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PAIR INFLUENCE OF WIND SPEED AND MEAN RADIANT TEMPERATURE ON OUTDOOR THERMAL COMFORT OF HUMID TROPICAL ENVIRONMENT

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Abstract: The purposes of this article is to explore knowledge of outdoor thermal comfort in humid tropical environment for urban activities especially for people in walking activity, and those who stationary/seated with moderate action. It will be characterized the pair influence of wind speed and radiant temperature on the outdoor thermal comfort. Many of researchers stated that those two microclimate variables give significant role on outdoor thermal comfort in tropical humid area. Outdoor Tropical Comfort (OTC) model was used for simulation in this study. The model output is comfort scale that refers on ASHRAE definition. The model consists of two regression equations with variables of air temperature, globe temperature, wind speed, humidity and body posture, for two types of activity: walking and seated. From the results it can be stated that there is significant role of wind speed to reduce mean radiant temperature and globe temperature, when the velocity is elevated from 0.5 m/s to 2 m/s. However, the wind has not play significant role when the speed is changed from 2 m/s to 3.5 m/s. The results of the study may inspire us to implement effectiveness of electrical-fan equipment for outdoor space in order to get optimum wind speed, coupled with optimum design of shading devices to minimize radiant temperature for thermal comfort.

Keywords: Thermal-comfort; tropical-humid; urban-outdoor

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INTRODUCTION

The success of open space architecture and urban design of the cities are determined partly by the creation of the thermal comfort environment of outdoor spaces perceived by the users. Hence, climatic architecture of outdoor space should also be developed towards the need of thermal comfort in outdoor area. The green city’s principles give examples how outdoor space has to be comfortable for people’s activities in urban areas. Outdoor spaces (public open space/ pedestrian/ playground) are also areas for socializing among the different communities. The spaces require comfortable condition to support the success of such people meeting (Sangkertadi & Syafriny, 2014; Sharmin & Steemers, 2013; Sangkertadi *et al.*, 2009; Syafriny & Sangkertadi, 2010; Prijadi *et al.*, 2014)

Nowadays, climatology, thermal comfort, and walkability have already become the main issues of some researches in an urban context in the term of to make urban area to be convenience to live in. The people' awareness of open space and green area is emergent in order to provide opportunities for people interaction, physical exercise and leisure especially for the children and the elderly (Koerniawan & Gao, 2014). The issues of city climate and global warming are actually become to be the community issues. People become more interested with the topic of thermal comfort and microclimate.

The need of thermal comfort at outdoor was also discussed broadly, since an increase of air temperature and humidity in urban areas. The increase of world surface temperature is actually the impact of global warming due to human activities as effect of urbanization as well change of land use (Coltri *et al.*, 2008). Many sources show information that nowadays more than 50% of the world population is living in urban areas. This is of the reasons that focus on greenery cities is more attractive in the recent times.

In tropical and humid area, highly value of radiant temperature and humidity are contributed by intensity of solar radiation and rain penetration. This hot and humid climate may cause feel uncomfortable for the people during the day and may produce sweat rate significantly especially in the hot-months season. In this climate, at noon people avoids receive direct sunlight that touch the body. High solar radiation that produces high radiant temperature may sting skin body of human and cause uncomfortable thermally. In this situation the sweat may be evaporated by the aid of wind flow with certain velocity and pressure and that touch the skin of body. There is significant effect of wind speed on human comfort for walking activities in open space (Arens & Ballanti, 1997). From the view point of comfort walkability in outdoor space, wind speed is also the significant factor that affect the walking distance by means of skin evaporative comfort (Koerniawan & Gao, 2014).

At outdoor area, especially in tropical regions, direct solar radiation and surface temperature of urban elements (material of streets, pedestrians, buildings envelop, and other surfaces of urban furniture) may affect significantly the average of radiant temperatures and may reach a value that much higher than the air temperature. This could lead us to put hypothesis that the mean radiant temperature contributes as the most sensitive micro climate component of human activities in humid tropical region.

