Investigation and Evaluation of Thermal Comfort and Walking Comfort in Hot-Humid Climate Case Study: The Open Spaces of Mega Kuningan-Superblock in Jakarta

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Abstract

This paper investigated and evaluated outdoor thermal comfort and walking comfort in the hot-humid city in Jakarta. This paper used two approaches to show the valid result, through the field measurement of thermal comfort and simulation of the walking comfort of Indonesian people. The simulation of walking comfort was used to calculate how far an individual might be able to walk before experiencing discomfort in an outdoor environment in the hot humid city. Mega Kuningan-superblock in Jakarta, the first superblock developed in Jakarta, was the study area. The interesting factor why this superblock chosen was the compact design. The thermal comfort indices used The Physiologically Equivalent Temperature (PET) calculated using Rayman Software. Walking comfort indices used skin wettedness to simulate the physiological of body that react to environment and use the information to define how far an average Indonesian people can walk while keeping thermal comfort. The three condition were made during simulation, shaded area, light shaded area, and open area, to promote different possibilities of thermal conditions. The results show thermal comfort was difficult to be achieved during the daytime. The heat trapped amongst the buildings in the nighttime affect the temperature in the morning, thus made Tmrt rise significantly during the daytime that affect thermal comfort in next day. Tmrt did not only affect the thermal comfort in open space, but also affect the walking comfort. Shadowing affects the walking distance, the four minutes walking distance or 320 m average is the propose to revise the standard of facilities placement in the urban design.

Keywords: Open space, Superblock, Thermal comfort, Walking comfort, Walking distance, Skin wettedness, Jakarta

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1. Introduction

Jakarta, the capital city of Indonesia, has been experiencing increasing temperature since 1990 (Katarina & Syaukat, 2015). Abundant sunshine, high humidity, and rainfall are conditions can be felt daily in this city. There are leaks of information of outdoor thermal comfort studies in tropical cities needs to consider. This paper seeks to investigate and evaluate the thermal comfort and walking comfort in the hot-humid city. This paper try to find recognize policy and design guideline, which can mitigate the challenges that climate carriage to creating thermal comfort and walking comfort areas. The results can be used as information creating walkable and comfort area in an outdoor environment in the superblock for urban designer and architect.

Every day people come to the office or their destination by walk in Jakarta. According to Hyodo et al. (2005), research in urban travel behavior characteristic of 13 cities based on household interview survey data, 30% of all trips in Jakarta begin around 7 am go to work, at 13 pm go to business outside and lunch, and at 5 pm go to back home. Because of poor public transportation, almost 50% of Jakarta citizen go outside by taxi, and continue by walk to reach the office or their destination. In lunch time, people frequently walk to reach their destination to find the nearest restaurant or café from their office or job's places. People in Jakarta spend 30% activities in outdoor in day time, open spaces are used almost during the years. Therefore, they must have thermal comfort properly. Climate circumstances take part in a particular responsibility in this context not only because climate change causes new challenges for urban areas, but also because urban areas can play a lead task in humanity's pursuit for an association with the natural environment that permit societies to thrive and prosper for a long time to come. One proposed definition of a better place of the city is how much outdoor space is acceptable in the presence of people activity.

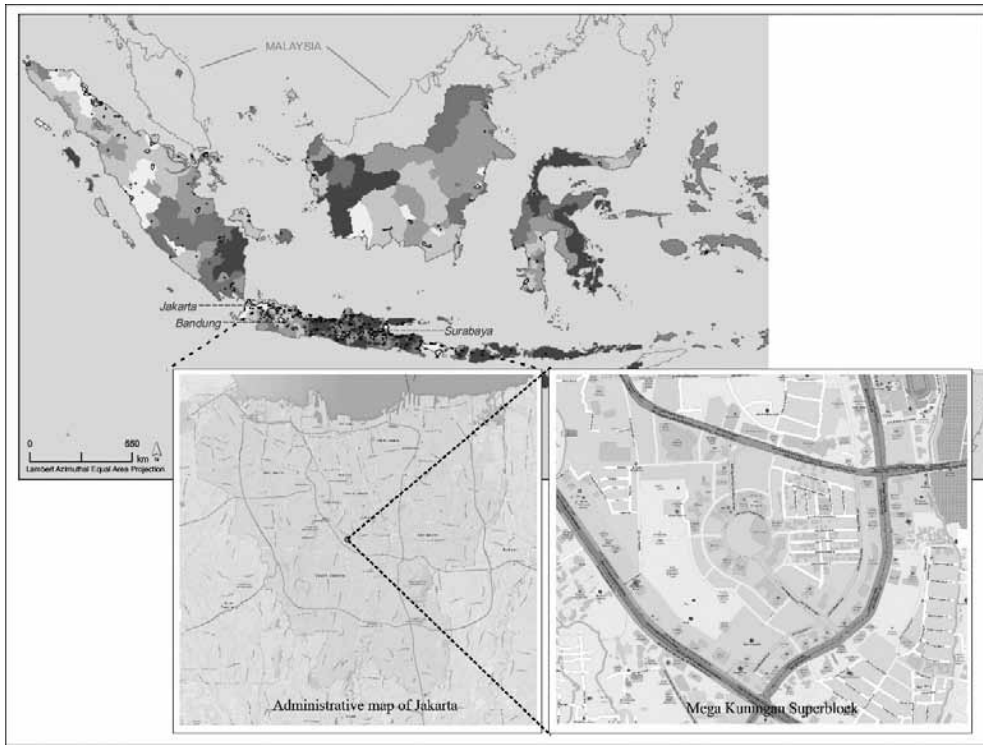
A better understanding of climate and thermal comfort, especially outdoor environment, can contribute improving the quality of urban spaces to live (Nikolopolou, Baker & Steemers, 2001, pp. 227-235).

There is a relationship between open spaces users and thermal comfort that stated by several studies (Nikolopolou, Baker & Steemers, 2001, pp. 227-235; Thorsson, Lindqvist & Lindqvist, 2004, pp. 149-156; Zacharias, Stathopoulos & Wu, 2004, pp. 638-658; Nikolopolou & Lykoudis, 2006, pp. 1455-1470; Lin, 2009). Outdoor thermal comfort is one of the most important impacts immediate and directly can be recognized that influenced by the built environment. Recent years, most thermal comfort studies are about built environment post-occupancy evaluation by applying field measurements or simulation of outdoor thermal comfort parameters to predict models of human thermal comfort. Moreover, the field measurement by involved large samples of actual occupants can lead to a clearer understanding of thermal interactions between occupant and built environment, a more comprehensive understanding of how thermal comforts interact with outdoor built environment elements to impact overall occupant satisfaction. Understanding outdoor thermal comfort is needed to improve the design of outdoor more attractive and increase the quality of life of outdoor. The thermal comfort studies in this open space are important for evaluation studies and as a guideline to urban design and architectural projects.

1.1 Research Area

Indonesia is an archipelago country consists of about 17.000 islands. Break-up by the equator, Indonesia is almost entirely in tropical climate. The coastal plains average temperature is 28°C, the

Figure 1. Location of research.



inland and mountain 26°C, and the higher mountain regions 23°C. The east monsoon from June to September brings dry weather while the west monsoon from December to March is moisture laden bringing rain. The transitional period between these two is interposed by occasional rain showers, but even in the midst of the west monsoon seasons, temperatures range still from 21°C to 33°C except at higher altitudes, which are much cooler (Figure 1).

