Adaptive thermal comfort for energy saving office building design- A literature review

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Abstract. Office building thermal environment quality is essential since thermal comfort and worker productivity are closely related. As thermally comfortable condition is determined by the climate, geography, and surroundings, it is vital to have thermal comfort standards to guide the building designers to create a comfortable indoor thermal environment. The current paper reviews studies on adaptive approach of thermal comfort carried out in offices across the world. It has analyzed many research papers through Scopus. This study reveals that indoor thermal condition is impacted by outdoor climates and the impact is higher in naturally ventilated building. Building with natural ventilation has 17.6°C to 31.2°C rage of comfortable temperature. Adaptive comfort models have also been proposed to predict the comfortable indoor temperature in different modes. According to several studies, lowering the set point and using natural ventilation may result in considerable energy savings. The importance of developing climate specific thermal comfort guidelines in order to create energy efficient designs is also emphasized in this study, as present comfort standards may not be suitable for all climates.

1 Introduction

People spend 87% of their time indoors, therefore there has been substantial growth in the research on indoor thermal comfort [1]. Studies on thermal comfort over time indicate that climate, location, and build environment all have an impact on thermal comfort [2-5]. In office buildings, thermal sensation may be crucial, because thermal discomfort affects human productivity [6-8]. People's interactions with their thermal environment are observed by adaptive thermal comfort [2, 5, 9]. Occupants will respond to make them feel more comfortable if a change creates uncomfortable [2,5,10-15]. Behavioural, physiological, and psychological adaptations are the three main types of adaptations [4, 5, 16]. It is important that all these three adaptations take place together, which makes challenging to foresee how each will impact the situation separately [16–18]. Various adaptive comfort models have been emerged, some as part of global comfort standards [19-21] and others for particular climatic zones [22-25]. Yet, we are unaware of how the slope trend differs among nations, and the effect of outdoor temperature to the comfort temperature in various climate.

Apart from thermal comfort, energy saving through HVAC systems is important since it affects the system's operational expenses and environmental effect [11, 26-28]. Around 50% of the energy in a building is used by the mechanical systems to produce an improved indoor thermal environment [29]. To clearly understand the possible impact of an energy-saving indoor setpoint in HVAC buildings, it is important to study energy conservation utilizing adaptive models from many research.

2 Methodology

The current study gives a thorough summary of the thermal comfort research that has been done in office buildings all over the globe. As indicated below [30], various studies have distinct features of office.

- Naturally ventilated (NV): An office runs continuously freely.
- Free running (FR): An office has an HVAC system or is naturally ventilated, however throughout the research time, HVAC system is turned off.
- Heating, ventilation, and air conditioning (HVAC): One of the heating and cooling systems in the office was operational during the research time.
- Mixed Mode (MM): MM buildings are divided into three categories: concurrent (HVAC and natural ventilation occur at the same time), zoned (natural ventilation and HVAC occur in distinct parts of the building), and change-over (HVAC and natural ventilation occur at different times in the same area)

In this research, the adaptive thermal comfort models and regression equations were studied in a variety of office running modes. Only a few studies have given adaptive thermal comfort models. Apart from thermal comfort, the energy-saving potential of the adaptive model has been studied in numerous research. Natural ventilation is another smart approach for buildings to use less energy. Various studies have been conducted to assess the prospects for energy savings by using natural ventilation.