Moreover, the radiant temperature is not only affect the thermal comfort in open space but also affect the walkability (Koerniawan & Gao, 2014). In tropical humid regions, implementation of trees and other vegetation scheme are strategies in order to minimize mean radiant temperature and to control air velocity for cooling effect. The tree shades sustained the microclimate of the park; lower the air temperature controls the thermal comfort and maintained the wind flow. It was also showed that by implemented of extra trees, the mean radiant temperature of a site may lower with difference up to 20 ^{0}C compare to the site that apply ground cover only (Nasir *et al.*, 2015).

The definition of thermal comfort is a condition or feeling of satisfaction of the human face thermal environment as benchmarks to determine the physical comfort are the changes that occur in a person's biological characteristics (Fanger, 1970). That is a biological response to sensorial state or the surrounding thermal environment. Ability to maintain thermal equilibrium between the human body with the surrounding environment is one of the prerequisites of health compliance, as well as comfort.

Researches on modeling the thermal comfort calculations for outdoor space, especially in the case of humid tropical climate are still relatively rare, mostly more interested for the cases of indoor space. If anything, the models are based on empirical studies of outdoor space in cold, temperate and sub-tropical climate areas, which were generally based on field studies in cities in America, Europe, Japan, China, and Australia. Those researches carried out for example by Huang (2007), Matzarakis *et al.* (2003), Nikolopoulou *et al.* (2008), Scudo & Dessi (2006), Spagnolo & de Dear (2003), Monteiro & Alucci (2009), Nicol *et al.* (2006), Cheng & Ng (2008) etc. Thermal comfort calculation model that be generated through a number of studies by those researchers may not be necessarily appropriate to be applied in cases of humid tropical climate, because of possible differences in the perception of comfort by people in different geographical habitation.

Some of the researchers on outdoor thermal comfort, proposed regression equations as contribution in modeling calculation of scale of outdoor thermal comfort. The regression equation is mostly functions of climate variables such are solar radiation, air temperature, air humidity, wind speed, and radiant temperature.

Authors have developed correlation-model for estimating outdoor thermal comfort in tropical-humid climate, by means of field research in period 2011 to 2012 (Sangkertadi & Syafriny, 2014, 2012), Sangkertadi (2014). The model is now declared as OTC (Outdoor Tropical Comfort). The output is comfort scale for adult people wearing tropical cloth (0.5 to 0.7 clo) in walking activity with normal speed as well as for seated people with a moderate work. The two equations of the regression model are as follow:

$$OTC_w = 0.04\,T_a + 0.08\,T_g - 0.01\,RH - 0.36\,v + 0.96\,A_{DU} - 3.4 \quad (1)$$

$$OTC_S = 0.0468\,T_a + 0.1673\,T_g - 0.0007RH - 0.5215\,v + 1.4329\,A_{DU} - 7.9122 \quad (2)$$

where: OTC_w : comfort scale for walking people with normal speed, OTC_S : comfort scale for seated people with moderate activity, Ta : air temperature (°C), Tg: globe temperature (°C), RH : relative humidity (%), v: wind velocity (m/s), and A_{DU}: area of body skin (m^2).

Interpretative description of the value of OTC to the feel comfort perception refer to ASHRAE comfort scale, ISO 7730 (2003) and the PMV (Fanger, 1970), as described in **Table.1**

METHODOLOGY

In principle, the study applied model correlation OTC (**Eq. 1 and 2**) where the term of radiant temperature (*Tmrt*) is to be represented by globe temperature (*Tg*). The Mean Radiant Temperature (*Tmrt*) is defined as the 'uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure'(definition from ASHRAE, 2004). By approximation, the *Tmrt* and *Tg* can be estimated. There is procedure of calculation to determine *Tmrt* and *Tg* as is shown in **Fig.1**, and as expressed through equations (3a) to (3i) (Dimiceli *et al.*, 2011; Huang, 2007). As is shown as well, that there is influence of wind velocity to the values of globe temperature (*Tg*) and mean radiant temperature (*Tmrt*). Application of OTC model (**Fig. 1**) depend only common microclimate data such are: air temperature, wind speed and humidity that can be found by simple measurement or from the documents of meteorological stations.