The seasons in Indonesia are divided into two distinct seasons, wet and dry. The climate is fairly even all year round. Heaviest rainfalls are recorded in December to January. Being in the tropical zone, Indonesia has an average humidity 80%, with a minimum of 70% and maximum of 90%. The main variable of Indonesia's climate is not temperature or air pressure, but rainfall. The equatorial air circulation and the meridian air circulation form the characteristic of climate and weather in Indonesia. Throughout the year, the temperature of Java Island, the main and populated island in Indonesia, is between 22°C to 29°C with humidity 75% average. The wet season is from October to the end of April. North equator the heaviest rainfall is between November and April and dry seasons between May to October. In the south equator, the heaviest rainfall is between Decembers to February. Winds are moderate and predictable, with monsoons, usually blowing in from the south and east in June through September and from the northwest in December through March. Prevailing wind patterns interact with local topographic conditions to produce significant variations in rainfall throughout the archipelago. In general, western and northern parts of Indonesia experience the most precipitation; from the north and westward-moving monsoon clouds are heavy with moisture, by the time they reach these more distant regions.

1.2 Jakarta's Climate Condition

Jakarta located at 6° 13' S 106° 50' E on the northwest coast of Java, at the mouth of the Ciliwung River of Jakarta Bay, which is an inlet of the Java Sea. The city is a lowland area, average height is 7 meters above sea level. Officially, the area of the Jakarta is 662 km2 of land area and 6,977 km2 of the sea area. Rivers flow from the hilly southern parts of the city northwards towards the Java Sea. The most important river is the Ciliwung River, which divides the city into the western and eastern principalities.

Jakarta is a hot-humid tropical climate city that located in the western-part of Indonesia in South Equator. Jakarta's wet season rainfall peak is in January with average monthly rainfall 400 millimeters (16 in), and its dry season low point is in August with a monthly average 70 millimeters (2.8 in). The average daily temperatures range is from 25° to 36°C, which the hottest month is October and the coldest month is January. Jakarta area has an average wind speed three ms-1 with south direction annually (Figure 2 and Figure 3).

The Jakarta famous name is Daerah Khusus Ibukota-Special Capital City Region of Indonesia. Jakarta had become the capital city since 1945 when Indonesia proclaimed as an independent state. Since then apart as the state capital, Jakarta is also a center of economic growth in Indonesia. Jakarta has grown faster than Kuala Lumpur, Beijing and Bangkok leaped from ranking 171 to 17 in 2007 among the 200 largest cities in the world. Jakarta Megapolitan City's area is 662 square kilometers with almost 10.000.000 population in 2011 (Figure 1).

Recently the concept of city development known as the superblock concept has been integrated with the urban. The Superblocks are developed to overcome the increasing scarcity of land and to comprehend the explosive population growth. The purpose of superblock developing in the city center is to manage construction management efficiently, to realize sustainable development, and to use the available land efficiently. Jakarta's superblocks are developed to integrate the groups of high

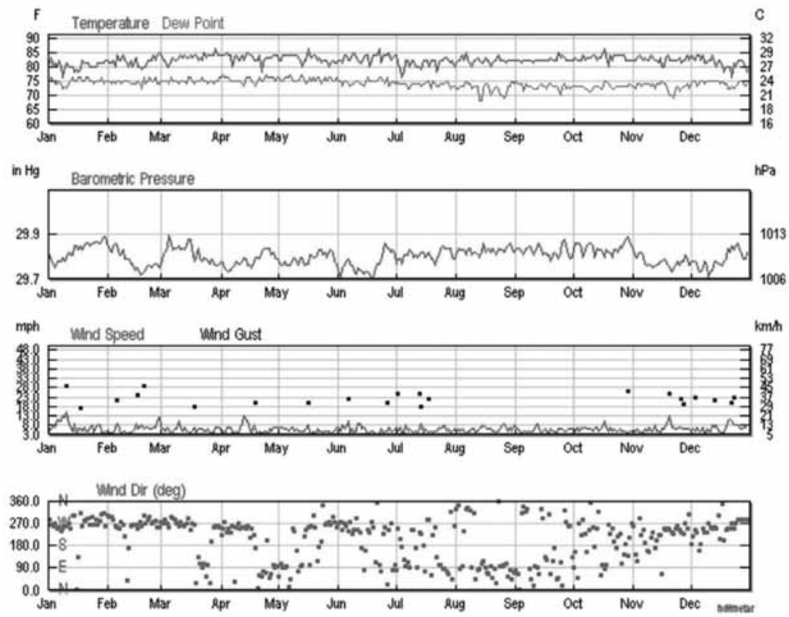


Figure 2. Seasonal pattern of temperature, air velocity, and relative humidity in Jakarta, 2013 (Source: Wunderground.com).

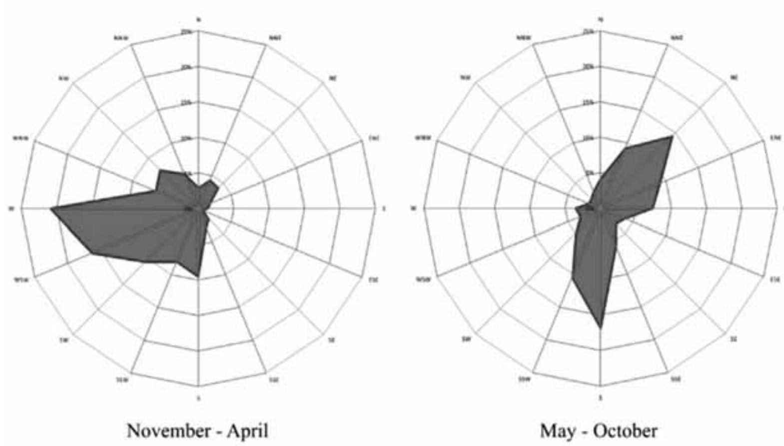


Figure 3. Wind direction at Jakarta on rainy season (November-April) and dry season (May-October), 2013. Jakarta's Superblock

rise buildings and the high density of mixed-used lands, which consist many activities and functionality such as hotel, office, shopping center, mall, apartment, and other facilities in the center of the city.

Based on Ordinance of DKI Jakarta Number 6 of 1999 on Regional Zoning Plan of Special Capital City Region of Jakarta on Article 43 paragraph (4) (Indonesia Real Estate Law, 2013), superblock has to consist of a combination of housing and other facilities. The other facilities have to exist besides housing, i.e., mall, shopping center, apartment, and public facilities. The space range of housing is between 35%-65% of the total available space. Another space requirement related to the housing structure and other facilities also known as a part of the superblock. The public utilities, social facilities, and parking lot, which type and amount of that area, have to be adjusted to the standard of urban planning. Green Basic Coefficient is a green open space that must be part of every superblock consisted a certain amount of plants/trees present as a protected garden.