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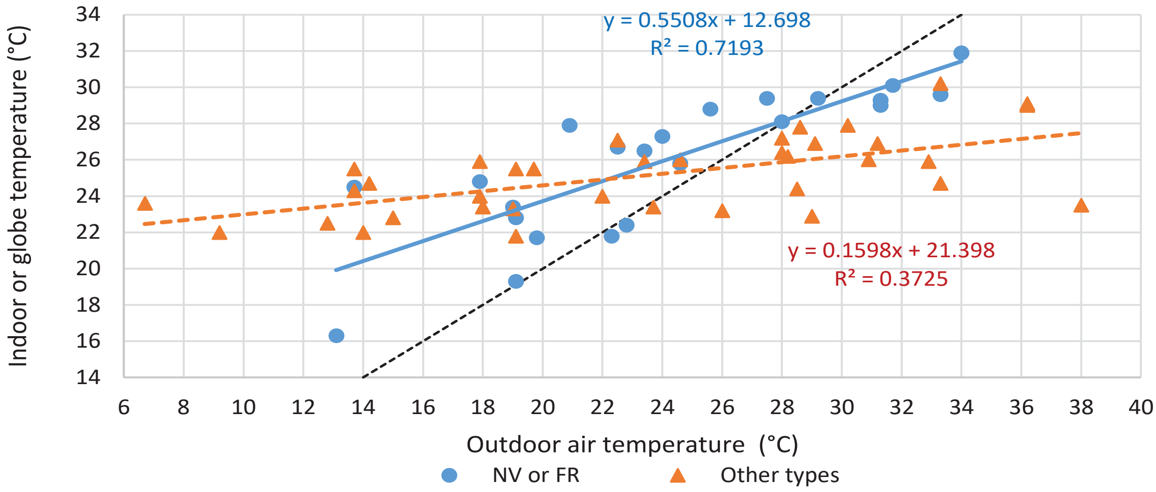

Figure 1. Relation between outdoor temperature and indoor air or globe temperature [30].

3 Adaptive thermal comfort in an office building

3.1 Indoor and outdoor thermal conditions

The indoor heating and cooling system in HVAC buildings causes a decoupling between outdoor and indoor temperatures. While a building is operating freely, its outer shell acts as a conduit between the inside and outside temperatures. Figure 1 shows the relationship of outdoor temperature to the globe or indoor temperature of office buildings in air-conditioned buildings and naturally ventilated or free-running from different literature [22-24,31-49]. In naturally ventilated buildings, as in Figure 1, there is a substantial interrelationship of outside temperature and indoor or globe temperature (R^2=0.72), However in air-conditioned buildings the correlation is significantly low. This suggests that, as indicated by Dhaka et al. [36] the outdoor temperature is likely to have an impact on the comfort temperature and thermal sensation in NV buildings. In contrast, regardless of the weather outside, the indoor temperature maintains in air-conditioning buildings [3]. In other types of buildings (HT, CL, & MM), the range of indoor temperatures was 22 to 27.9°C and the range of outside temperatures was 6.7 to 38°C. Outside temperatures in FR or NV structures range from 13.1 to 34°C, and inside temperatures range from 16.3 to 31.9°C [30].

3.2 Relation of indoor temperature to thermal sensation vote (TSV)

Regression analysis has been used extensively in studies to establish the comfort or neutral temperature [36, 39, 48]. The indoor comfort temperature can be proposed as the temperature where the thermal sensation vote is zero or four. TSV and indoor temperature are connected. To find the comfort temperature, regression analysis was normally been employed. A temperature shift of 3°C (=1/0.33) is claimed to modify one vote on thermal sensation, according to Fanger [50], who found a regression coefficient of 0.33 in a climate chamber. Data from several field surveys have been used to investigate the regression equation [30]. Field studies frequently found coefficients of 0.25 to 0.33 for NV buildings [22,32,39,51] and 0.2 to 0.3 for HVAC buildings [24,32,47,52]. These values imply that a temperature shift of 3 to 5 °C is needed to alter one scale unit of thermal sensation. Some field studies have regression coefficients of less than 0.2 [24,35-38,40,44,51], which means that a temperature change of more than 5°C is necessary to alter one vote for thermal sensation, it looks doubtful to estimate the comfort temperature, which shows that we should be cautious when estimating the comfort temperature using the regression method. As a result, several studies have lately begun adopting Griffiths' method [22-24,32-34,38,40].

3.3 Comfort temperature based on field studies

Many research on comfort temperature have been reviewed [30]. The comfort temperature may vary between 17.6°C and 31.2°C [22-24,31-61]. Humphreys [62] identified a comfort range of 17 to 30°C in 1978. The temperature at which occupants feel comfortable in a naturally ventilated building can vary between 17.6°C and as high as 31.2°C [40, 61], but it is substantially lower in an air-conditioned building, ranging from 20.3 to 27.5 °C [37, 47]. This suggests that because people tend to adapt in different ways, naturally ventilated buildings endure greater swings in comfort temperature.