Table.1. Description of OTC

Value (rounded) of OTC	Comfort perception
-1	Cool
0	Comfort/ Neutral
1	Warm/ Slightly Uncomfort
2	Hot / Uncomfort
3	very hot/ Very Uncomfort
4 and greater	very very Hot/ very very uncomfort (sense of sick)

Through this study, it would be known the role of wind velocity to reduce *Tg* and *Tmrt*, and how important of its impact on outdoor thermal comfort consequently. There were 7 values of wind speed that have been evaluated: 0.5, 1, 1.5, 2, 2.5, 3.0 and 3.5 m/s. **Figure 3** shows the flowchart of the simulation of the study. Climatic data of Manado city in Indonesia was applied for the simulation. The city is sited on 1.5 deg. of North Hemisphere, and characterized by humid tropical climate. Meteorological data of the city on July was collected and compiled for inputs of the simulation. The data consists of air temperature, humidity, and sky-cloudy.

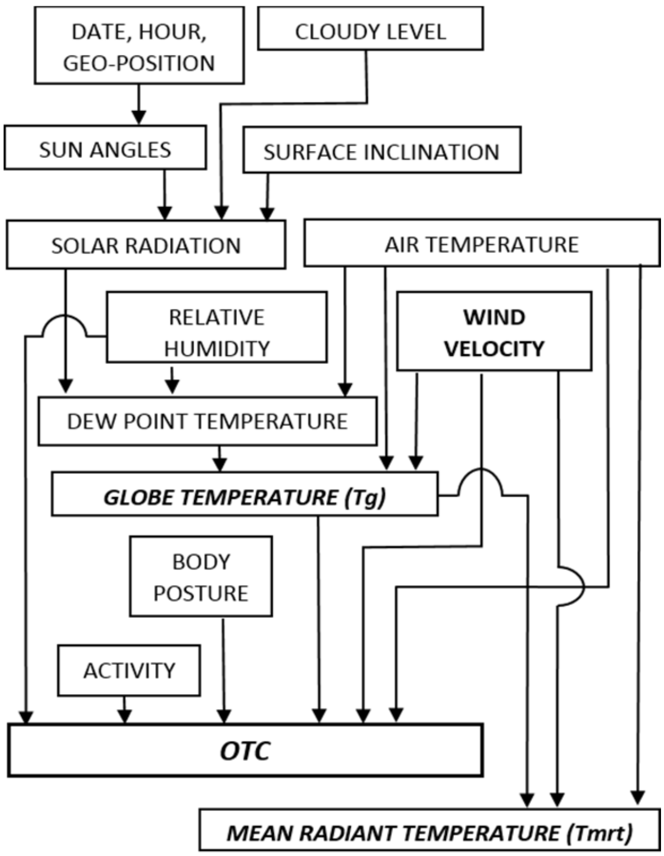

Fig. 1. Structure Model of OTC and Flowchart for estimation of T_g and T_{mrt}

Figures 2–3 show illustration of the simulation of the study in which hourly calculations were realized, with considering a one day of sun path of July that represent hot season in tropical area.

In this study, sun-shadow devices were neglected, then the situation is as at spaces under fully open sky and receive direct solar radiation without any obstacles and louvres. The sky view factor (SVF) is then to be assumed as 100%. This is to know how the wind-speed can play role in such situation to support outdoor thermal comfort. Value of solar radiation vary follows the time, and implicate changes mean radiant temperature and globe temperature. In this study air temperature and relative humidity were set following meteorological data in hourly. The human body that was applied for the simulation was typical Indonesian adult with skin surface area (A_{DU} = Area of Du Bois) of 1.7 m².

Since the meteorological data such are air temperature, solar radiation, humidity and wind speed are available, then the globe temperature (Tg) can be calculated by using equations as mentioned in equations 3a to 3e (Dimiceli *et al.*, 2011; Huang, 2007):

$$T_g = \frac{B + C\,T_a + 7680000}{C + 256000} \tag{3a}$$

where:

$$C = \frac{h\,v^{0.58}}{5.3865 \times 10^{-8}} \tag{3b}$$

$$B = S\left(\frac{f_{db}}{4\sigma\cos(z)} + \frac{1.2}{\sigma}f_{dif}\right) + \varepsilon_a\,T_a^4 \tag{3c}$$

$$\varepsilon_a = 0.575\,e_a^{(1/7)} \tag{3d}$$

and

$$e_a = \exp\left(\frac{17.67(T_d - T_a)}{T_d + 243.5}\right) \times (1.0007 + 0.00000346\,P) \times 6.112\exp\left(\frac{17.502\,T_a}{240.97 + T_a}\right) \tag{3e}$$

