REGULAR ARTICLE

REDEFINING "DOMINATING" AND "CONTRIBUTING" PHYSICAL FACTORS OF INDOOR THERMAL COMFORT IN HOT-AND-HUMID CLIMATE OF MALAYSIA

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ABSTRACT

In many tropical countries, the cause of the thermal discomfort is mostly due to the presence of high humidity and high air temperature. Air movement, on the other hands, has been considered as the best method in improving the thermal comfort level for this region. Many researches had been conducted regarding the factors affecting thermal comfort for tropical countries and as a result several ideas had been introduced on how the factors affecting the thermal comfort. Most of the research conducted on thermal comfort for tropical countries combined two or more factors as a joint factor such as air temperature and humidity. With the combination of two or more factors (joint factors), the dominant factor among the main factors and how people react to each of these factors especially with the presence of other factors are still in question. The research explore on how people react to each of these three main factors which consequently provides the hierarchy of importance among the three factors. The paper exposes the 'dominating" factor which is the air temperature that must be presence at all time to affect thermal comfort. The humidity level and air movement are defined as 'contributing' factors rather than joint factors in affecting thermal comfort for tropical countries since the presence of both factors can only influence the thermal comfort level depending on the air temperature level.

Keywords: *: Thermal Comfort, humidity, air temperature, tropical countries air movement.*

1. INTRODUCTION

Thermal comfort in tropical countries has always been a great issue to discuss due to the extreme climatic factors existed in this type of climate especially the high air temperature and high humidity level. Based on the Psychrometric chart, the thermal comfort level is almost impossible to be achieved based on the presence of high air temperature and high humidity that occurred in many tropical countries(deDear and Auliciems, 1993). However, many field studies conducted in tropical countries showed that respondents were able to feel comfortable under certain circumstances. In many cases, the researchers found that the air movement can improve the indoor thermal comfort level. Each of these factors has its own influencing factors under certain circumstances and it varies based on the climate condition. Therefore, it is important for designers and architects to understand how these factors influence indoor thermal comfort to minimize the discomfort through design strategies that can be developed based on the level of importance of these factors.

2. BACKGROUND

The research on thermal comfort had started a long time ago and mostly in evaluating the thermal comfort level in many buildings especially housing. Along with the study, the researchers had also studied the factors affecting the thermal comfort for the tropical climate countries. One of the earlier research had been started by Webb in 1949 which led to the derivation of the Equatorial Climate Index (ECI). Based on the index, the ideal air velocity is 0.2 m/s with the relative humidity of 70% and the ideal temperature of

28.860 Celsius. Another study was conducted in 1978 which corrected the optimum ideal temperature to 26.4o Celsius. The study was conducted at the hawker centres in Singapore and found that the thermal comfort condition is affected by the combination effects of air temperature, relative humidity and roof thermal radiation (Rao and Ho, 1978). In 1990, Busch conducted a study on offices in Bangkok, Thailand. The neutral temperature or effective temperature for the air conditioned buildings and naturally ventilated building is 24.54o Celsius and 28.54o Celsius respectively.

Mallick (1996) in his investigation had also discovered that people are highly adaptive to the surrounding environment by changing the behavioural patterns and lifestyle preferences. The process of acclimatization also had a strong influence in the comfort preferences study. In his 1996 study involving a group of architectural students living in urban housing in Dhaka, Bangladesh, Mallick (1996) discovered that the participants were able to tolerate high relative humidity and temperature for comfort mainly due to the adaptation to the specific climate. The study also found that the estimated comfort temperature was between the range of 240 Celsius and 320 Celsius with the relative humidity between 50% and 90% under still-air condition and with the movement of air at 0.3 m/s, the range increased by 2.40 Celsius for the lower count and 2.20 Celsius for the upper limit. The air movement was a contributing factor in providing thermal comfort environment, on the other hand, according to this study, despite a wide range of recorded relative humidity which ranged from 50% to 95%, the humidity had little influence to the thermal comfort level due to the long term conditioning even though there is a decrease in comfort temperature when the humidity is higher (Mallick, 1996).

