperature Tc and outdoor temperature are remarkably stable. The supplement of ASHRAE Standard 55-1992 [34] proposed an 'adaptive temperature' based on the relations between indoor neutral temperatures and outdoor temperature. The similar method of adaptive temperature, where Tn lies close to the mean Ta, is an indication of the influence of the subject's recent experience. Some studies conducted by Nikolopoulou, involving 1431 people, showed that Humphrey's suggestions seemed to apply outdoors, too [35]. The idea of indoor thermal comfort theoretically can also be applied to outdoor environments. Honjo described indices of indoor thermal comfort most broadly used such as SET, PMV, and PET, which is also used for outdoor thermal comfort indices [36]. Study on this has been rising in temperate climatic regions and the method of outdoor thermal comfort has been developed since early 2000's.

Tahbaz [37] clustered the model for outdoor thermal comfort especially on the heat budget model, which are PT, THI, PET, and UTCI. Although many indices are used in hot-humid areas, this research focused on PET (physiologically equivalent temperature). Among those based on the energy balance of the human body are PET; it was developed based on MEMI (Munich Energy Model for Individuals) [38]. Here, PET has been estimated using RayMan [39]. Air temperature, air humidity, and wind speed are the parameters in the simple and complex environment to develop the mean radiation temperature and thermal indices from the RayMan model. The relevant radiation fluxes (short and long wave) are calculated using existing or non-global radiation in different ways, and the modification of them by obstacles (natural or artificial). The study in a hot-humid climatic region started in Dhaka in 2003 and found comfort in urban spaces by reducing radiant temperature by shading [22]. A study in Sri Lanka adopted PET to determine the worst condition in a wide street with low-rise buildings and no shade trees [25]. Later, Lin et al. [40] conducted a study based on 1644 interviews in Taiwan and developed a PET range for Taiwan's hot and humid climate, as shown in Table 1.

Table 1. Thermal sensation classification for Taiwan and western/middle Europe.

Thermal Sensation	PET Range for Taiwan (°C PET)	PET Range for Western/Middle Europe (°C PET)
Very cold	<14	<4
Cold	14–18	4–8
Cool	18–22	8–13
Slightly cool	22–26	13–18
Neutral	26–30	18–23
Slightly warm	30–34	23–29
Warm	34–38	29–35
Hot	38–42	35–41
Very hot	<42	<41

Source: Lin et al., 2010.

Study of PET in the southeast area, Malaysia, also reported that even if the neutral temperature is set for >30 °C, the acceptable temperature is within the range of less than 34 °C [41]. Meanwhile, in Singapore, to reduce Tmrt to a desirable level for a specific time range, use of trees, shrubs, and green walls is suggested [42]. Among those studies on PET, there is no specific discussion on how to manipulate the microclimate through building configuration to achieve outdoor thermal comfort.

4.5. Result

4.5.1. Rusun Buiding Form and Configuration

The value of floor area ratio (FAR) in these five models is within the similar range of values, which are between 0.76 and 1.13. In addition, the value of building coverage ratio (BCR) in the five samples has a range between 15.2% and 33%. Vegetation value (GCR) appears to have an enormous gap from one model to the next. Model E has the lowest value of vegetation coverage at 6%. Meanwhile, Model B has the highest amount of vegetation coverage at 17.25%. Surface area (SA), which is in correlation with FAR, shows that the higher the value of FAR, the higher the surface area ratio. In this case, Model C and Model A have the highest value at 0.35. The lowest value is Model D at 0.12.

4.5.2. Rusun's Microclimate

The urban microclimate measurement for air temperature (Ta), humidity (RH), and wind speed (v) is conducted in three different types of weather: sunny, cloudy, and rainy. The result of the daytime temperature of five *rusuns* is as follows (1) The diurnal temperature comparison between the five *rusuns* shows that square plot like Model D has recorded the highest air temperature (Ta_{max}) on a sunny day in open space, which is 43.3 °C at 2 p.m., as well as on cloudy day, which is 43.1 °C as shown at Figure 4. The building configuration with wide open space and less vegetation coverage in Model D seems to influence the high temperature. The highest air temperature is also recorded in another model in an open space spot compared to other spots, such as shaded areas and terraces.

