EFFECT OF THE THERMAL COMFORT IN BUILDING

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ABSTRACT:
This paper discusses some recent trends in worldwide thermal comfort studies and presents a proposal of research for this building through a series of questionnaire tables. A comprehensive study of thermal comfort in a naturally ventilated education building (88,000 ft2) in a Chicago suburb will be conducted with 120 student subjects in 2007. Two research methods used in thermal comfort studies are field studies and laboratory experiments in climate-chambers. The various elements that constitute a "comfortable" thermal environment include physical factors (ambient air temperature, mean radiant temperature, air movement and humidity), personal factors (activity and clothing), classifications (gender, age, education, etc.) and psychological expectations (knowledge, experience, psychological effect of visual warmth by, say, and fireplace). Comparisons are made using data gathered from Nairobi, Kenya.

KEYWORDS:
Comfort, Temperature, Humidity, Ventilation

INTRODUCTION

The "comfort zone" is an appropriate design goal for a deterministic mechanical system but analysis of many international field studies by researchers has questioned its relevance to passive solar buildings (Humphreys, 1976; Auliciems, 1978; Forwood, 1995; Baker and Standeven, 1996; Standeven and Baker, 1995; Milne, 1995) [1, 2, 3, 4, 5, 6]. Givoni (1998) revised his already authoritative and notable work on the building bio-climatic chart having recognized this new position [7]. These revisions reflect a paradigm shift in thermal comfort for people relative to their thermal environment. The American Society of Heating, Ventilating and Air-conditioning Engineers (ASHRAE) has been discussing how people adapt to higher indoor temperatures in naturally ventilated buildings [8, 9].

There is mounting evidence (Humphreys, 1996; Karyono, 2000) that confirms that thermal perceptions are affected by factors that are not recognized by current comfort standards [10, 11]. The factors include thermal history, non-thermal stimuli and psychological expectations. These perceptions are most noticeable in naturally ventilated buildings where expectations are distinctly different from air-conditioned buildings. McIntyre (1980) stated that "a person's reaction to a temperature which is less than perfect will depend very much on his expectations, personality and what else he is doing at the time [12]. A study (Brager and de Dear, 1998) noted that "anecdotal evidence suggests that building occupants become accustomed to levels of warmth prevailing within buildings on time scales of weeks to months" [13]. They concluded that there is a distinction between thermal comfort responses in air-conditioned vs. naturally ventilated buildings. It leads to another emerging observation of psychological adaptation resulting from one's thermal experiences and expectations. Psychologically, people perceive or respond to the thermal experiences in apparently altered manner. Paciuk (1990) and Williams (1995) found that perceived degree of control is one of the strongest predictors of thermal comfort [14, 15]. Leaman and Bordass (1999), Bunn (1993), Raja et al. (2001) and Brager (2000) documented that people who have greater control over their indoor environment are more tolerant of wider ranges in temperature [16, 17, 18, 19]. These "adaptive errors" are the cause of discrepancy between observed comfort temperatures from field studies and predicted comfort temperatures from climate chamber experiments.

1. THERMAL COMFORT STUDIES

1.1. Climate-chamber studies and thermal comfort scales

The climate chamber is based on a heat-balance model whereby subjects in a carefully controlled environment are subjected to different levels of physical environmental parameters and their "neutral" heat balance point established. Pioneer thermal comfort work by International Standards Organization (ISO), ASHRAE (2005) and Fanger (1969) was based on this model. Subjects in the comfort studies were asked to judge the conditions (preferred temperature) in a space and record it using the ASHRAE thermal sensation numerical scale shown in Table 1. Other commonly used scales are shown in Tables 2 [20, 21].