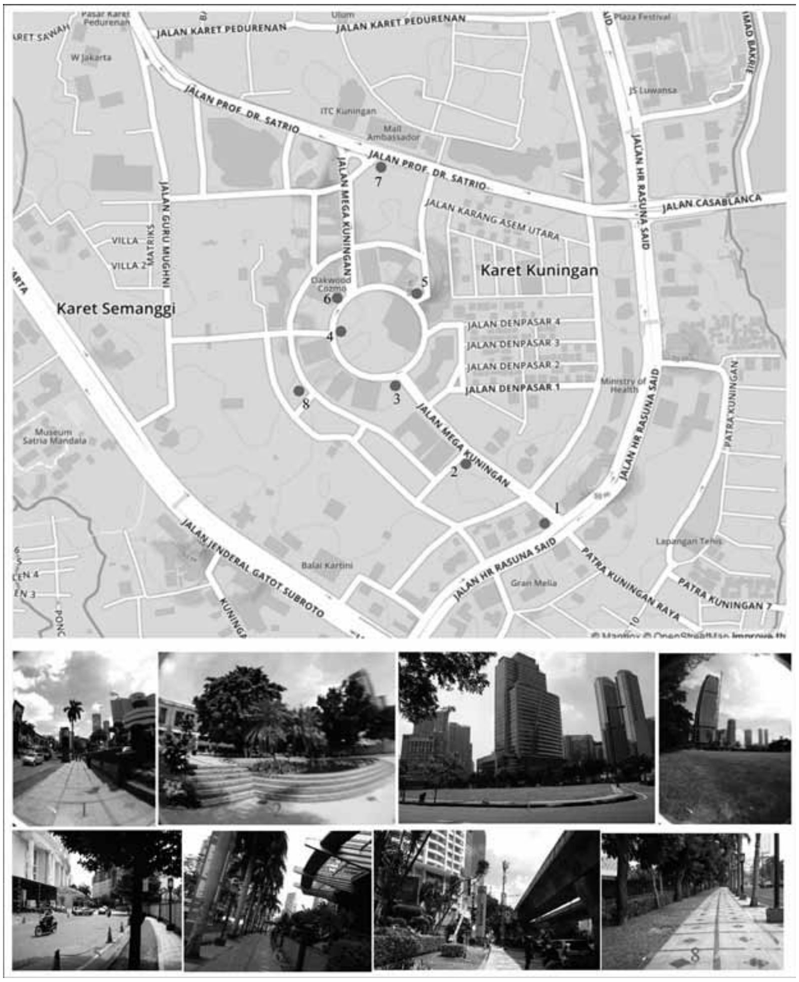
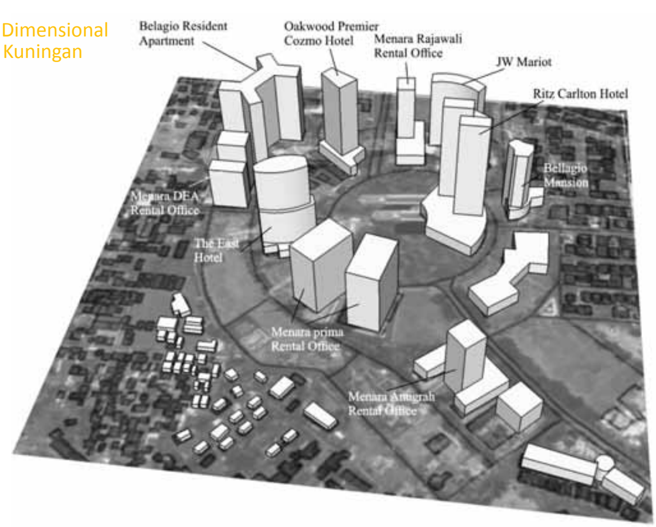


Figure 4. Mega Kuningan Superblock and selected survey zones. Number represent zones.

Mega Kuningan superblock, one of the famous and oldest superblock in Jakarta, is located in the southeast of Jakarta's Golden Triangle district sited on 55 ha land (Figure 1). The Mega Kuningan superblock has a concept split the land into small groups of buildings to make interlink easily among them. The groups of buildings integrate with circulation systems for pedestrians and vehicles. The form of the Mega Kuningan superblock is circular, each block at the center are facing the main circular road named Jalan Mega Kuningan. In the center of the superblock is the blocks for the business area, where hotels, malls, apartments, and hospitals are located (Pengelola Mega Kuningan, 2013). There are two main entrance to enter the Mega Kuningan superblock; north entrance is from Jalan Prof. Dr. Satrio, and the south entrance from Jalan Rasuna Said. See Figure 4.

Figure 5. Three Dimensional Model of Mega Kuningan superblock.



Mega Kuningan superblock integrates of high-rise buildings located in the middle, and two stories landed houses in its surrounding area. The highest building is

Ritz Carlton Hotel, 180 m high, located in the middle of the superblock. Besides high rise buildings, there is a park located in the middle of the superblock as well where people usually use to hang out (see Figure 5).

2. Background Studies

2.1 Studies of Heat Balance

The establishing of heat balance will work when heat is equal to gains and losses on the human body. Sometimes the external environment does not allow the heat balance work, and then the thermoregulation will be triggered. The human body will produce sweat; it may evaporate, to take the heat away from the body to restore the balance back (Hoppe, 1993, pp. 741-746). Producing extreme sweating to maintain the heat body balance can make an uncomfortable situation, besides the clothes getting wet; there will make the organic power tangled in the sweat secretion, and cause to the undesirable effect leave on the skin (Alvarez, Guerra & Velazquez, 1991). The ideal thermal comfort can be achieved when the balancing of different energy/heat flow's works, so the heat loss through sweating can be negligible in the summer. Even so, sweating will be required when one the source of the heat gain increase, in terms of losing heat from the body and getting thermal comfort. Regarding the heat balance equation, it is potential to calculate all the parameters and to measure the different gains and the possibility of losses.

The thermal comfort situation can be achieved by increasing the favorable heat flows (losses) and reducing the unfavorable ones (gain) wherever possible or by transforming them into losses when the problems come. Natural techniques can be used as a tool of heat balance through shading, for example: via trees, or specific cultivation, as a natural shaded area, in other hand artificial shade has to be provided or with a combination of technique employed.

For urban planner or landscape designer, in practice, these issues should be taken into account to design open space which can control the variable such as solar radiation, one of the biggest sources of heat gain, or in which can eliminate extreme heat through convection by using the element of the landscape, such as water bodies or fountains. There are two focuses parameters has to be taken into account regarding open space design: 1) The meteorological parameters. Thermal comfort calculation cannot be taken just from general parameters of the city which, measured by the meteorological service bureau. The parameters have to be measured from field measurement because of the urban structure that surrounded by buildings, vegetation, and road, modify those parameters in micro-spaces. 2) Measurement in situ of the meteorological parameters should involve human-biometeorological indices to calculate the balance equation with the values obtained.

2.2 Outdoor thermal comfort indices

Morgan and Baskett (1974) stated current studies of thermal comfort based on two basic approaches: 1) An analytical or rational approach. The human energy balance is used as a basic theory of this approach. 2) A synthetic or empirical approach. The combination of variable of various meteorological is used to calculate the formula of thermal comfort, unfortunately this approach does not consider the key role played by human activity, thermal physiology, clothes and other human's personal data (sex, weight, height, age, etc.). Currently, as what Hoppe (1993) stated Rational indices much to be used, relatively newer, match to the human energy balance, and easy to be used by computing technique.

Recently, rational indices are widely used by many international researchers and closely linked to the urban planning research. The Rayman Model by Matzarakis developed for the calculation of the mean radiation temperature and thermal indices in simple and complex environment, which based only on data of air temperature, air humidity, and wind velocity (Matzarakis, Rutz & Mayer, 2007), the model based on VDI Guideline 3787, published by the Association of German Engineers (1998). Ochoa et al. (1998) from The University of Sonora has published Microclimatic analysis of some urban scenarios, based on research of Brown and Gillespie (1995). Nikolopoulou et al. (2004) carried out the RUROS (Rediscovering the Urban Realm and Open Spaces) Project for the European Union.