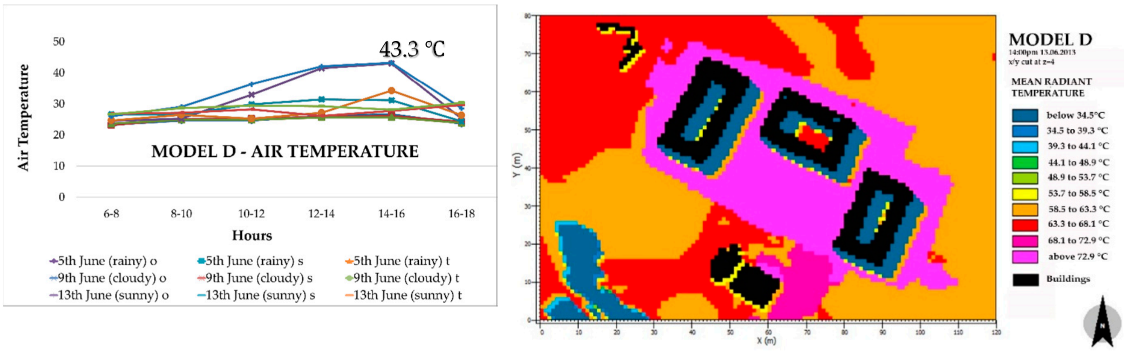

Figure 4. Model D—Square Plot Microclimate.

Ta_{max} in Model E (Figure 5) and Model C (Figure 6) record the same value 40.1 °C; Model B (Figure 7) recorded 32.1 °C while Model A (Figure 8) had 31.4 °C. The air temperature (Ta) somehow has a linear correlation with globe temperature (Tg) and it shows the highest temperature occurs during the day until noon on the open space spot measurement. This insolation has a significant impact on the mean radiant temperature (Tmrt) as an expression of the influence of surface temperature on the occupant's comfort.

Thus, Tmrt is one of the most important parameters in the microclimate. It is also supported by the opinion that during sunny weather, a meteorological input parameter like Tmrt is significant for human energy balance [39]. Later, the simulation using ENVI-met vr 3.1 would only take from the hottest Ta of open space measurement to find the value of Tmrt, as shown in each *rusun's* plot. From the ENVI-met simulation, it shows that Model D has the highest average Tmrt at 53.7 °C followed by Model E at 51.53 °C, Model B at 50.37 °C, Model C at 49.87 °C, and Model A with the lowest Tmrt at 49.30 °C.

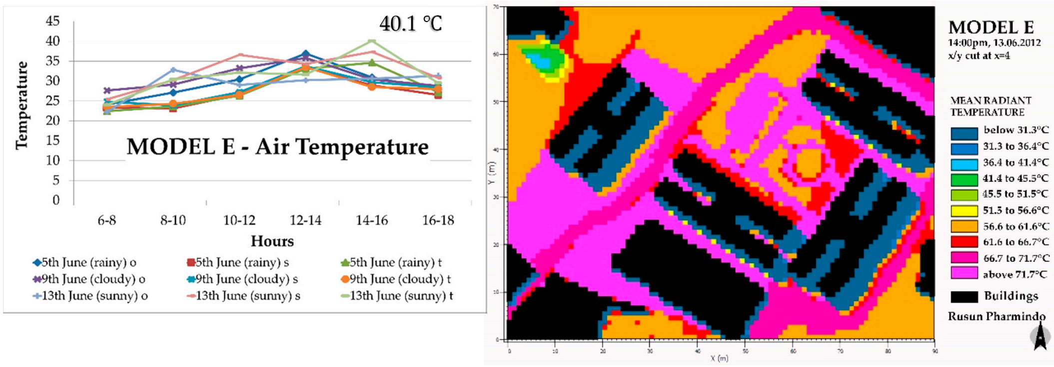

Figure 5. Model D—Square Plot Microclimate.