Table 1: ASHRAE Thermal Comfort Scale [22]

QUESTION	SCALE	THERMAL SENSATION	VOTE
How Do You Feel About The Thermal Environment In This Room?	+3	Hot	
	+2	Warm	
	+1	Slightly Warm	
	0	Comfortable, Neutral	
	-1	Slightly Cold	
	-2	Cool	
	-3	Cold	

Table 2: McIntyre Scale [10]

QUESTION	RESPONSE	VOTE
I Would Like To Be. …	Cooler	
	No Change	
	Warmer	

Table 3: Humidity Scale [10]

QUESTION	SCALE	THERMAL SENSATION	VOTE
How Do You Feel About The Humidity In This Room?	+3	Much Too Dry	
	+2	Too Dry	
	+1	Slightly Dry	
	0	Comfortable, Neutral	
	-1	Slightly Humid	
	-2	Too Humid	
	-3	Much Too Humid	

Table 4: Air movement Scale [23]

QUESTION	SCALE	THERMAL SENSATION	VOTE
How Do You Feel About The Air Movement In This Room?	+3	Much Too Still	
	+2	Too Still	
	+1	Slightly Still	
	0	Comfortable, Neutral	
	-1	Slightly Breezy	
	-2	Too Breezy	
	-3	Much Too Breezy	

Climate-chamber studies done in the 1970's at the Institute for Environmental Research at Kansas State University by Rohles and Nevins (1971) and Rohles (1973) showed that there are correlations between comfort level, temperature, humidity, sex, and length of exposure [24,25]. Rohles (1980) concluded: "To deny or ignore the psychology involved in comfort measurement is not only short-sighted, but treats the human subject as a machine, which it is not" [26]. Rohles (1981) also indicated that alongside control of physical variables, adjustments in the amount of furnishing in a space and lighting levels could probably provide a solution to improving thermal comfort [27]. Their results, with various equations for predicting thermal sensation, have been published in ASHRAE Handbook of Fundamentals.

While climate chambers lack the realism of an actual building and are unsuitable for longitudinal studies (those in which the thermal experience of a relatively small number of subjects is monitored over a period of time) or transverse surveys (those in which a larger group of subjects, being a more representative sample of the population, is polled on a smaller number of occasions but with less information on each subject), they are nonetheless useful tools due to their high degree of control and reproducibility. These methods (longitudinal and transverse) are most suitable in field studies.

1.2. Field studies

Humphreys (1975) in summarizing 36 previous field studies on comfort in different countries derived a formula correlating comfort temperatures (T_{co}) with mean monthly outdoor air or globe temperature (T_m) of the location [28].:

$$T_{co} = 2.56 + 0.831\ T_m \quad (1)$$

Humphreys (1978) also compared "free-running" buildings (passive and naturally ventilated) with mechanically controlled buildings [29]. He observed that:

$$T_{co} = 11.9 + 0.534\ T_m \quad (2)$$

$$T_{co} = 0.0065\ T_m{}^2 + 0.32 T_h + 12.4 \quad (3)$$

Passive solar building ranging between $100 \le T_m \le 34^o$

Mechanical-systems building ranging $240 \le T_m \le 230$ and $180 \le T_h \le 30^o$

Where T_h is the average daily maximum temperature of the hottest months of the year

Nicol and Roaf (1996) proposed an adaptive algorithm suitable for determining comfort temperatures (T_{co}) in Pakistan [30]. It used simple outdoor temperature calculated from the preceding month ($T_{m'}$):

$$T_{co} = 17 + 0.38\,T_m \tag{4}$$

Passive solar building
A similar relationship of comfort temperature on mean outdoor temperature by Auliciems and de Dear (1978) is [2]:

$$T_{co} = 17.6 + 0.31\,T_m \tag{5}$$

The above algorithms were made in studies done under "free-running", or natural or passive solar conditions in various climates. There are limitations to using these equations in differing locations like Chicago, IL or Nairobi, Kenya, because of the differences of latitude, altitude, geography, climate and the need to establish a localized thermal comfort standard. Climatic conditions for equatorial highland regions tend to be generally the same all year round [31]. As an example, using outdoor temperature in Nairobi and the above stated equations for passive solar buildings, the following speculative comfort temperatures in Table 5 were established for the hottest month (February):