To calculate Td (dew point temperature), it can be used simple equation from Snyder (1984):

$$T_d = \frac{237.3 \times Z}{(1 - Z)} \tag{3f}$$

where:

$$Z = \frac{\left[\ln\frac{HR}{100} + \left(\frac{17.27 \times T_a}{237.3 + T_a}\right)\right]}{17.27} \tag{3g}$$

Mean radian temperature (T_{mrt}) can be calculated by using following equation from Huang (2007):

$$T_{mrt} = T_g + 0.237 \times v^{0.5} \times (T_g - T_a) \tag{3h}$$

Or by equation refer to ISO 7726 (Cheng & Ng, 2008; Sangkertadi & Syafriny, 2014):

$$T_{mrt} = \left\{(T_g + 273)^4 + \left[\frac{(1.1 \times 10^8 \times v^{0.6})}{(\varepsilon_g \times D^{0.4})}\right] \times (T_g - T_a)\right\}^{1/4} - 273 \tag{3i}$$

where ε_g is globe's emissivity and D is the diameter of globe thermometer.

RESULTS AND DISCUSSION

At first, the solar radiation has to be calculated for case of July 15th from 7 am to 5 pm at location of Manado city, Indonesia (1.5° N Lat, and 115° E). The method for estimating solar radiation for horizontal and tilt surfaces refer to common method and can be found in literatures of architectural sciences or building physics, such from Szokolay (1980) and Bernard *et al.* (1979). Other values of urban microclimate those are air temperatures, humidity and cloudy factor, were given from meteorological data of Manado city (average values of 15 July 2005 to 2010). Calculation results of global solar radiation on a horizontal surface show that that maximum value may reach almost 800 W/m² at noon, as is shown in **Fig. 4** and **Table 2**.

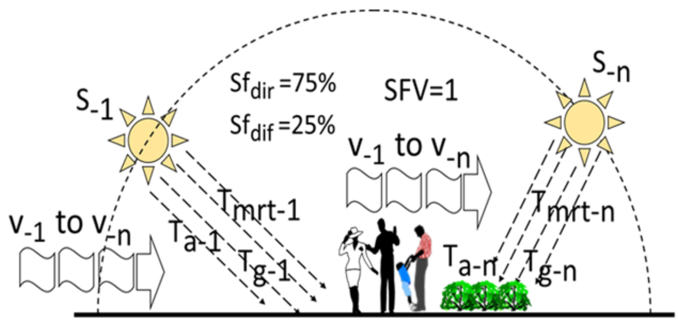

Fig. 2. Illustration of simulation principle of the study (without existence of shadow devices). Sun path from 7.00 (7 am) to 17.00 (5 pm). 'n=7 to 17'.

Table 2. Microclimate variables for input of calculation

Hour	From Meteorological Data		By Calculation
	RH (%)	Ta (°C)	S (W/m²)
7	57	27.5	113
8	56	28	305
9	55	30.2	489
10	51	31	635
11	52	31.5	728
12	51	31.2	761
13	52	31.9	728
14	52	31	635
15	56	28.4	488
16	59	27.1	305
17	59	27.3	113

The results solar radiation were then as input for the calculation of *Tg* and *Tmrt.* The trend-lines of *Tmr*t and *Tg* would be similar to the trend-lines of solar radiation, due to significant influence of solar radiation to radiant temperature.

By entering the variation values of wind speed and other micro-climate data into the **Eqs (3)** to **(5)**, it can be generated values of *Tg* and *Tmrt* from 7.00 (morning) to 17.00 (afternoon) as tabulated in Tables 3,4.and presented in **Figures 5–6**. As it is shown by those figures that with a very low of wind speed, 0.5 m/s, *Tmrt* may reach a highly value that exceed 100°C. at noon with SVF (Sky View Factor) equal to 100%. A study of Tania Sharmin and Koen Steemers (Sharmin and Steemers, 2013) was also found similar situation, where *Tmrt* in a warm humid climate of Dhaka city, Bangladesh - may reach about 90°C. at noon. Another study in tropical humid city found that *Tmrt* may reach of 70°C with SVF of about 60% (Paramita & Fukuda, 2014).