3.3 Seasonal variations in comfort temperature

Seasonal fluctuations in comfort temperature of office buildings have been studied worldwide [30]. Seasonal changes ranging from 0.3 to 5.4 K have been revealed in several field investigations [24,36,38,40,47-49]. The seasonal variation in dwellings [62-66] is, however, larger than in office buildings as occupants of offices have fewer adaptation options than dwelling occupants. These seasonal fluctuations in comfort temperature imply that climate-specific adaptive models are needed to conserve energy in different modes of buildings.

3.4 Relation of indoor temperature to comfort temperature

Individuals have a wide variety of potential adaptive responses, and different populations encounter different environmental conditions, therefore the temperatures at which people feel comfortable should vary [2]. Figure 2 depicts the relationship between comfort temperature and indoor or globe temperature of workplaces in air-conditioned and naturally ventilated buildings. When compared to both modes, a naturally ventilated building has a better link between indoor and comfort temperature. From the given figure, we can observe that the comfort temperature is always greater than the indoor air or globe temperature if it is less than 24.5°C, and it is always less than the indoor air temperature if it is greater than 24.5°C [30].

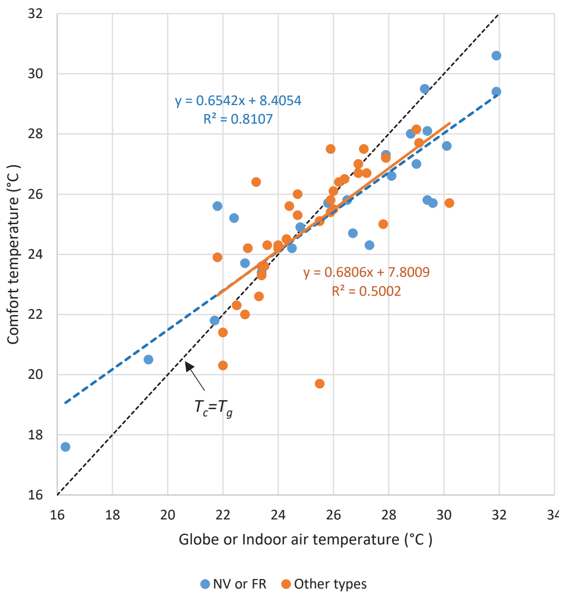

Figure 2. Relation of comfort temperature to globe or indoor air temperature [30].

3.6 Relation of comfort temperature to outdoor temperature

There is a powerful connection of outside temperature to inside comfort temperature [62]. It has been found that the comfortable condition indoors is dependent on the external temperature because people adjust well in their offices using adaptive mechanisms [2,5]. According to different thermal comfort research, the indoor comfort temperature is dependent on the outside temperature [62,67]. As a result, we can link the weather and season to the appropriate temperature for indoor comfort. Standards based on this type of connection would improve adaptive thermal comfort while simultaneously lower energy usage [68]. The link between comfort temperature and outdoor temperature will be useful in designing comfortable structures [10].

Figure 3 depicts a relationship that may be used to explain the difference in comfort temperatures between air-conditioned and naturally ventilated buildings. Individuals within naturally ventilated buildings acclimatize to the outside temperature via the building's envelope. The thermostat of a heated or cooled building, which is typically controlled by the building management, regulates the temperature, and the residents become used to of this predefined temperature. Figure 3 shows how peoples of naturally ventilated buildings have greater comfort temperatures and has better connection to outdoor temperatures than peoples of air-conditioned structures. We found the following equations using regression analysis [30].

NV buildings, $T_c = 0.43T_o + 14.93$ ($R^2 = 0.71$) (1)

HVAC buildings, $T_c = 0.22T_o + 19.45$ ($R^2 = 0.52$) (2)

MM buildings, $T_c = 0.18T_o + 20.31$ ($R^2 = 0.54$) (3)

Other type buildings (HT, CL, EC & MM)

$$T_c = 0.21T_o + 19.66 \quad (R^2 = 0.54) \quad (4)$$

The thermal design of buildings will improve from these equations. We estimated a regression coefficient of 0.43 for NV buildings, This has a greater gradient than the ASHRAE standard. Similarly, for HVAC building, we find 0.22 coefficient, which is also steeper than CIBSE guide. This could be due to the larger range of outside climatic fluctuation investigated by this study. In contrast, the regression coefficient of 0.31 obtained in MM building is more similar to that found in field studies by Manu et al. [41] and Trebilcock et al. [49].