Wong and Khoo (2003) conducted a thermal comfort study in naturally ventilated classrooms in Singapore. The study discovered that the neutral temperature derived from the TSV is 28.80Celsius. Earlier studies conducted by Busch(1990) in Thailand and deDear and Auliciems (1993) in Singapore have also found that 28.50 Celsius is the neutral temperature for a naturally ventilated building. The readings obtained are quite close for the neutral temperature in the similar climate region. The study by Wong et al in 2002 in naturally ventilated public housing in Singapore revealed that there is a strong correlation between the thermal comfort perception and wind sensation.

In 2004, Feriadi and Wong conducted an investigation regarding the thermal comfort perception, evaluation of the thermal comfort prediction and the behavioural action that influence thermal comfort perception in naturally ventilated houses in Indonesia. The finding suggested that adaptive behaviour may influence the neutral temperature to be higher than it was supposed to, however, cooler temperature is still preferable, if possible. Earlier, Karyono(2000) conducted a field study on the thermal comfort, which samples are divided into various categories and groups, for a multi storey office building in Jakarta, Indonesia. The groups are categorized by gender, age, ethnic background and physical characteristics. The study concluded that it is statistically insignificant between the neutral temperature between male and female, subjects under 40 and over 40 years old and between different ethnic backgrounds as well as between thin and normal subjects. The study also revealed that the neutral temperature is increased in the late afternoon compared to the early morning by 30 Celsius.

The majority of the research conducted in tropical countries focuses on predicting the thermal comfort based on the neutral or comfort temperature for specific building types which include residential, offices and schools. The research had also investigated three main physical variables which are air temperature, relative humidity and air movement. They have been proven to tremendously affect the thermal comfort level. However, the interdependent of the variables in influencing thermal comfort for this region has not been investigated. Each of the factors is important but the determination of which factor is more dominant than the others is still unknown.

3. METHODOLOGY

The objective of the research is to acquire the perception of the users on the indoor thermal comfort condition of a naturally ventilated space and their preferences according to the condition experienced. To achieve this, prayer rooms from four naturally ventilated mosques are selected as the experimental spaces. The prayer hall was selected because of the activities conducted and the clothing value are less varied among the users of the space. This will minimize the influences of other thermal comfort factors to the results produced by the respondents. Focus can be given to the three main physical factors which are the air temperature, relative humidity and air movement. 529 respondents whom are randomly selected among the users of the spaces involved in the survey. The main objective of the study is to investigate the thermal comfort condition and the factors affecting the condition as well as other related issues. To obtain this information, two approaches have been chosen. They are the physical measurement of the main factors affecting the thermal comfort and the survey inquiring the perception of the users on the thermal comfort condition. Prior to the actual data collection, a set of questionnaire has been produced and a pilot study has been conducted to inquire the suitability and applicability of the questions and the methods. Adjustments and improvements have been made to the questionnaires to ensure that the questionnaires are clear and they cover the necessary information required for the study. Before proceeding to the data collection process, permission to sample the buildings is obtained from the authority. It is important to ensure that the activities conducted do not interfere with the activities and users inside the buildings. For the data collection, a set of questionnaires is distributed to the volunteered participants inside the space. The participants are randomly selected among the users. Before the questionnaire is distributed, a brief explanation on the survey objective is given. The time is recorded on the form when the participants start to answer the questionnaire and they are left to answer the questions which may take them about ten to fifteen minutes. The set of questionnaires has been carefully produced to allow the participants to evaluate and select the thermal sensation they experienced while in the space by marking the thermal sensation level based on ASHRAE 7-point scale and the Bedford scale as shown in Table 1. The ASHRAE 7-point scale is used to inquire about the thermal sensation and the Bedford scale is used to indicate the level of thermal comfort that the respondents have experienced while in the space.