Psychological factors in the perception of individual comfort become an important factor in research of thermal comfort in open space (Nicolopoulou & Steemers, 2003; Nikolopoulou & Lykoudis, 2006; Lin, 2009; Lin et al., 2011; Lin & Matzarakis, 2011; Lin et al., 2012, 2013). Jendritzky et al., (2012), studied about comparing UTCI and PET last ten years, and some studies latter highlighted both indices are ease to use.

The physiological equivalent temperature, PET, is used to calculate the thermal comfort indices because of it is widely known using °C in its unit. Therefore, PET has the advantage compared to other thermal indices. Base on the human energy balance of the human body PET is very well matched to the humanbiometeorological evaluation of the thermal component of different climates. Therefore, PET significantly and consistently matches to thermophysiologically (Mayer & Hoppe 1987, pp. 43-49; Hoppe, 1999, pp. 71-75; Matzarakis, Mayer & Iziomon, 1999, pp. 76-84).

PET value can be calculated using free software packages by Rayman (Matzarakis, Rutz & Mayer, 2007), which can make precise predictions of thermal environment (Gulyas et al., 2006; Lin et al., 2006). Rayman has been used to calculatein several of outdoor thermal comfort with complex shading patterns. PET is easier to estimate by temperature, RH (or VP), v, Tmrt, human clothing, and activity in the model (Lin et al., 2010). Several parameters can be added to calculate following analyses, i.e. Tmrt (the most important factor during hot condition when calculating PET). Using Rayman Tmrt can be also estimated by global radiation (Gr), cloud cover (Cd), fisheye photographs, and albedo. The Bowen ratio of ground surface and the Linke turbidity including the shading effect can be estimated while calculating short- and long-wave radiation fluxes.

Table 1. PET value Source: aMatzarakis and Mayer (1996); bLin and Matzarakis (2008)

PET[a] Moderate Region (°C)	PET[b] (Sub) Tropical Region (°C)	Thermal Perception	Grade of Physiological Stress
		Very Cold	Extreme Cold Stress
4	14		
		Cold	Strong Cold Stress
8	18		
		Cool	Moderate Cold Stress
13	22		
		Slightly Cool	Slight Cold Stress
18	26		
		Comfortable	No Thermal Stress
23	30		
		Slightly Warm	Slight Heat Stress
29	34		
		Warm	Moderate Heat Stress
35	38		
		Hot	Strong Heat Stress
41	42		
		Very Hot	Extreme Heat Stress

Outdoor thermal comfort studies have been conducted in various spaces. Nikolopoulou and Lykoudis (2006) conducted thermal comfort study in outdoor and semi-outdoor environment in five European countries (subtropical country) and found there is a strong correlation between thermal comfort and microclimate. Lin and Matzarakis (2008) studied outdoor thermal comfort in Taiwan showed that the neutral temperature of Taiwan is higher than that of western and central Europe.

Makaremi et al. (2012) studied outdoor thermal comfort in a context of hot-humid climate at a university in Malaysia. Their results showed that the value of the thermal comfort index (PET) in the selected shaded outdoor spaces was higher than the comfort range defined for tropical climate (PET < 30 degree Celsius). Normally condition that acceptable (PET < 34 degree Celsius) occurred during the early hours of their measurement (9-10 am) and late afternoon (4-5 pm) while the high level of shading is obtained from the plants and surrounding building had a longer thermal acceptable period.

According to the previous investigation, research on outdoor thermal comfort in hot-humid region is still incipient. Makaremi et al. (2012) in their research outdoor thermal comfort in Malaysia used thermal comfort index from Lin and Matzarakis (2008). In order to identify thermal comfort range for hot-humid tropical region, Lin and Matzarakis (2008) conducted thermal comfort study in an outdoor environment of Taiwan. Their study focused to modify PET classes from moderate climates to suit the condition of tropical and subtropical climates. Table 1 shows the comparison between PET index hot-humid climate and subtropical region climate. In comparison with the Western/middle European scale where the neutral temperature of PET between 19 and 23°C, the tolerance of higher neutral temperature of Taiwan’s resident corresponds to PET values between 26 and 30°C. The result showed that the thermal comfort range of Taiwan's respondents was significantly higher than in Europe represented of the moderate climatic condition. In this study, the thermal comfort range is applied from the value of a PET hot-humid/ Tropical region stated by Lin and Matzarakis (2008), see Table 1.

2.3 City and walkability

City significantly modifies meteorological of surrounding conditions. The city can increase the radiation higher cause the average temperatures of the city become hotter than the surroundings. The presence of buildings can decrease wind velocity in the city, therefore, make relative humidity much lower in the city than surrounding (Landsberg, 1981). Planning and urban design can improve or worsen this situation.

O'Hare (2006) stated that urban development tends to steer the development in the use of private transport modes and excessive air conditioning appliances. System development and use of technology is not friendly to the environment. The city must understand microclimate if a city does not want to tend to develop oriented mode of personal transport. Activities conducted the city residents outside of the building, such as walking and using public transportation should be convenient and possible widely can interact with the urban environment comfortable.

A social interaction in the city is a key asset of livable cities which people can access a wide range jobs, goods, services, and location for business. A walkable place, which more convenient and livelier is a place with a variety of services and destination in close proximity to one another. Walking is a marker of urban spaces-places where people walk between destinations than to take other modes of transportation.

Jacobs (1961) stated that the heart of urban vibrancy is walkability, where there are a mix of urban function like short blocks, population density and diversity and a mix of user, and building types and ages that all play out in their own role. A walking places that frequently used have characteristic: they are generally denser, better served by transit, more central, and have more of a mix of different land uses. Litman (2007) stated most walking research is a part of the urban transportation system study, which transportation often focus exclusively on car and transit trips, ignoring pedestrian travel as an important component. Consequently, they did not put walkability as a vital form of urban transportation.

Carvaro et al., (2003) stated outdoor activities like walking, and using public transportation naturally require interaction with the natural environment. Exposure to extreme heat,humidity, and rainfall conditions are recognized as a significant barrier in outdoor activities. The extreme heat conditions, high humidity and low air velocity are a challenge for urban designers and architects to create a more comfortable space atmosphere in Jakarta.

The study of the impact of climate on the walkability in the pedestrian has not been extensive. However, the studies from the thermal comfort literature found that variables of biometeorological could be used to calculate the walkability. Furthermore, walkability that affected by climate is implied walking comfort in this paper. It is how far an individual might be able to walk before experiencing discomfort in an outdoor setting. The distance is examined for how far the body's physiological response can walk while maintaining thermal comfort; it is called comfort shed (DeVau, 2011).