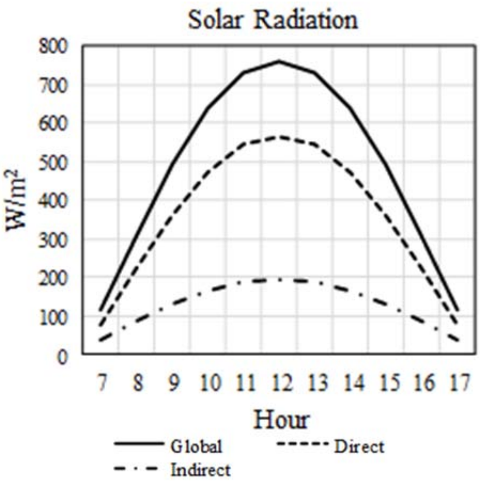

Fig. 4 Solar radiation on horizontal surface.

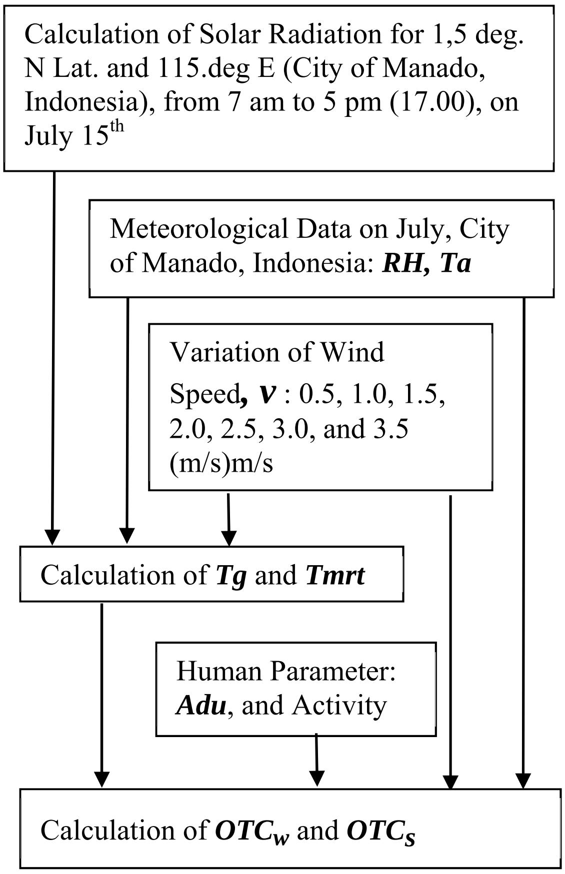

Fig. 3. Flowchart of methodology

It was shown that the wind-speed plays significant role in this case. It was found when wind speed was elevated from 0.5 to 1 m/s there was a significant change of *Trm*, where the *Tmrt* may decrease more than 30% (from 106°C to 68°C, at noon). Otherwise when wind speed change from 1 to 2 m/s, the *Trm* may still