Table 1: The ASHRAE 7 Thermal sensation scale and Bedford Scale

ASHRAE	**Scale**		**Bedford**
Too Hot	3	7	Much Too Warm
Hot	2	6	Too Warm
Warm	1	5	Comfortably warm
Normal	0	4	Comfortable
Cool	-1	3	Comfortably cool
Cold	-2	2	Too Cool
Too Cold	-3	1	Much Too Cool

Along with these questions, the participants are also asked about the sensation they experienced regarding the level of air movement, humidity level and their preferences to the existing condition. The air movement inside the space is rarely consistent at all time unless mechanical equipment is used. It is therefore difficult to specify the wind condition and the speed at the various space and time during the measurement. Therefore an assumption of wind speed is made to the speed of air felt or experienced by the users at the point of time they answer the question. For the purpose of this study, the wind condition is divided into four categories based on the previous studies which are calm (< 0. 5 m/s), breezy (between 0.5 m/s and 1.5 m/s), windy (between 1.5 -2.0m/s) and very windy (more than 2.0 m/s). The humidity level they experienced is measured by the level of sweating. It is difficult to sense the level of humidity with our bare skin. The only easy explanation to measure the existence of humidity in the air is through the level of sweat accumulation on the skin which is closely associated with the content of humidity in the air. Due to the fact that the air temperature for the country's climate is almost high and people tend to sweat at all time, the method selected for measuring the perception of the humidity level through the level of sweating is appropriate. Four scales are given which are dry, normal, sweating (humid) and heavy sweating (very humid). In addition, the participants are also asked to choose the condition they would like to be if they were given the chance to change the existing environment. They are provided with three options to change which are to reduce, unchanged or increase to the three physical environmental conditions which include air temperature, humidity level and air movement condition. The survey is only conducted during the specific time which is after each congregational prayer. Even though the mosques are open from as early as 5.00 am in the morning until 10.00 pm in the evening, the occupancy level is better during the congregational prayers. Depending on the size of the mosque, 5% to 20% capacity can be achieved during daily congregational prayer. A full capacity can only be achieved during weekly congregational prayer which is on Friday. There are five congregational prayers conducted each day which are:

i. Dawn prayer (subh) – 6.00 am – 7.30 am
ii. Noon prayer (Zuhr) – 1.00 pm – 4.30 pm
iii. Afternoon prayer (Asr) – 4.30 pm – 7.00
iv. Dusk prayer (Maghrib) - 7.30pm – 8.30pm
v. Evening prayer (Isya) – 8.30 – until Dawn prayer
For the purpose of the analysis, three periods of time which are the noon (from 1.00 pm until 2.30 pm), afternoon (from 3.30 pm until 5.00 pm) and evening (from 7.00 until 9.30 pm) are established. These are the duration of time that the mosques are mostly occupied.

The analysis of the collected data is intended to provide information regarding the dominating factor and other contributing factors of thermal comfort inside the selected area. Included in the set of questionnaires is the inquiry about the sensation of the factors affecting the thermal comfort that the participants have experienced. The factors include thermal sensation, humidity level and air movement condition. Votes from both of the scales will be compared to determine the response towards the three main factors in relation to the thermal comfort. The votes received are collected and tabulated using the bar chart. Cross tabulation analysis between the votes on the thermal comfort sensation and the votes of the sensation on the other factors described earlier can suggest how thermal comfort can be affected by each factor. It can also suggest which factors are more dominant in influencing the thermal comfort sensation. The votes on the preferences are also investigated to confirm the desired conditions affecting the thermal comfort level.

