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A Conceptual Review on Residential Thermal Comfort in the Humid Tropics

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***Abstract* — In the era of increasingly expensive fuel and with the theoretical complication and the limitation of comfort prediction in naturally ventilated buildings based on thermal balance approach, researchers were motivated to go beyond heat balance approach to predict occupants' thermal comfort using statistical approach known by adaptive models. The most established recognized model was developed mostly from the worldwide database recorded in office buildings. This poses validity problem when the model is applied for residential buildings. From a practical point of view using this model for the determination of neutral temperature in residences is likely to leads to errors in prediction which in turns are likely to have detrimental effect on occupants' satisfaction, not to mention the potential effect in terms of energy consumption. This paper presents a conceptual review on indoor thermal comfort based on heat balance and adaptive models. The validity of international thermal comfort standards for residential buildings for neutral temperature prediction specifically in the hot-humid tropics is addressed. The need of database from field studies in residential buildings is emphasized.**

***Keywords* — Thermal Comfort, PMV Model, Adaptive Model, Hot-Humid Climates, Naturally Ventilated Residences.**

I. Introduction

Thermal comfort is generally defined as that state of mind which expresses satisfaction with the thermal environment (e.g. in ISO 7730; ASHRAE 55); it is associated with a neutral or near neutral whole body thermal sensation [1, 2]. The temperature in which the thermal environment is perceived by people neither cool nor warm is termed neutral temperature. Comfort temperature is usually referred to it as neutral temperature. Two approaches are commonly used to predict a thermally comfortable indoor climate.

The first approach is more related to laboratory studies using comprehensive indoor climatic measurements in well-controlled climate chamber with a sound experimental design. The best known model is PMV Fanger model [3, 4]. The limitations of laboratory studies are that the validity and the reliability of the models under real world are questionable for several reasons among them the parameters under study are kept invariables which is not the case in the real world. Metabolic rate and clothing insulation level of occupants usually are very difficult to predict accurately except in climate chamber and those are primordial parameters in the prediction of neutral temperature by the model [5]. The second approach is field survey. The researcher does not control the research setting as opposed to climate chamber but rather seeks to understand naturally occurring events in their natural states. Adaptive model is the most widely known approach with the principal method is the field survey [4]. The method requires huge database from field studies of the majority of worldwide climatic zones.

II. The PMV Model

Predicted Mean Votes (PMV) model stand among the most recognized model developed in controlled climate chamber from the heat balance approach under steady-state condition. The PMV model has been established as an international standard since the 1980s [6]. It has been also incorporated in ASHRAE 55 since 92 [7]. This model assumes that the body under comfortable condition is in a thermal equilibrium and the stored energy is very small [8]. Despite that the PMV Fanger model was developed in a controlled environment and has shown some of its limitations in field studies, the Fanger model stand among the most widely accepted model. The PMV model can be applied only within the intervals shown in Table 1. The prediction of neutral temperature as listed in the table is not applicable for higher air temperatures above 30^{0}C and for air velocities over 1 m/s. Indoor air temperature above 30^{0}C is commonly recorded in naturally ventilated buildings located in Kota Kinabalu [48] and this again shows that PMV model cannot be used for comfort temperature prediction in the hot-humid tropics at least in naturally ventilated building.

Table I : PMV Model Acceptable Indoor Range

Parameters	Units	Lower Limits	Upper Limits
Air Temperature	^{0}C	10	30
Radiant Temperature	^{0}C	10	40
Relative Air Velocity	m/s	0	1
Water Vapour Pressure	P_a	0	2700
Clothing Insulation	m^2. k/W (clo)	0 (0)	0.310 (2)
Metabolic Rate	Met (W/m^2)	0.8 (46)	4 (232)
Predicted Mean Vote	Scale	-2	+2

Source: ISO 7730 -2005

Several researchers found that the PMV model can predict comfort temperatures with reasonable accuracy in most building with HVAC systems [9, 10, 11, 12], though, there are disagreeing conclusions in other studies such the results of Abdulshukor [13] who found in a cited study by Humphreys [14] that Malay subject in a Malaysian climate chamber preferred warmer temperature at 28.7^{0}C, whereas in a London climate chamber preferred lower temperature of 25.7^{0}C. Such result was unexpected in chamber test. This is because it was recognized that people perception to the indoor environment in climatic chamber is the same regardless of race, location and outdoor climatic environment and PMV model is considered accurate for thermal comfort prediction under such case. This also contradicted the result of a chamber study carried out in Singapore by de Dear *et al*. [9]. The authors acknowledged that the results are quite confusing but there was no explanation behind the discrepancy between both studies [11].