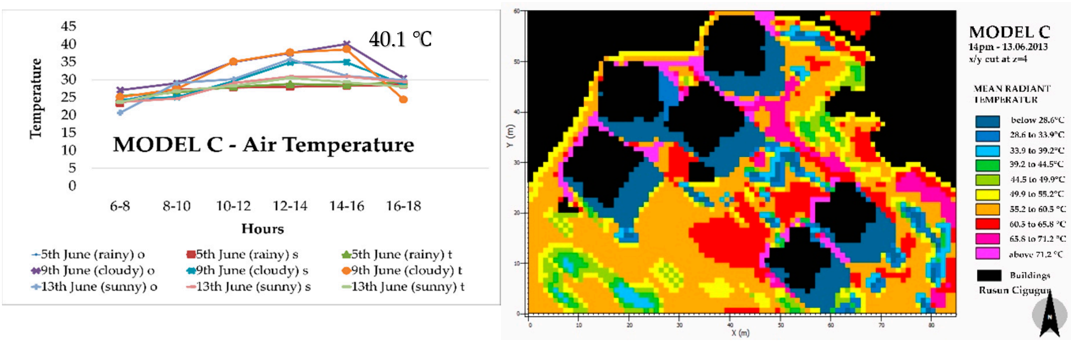

Figure 6. Model C—Interspersed Plot Microclimate.

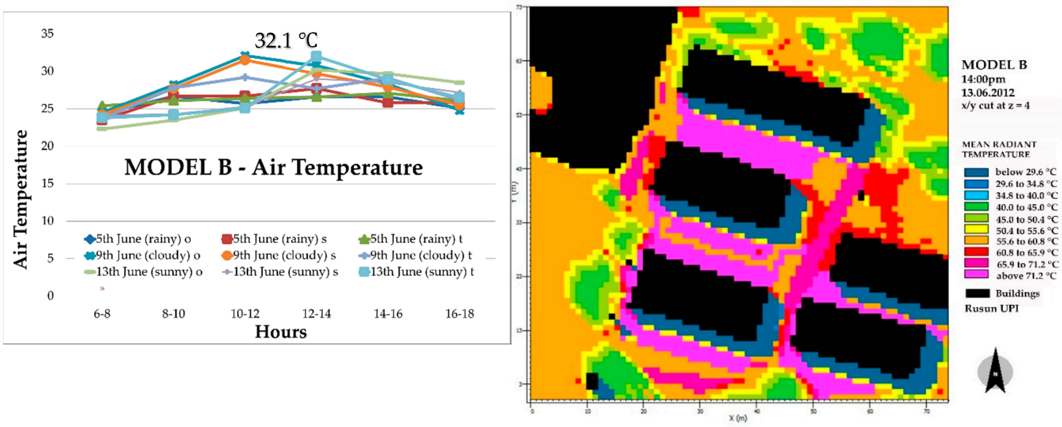

Figure 7. Model B—Parallel Plot Microclimate.

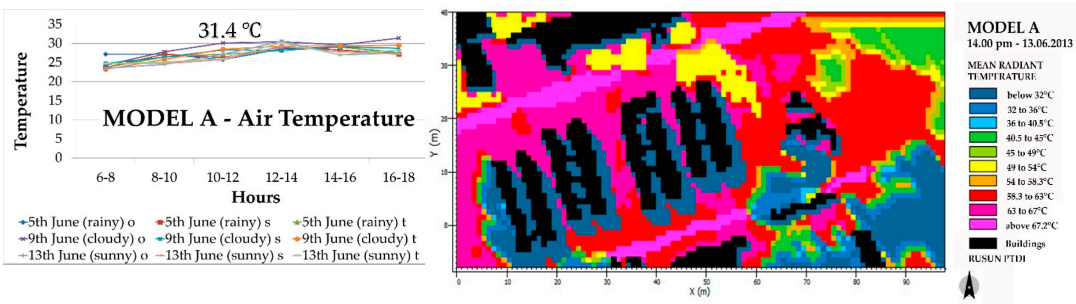

Figure 8. Model A—Parallel Plot Microclimate.

4.5.3. Outdoor Thermal Perception Based on PET

PET has been estimated using RayMan 1.2. Figure 9 shows that Model D with the square plot obtains the highest PET value as 41 °C at 1 p.m. Model E with the square plot and Model A with the parallel plot (W-E) reach the maximum PET at the same value of 37.6 °C but at different times. The max PET for Model E was 1 p.m; meanwhile, for Model A, it was at 9 a.m. Model C with the interspersed plot came to the highest value of PET at 10 a.m. on 36.8 °C whereas Model B with a parallel plot (N-S) has the lowest PETmax value at 34.2 °C at 3 p.m. The figure of PET also describes that the rise of PET has a linear correlation with solar insolation, which shows on the Tmrt value.