4. RESULT AND DISCUSSION

Figure 1, 2 and 3 show the votes of the variables in relation to the thermal comfort vote at a selected space during the noon, afternoon and evening time respectively. Based on Figure 1, it shows that the participants who voted 'too warm' for the thermal comfort vote, also experience the thermal sensation as either 'warm' (38%) or 'hot' (62%) with 'humid' condition and 'calm' air movement. This condition indicates that high humidity with relatively no air movement can cause thermal discomfort with either 'warm' or 'hot' categories of air temperature. In this figure, it is also pointed out that the participants feel 'comfortably warm' which is better than the 'too warm' condition when the thermal sensation is either 'warm' (67%) or 'neutral' (33%) with 'neutral' level of humidity (100%) and 'breezy' air condition (67%). However, 33% still votes the condition to be 'comfortably warm' even though the air movement is in the 'calm' condition.

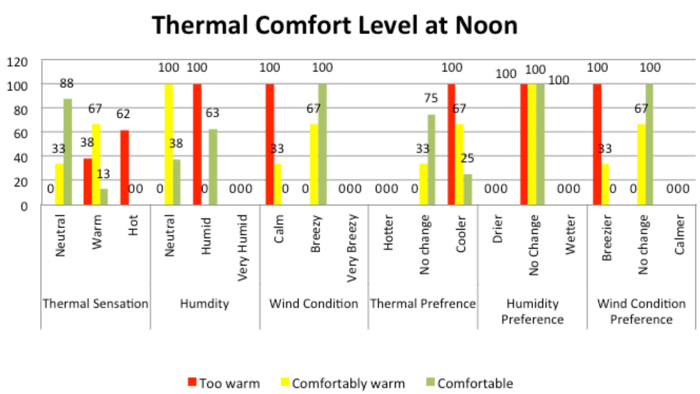

Figure 1: Thermal Sensation and comfort vote at noon

This is possible because the thermal sensation they experience is 'neutral' and with no air movement it is still considered 'comfortably warm' due to the acceptable thermal sensation. This suggests that the thermal comfort level improves with the reduction on the air temperature. In many cases the reduction in the humidity level also helps to improve the thermal comfort level depending on the air temperature and wind condition. When the air temperature is considered 'warm', the reaction to cooling down the body by sweating is more likely to happen. When the humidity level is high the ability for the evaporative process of the sweat may not be efficient enough to cool down the body. The reduction of the humidity level in this case, helps the evaporative process by increasing the ability of the air to contain more humidity. When the air temperature is at the 'neutral' level, the ability of the body to react and produce sweat is slower or at minimal rate. The high level of humidity may not be very significant in influencing the thermal comfort level at this condition, however, in some cases that have been discussed earlier it affects the thermal comfort perception especially when there is little air movement. The increment in the air movement has certainly helped to improve the thermal comfort condition which can be clearly evidenced in the votes received by the 'comfortable' condition in which the increment in the wind condition along with the reduction of the air temperature has help the thermal comfort condition even though it shows an increment in the relative humidity. This also suggests that the humid condition can be tolerated when the condition of the air is 'breezy' and the thermal condition is 'neutral'.

The preferences vote has also suggested the importance of the variables to the thermal comfort condition. For examples, all of the participants who felt 'too warm' preferred the air temperature to be cooler as most of them feel 'hot'. Similarly, for those who feel 'warm' also vote the air temperature to be cooler. Only those who feel 'neutral' choose the thermal sensation to remain. This suggests that only 'neutral' thermal sensation is acceptable since there is no change requested for this condition. Similarly, breezier condition is preferred for all thermal comfort conditions which is shown in Figure 5.5. The 'no change' votes on the air movement is from those who have experienced the condition to be breezy. Therefore, it can be assumed that the wind movement is a variable that is important in providing thermally comfortable indoor. In the case of the relative humidity, regardless of the condition felt, all the participants prefer the condition to stay the same. This reflects that the influence of the humidity in the air may not be very critical in influencing the thermal comfort condition. Another assumption that can be made is that the level of sensitivity of the human body to react to the change in relative humidity is very poor. Therefore, the presence of the humidity in the air may not be realised.