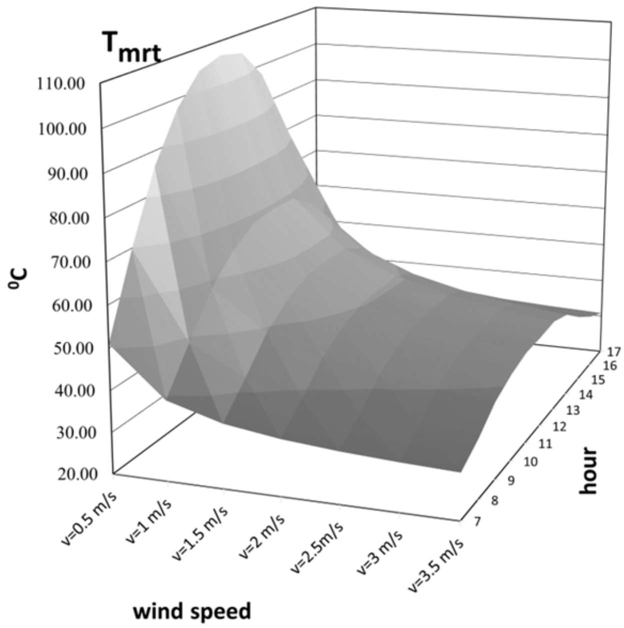

Fig. 5a. Three dimensional curve of *Tmrt.*

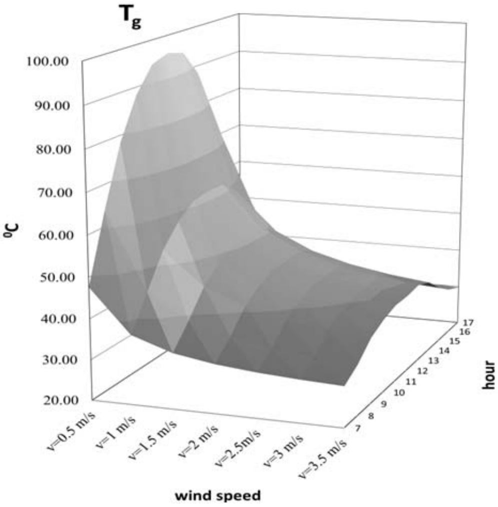

Fig. 5b Three dimensional curve of T_g.

decrease of about 25%. In the next simulation it was shown that the change of wind speed from 2 to 3.5 m/s, was not affect to lower T_{mrt} and T_g significantly, it is only make decrease of about 10%. It is shown in **Fig. 5**, that the decrease-line of T_{rm} as function of wind speed is characterized as a power-law line or logarithmic curve. This is due to the exponential equations in the sequence of calculation. From those results in can be stated that there is significant role of wind speed to reduce T_{mrt} and T_g, when the speed was elevated from 0.5 m/s to 2 m/s. However, the wind has not play a significant role when the speed is changed from 2 m/s to 3.5 m/s.

Calculations of thermal comfort by using OTC equations (**Eqs 1–2**) give results that wind speed play also important role in increasing feel of thermal comfort both for seated people and walking activity, as is shown in **Fig.7** and **Table 5**. The trend-lines of OTC are found similar to the trend-lines of T_{mrt} and T_g, and it indicates that there is also significant influence of radiant temperature on outdoor comfort. **Table 5** presents the results which are more detail for cases of early morning from hour 7.00 to 9.00 am.

As shown in **Fig. 7** and **Table 6**, it was found that there are many of uncomfortable situations during the day at outdoor space under open-sky of tropical climate, especially when the wind speed was low. In case of people in walking activity, it is indicated that the role of mean radiant temperature is more dominant than the influence of wind speed. Almost during the early morning, the role of wind speed is not significant to elevate comfort scale for people in walking activity.

Based on those results, in practice, urban design of pedestrian area in tropical humid regions is heavily suggested to be equipped with architectural devices to avoid highly mean radiant temperature, so that the mean radiant temperature may not exceed 35°C with wind speed of environment is about 1 m/s (condition of still air).

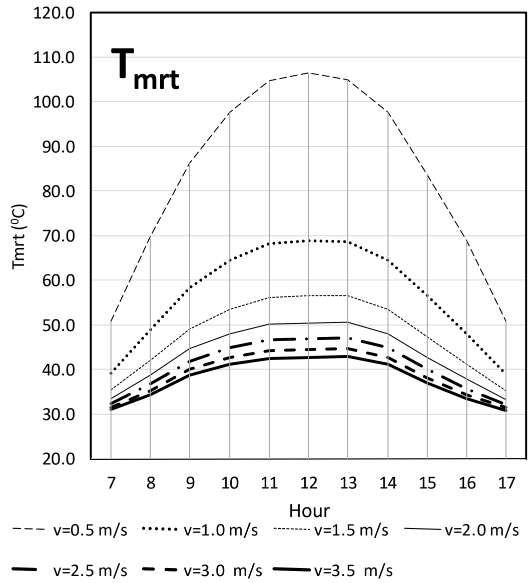

Fig. 6a Curves of T_{mrt} as function of time and wind-speed.