2.4 Walking Activity and Climatic factors

More than 15 years, researchers on urban design have investigated that well-connected street are associated with more walking. In the theory of urban design, the basic building block of walkable neighborhoods is defined as the area covered by a 5-minute walk (about 400 meters). Handy (2005) found that built-environment causes some measure of physical activity. The key role of placing residential density, commercial destination, and transit connectivity contribute make walking a more efficient form of transportation and allow individuals to complete the tasks of daily living without needing a car. The physical and social environment constructions that builds surround us create a healthy context for our lives (Lovasi, 2012). While walkability as topics are frequently discussed, climatic factors is not a significant theme. Eliasson (2000) found the result from the survey that the majority of urban designers did not take into account climatic factor in their decision-making process. Some literature reviews have discussed walking activity in detail but did not mention to climatic factors. Greenwald and Boarnet (2001) stated that Pedestrian Environmental Factor was significant in determining the probability of non-work walking travel at the neighborhood level but did not significantly talked about climatic factors. Cervero and Duncan (2003) found that well-connected streets, small city blocks, mixed land uses, and proximity to retail activities could induce nonmotorized transport. They emphasized there were other stronger factors affected walking and bicycling choice than built-environment factors; such as topography, weather, and demographics, but they need more evidence data. The climate is barely mentioned in several literature that discussed about neighborhood design and walkability from urban planning, transportation design, and environmental health fields (Besser & Dannenberg, 2005; Ewing et al., 2006; McGinn et al., 2007; Kashef, 2010).

The literature of walking comfort has a limitation; much of them comes from the public health field and public transportation fields. O'harre (2006) stated walking, including walking to public transit is a part component of physical activity that relate to active public transportation. Buys and Miller (2010) conducted research using 24 qualitative interviews with resident of high-density dwellings in the subtropical climate of the inner city of Brisbane, Australia. The study showed a general perception that walking in the climatic condition of Brisbane is difficult to achieve especially walking in hot weather. Uncomfortable position also was seen when combining walking with the use of public transit. In the other hand, they remarked that walking in sweaty condition to public transport stop on hot-humid subtropical summer day was unbearable.

The most literature stated how climate affects the walkability in the urban setting comes from the public health field. O'Hare (2006) noted about active transportation, it recognizes that walking, a part of the physical activity is an inherent component of transit use. Buys and Miller (2010) found that walking was more difficult in the climatic conditions in Brisbane, Australia. Merril et al. (2003) found the physical activity has been affected by the season and climate for adult in the United States. Psychological factors play an important role in how people perceive weather and climate, stated by Hoppe (1999); Nikolopoulo (2001); and Ahmed (2003).

Merril et al. (2003) showed their research result at United State that season and climate have a significant impact on the physical activity of adults. They remarked that the results had stronger effect in areas with climates similar to Florida's. Eves et al. (2008) found physical activity can be more depressed in the summer season at subtropical climate. They observed the number of individuals willing to climb stairs or walk at least half of length of moving sidewalk in hot-humid climate of Hong Kong, and the result showed the willingness of individuals to climb stairs or walk decreased along with humidity increased. Brown and Banister (1985) stated that solar radiation significantly increased heart rate and cardiovascular strain. Meanwhile Eve et al. (2008) stated that high humidity is an obstacle removing heat from the human body. Sheffield et al. (1997) showed from their research that the humid condition and lower humidity could increase rates of perceived exertion and discomfort.

3. Research Methods

3.1 Thermal Comfort Measurement

A Sunny day without rain is an essential day to make field measurement in urban open space. Temperature (Ta), relative humidity (Rh %), and wind velocity (v, m/s) are measured based on the climate condition in Jakarta. The coldest month of the rainy season and hottest month of the dry season were the best periods to carry out the physical measurement. February and October are the best conditions to be chosen as months to measuring, see Figure 6. The weather in February and October in Jakarta is very stable, without rain and clouds, lower thermal oscillation and small variation of the relative humidity day by day.

The measurements were made on 3 February and 10 October 2013 (Koerniawan, 2015) in a clear sky, during 24 hours, from 1 am to 12 pm. The 8 points were chosen in the area include shaded, half-shade and opened areas to promote different possibilities of thermal conditions, see Figure 4. The eight points of measurement can be seen in Figure 2. The tools were used in the field measurement, i.e., Thermo Recorder RT 13 to measure temperature and relative humidity, LM 8000 to measure wind velocity, and EM 528A to measure Surface temperature. All sensors installed in 1.5 m above the ground and under factory calibrated. All data results were made into hourly means.

GIS data were used to obtain the urban structure data of Mega Kuningan Superblocks. The sky view factor (SVF) was made from Nikon DSLR and fisheye lens that captured from each measurement point. The RayMan 1.2 software from Matzarakis, Rutz, and Mayer 2007 is used to calculate SVF from the DSLR image, see Figure 7.

3.2 Walking Comfort Measurement of Skin Wettedness

According to (deVau, 2011, p. 46) skin wettedness (w) are a suitable measurement to calculate walking comfort. There are three variable to calculated skin wettedness: subject surface area (m^2), clothing units (clo), and metabolic rate ($W.m^{-2}$). The equation of skin wettedness is derived from (Fukuzawa & Havenith, 2009):

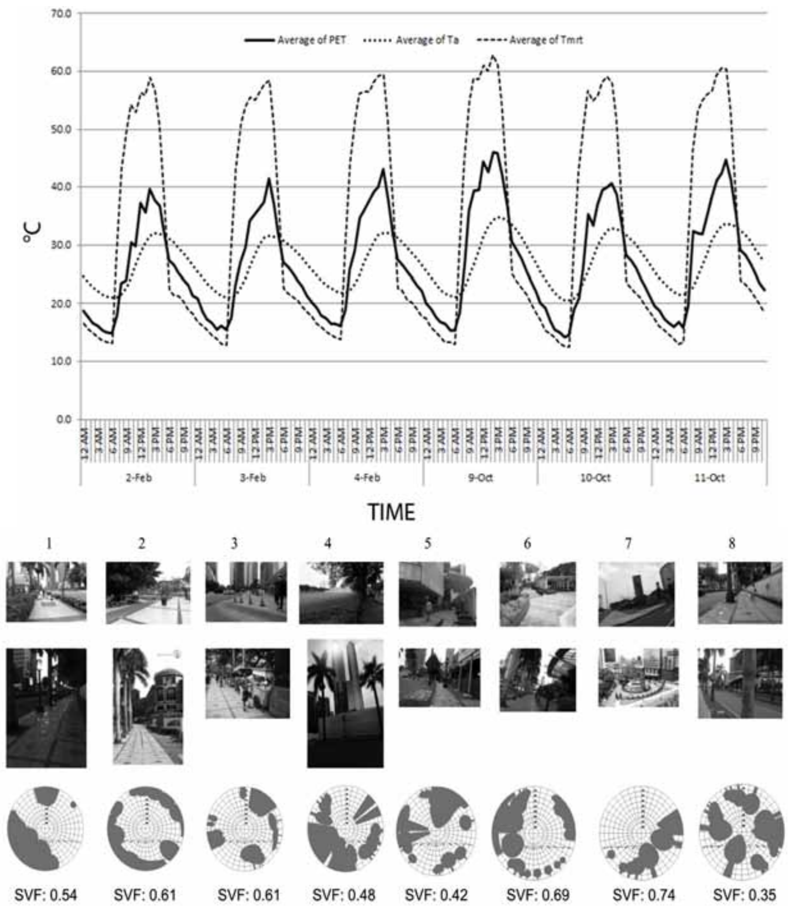


Figure 7. Environmental Characteristic at each points measurement.

$$w=(q_{max}/q_{emax})+ 0.06 \qquad (1)$$

Where; Qsw = required evaporative heat loss (W/m²)
and Qemax= maximal evaporative capacity of the environment (W.m-2), 0.06 is dimensionless of minimal skin wettedness by skin diffusion.