Figure 2 shows the relation of the variables to the thermal comfort vote during the afternoon time at the same space. Based on the figure, it is obvious that respondents feel 'comfortable' when the thermal sensation and humidity level are at 'neutral' level and the air condition is 'breezy'. This is the ideal situation that makes the majority of the respondent feel 'comfortable'. With the change in the thermal sensation from 'neutral' to 'warm' as shown in Figure 2, the thermal comfort vote has also changed to 'comfortably warm' when the other two variables remain unchanged. The 'warm' thermal sensation however, may have resulted in poorer thermal comfort condition as shown in the Figure 2 when the humidity level is increased and with relatively little air movement. As expected, 'breezier' wind condition is preferred not only by those who experienced 'calm' air condition but also by some of those who have considered the condition to be breezy. Again, for those who have sensed the thermal condition as 'warm' or 'hot', they prefer the condition to be cooler and similarly, the humidity level to be drier for those who have experienced the condition to be 'very humid'.

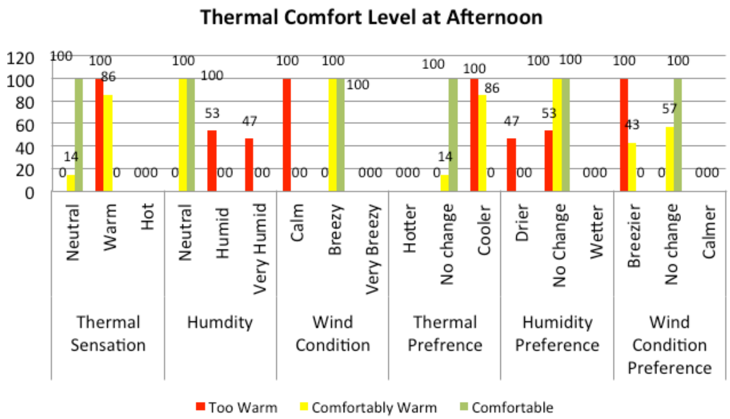

Figure 2: Thermal sensation and comfort vote at afternoon

A similar result is obtained in Figure 3 which shows the percentage of votes of the variables in relation to the thermal comfort perception during the evening time. In Figure 3, all of the respondents who feel 'too warm' experience the thermal sensation to be 'warm'. However, with the 'humid' and 'very humid' condition and little air movement, the thermal comfort condition cannot be tolerable. It is also shown here that when the air temperature and the humidity level are considered 'neutral' and the wind condition is 'breezy', the majority of the participants will considers this condition as 'comfortably warm'. The major difference among Figure 1,2 and 3 is that the survey taken for both Figure 1 and 2 is during the daytime, whereas the survey for Figure 3 is taken during the evening time. With the outside temperature lower than the indoor air temperature during the night time, there is a possibility that this condition may have influenced the result. The reduction of the outside temperature creates smaller differences between the inside and outside air temperature and this condition may have reduced the movement of air through the temperature difference between the inside and outside. Less air movement means less humidity is transferred from the inside to the outside and this may cause the effect of stuffiness.