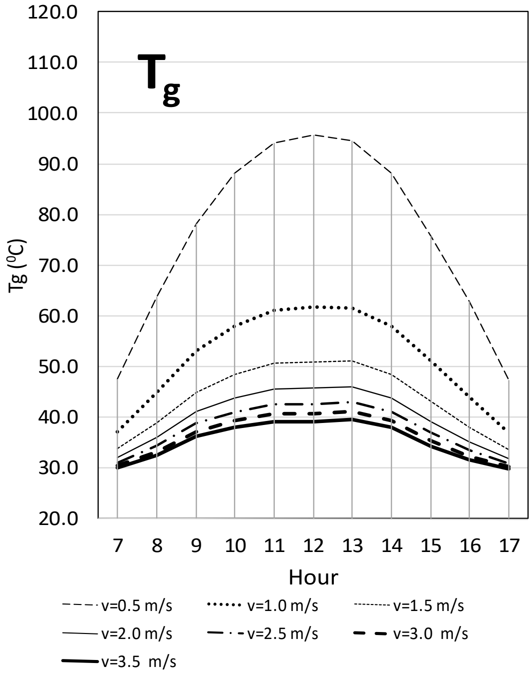

Fig. 6b. Curves of *Tg* as function of time and wind speed.

Table 3. Values of *Tg* by calculation (v=0.1 to 1.5 m/s)

Hour	T_g (°C)		
	v = 0.5 m/s	v =1 m/s	v = 1.5 m/s
7	47.57	37.01	33.64
8	63.77	44.94	38.94
9	78.23	52.95	44.89
10	88.02	58.01	48.44
11	94.09	61.14	50.64
12	95.64	61.72	50.91
13	94.51	61.55	51.05
14	88.03	58.01	48.44
15	75.70	51.12	43.07
16	62.86	44.04	38.03
17	47.37	36.81	33.44

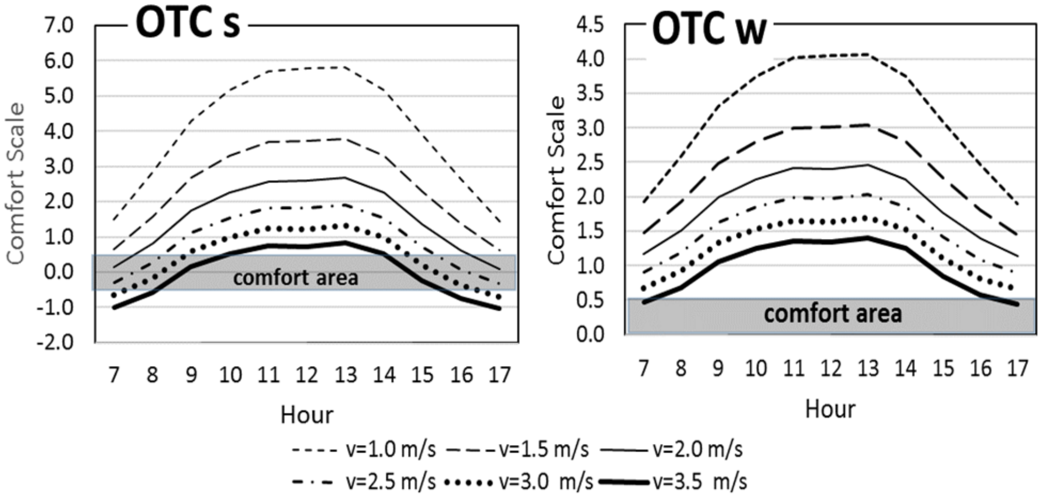

Fig. 7 (a) Curves of comfort scale by Outdoor Tropical Comfort for seated/stationary people, and (b) Curves of comfort scale by Outdoor Tropical Comfort for people in walking activity.