The regression line for HVAC buildings is shown in Figure 3, and it may be used to determine if a building needs to be heated or cooled. In many situations, there ought to be a way of obtain the comfortable indoor temperature without using a heating system because the comfort indoor temperature in air-conditioned buildings is consistently higher than the mean temperature of outdoor. It is possible not to provide cooling facility in numerious situations through the careful design of building [30]. In some areas when the mean temperature of outdoor surpasses 25°C, the indoor comfortable temperature is consistently less than the mean temperature of outdoor.

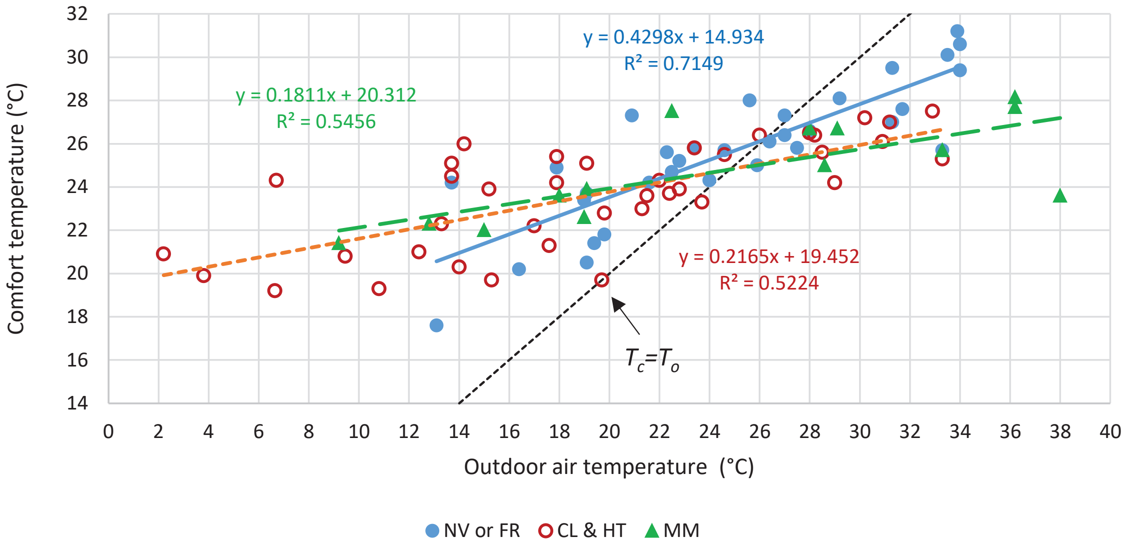

Figure 3. Relation between comfort temperature and outdoor air temperature [30].