III. The Current Issue with the PMV Model

Humphreys and Nicol [15] argued about the validity of PMV model in air-conditioned buildings. The authors stated that the error in the PMV model in such buildings was rather masked by the narrow range of the indoor environments. This has previously been raised as well by Fountain *et al.* [16]. The authors observed that air-conditioned office buildings were controlled within a very restrictive range of temperature as opposed to what was allowed by ASHRAE 55 standards. Thus people were adjusting their thermostat to a narrower comfortable range compared to what was allowed by PMV.

The situation is different in naturally ventilated building. There is almost total agreement among researchers that PMV model especially in warm to hot climates do not predict occupants thermal sensations well in naturally ventilated buildings and the findings of many researchers do not support the applicability of PMV in hot to warm environment [15, 17, 18, 19, 20, 21). This has been admitted by the author of the PMV model as well [6].

Fanger and Toftum [6] attributed the discrepancy of the results between PMV and field studies in hot climate to the low expectation of the local population as they are not used to air conditioning. It must be emphasized that the Fanger and Toftum [6] explanation was rather defending the PMV model then analyzing real data. Researchers do agree that expectation affects people thermal sensation in naturally as well as in air-conditioned spaces [16, 22]. Hence recognizing the presence of the effect of expectation in the prediction of neutral temperature proves that thermal comfort is not solely associated to a physiological condition which can be predicted from heat balance approach only; it is also a state of mind as defined by the standard. Further discussion about the issue can be found in Fountain *et al.* [16].

It is necessary to mention that many studies in hot climates have found that subject can be comfortable at temperature up to 30^{0}C and even higher when occupants were especially using fan [23] whereas PMV model predict much lower temperatures compared to field studies. Djongyang *et al.* [24] quoted an important statement by Fanger [25] related to human adaptation with the environment for achieving a neutral thermal sensation which was that:

"Man's thermoregulatory system is quite effective and will therefore create heat balance within wide limits of the environmental variables, even if comfort does not exist".

ISO 7730 [2] offered to the designer a possibility to extend acceptable indoor environment range in warm climate regions in naturally ventilated spaces, whereas no specific approach is specifically recommended in the standard, although the recommendation was under heading 'adaptation'. ASHRAE 55 recognized since 2004 [26] the adaptive approach and provided a chart for the prediction of acceptable temperature range for naturally conditioned space [27]. It must be emphasized that naturally conditioned space is referred to the space regulated primarily by the opening and closing of windows by the occupants [27]. Failure to understand fully the relationship between occupant thermal perception toward indoor environment and all the parameters which have an affect occupant thermal comfort prevented researchers from learning about boundary conditions of the heat balance approach.

IV. Adaptive Thermal Comfort Approach

It has taken about 26 years worldwide extensive observations since the first adaptive approach model suggested by Humphreys [28] to be recognized by ASHRAE 55 [26]. Researchers in thermal comfort field studies have found many times that people are not static receptor of their thermal environment as formulated in PMV approach but rather they are active and could significantly enhance the indoor comfort through the control of their local surroundings or acclimatize to the indoor and outdoor climate [29, 23]. They have also pointed to the potential benefit in terms of energy savings associated with the use of the available passive controls to enhance their thermal state

Adjustments and expectations are important factors in human response to comfort and those are omitted in the thermal comfort heat balance in the PMV model. The consequence of adaptive behaviors on optimum comfort temperature can be found in reference [30]. The principal of the adaptive approach is that the indoor neutral temperature is highly correlated with the outdoor temperature and hence it can better predict neutral temperature of occupants in naturally ventilated buildings compared to the PMV model. The approach requires huge worldwide quality database as it can not be developed in a narrower indoor and outdoor temperatures range such that of the humid-tropics. Fig 1 shows the main variables that affect indoor thermal comfort for naturally conditioned spaces.