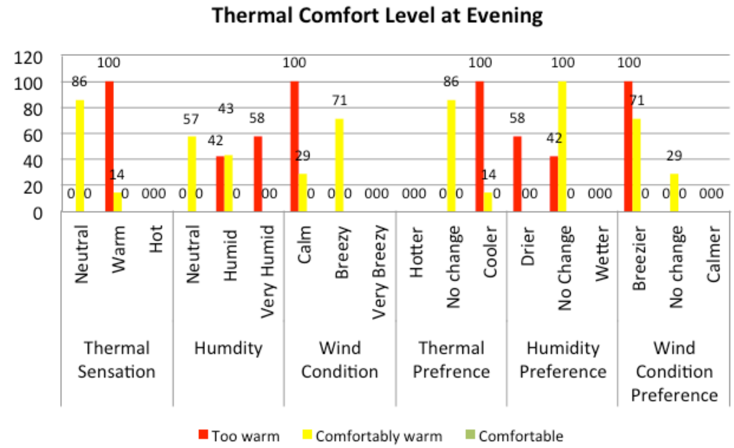

Figure 3: Thermal sensation and comfort vote at evening

Note: Seven levels of Bedford scale are used for the thermal comfort level but only the three levels are shown because no vote is received for comfortably cool, too cool, much too cool and much too warm.
ASHRAE 7-point scale is used for the thermal sensation but only three points which are neutral, warm and hot are shown because other points do not receive any vote for the period of time investigated

Based on the analysis conducted, it can be summarized that the air temperature and wind movement are important factors in influencing the thermal comfort condition for the countries in the hot and humid region such as Malaysia. The relative humidity too, plays a significant role depending on the condition of the previous variables. The high temperature throughout the day, to a certain extent is tolerable due to the process of acclimatization. It is also undisputable that the high temperature throughout the day triggers the body to produce sweat in reaction to cooling it down naturally. Whenever this happens, the presence of the humidity in the air and the air movement plays enormous role in influencing the thermal comfort condition. For examples, with the abundance of humidity in the air, the sweat produced is incapable of reducing the heat through the process of evaporation which is hampered by the high content of humidity in the air. It is also evidenced that when the air temperature falls, the relative humidity increases. This may explain why many participants feel more uncomfortable during the night time compared to the day time even though the air temperature is the same.

The presence of air movement also helps to improve the thermal comfort condition. It assists the cooling down process by transferring the humidity from the body to the air which involves energy exchanges. For the country that has high air temperature and relatively high humidity content, the breezy air condition is favourable. Continuous and strong air movement is required to help to cooling down the body. Figure 4 shows the flow of influences in thermal comfort based on the three main factors which are air temperature, relative humidity and air movement.

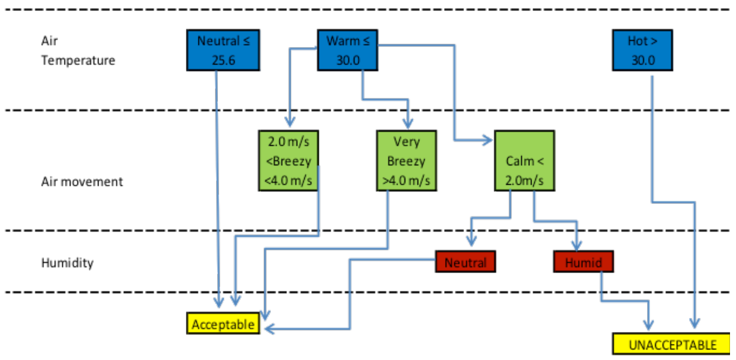

Figure 4: The filtration process to show the importance of physical factors in affecting thermal comfort

5. CONCLUSION

The investigation using the survey on the thermal comfort perception of prayer hall users in Malaysia has revealed that the three main physical factors of thermal comfort have various impact on the indoor thermal comfort depending the condition of each factors. For examples, the users feel thermally comfortable when the air temperature is in the neutral level of heat sensation regardless of the condition of relative humidity and air movement. At this range, it can be assumed that the influence of other variables such as humidity and air movement does not affect the thermal comfort perception. Humidity, however, will become effective in influencing the thermal comfort perception after the air temperature exceeds the neutral temperature making the air temperature as the 'dominating' factor in influencing thermal comfort. Similarly, air movement, is only needed when the air temperature is exceeding the neutral level. In some cases, the presence of air movement is only desirable when the air humidity is higher than normal. Based on the finding, it is clear that the air temperature is the 'dominating' factor which the indoor thermal comfort is highly dependent on the air temperature condition. The relative humidity and air movement, on the other hands, are only assisting in the presence of air temperature in influencing the indoor thermal comfort. They are the "contributing" factors as their influence can only be effective depended on the condition of air temperature.

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