Table 4. Values of *Tmrt* by calculation (v=0.5 to 1.5 m/s)

Hour	T_{mrt} (°C)		
	v = 0.5 m/s	v =1 m/s	v = 1.5 m/s
7	50.94	39.26	35.42
8	69.77	48.96	42.11
9	86.28	58.34	49.15
10	97.58	64.41	53.50
11	104.58	68.17	56.19
12	106.44	68.95	56.63
13	105.00	68.58	56.60
14	97.58	64.41	53.50
15	83.63	56.51	47.33
16	68.85	48.05	41.21
17	50.74	39.06	35.22

Table 5. Results of simulation of thermal comfort (case at.7.00 am)

Time : 07.00 AM						
*)RH=	*)S=	*)Ta=	Comfort Scale and perception			
57%	113 W/m^2	27.5 ^{0}C				
other micro climate variables:						
v ***)	Tg **)	Tmrt **)	OTCs (Seated)		OTCw (Walking)	
(m/s)	(^{0}C)	(^{0}C)	scale	perception	scale	perception
0.5	47.6	50.9	3.5	very uncomfort	3.0	very uncomfort
1	37.0	39.3	1.5	slightly uncomfort	1.9	uncomfort
1.5	33.6	35.4	0.7	slightly uncomfort	1.5	slightly uncomfort
2	32.0	33.5	0.1	comfort	1.2	slightly uncomfort
2.5	31.0	32.4	-0.3	comfort	0.9	slightly uncomfort
3	30.4	31.6	-0.7	cool	0.7	slightly uncomfort
3.5	30.0	31.0	-1.0	cool	0.5	comfort

(*) from data meteorology; (**) by calculation; (***) adjustment

CONCLUSION

Through this paper it has been demonstrated and described the influence of wind speed and other microclimatic variables on outdoor thermal comfort in humid tropical area. The results of the simulations show five points of interest which could be underlined as general and specific conclusions:

(a) OTC (Outdoor Tropical Comfort) is one of alterative formulation for estimating outdoor thermal comfort in humid tropical regions. Simple applicability of OTC model, that is the model depends only common meteorological data, such are: air temperature, humidity, and sky-cloudy or solar radiation. The globe temperature (T_g) as another input into OTC model, can be approached by calculation using equations as were explained in this article.

(b) There is a significant contribution of wind speed to reduce T_{mrt} and T_g, when the speed is to be elevated from 0.5 m/s to 2 m/s and where existence of T_{mrt} and T_g are relatively high. However, the wind has not significantly role when the speed is changed from 2 m/s to 3.5 m/s.

(c) In outdoor space under a fully open sky in humid tropical environment, at day time, it is difficult to find comfortable situation, due to highly mean radiant temperature which is influenced by a highly solar radiation and surfaces characteristic.

(d) For practice application in urban area of tropical humid regions, it is suggested for pedestrian area to be equipped with architectural devices to avoid overheated, so that the mean radiant temperature may not exceed 35 ^{0}C with wind speed that touch the body is about 1 m/s.

Table 6. Results of simulation of thermal comfort (case at.9.00 am)

Time : 09.00 AM						
*)RH= 57%	*)S= 113 W/m^2	*)Ta= 27.5 ^{0}C	Comfort Scale and perception			
other micro climate variables:						
v ***)	Tg **)	Tmrt **)	OTCs (Seated)		OTCw (Walking)	
(m/s)	(^{0}C)	(^{0}C)	scale	perception	scale	perception
0.5	78.2	86.3	8.8	very very uncomfort	5.5	very very uncomfort
1	52.9	58.3	4.3	very very uncomfort	3.3	very uncomfort
1.5	44.9	49.2	2.7	very uncomfort	2.5	uncomfort
2	41.0	44.6	1.7	uncomfort	2.0	uncomfort
2.5	38.7	41.8	1.1	slightly uncomfort	1.6	uncomfort
3	37.2	40.0	0.6	slightly uncomfort	1.3	slightly uncomfort
3.5	36.1	38.7	0.1	comfort	1.1	slightly uncomfort

(*) from data meteorology; (**) by calculation; (***) adjustment

(e) The results of this study may inspire installation of effective coupled shading devices and outdoor electrical fan in order to reduce radiant temperature as well as to maintain optimum wind speed, for open space of urban area in humid tropical environment.

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