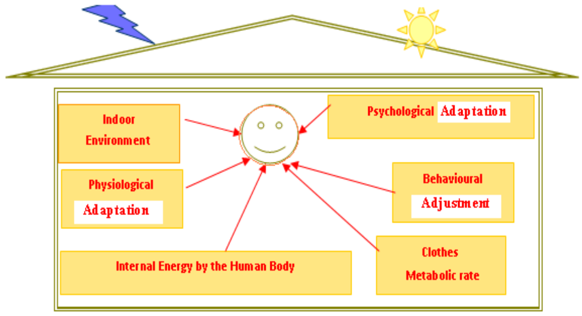

Fig.1.Variables That Affect Occupant Thermal Comfort

The most worldwide established adaptive model specified for thermal comfort in naturally ventilated buildings was proposed by de Dear and Brager [31] recognised as the adaptive comfort standard in ASHRAE 55 since 2004[26]. The raw data of their studies are from researchers' works in which some has been funded earlier by ASHRAE. A global database [32] considered in their analysis taken primary in office buildings from several worldwide locations namely England and Wales, Bangkok Thailand, several Californian locations, Montreal and Ottawa in Canada, six cities across Australia, five cities in Pakistan, Athens in Greece, Indonesia, Singapore, and Grand Rapids in Michigan, nearly 22,000 raw data.

The adaptive comfort standard for naturally conditioned spaces is only applicable when windows can be readily opened to outdoor and adjusted by occupants. This model is valid when the mean monthly air temperature is between 10 and 33.5 °C [27]. Earlier, Humphreys [26], Auliciems [33], Auliciems and de Dear [34] also have developed their adaptive models having mostly limited database

V. The Current Issue with the Adaptive Model

Although the adaptive model has been recognised by ASHRAE 55 standard since 2004, there are limited worldwide publications for external validation of the model, though some investigations carried out mostly by expert in the field have been found in reliable publications. Some supported and others argued about the model limitation. Fanger and Tofum [6] admitted earlier that the adaptive model is quite good in the indoor thermal comfort prediction for non air-conditioned buildings but it was considered too simple to be adequate. The authors stated that the adaptive model is a regression equation which ignores many important parameters that change according to the indoor environment and personal parameters. The authors raised also an important question about the model in the future when the occupants may either change their clothing insulation or their activity pattern.

Nicol and Humphreys [35] clarified the concept of the adaptive approach by explaining that clothes worn by the subject as those the use of building controls depends on the outdoor temperature and hence most of the significant thermal comfort parameters can be explained by the outdoor temperature. The author strengthened his arguments from researchers' observations in several field studies [36, 37, 38, 39]. In a subsequent work by Nicol [23], the author provided a better explanation about the model and the following is quoted from the author publication:

One way around this is to treat the process as a black box where the internal mechanisms of the relationship between comfort and the environment are less important than the outcomes. This is the approach taken by those who use field survey to investigate the problem

In addition, it is known in statistic that correlation does not imply causality and thus a lurking variable which may not be included in the regression does not affect the regressed model. Lurking variable is one that affects the variables being studied, but it is not included in the study [40]. This is another way to explain the above concept quoted from the author statement.

Despite the full support of the adaptive approach by Nicol [23], the author however showed that in the hot climate occupants subjected to high relative humidity may have a different thermal sensation then that in hot dry climate when subjected to similar indoor temperature and highlighted the urgent need for more field studies in the tropics when the current adaptive model is weakest. His conclusion was drawn from a meta-analysis of field studies in the hot to warm climates [23]. Fanger and Toftum [6] also highlighted the need of more field studies in warm to hot climates.

Another important issue of the adaptive model raised by some authors is related to the limited thermal comfort worldwide database in residential buildings. ASHRAE 55 [27] has already clearly stated that the chart generated from the adaptive model was derived primarily in office buildings. ISO 7730 [2] also mentioned that the standard is specifically developed for the work environment but then it can be applied to other kind of environment according to the same reference, whereas the same standard highlights that ethnic, national or geographical differences need to be taken into consideration for non-conditioned space. Further details were not provided.