Fukuzawa and havenith (2009); Djongyang et al. (2010) stated that discomfort is strongly associated with skin wettedness in warm environments than skin temperature. Gagge (1937) developed the measurement of skin wettedness over the body (w), and Winslow et al. (1939) suggested as well measuring thermal discomfort using skin wettedness (w). Havenith (2002); Fukuzawa and Havenith (2009) recognized skin wettedness as one of the most convenient indices to predict the thermal comfort level for human in warm conditions.

Djongyang (2010) stated the skin wettedness is a rationally derived from physiological index. Skin wettedness is the ratio of the actual sweating rate to the maximum sweating rate that occur when the skin is completely wet, and related to the skin temperature that indicate the sensation of comfort and discomfort caused by perspiration. Skin wettedness is used to determine the evaporative heats lose. The value of skin wettedness ranges from 0.06 to one. The value of 0.06 caused by the evaporative heat loss due to the moisture diffusion through the skin alone (i.e. with no regulatory sweating) for normal condition, and the value 1 occurs when the skin surface totally wet with perspiration, a condition that occurs rarely in practice (Djongyang, 2010, p. 2364).

De Dear from the University of Sydney in Australia developed the web-based tool calculator of Human-Heat Balance; he uses the source code originally developed by Huizenga (1995) for ASHRAE's comfort tool. The web-based calculator is available at http://web.arch.usyd.edu.au/~rdedear/. De Dear calculator calculates values of thermal comfort indices such as PMV/PPD and SET* using standard biometeorology inputs. Furthermore, de Dear calculator displays the results of two-node models main physiological models (UTCI, 2011). One of these values is total evaporative heat loss from the skin (Esw) that is equivalent to qsw defined by Fukuzawa and Havenith (2009), see equation 1. Another value, which is important, is skin temperature (Tsk). Tsk is necessary to calculate qemax later. De Dear's calculator not only can display the result of qsw and Tsk as final values at the end of a set period of time, but also can display values for each minute over a period of time. The result of every minute over a period of time is needed for the purposes of the walking comfort analysis. All qsw and Tsk values on this paper were calculated using this tool.

3.3 Partitonal Calorimetry

Atkin and Thompson (2000) from University of Sydney developed Partitional Calorymetry Calculator using a spreadsheet. This program uses Visual Basic to calculate the heat storage and heat lost or gained through dry and evaporative heat transfer pathways. The spreadsheet can be downloaded at http://www.sportci.org/jour/003/ka.html. Atkins and Thompson (2000) explain the calculation manual in the accompanying article.

q_{emax} is calculated by Atkins and Thompson (2000), as follows: Calculation of q_{emax} (the maximal evaporative capacity of the environment) formula is taken from McIntyre (1980):

$$q_{emax}\ (Wm^{-2}) = f_{pd} \times h_e \times (P_s - P_a) \qquad (2)$$

Where f_{pd} is the permeation efficiency factor of clothing, h_e is the evaporative heat transfer coefficient (W.m^{-2}.kPa^{-1}), P_s is the partial water vapor pressure at the skin surface (kPa), and P_a is the partial water vapor pressure of ambient air (kPa) (McIntyre, 1980).

Beginning calculation, there are two variable that have to be calculated using automated Visible Basic element on the EnvironData tab of the spreadsheet, i.e.: radiative heat transfer coefficient hr (W.m^{-2}.K^{-1}) and the partial water vapor pressure of ambient air Pa (mmHg). To calculate hr require specific data of human activity (in this case, walking) not include the clothing temperature, and to input Tmrt values in degrees Celsius along with the relative humidity (Rh).

The converted Pa value from mmHG to kPa use the following equation by Atkins and Thompson (2000):

$$Pa\ (kPa) = Pa\ (mmHg)*0.1333 \qquad (3)$$

Where f_{pd}, the permeation efficiency factor of clothing is taken from Parson (1993) formula:

$$f_{pd} = 1/[1+(0.344 \times h_c \times I_{cle})] \qquad (4)$$

Where h_c is the convective heat transfer coefficient (W.m^{-2}.K^{-1}), and I_{cle} is the effective clothing insulation (clo units) (parson, 1993).

Effective clothing insulation (I_{cle}) is taken from McIntyre (1980);

$$I_{cle}\ (clo\ units) = I_d - \left[\frac{(f_{cl}-1)}{0.155 \times f_d \times h}\right] \qquad (5)$$

Where I_d is the intrinsic clothing insulation (m^2.°C.W^{-1}), f_{cl} is the clothing area factor (ND), and h is combined heat transfer coefficient (W.m^{-2}.K^{-1}) (McIntyre, 1980). The I_d is determined from the standard clothing values from a variety of sources, including ASHRAE 55P table.

Clothing area factor (f_{cl}) (Parson, 1993), as follows:

$$f_{cl} = 1 + \left[0.31 \times \left(\frac{I_{cl}}{0.1555}\right)\right] \qquad (6)$$

Where I_{cl} is the intrinsic clothing insulation (m^2.°C.W^{-1}) (Parson, 1993). I_{cl} values is determined from values given in the literature.

h_c (Convective heat transfer coefficient) is taken from (Kerslake, 1972), as follows:

$$h_c\ (W.m^{-2}.K^{-1}) = 8.3 \times (v_a^{0.6}) \qquad (7)$$

Where v_a is air velocity in m.s^{-1} (Kerslake, 1972).

Calculation of evaporative heat transfer coefficient (h_e) is taken from Kerslake (1972), as follows:

$$h_e\ (W.m^{-2}.K^{-1}) = h_c*16.5 \quad (8)$$

Calculation of Combined heat transfer coefficient (h) is taken from Parson (1993), as follows:

$$h(W.m^{-2}.K^{-1}) = h_c+h_r \quad (9)$$

Where h_c is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$), and h_r is radiative heat transfer coefficient

Calculation of h_r as follows (Parson, 1993):

$$h_r(W.m^{-2}.K^{-1}) = 4.E.s.A_1\,A_{d.}\ ((273.2 + ((\frac{T_{cl}+T_{mrt}}{2}))^3) \quad (10)$$

Where E is the emissivity of the skin surface (0.98: Gonzales, 1995, p.299), s is Stefan-Boltzmann constant (5.67×10^{-8} $W.m^{-2}.K^{-4}$), A_1A_d = ratio of the area of the body exposed to radiation versus total body surface area (0.70 for seated postures, 0.73 for standing postures), T_{cl} is mean surface temperature of the body, and T_{mrt} is mean radiant temperature.

Calculation of saturated water vapor pressure at skin surface is taken from Fanger (1970), as follows:

$$P_s\ (mmHg)=1.92 \times T_{sk} - 25.3 \quad (11)$$

Where T_{st} is skin temperature in degrees Celsius (Fanger, 1970). This calculation of skin temperature is valid for skin temperature between 27 and 37 °C (Atkins &Thompson, 2000). Transient values of skin temperature are provided by de Dear's calculator. Some of the values are constant while others change depending on environmental and physiological variables. Clothing area factor (f_{cl}) is directly change based on the clo values which derived from literature, in this case clo clause use typical tropical business clothing, 0.49. The clothing variables (f_{pcl}) and I_{Cl} are changed along with altered in heat transfer coefficient and/or clo value. P_s changes along with altered skin temperature of the subject.

It is important to calculate q_{emax} value in minute-by-minute in order to calculate skin wittedness at the same resolution as skin temperature values (t_{sk}) provided by de Dear's calculator.