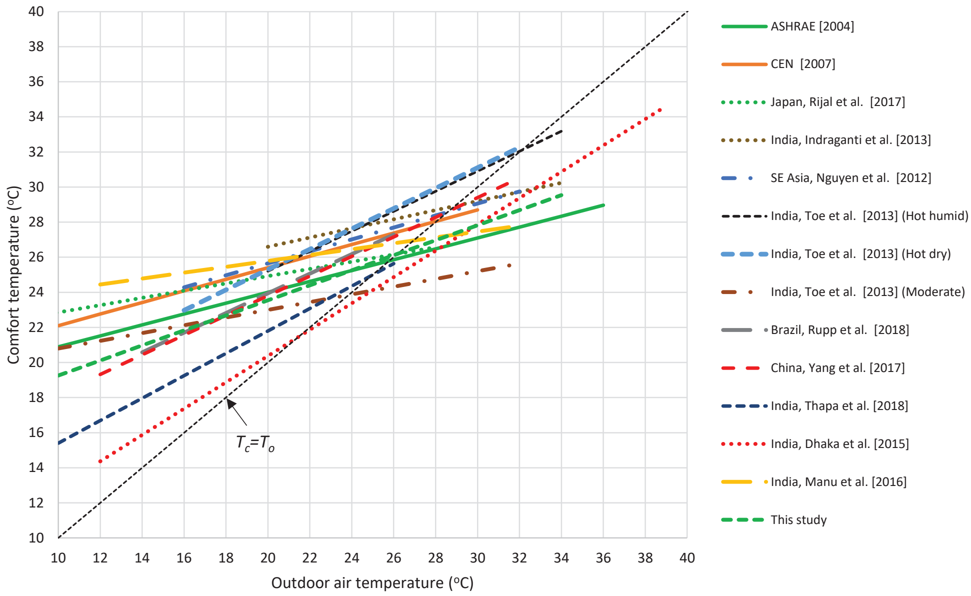

Figure 4. Adaptive thermal comfort model in NV or FR modes [30].

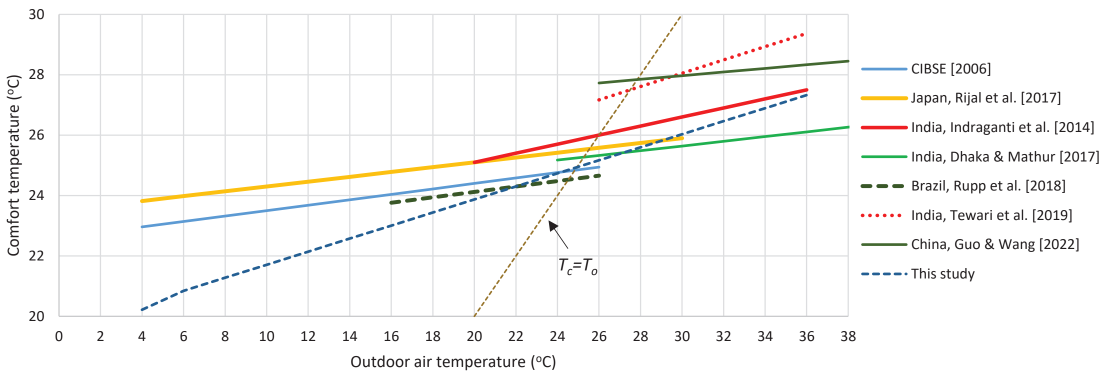

Figure 5. Adaptive thermal comfort model in CL, HT, and EC modes [30].

Adaptive model of thermal comfort from various field studies were investigated, as in Figures 4 and 5. Various studies has different adaptive thermal comfort model, and they are identical in terms of their tendency, the comfort temperature and exterior temperature are directly proportional to each other. That line's length shows the diversity of comfort temperature of a specific location. The line's length varies due to the wide range of outdoor temperatures. The comfort temperature rises as the exterior temperature rises. However, the coefficient varies across countries.

4 Energy saving by thermal adaptation

Peoples are active elements in terms of diverse adaptations, not only passive thermal environment objects [5, 65]. High energy consumption from HVAC system in order to keep precise control of the room's temperature is directly connected to human thermal adaptation [69].

4.1 Energy saving by changing temperature settings found in various studies

According to various field research [45,70-75], peoples are ready to tolerate significantly higher temperature scale than is normally been employed. Additionally, users of personal environmental control (PEC) systems have the ability to increase the allowable ambient temperature scale from 18 to 30ºC [75]. According to previous research, occupant satisfaction increases when they actively participate for the control of thermal parameter, like using the thermostat [2, 76]. Compared to homeowners, tenants of workplace has very few options of adaptations [76].

The energy consumed by HVAC system may often be reduced by 10% by improving the indoor temperature by 1 K [77]. There can be significant energy savings when the temperature setting for cooling is raised and the temperature setting for heating is lowered, according to several field studies [30]. There is no doubt that significant energy savings are possible; examples include a 37% lessen in total energy expenditures for small office buildings (1 story) in the USA [73] and a 6% decrease in expenses for office buildings of Australia by lowering set point temperature by 1°C [78]. Similar investigations done by Rijal et al. [79] and a literature review by Yang et al. [80] also corroborate above findings. Also, by implementing a passive building design and adopting various adaptation mechanisms, the HVAC system may use less energy.