Table 5: Comfort temperatures in February for Nairobi, Kenya

	OBSERVED	HUMPHREYS	NICOL AND ROAF	AULICIEMS DE DEAR
F°	71.1	74.3	77.4	75.7
C°	21.7	23.5	25.2	24.3

1.3. Adaptive "errors" in thermal comfort

Humphreys defined comfort as "the absence of discomfort, and discomfort is alleviated by making adjustments". He is a strong proponent of the adaptive model, i.e. thermal neutrality can be attained by more human involvement rather than just more mechanical controls. Thermal neutrality is a temperature at which a sample population feels neither too hot nor too cold. Field studies on adaptive models have shown that thermal neutrality is a function of the climate that people are acclimatized to. Researchers are increasingly questioning whether the simplistic cause-and-effect approach embodied in these laboratory-derived models can be applied, without modification, to describe real-world thermal perception.

The adaptive model is the most effective way of assessing passive solar buildings, or what is sometimes called free-running buildings. The adaptive models allows people to make adjustments to their clothing, activity, posture, eating or drinking, shifting position in a room, operating a window or shading device, or other adaptive opportunity in order to achieve or maintain thermal comfort. It appears that when people are allowed greater adjustment and control over their own indoor environment, it extends the comfort zone. The adaptive model acknowledges that the occupant is not just a passive recipient of the environment but an active member.

2. OBSERVATIONS

Many studies are now being undertaken to establish thermal comfort standards around the world. Even ASHRAE commissioned a project to collect field-study data worldwide to relate comfort temperature and climate. There are limitations to using the previously stated models because "The use of ISO-PMV could lead to unnecessary cooling in warm climates and unnecessary heating in cool ones, and if applied in developing countries would lead to needless economic and environmental penalty" [10].

A survey in Zambia in central Africa between latitudes 8° and 18° south, established the comfort temperature as 22.2°C, and comfort zone as 19.7–24.7°C for the cool season; ASHRAE Standard 55 overestimates the lower comfort limit for this region by 2.7°C [32].

A recent study (Ogoli, 2000) was undertaken in Nairobi, Kenya, to observe indoor temperatures in passive solar buildings with different amounts of thermal mass [31]. The stratified indoor temperatures in light mass building (Figure 1) and high mass building (Figure 2) are shown below. The low mass building was made of timber walls and galvanized corrugated iron (GCI) sheet roof while the high mass building was made of stone walls with concrete tile roof. These figures illustrate that the proper use of thermal mass can control indoor temperatures that in turn allow more "adaptive" adjustments for occupants. Temperatures in the low mass building generally follow the outdoor trends. In the case of the high mass building, indoor temperatures remain relatively in a narrow band, thus increasing the potential of thermal comfort through adaptation. A follow-up study was made in the prediction of indoor temperatures of closed buildings with high thermal mass [33].