As mentioned by Gagge, Fobelets and Berglund (1986), Hartog and Havenith (2009), 0.3 of wettedness is the limit condition of thermal comfort in the whole body. Whilst Djongyang, Tschinda and Njomo (2010) mentioned that thermal discomfort would progressively increase when the value of whiteness reaches 0.3-0.05. An offering by Havenith, Holmer and Parsons (2002) the comfortable of walking comfort based on skin wettedness is reliant on activity level when w is less than 0.0012 M (metabolic rate) + 0.15.

3.4 Step-by-step walking comfort simulation

Matt deVau (2011) made simple to calculate walking comfort. He shows step-by-step how to simulate walking comfort, as follows:

1. Identify the study area and the time of year to collect the information of weather data.
2. Determined the four climate-based biometeorology inputs: use average field measurement to determine air temperature, relative humidity, and wind velocity on a typical day for three times of day – 7 am, 1 pm, and 5 pm. Used Rayman software to determine the mean radiant temperature (T_{mrt}) value for three sample urban environments, shaded area, light shaded and unshaded area.
3. Used the established values in literature to determine the two behavioral biometeorology inputs, i.e.: clothing value (clo) for typical tropical business clothing for male, and metabolic rate for individual walking at speed 1.34 $m.s^{-1}$, or 80.4 meters per minute.
4. Identify the case study and determined the body surface area of the model, in this case, the model is Indonesian male.
5. Used de Dear's Human Heat Balance calculator to calculate skin temperature (T_{sk}) and evaporative heat loss through regulatory sweating (q_{sw}) minute-by-minute for every combination of urban environment and time of day.
6. Used the partitional calorimetry spreadsheet (Atkins & Thompson, 2000) to calculate the maximal evaporative capacity of the environment (q_{emax}) for every combination of urban environment and time of day. The partial water vapor pressure of ambient air (P_a) is calculated using the Visual basic interface in EnvironTab of the spreadsheet.

The saturated water vapor pressure of skin surface (P_s) is determined from skin temperature (T_{sk}) values calculated by de Dear's calculator. All other calculation are made using equation 2-11.

Calculation skin wittedness (w) of the model in every environment, and the combination of time using equation 1 and q_{sw} and climax values determine from above methods. The values are calculated for each minute of the 30 minute period, and then every minute result values

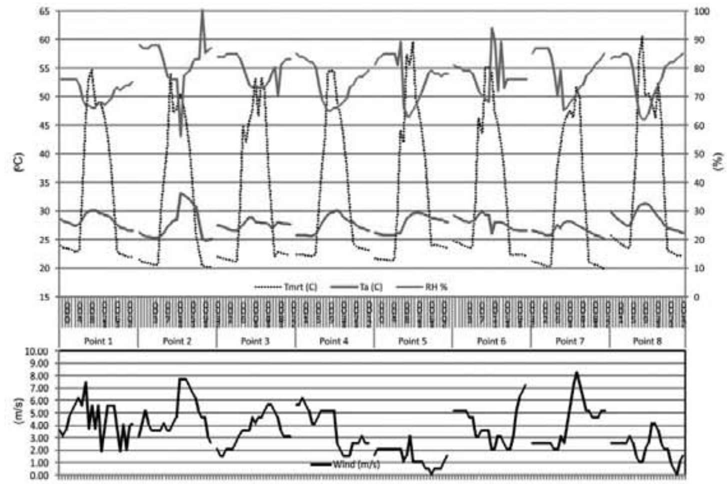


Figure 8. Graphic of Tmrt, Ta, RH and Wind speed measurement data obtained from 8 points on 2 February.

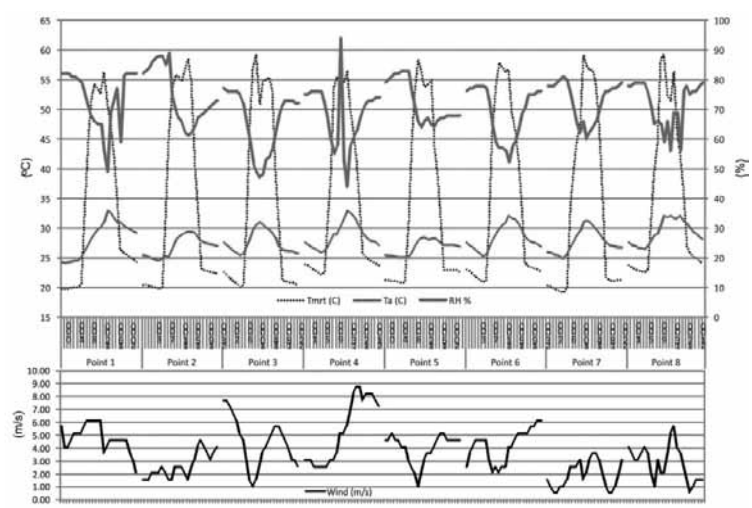


Figure 9. Graphic of Tmrt, Ta, RH and Wind speed measurement obtained from 8 points on 10 October.

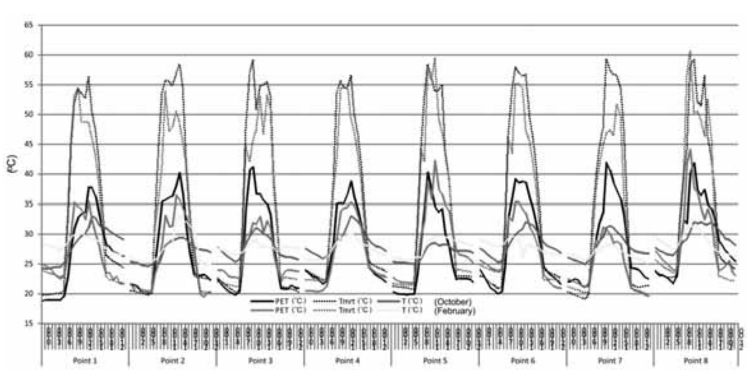


Figure 10. PET result on February and October.

are compared with 0.3 wettedness values, which is the required value of comfort condition by (Gagge, Fobelets & Berglund, 1969, pp. 270-290); and 0.5 as the thermal comfort limitation by (Havenith, Holmer & Parsons, 2002, pp. 23-38).

3.5 Walking Comfort model of Indonesian People

This research simulates an average of Indonesian people which met on site, i.e. male; tall 170 cm; and weights 70 kg, Clo (Clothing value) is 0.49 (typical tropical business cloth, trouser short-sleeved shirt) for all simulations, and activity (metabolic rate) is walking/light activity (150w/m^2) equals to 134 ms^{-1} according to de Dear's calculator. Use the data assumed by average Indonesian people and the variability of weather data, the distance of walking comfort in the superblock's open space can be calculated.

The surface area of the subject is calculated using the formula as follows (Atkins & Thompson, 2000):

$$\textit{surface area } (m^2) = 0.00718 \times \textit{weight}^{0.425}\ \textit{height}^{0.725} \qquad (12)$$

The result of surface area of the average Indonesian male is 1.81 m^2.

To provide an accurate assessment of climate effect on walking comfort, it was important to select the hours when people typically travel during the day in which weather condition were the most extreme.

Three observation times were selected in this research are 7 am, 13 pm, and 5 pm. These times reflected typical times of morning and evening commutes, and time close to the midday when the radiation is the highest, according to the field measurement shown in Figure 8 and Figure 9.