4.2 Energy saving by using natural ventilation and adaptive model

Natural ventilation is a technique where, fresh outer air continually replenishes the inside air of an occupied area through the openings [81]. Natural ventilation is an effective approach to minimize building energy use. Natural ventilation has the ability to remarkably reduce HVAC system costs and energy consumption without using mechanical equipment to deliver and remove air from an indoor environment [82,83]. In North America and Europe, different advanced technologies like solar chimneys, automated window controls, and wind towers getting popular [5,84,85] and they can reduce cooling energy use by up to 40-50% in some cases [86]. Natural ventilation uses no electricity and doesn't require a mechanical system [87]. By using natural ventilation, buildings consume less energy, maintain thermal comfort, and keep occupants healthy [88]. Depending on the temperature and ambient air quality, adaptive control algorithms have been reported to save up to 27.5% of cooling energy and natural ventilation up to 78% [30]. Adaptive thermal comfort models will be benchmark to design energy efficient building since it has numerous adaptive actions such as clothing modifications and window opening.

5 Overall discussion

As shown in Figure 6, the comfort temperatures indicated by several research for NV or FR buildings are displayed on the ASHRAE 55 comfort standard. The slope of this research is steeper since the coefficient is higher than in ASHRAE 55. This might be due to the larger range of outside climate fluctuation investigated by this study [30]. The majority of the comfort temperature is determined to fall within the ASHRAE band of comfort, and comfort temperature rises as the external temperature rises. Adaptive behaviour is, as we all know, embedded into climate and society.

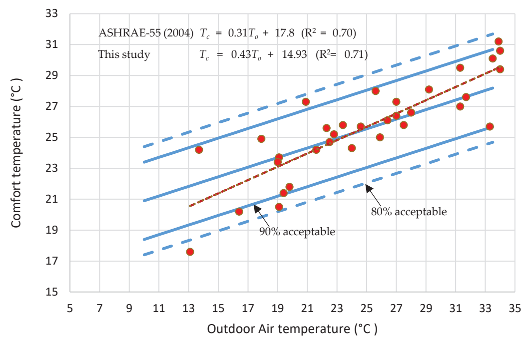

Figure 6. Plot of comfort temperatures found by several studies on comfort band of ASHRAE [30].

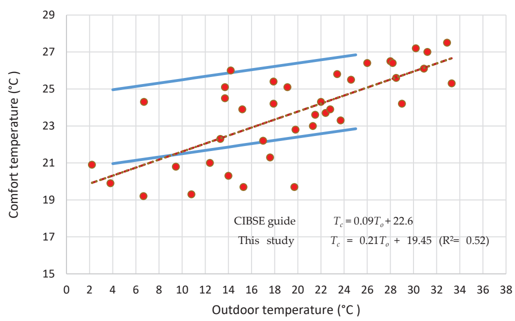

Figure 7. Comfort temperatures on CIBSE comfort bands [30].

As indicated in Figure 7, in CIBSE guide comfort temperatures from different studies of air-conditioned buildings has been mapped out. The slope of this research is steeper because the coefficient is greater than in the CIBSE guide [30]. This could be because this standard was developed in a European context, but our study included global studies. As a result, greater than 30% of comfort temperature is over the CIBSE comfort zone. Figure 7 evidently displays that the CIBSE guide in an air-conditioned building may be inappropriate in other contexts.

6 Conclusions

Based upon the literature, the following findings were made on office buildings for adaptive thermal comfort:

- Considerable association between outside and inside temperatures in naturally ventilated buildings has been seen. Nevertheless, the association is substantially weaker in air-conditioned buildings.
- When utilising the regression technique to calculate comfort temperature, we must be cautious since it may take greater than 5°C to alter one thermal sensation vote, which is inappropriate.
- A range of 17.6°C to 31.2°C can be considered to be comfortable in office buildings.
- Several field investigations have found that the seasonal change in comfort temperature in office buildings is lesser than in dwellings, ranging from 0.3 to 5.4 K.
- The new adaptive model of thermal comfort equations (1-4) has been developed based on several field studies for NV, HVAC, MM, and other types of office buildings. It will be supportive for designers to determine the comfort temperature in a different mode of the office building.
- A number of studies suggest that adjusting the set temperature and utilising natural ventilation may result in considerable energy savings.

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