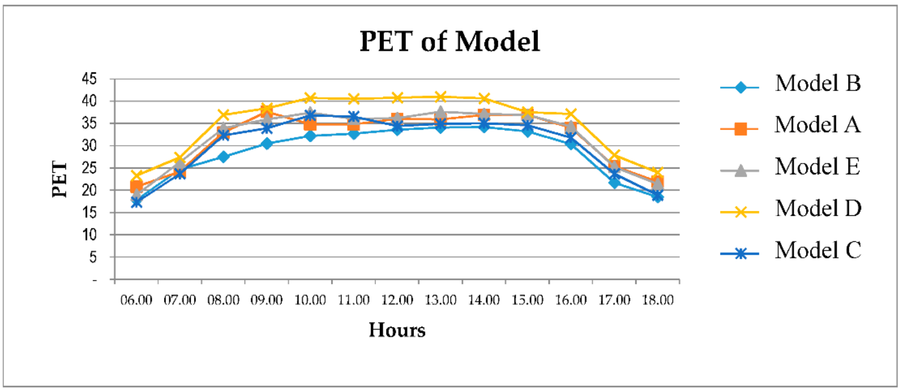

Figure 9. PET of Five Model. Generated by RayMan 1.2.

The PET within the configuration of the Model A, B, C, D, and E are then shown in Table 2.

Table 2. Building Form and Configuration.

Model	Plot	H/W	FAR	BCR (%)	GCR (%)	SA (%)	PET max (°C)	Perception
A	Parallel (W-E)	2.73	1.08	29.0	9.00	0.35	37.6	Warm
B	Parallel (N-S)	1.60	1.13	33.0	17.0	0.15	34.2	Slightly warm
C	Interspersed	5.55	0.92	15.2	9.00	0.35	36.8	Warm
D	Square	0.32	0.76	18.0	2.00	0.12	40.8	Hot
E	Square	0.61	1.10	23.0	6.00	0.14	37.6	Warm

5. Conclusions

The comparison between the five *rusun's* building form and configuration shows that the microclimate plays an important role in achieving outdoor thermal comfort. It also generates specific information about the mean radiant temperature (Tmrt) as the meteorological input parameter for human energy balance, which shows the biggest variability. The building form and configuration such as parallel, square, and interspersed plot, each with a different compactness, provide different situations in their microclimate. The highest temperature in an open space indicates that insolation through urban form has a significant impact on temperature alteration. The urban form characteristic and microclimate on the hottest day, which was altered as the building plot with the main orientation facing west-east, reached the highest RH compared to the other four models. Whereas, building plot with North-South orientation attains the lowest air temperature and the building block with the square plot hits the highest wind speed.

The square plot somehow provides uncomfortable perception for the inhabitant, because of the absence of building shade within the wide open space or ground cover to absorb the insolation. It shows that building canyon (H/W) and green coverage ratio (GCR) has a significant impact on the microclimate. The parallel plot is then more recommended for building configuration by taking consideration of building distance for shadowing and the availability of daylight within an urban canyon.

Parallel plot with building orientation toward north-south has been found as the most beneficial building form and configuration to achieve physiological equivalent temperature (PET). The building orientation becomes important because they receive a different amount of insolation, which then increases the mean radiant temperature (Tmrt). In addition, it appears that building blocks with the highest Tmrt come to the highest PET value, which also has the lowest green coverage ratio. Nevertheless, this study is limited to the influence of building configurations on the microclimate and illustrates that building configuration can be optimized to achieve outdoor thermal comfort. As mentioned earlier, the prototype in the *rusun's* legal aspect did not offer the range of outdoor thermal comfort. This precedent can be a good input for the National Standard Agency of Indonesia (BSN) to re-evaluate the *rusun's* prototype, which was referenced in 05/PRT/M/2007. Later, the standard of planning and design for public buildings needs to be explained in detail especially in the building element. The building standard (Indonesian National Standard/SNI) for public buildings must be an obligation for architects and urban designers in the planning and design process. This issue has to be a priority to reduce environmental burdens in the future.

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