4. Results and discussion

4.1 Thermal Comfort

Figure 10 shows all points measured were uncomfortable either in the dry season in October or in rainy season in February. During the daytime, the PET values of measurement of 8 points are uncomfortable, started at 9 am PET values tend to be in a slight warm situation, 32 °C, and reach its peak value at 1 pm, 40 °C.

The Tmrt value has begun to rise since 9 am and reached its peak at 1 pm. Tmrt value was rapidly rising due to the ambient temperature at night time still remain high, 24 °C. The wind velocity were not strong enough to drive away the hot air around the areas at the night time. Meanwhile the humidity was still high as well.

Point 7 shows the significant difference PET value in October and February, the location of point 7 is located the open space area where on the north side of the area is the highway road and a row of high density commercial buildings, south and east side is open space, west side is sparse density commercial buildings. In October the PET value of point 7 reached 42 °C at the peak point at 1 pm and 31 °C in February at the peak point at 12 am. Wind speed in October tends to be low and come from the northeast side that carries the heat from the highway road and a row of high-density commercial buildings (see Figure 2). Meanwhile, in February wind speed is high, 5 ms^{-1} average, carrying cold air tends to come from West South where the buildings are rarer and has many parks (see Figure 2).

According to the overall evaluation of the thermal condition of the selected areas showed PET value of open space and the spaces amongst buildings is not significantly different, as shown at point 2, 3, 4, 7, and 8 and point 1, 5, and 6. Point 1, 5, and 6 show that the temperature during the night time trapped between the buildings, but in the day time the advantage of this point is the buildings can block the sun's radiation through that area, accordingly the temperature at that point is not significantly rose in the daytime. But the wind speed at that point is less than at open space. The solar radiation directly made open space fast to be hot, the advantage of open space is the wind speed is higher than the space amongst buildings.

The findings also illustrate that the use of natural and artificial shading lead to reduction of PET values of area of protection from direct solar radiation. Shading is the important characteristic that leads to a moderate reduction in Ta value while Tmrt value is strongly reduced. Accordingly, the shaded area that is covered by buildings and vegetation show tends to be slightly cooler than the others areas due to their lower exposures from the direct solar radiation. Hence, the high shading level is needed in outdoor environments to increase thermal comfort and extend the stability of the acceptable thermal condition during the day.

Overall measurement and analysis of the thermal comfort condition showed that an acceptable range of thermal comfort (<34 °C) only happened during the early morning (7-10 am) and late afternoon (4-5 pm). At the location with a high level shading area the duration of thermal comfort can be accepted more than 5 hours in the morning (7-12 am). The research also found that almost 6 hours a day, from 11 am – 4 pm is considered having the uncomfortable condition due to the high amount of solar radiation.

PET mostly affected by the Tmrt rather than by Ta. It can be proved during the measurement of ambient temperature (Ta) show very small differences between the selected areas (with maximum value 4 °C) whereas the PET values show significantly different between the selected location (with maximum values of about 15 °C). The results show the same result with previous studies (Mayer et al., 2008; Ali-Toudert & Mayer, 2007) that indicated air temperature alone is not significantly affect the thermal comfort in an outdoor environment. The stronger affect the thermal comfort values are radiant temperature than air temperature in an outdoor environment. It also should be noted that, air velocity can decrease the PET values although, solar radiation is more the important key factor calculating thermal comfort index (PET).

4.2 Walking comfort

The walking comfort was calculated in 3 different times; (1) in the morning at 7 am; (2) in the highest value of Tmrt at 1 pm; (3) and in the evening at 5 pm. The simulation data use the subject of Indonesia male 1.70 m height, 70 kg weight (surface area of the body 1.81 m^2 according to formulae 2), wearing common clothing with Clo value is 0.5 and walking is the activity in the simulation (the metabolic rate is 150 W/m^2). The Tmrt, temperature, relative humidity, and wind speed used the data, which are combined with the data of environment treatment, and time is shown in Table 2.

	Shaded Area				Light Shaded				Open Area			
	Tmrt °C	Ta °C	RH %	v m/s	Tmrt °C	Ta °C	RH %	v m/s	Tmrt °C	Ta °C	RH %	v m/s
7 am	30.5	23.9	85	4.2	58.7	24.1	96	0.5	57.1	22.9	97	0.7
1 pm	57.7	30.7	63	1.7	62.9	27.9	81	0.2	61.8	30.6	85	1
5 pm	50.7	28.9	72	1	60.7	29	79	0.7	58.9	30.4	75	0.9

Table 2. Climate data, which are used in walking, comfort simulation.

7 am walking distance threshold values			
	Minutes where w < 0.33	Approximate walking distance in "comfort" w < 0.33 (m)	w value at 5 minutes
Shaded Area	13	1045.2	0.252748357
Light Shaded	4	321.6	0.349315888
Open Area	4	321.6	0.351612304
1 pm walking distance threshold values			
Shaded Area	6	482.4	0.285632914
Light Shaded	4	321.6	0.335885597
Open Area	3	241.2	0.39096984
5 pm walking distance threshold values			
Shaded Area	5	402	0.285632914
Light Shaded	4	321.6	0.327659274
Open Area	4	321.6	0.322438126

Table 3. The result of Walkability simulation (w = skin wettedness).

The result of walking comfort simulation shown in Table 3. The shortest distance of walking in this simulation is found at 1 am, where the people walk in the Open Area with the mileage of people can walk before they feel uncomfortable is 241.2 m (3 minutes).

In the morning time (7 am), people can walk more than 1 km in the shaded area before they feel discomfort. Meanwhile, in the light shaded and open space, in the morning, the distance people could walk is similar, about 320 m.

At 5 pm people could walk no more than 405 m, they feel uncomfortable after 5 minute walking. In the term of climate in the hot-humid tropical country like Jakarta, all day is almost similar, the significant differences are the temperature and the Tmrt see Table 2. The average mileage of people could walk in the tropic is 482 m in shaded area, 321 m in Light shaded area, and 241 m in open area in the daytime.

Shading area is the main factor make the walking more comfortable, all the shaded areas in every hour simulation show the longest distance of walking. Meanwhile the light shaded area and open space almost have the same result.

The calculation of the skin wettedness shows that the relative humidity and the wind speed are the significant factor affect the walking distance. The relative humidity and wind speed can affect the heat evaporation in the body (Eves et al., 2008; Murakami, Ooka, Mochida, Yoshida & Kim, 1999, pp. 57-81).

5. Conclusions

This paper shows the result of the climate challenges creating thermal comfort and walking comfort in Jakarta, and provides the methodology for calculating the thermal comfort and simulating walking comfort through skin wittedness in hot humid outdoor environment. In the tropical hot-humid climate, outdoor spaces are used during the year, and they must provide proper levels of thermal comfort and walking comfort. Based on this paper finding, it established the new walking comfort distance in hot humid city like Jakarta, a four minutes walking distance or 321 m average. This walking distance is important to be known by the planner or architect when they design to place the facilities in the urban.

PET and skin wettedness can be used as tools to help urban designers and architects before making design decisions. The simulation and the result from the field measurement are important information related to the climate and outdoor urban environment design. In conclusion, the results present the thermal condition of open spaces together with walking comfort can be integrated in design guidelines to enhance the quality of livable and walkable outdoor spaces for human life in the hot humid tropical areas.

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