When developing the adaptive model, de Dear *et al.* [11] also pointed out that the majority of buildings were offices and therefore the conclusions drawn from their study as stated exactly by the authors apply primarily to this. It must be emphasised that the number of residential buildings included in the development of the adaptive model for summer is less than 8% which contain many locations from the humid to the dry climates. In fact the majority of the databases in the humid-tropics were primary from offices. de Dear *et al.* [11] have noted when comparing between residential and office buildings a distinct differences in the degree of behavioural thermoregulatory adjustment made by residential building occupants compared to office workers. For example, seasonal clothing insulation distinctions were more noted in the residential as opposed to office setting. It must be also emphasised that people in their dwelling have more control in improving their thermal sensation by sitting near fan or window, keeping their clothing insulation level to the minimum, having bath and other behavioural

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adaptation than in the offices. For instance, it has been already shown that people having a higher degree of control over the windows were thermally comfortable at warmer temperatures of 1.5^{0}C than the group with lower level of control [22]. A difference in neutral temperature of about 1.4^{0}C also was reported of subjects with desktop task conditioning system compared to those without [41]. Tables 2 summarize some of the available adaptive models.

Table II : Adaptive Models for Indoor Neutral Temperature Predictions

Equation	Author [Reference]
$T_c = 11.9 + 0.534 T_{out}$ (1)	Humphreys [28]
$T_c = 9.22 + 0.48 t_a + 0.14 T_{out}$ (2)	Auliciems [38]
$T_c = 17.6 + 0.31 T_{out}$ (3)	Auliciems & de Dear [34]
$T_c = 17 + 0.38 T_{out}$ (4)	Nicol & Roaf [42]
$T_c = 17.8. + 0.31 T_{out}$ (5)	Brager & de Dear [43]

Note: T_{out} : mean outdoor dry bulb temperature (^{0}C); t_a : indoor air temperature (^{0}C).

Equation 5 is the adaptive model recognized by the ASHRAE 55 [26] which was used for the elaboration of the adaptive chart in the standard. Using the monthly mean outdoor air temperatures of kota kinabalu, Malaysia, the indoor neutral temperatures were estimated. These are the mostly available climatic data to designer and researchers. The results are summarized in Fig 2.

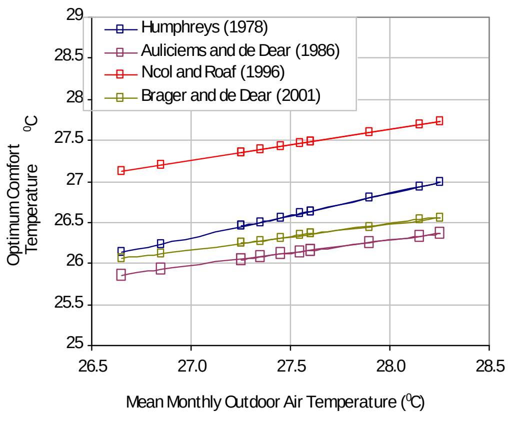

Fig.2. Determination of the Optimum Comfort Temperature with the Adaptive Approach

A glance at the figure reveals that the predicted indoor neutral temperatures using adaptive models are lower than 28^{0}C. The lowest neutral temperature was found by applying Auliciems and de Dear [34] equation, whereas the highest neutral temperature was obtained by using Nicol and Roaf [42] equation. Table 3 summaries the mean indoor neutral temperatures based on the adaptive models calculated from the average annual outdoor temperature (27.5^{0}C) of Kota kinabalu (1968-2003).

Table III : Determination of Neutral Temperature from The Adaptive Models

Equation	Neutral Operative Temperature	Comfort Zone Band 80% Acceptability
1	26.6	24.1-29.1
3	26.1	23.6-28.6
4	27.4	24.9-29.9
5	26.3	23.8-28.8

Note: - 80% acceptability is centered on the optimum comfort temperature of 5^{0}C based on ASHRAE Std 55.
-Equation 3 excluded because it requires indoor air temperature records.