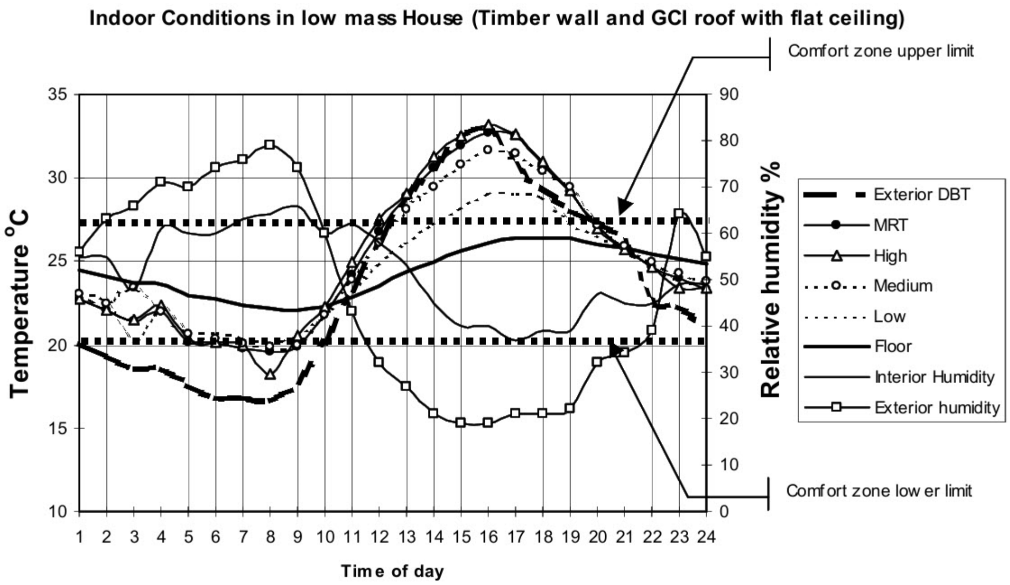

Figure 1: Conditions in a low mass building in Nairobi

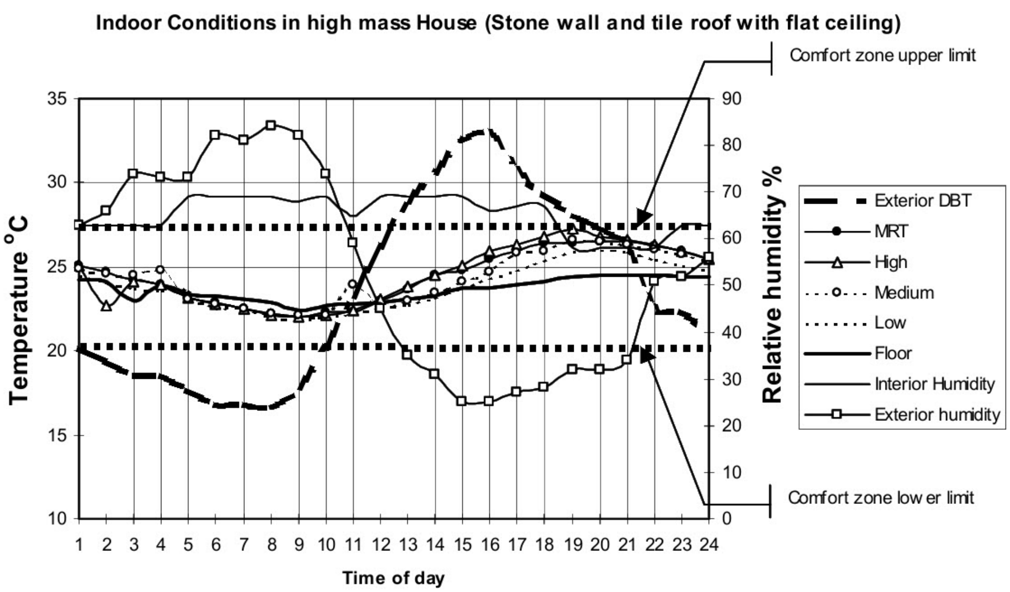

Figure 2: Conditions in a high mass building in Nairobi

3. ANALYSIS AND DISCUSSION

3.1. Proposal for thermal comfort studies (Questionnaires)

To fully determine the thermal comfort conditions in a given environment, there are a number of questions that should be administered to correct “adaptive errors” that account for the discrepancy between observed comfort temperatures from field studies and predicted comfort temperatures from climate chamber experiments. Five questions from precious studies that need to be asked are:

- How do you feel about the thermal environment in this room?
- Is the present environment acceptable?
- Would you prefer some mechanical ventilation and air-conditioning?
- What personal adjustment(s) have you made to yourself or to the room?
- At the present moment would you like more, less, or no change in the level of air movement in this room?

