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RESEARCH ARTICLE

Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates using ASHRAE RP-884 database

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Abstract

The objective of this study was to develop an adaptive thermal comfort equation for naturally ventilated buildings in hot-humid climates. The study employed statistical meta-analysis of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) RP-884 database, which covered several climatic zones. The data were carefully sorted into three climate groups including hot-humid, hot-dry, and moderate and were analyzed separately. The results revealed that the adaptive equations for hot-humid and hot-dry climates were analogous with approximate regression coefficients of 0.6, which were nearly twice those of ASHRAE and European standards 55 and EN15251, respectively. The equation using the daily mean outdoor air temperature had the highest coefficient of determination for hot-humid climate, compared with other mean temperatures that considered acclimatization of previous days. Acceptable comfort ranges showed asymmetry and leaned toward operative temperatures below thermal neutrality for all climates. In the hot-humid climate, a lower comfort limit was not observed for naturally ventilated buildings, and the adaptive equation was influenced by indoor air speed rather than indoor relative humidity. The new equation developed in this study can be applied to tropical climates and hot-humid summer seasons of temperate climates.

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1. Introduction

Defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) as that condition of mind that expresses satisfaction with the thermal environment (ASHRAE, 2010), thermal comfort is one of the most essential aspects of user satisfaction and energy consumption in buildings (Nicol et al., 2012). This subjective term is far-reaching; indoor thermal environment standards are also important factors considered in building designs. In view of the current energy challenges, such standards must balance reductions in cooling/heating energy requirements of a building with improvements in occupant comfort.

Current standards are essentially based on either heat balance or adaptive models. The most notable example of the former is the predicted mean vote (PMV) model developed by Fanger (1972), which is applied in International Organization for Standardization (ISO) 7730 (BSI, 2006) and ASHRAE Standard 55 (ASHRAE, 2010). The latter model is also used in ASHRAE Standard 55 (ASHRAE, 2010) as the code for naturally conditioned spaces and in European Standard (EN) 15251 (BSI, 2008) for buildings without mechanical cooling systems. In principle, the heat balance model analyzes thermal physiology in detail by assuming controlled steady-state conditions and high accuracy for all analyzed variables such as activity level, thermal resistance of clothing, air temperature, mean radiant temperature, relative air velocity, and water vapor pressure in ambient air (Fanger, 1972). In contrast, the adaptive model investigates the dynamic relationship between occupants and their general environments based on the principle that people tend to react to changes that produce discomfort by seeking methods of restoring their comfort levels (Humphreys and Nicol, 1998). Such adaptation encompasses physiological, psychological, and behavioral adjustments simultaneously (Brager and de Dear, 1998; Humphreys and Nicol, 1998; Humphreys et al., 2007). Therefore, the adaptive model provides greater flexibility in matching optimal indoor temperatures with outdoor climate, particularly in naturally ventilated buildings (de Dear and Brager, 2002; Deuble and de Dear, 2012; Humphreys, 1981; Nicol and Humphreys, 2010). Adaptive standards are thus considered more appropriate for supporting comfort in low-energy buildings (de Dear and Brager, 2002; Humphreys et al., 2007; Kwok and Rajkovich, 2010; Nicol and Humphreys, 2002; Nicol et al., 2012).

In hot-humid regions, many large developed and rapidly developing cities face increasing energy use for air-conditioning in buildings. Natural ventilation is a traditional, well-accepted passive cooling technique used in such regions. Previous studies have shown that the PMV model covers narrow ranges of moderate climatic conditions and is not applicable to warm environments in buildings (Humphreys and Nicol, 2002). Because climatic context is a primary consideration in the adaptive model, it is imperative to evaluate the comfort requirements of people worldwide, particularly in tropical regions that lack comprehensive standards (Nicol, 2004; Toe and Kubota, 2011).

General standards may not be appropriate for all climates, however. In a Brazilian study, Cândido et al. (2010, 2011) demonstrated that although thermal acceptability was determined to be within the ASHRAE adaptive standard (ASHRAE, 2010), occupants required more air velocity. They proposed minimum air velocity at three ranges of operative temperature including 0.4 m/s at 24–27 °C, 0.41–0.8 m/s at 27–29 °C, and >0.81 m/s at 29–31 °C (Cândido et al., 2011). In addition, they determined that neutral operative temperatures were nearly the same as mean daily outdoor air temperatures at Brazil's northeast coast (Cândido et al., 2011). This relationship had a higher gradient than those specified in the existing adaptive standards (ASHRAE, 2010; BSI, 2008).

On the contrary, Nguyen et al. (2012) determined that the adaptive algorithm of EN15251 (BSI, 2008) was appropriate to their adaptive comfort equation derived from southeast Asian studies in naturally ventilated buildings. They indicated that air velocity and humidity were negligible factors in comfort temperature (Nguyen et al., 2012). However, their database and analysis also contained data of mild cold-dry seasons (Nguyen et al., 2012). These conflicting results warrant further investigation through collective analysis of larger regions that share a clearly defined similar climate.

One of the main methods applied to form the adaptive model is meta-analysis of a larger database that includes several thermal comfort field surveys. Several such resources include the Humphreys 1975–81 database (Humphreys, 1981); the ASHRAE RP-884 database (de Dear, 1998; de Dear et al., 1997), which was used to develop the ASHRAE adaptive standard (ASHRAE, 2010); and the European Smart Controls and Thermal Comfort (SCATs) Project database (McCartney and Nicol, 2002), which was used to develop the EN15251 adaptive standard (BSI, 2008). Among these well-established resources, the comprehensive ASHRAE RP-884 database, which consistently covers several climatic zones including hot-humid, has been analyzed by numerous researchers including Arens et al. (2009, 2010), de Dear et al. (1997), de Dear and Brager (1998), Farghal and Wagner (2010), Humphreys et al. (2007, 2010), Humphreys and Nicol (2000a, 2000b, 2002, 2004), Nicol (2004), Schweiker and Shukuya (2012), and Toftum (2004). However, with the exceptions of Nicol (2004) and Farghal and Wagner (2010), none of these studies explored climatic classification; that is, data from different climates were not analyzed separately. To examine the relationship between comfort and humidity, Nicol (2004) classified the data from ASHRAE RP-884 into three datasets according to mean outdoor relative humidity. His study suggested that occupants may require comfort temperatures approximately 1 °C lower than that specified by the overall data when the outdoor relative humidity is greater than 75%.

In addition, Farghal and Wagner (2010) used the ASHRAE RP-884 database to classify naturally ventilated buildings into seven climatic zones among which significant differences were noted in thermal neutralities. Their analysis utilized only a mean neutral temperature for each building