The indoor neutral temperatures from the adaptive models were lower compared to the indoor neutral temperature determined by researchers in the humid tropics having almost similar climatic conditions as the case of Malaysia. Feriadi and Wong [19] in their field investigation found that the indoor neutral temperature was 28.8 ^{0}C air temperature or 29.2^{0}C operative temperature for naturally ventilated houses in Jakarta. The indoor neutral temperature predicted by de Dear *et al.* [44] in naturally ventilated residences in Singapore was about 28.5^{0}C (having operative temperature as an independent variable). In another study conducted in residential buildings in Malaysia, the neutral temperature was close to 30^{0}C. This study was carried out for one year duration in kota kinabalu having a sample size of 890 [45]. It must be emphasized that the annual outdoor temperature in Singapore is lower than the case of Malaysia by 1.0^{0}C. The predicted neutral temperature in Singapore in mechanically ventilated classroom was found to be 28.8^{0}C (Operative temperature)[49]. It appears that adaptive models underestimate the comfort temperature in the humid tropics. The limited literature reports and data on indoor occupant's thermal comfort in residential buildings were also addressed in recent publications by Djongyang *et al.* [24]. The following is quoted from de Dear as a co-author of this statement [46]:

"It must be emphasized that there is only a limited amount of data residential thermal comfort. If and when a large, quality assured, database of residential comfort data becomes available the here defined comfort relation might need to be revised."

In fact, an important question that is raised in the present review is that how accurate the adaptive model when it is used for occupants living in wooden or lightweight buildings as opposed to concrete buildings since occupants in wooden houses are subjected to higher indoor air temperatures in the humid tropics as opposed to these living in concrete buildings. This is not stated in the standard. It is necessary to report that the adaptive model was validated in few studies such the conducted investigation in a hot-humid climate for non residential buildings [47] and in previous investigation in a workstation located in the Berkeley Civic Centre [22].

Another interesting point of view worth to be discussed is related to the plot of outdoor air temperature of Kota Kinabalu as illustrated in Figure 3 which shows that the mean annual outdoor temperature of the location is not

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constant but rather varies over years. This raises an important question of whether or not such annual outdoor temperature variation would have effect as well in the prediction of indoor neutral temperatures within the same location or in any location having similar climatic conditions over time. This is because the neutral temperature is closely related to the mean temperature that occupants they experience (Nicol, 2004). Predicting and monitoring the neutral temperature variation over few years in a specific location is worth pursuing. This may uncover some of the many puzzles related to thermal comfort as it may help in the assessment of the long term effect of climate change over years on indoor thermal comfort. When the climatic data of Kota Kinabalu area were analyzed, it was found that the trend of the increase in the maximum outdoor temperature per decade was about 0.4°C with an average increase in outdoor temperature of 0.3°C. The maximum outdoor temperature seems to increase faster than the average value.

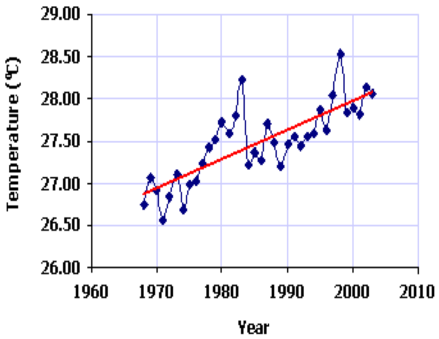

Fig.3. The Trend of the Outdoor Temperature in Kota Kinabalu over Years (1968-2003)

The data were collected by the 1st Author from Sabah and Kuala Lumpur meteorological stations. (F =58.23, P value=0.000; r^2=0.631, Slope=0.034, C.I. of the slope =0.025 to 0.044, Intercept=-40.991, n=36). The procedure used for the analysis is an approximate calculation. Smoothing the curve is necessary for a precise calculation which is beyond the scope of this study.

VI. Conclusions

From the review, it was found that both standards ISO 7730 and ASHRAE 55 have been developed mainly from workstation (offices) database although both standards are used for residential buildings. Very limited field studies have been carried out in residential buildings specifically in the hot-humid tropics. Therefore the validity of thermal comfort standards for residential buildings remains questionable. The worldwide need of new database in naturally ventilated residential buildings is further emphasized in the present review. It is apparent that the lack of fully understanding the psychological aspect of the occupants' perceptions toward indoor environment in residential buildings has implications in both theory and practice. Field thermal comfort studies in residential buildings have shown the diversity of the environment that population find comfortable to be greater than to be explained by the regression equation based on the current adaptive model. It is not possible to generalize the findings related to offices to that of residential buildings. Considerably more work will need to be done to determine the comfort model for the residential buildings.

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