These questions may be administered half hourly alongside the process of taking accurate measurements of the thermal environment. Tables 6-10 are an example for a proposed layout for a trial example of a 3-hour period. The tables are formulated using current technical literature and anecdotal evidence. The physical parameters that should be measured alongside the questionnaire include ambient air temperature, mean radiant temperature, air movement and humidity. The instruments should be accurate enough that meet specifications for accuracy and response times described by ISO Standard 7726 and/or ANSI/ASHRAE Standard 55-1992, shown in Table 11.

Table 6: How do you feel about the thermal environment in this room?

THERMAL SENSATION	VOTE	HOUR					
		0.5	1	1.5	2	2.5	3
Hot	+3						
Warm	+2						
Slightly Warm	+1						
Comfortable, Neutral	0						
Slightly Cold	-1						
Cool	-2						
Cold	-3						

Table 7: Is the present thermal environment acceptable?

RESPONSE	SCORE	HOUR					
		0.5	1	1.5	2	2.5	3
Yes	1						
No	0						

Table 8: Would you prefer some mechanical ventilation and air-conditioning?

RESPONSE	SCORE	HOUR					
		0.5	1	1.5	2	2.5	3
Cooler	-1						
None	0						
Warmer	1						

Table 9: What personal adjustment(s) have you made to yourself or to the room?

RESPONSE	SCORE RANGE	HOUR					
		0.5	1	1.5	2	2.5	3
Clothing	1 To 10						
Activity	1 To 10						
Posture	1 To 10						
Eat/Drink	1 To 10						
Moved	1 To 10						
Heat/Cool	1 To 10						
Window	1 To 10						

Table 10: At the present moment would you like more, less, or no change in the level of air movement in this room?

	SCORE	HOUR					
		0.5	1	1.5	2	2.5	3
Less Air	-1						
No Change	0						
More Air	+1						

Table 11: Measuring range and accuracy of instruments

PARAMETER	MEASURING RANGE	ACCURACY	RESPONSE TIME
Dry Bulb Temperature	5-40 ^{o}c	$\pm 0.2^{0}C$	Appropriate
Wet Bulb Temperature	5-40 ^{o}c	$\pm 0.2^{0}C$	Appropriate
Mean Radiant Temperature	5-40 ^{o}c	$\pm 0.2^{0}C$	Appropriate
Air Speed	0.05-0.5 M/S	$\pm 0.5^{0}C$	

The response time is the time to reach 90% of the final value with a step change. Source: ANSI/ASHRAE Standard 55-1992

3.2. Observations from other studies

Thermal comfort is a complex phenomenon, which is influenced by several parameters: environmental (physical), personal and psychological. Two of the most common ways to quantitatively expressing thermal comfort and thermal sensation is Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) after Fanger (1970). However, there have been several field studies that do not agree with the results of this method, especially in passive solar buildings [34].

Several extensive field studies summarized by De Dear and Brager (1998) show that the PMV model works best in buildings that have HVAC systems [23]. The studies also show that in naturally ventilated buildings (free running with no mechanical systems) people seem to adapt (behavioral, psychological) and can accept "higher indoor temperatures than predicted by the PMV model" [9].

Givoni defined thermal comfort as "the range of climatic conditions considered comfortable and acceptable inside buildings. It implies an absence of any sensation of thermal (heat or cold) discomfort" [7]. In 1976 he developed the building bio-climatic chart to address the problems associated with the charts by Olgyay. It was based on indoor temperatures and suggested boundaries of the climatic conditions on the psychrometric chart within which various building design strategies (including passive and low energy cooling systems) could provide indoor comfort in hot climates without air-conditioning. The boundaries of acceptable conditions for still air are shown on the psychrometric chart in Figure 3. They were extended due to the effect of adaptive factor

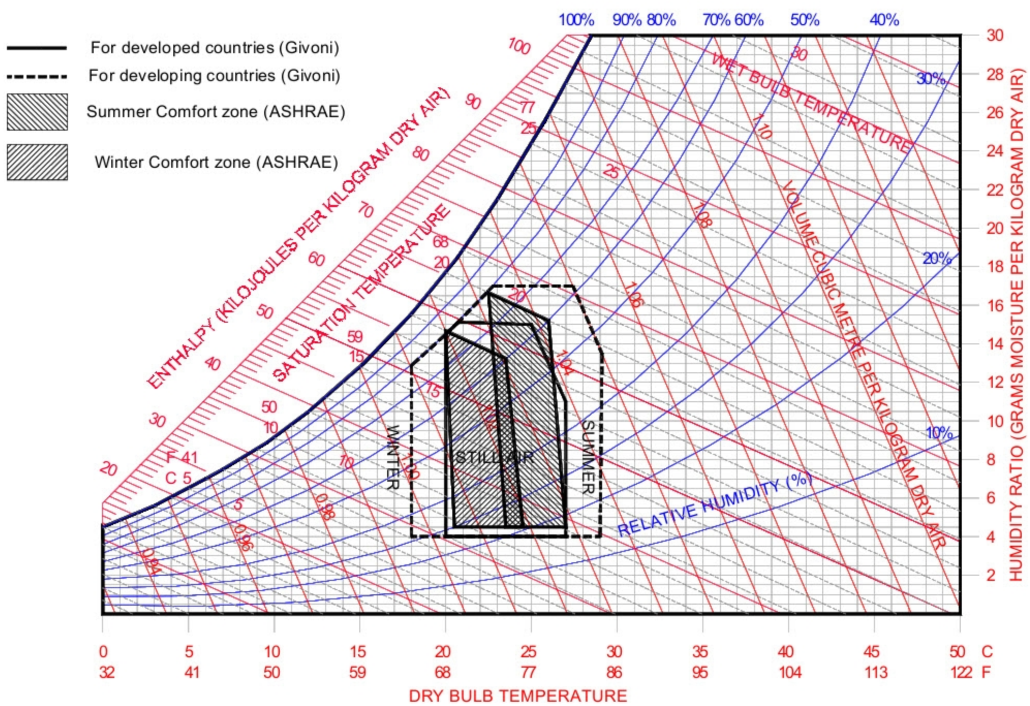

Figure 3: Boundaries of comfort conditions Source: (Givoni, 1998: 38)

Brager and de Dear in 1996 noted that field studies show that the two most widely used thermal comfort standards (ISO Standard 7730 and ASHRAE Standard 55) do not account for the effects of expectation, personal control and psychological adaptation [35]. In fact, they discourage the use of naturally ventilated passive solar buildings because of the narrow band of comfort limits. Occupants in passive solar buildings have more relaxed expectations and can tolerate a wider temperature swing. On the other hand, occupants of air-conditioned buildings have a narrow rigid thermal environment and are more sensitive to thermal environments.

CONCLUSION

Thermal comfort in Nairobi or Chicago may offer insight on the fact people with different expectations, culture and history all require thermal comfort. Adaptive factors may be more easily visible in a low-tech society but even in industrialized countries, they offer an opportunity for modern usage. The universality hypothesis of comfort temperatures based on ISO Standard 7730 and ASHRAE Standard

55-92 extrapolated as equally applicable to human beings around the world regardless of race, culture or climatic experience were the central theme of a strong argument made by Madhavi and Kumar (1996) [36]. Fanger in his work used a small group of "tropical travelers" winter swimmers and meat packers in two experiments in Copenhagen, Denmark, to derive the PMV. The sample size used was statistically too small and Auliciems succinctly put that: "It is not often realized that the claims of its universal applicability were based on remarkably limited and rather incompletely reported preference studies of only 16 travelers from Copenhagen and 32 Danes" [37]. This article is a preparation for further research of thermal comfort in a new naturally-ventilated academic building (88,000ft2) to be completed in spring 2007 on the College campus.

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