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The influence of relative humidity on adaptive thermal comfort

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ABSTRACT

Buildings generate nearly 30% of global carbon emissions, primarily due to the need to heat or cool them to meet acceptable indoor temperatures. In the last 20 years, the empirically derived adaptive model of thermal comfort has emerged as a powerful alternative to fixed set-point driven design. However, current adaptive standards offer a simple linear relationship between the outdoor temperature and the indoor comfort temperature, assumed to sufficiently explain the effect of all other variables, *e.g.* relative humidity (RH) and air velocity. The lack of a signal for RH is particularly surprising given its well-known impact on comfort. Attempts in the literature to either explain the lack of such a signal or demonstrate its existence, remain scattered, unsubstantiated and localised. In this paper we demonstrate, for the first time, that a humidity signal exists in adaptive thermal comfort using global data to form two separate lines of evidence: a meta-analysis of summary data from 63 field studies and detailed field data from 39 naturally ventilated buildings over 8 climate types. We implicate *method selection* in previous work as the likely cause of failure to detect this signal, by demonstrating that our chosen method has a 56% lower error rate. We derive a new designer-friendly RH-inclusive adaptive model that significantly extends the range of acceptable indoor conditions for designing low-energy naturally-conditioned buildings all over the world. This is demonstrated through parametric simulations in 13 global locations, which reveal that the current model overestimates overheating by 30% compared to the new one.

1. Introduction

According to the ANSI/ASHRAE Standard 55–2013 [1], thermal comfort is 'that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation'. Indoor thermal comfort is among the most important factors affecting occupant well-being, health and productivity in buildings [2]. This is important since people spend up to 90% of their time inside buildings, especially in developed countries [3]. However, typical buildings impose a substantive energy cost to heat or cool them to the desired comfort level. In developed countries, with largely saturated demand, this is estimated to be 20–40% of the total final energy use and nearly 30% of all CO_2 emissions [4,5]. This makes the building sector the single largest contributor to global CO_2 production and hence climate change. Thermal comfort standards are therefore central to not merely providing comfortable environments but also ensuring a sustainable design through low heating and cooling energy use in buildings.

Two types of comfort standards currently prevail in the literature: *steady-state* and *adaptive*. The steady-state model, pioneered by P.O. Fanger in the late 1960s, is a heat-balance model that defines combinations of a set of six indoor environmental variables that will provide acceptable thermal conditions to the majority of occupants [6]. The six variables are: air temperature, mean radiant temperature, air movement, relative humidity, clothing insulation and metabolic heat generated by human activity. These are folded into an empirical relationship to provide a Predicted Mean Vote (*PMV*) of thermal comfort, underpinned by the idea of a *neutral temperature* for a given value of the other parameters. In contrast, the relatively recent development of the ASHRAE adaptive model [1] and its European counterpart [7] are based on the idea that the range of acceptable temperatures in naturally ventilated (NV) buildings is larger than in air-conditioned (AC) buildings and dependent *purely* on the prevailing external temperature. Using large scale survey data, such as the ASHRAE RP-884 database [8,9], from different climatic zones around the world, these models derive a simple linear relationship between the indoor comfort temperature and the outdoor temperature.

According to Nicol and Humphreys [10], the reason for this extreme simplification is that some of Fanger's conventional

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thermal comfort factors, *i.e.* clothing insulation and metabolic rate, are significantly correlated to the outdoor air temperature. Interestingly, although relative humidity and air velocity are not shown to strongly depend on the outdoor air temperature [11], their effect is not seen to be large enough to warrant inclusion in the model [12]. However, their importance in determining physiological thermal comfort is well documented [13]. It is known, for example, that high indoor humidity impairs sweat-induced evaporative cooling, which is the principal physiological mechanism by which the body rejects heat, particularly in warm environments [14–18]. Air movement also influences the evaporative and convective heat exchange to and from the body, affecting its temperature [19].

The absence of a signal for relative humidity (RH) is surprising since outdoor humidity is likely to have a bigger effect on indoor humidity than parameters such as occupant density (which increases indoor moisture production) or window operation (which could decrease indoor humidity if external humidity is lower). This is supported by Fig. 1, which shows that the Pearson correlation coefficient between mean daily indoor (*RH*) and outdoor (*RHout*) relative humidity in the ASHRAE RP-884 database is significantly higher in naturally ventilated (0.52) than in air-conditioned (0.33) buildings. Hence, one might expect that the comfort response in NV buildings is significantly mediated by the internal relative humidity, which in turn is a function of the external humidity.

External and internal air velocities, on the other hand, are likely to be decoupled since occupant control of ventilation through window operation and use of fans is likely to have at least as great an influence on the indoor air velocity as the prevailing outdoor weather conditions. Since increased occupant control is now well established as a critical component in increasing occupant satisfaction [20], the absence of an air velocity signal could therefore be hypothesised to be due to the studied buildings having good occupant control of windows and fans [8]. However, unlike RH, the absence of recorded external wind data in the ASHRAE RP-884 database precludes a test of this hypothesis.

The lack of a clear humidity signal, upon which to differentiate adaptive indoor comfort in the present models, is therefore puzzling, and the subject of much previous work in the field [12,21–23]. However, no clear explanation for the lack of a humidity signal or a convincing formulation of the effect of humidity on adaptive thermal comfort has hereto emerged.

To address this, we begin by examining the effect of RH on occupant thermal sensitivity through an analysis of the regression gradient in Section 2. This analysis provides the first clear evidence that RH has a measurable impact on occupant thermal sensation. A second independent line of evidence emerges from the analysis in Section 3, which compares the ability of a range of statistical methods already used in the literature against new candidate methods, to explain the data contained in ASHRAE RP-884 database. Although both methods independently verify our hypothesis that RH has an important role to play in adaptive thermal comfort, neither is capable of a practical formulation that can be used by practitioners. Hence, using the knowledge gained in Sections 2 and 3, we cast the RP-884 data within a new formulation, but one that has the strength of being familiar to practitioners. This provides a new adaptive comfort model selectable by different classes of humidity. Finally, Section 5 demonstrates the use of the new model in building performance assessment across a range of global climates.

2. The effect of relative humidity on occupant thermal sensitivity

The current adaptive thermal comfort models are derived using a simple linear regression of neutral temperatures against the corresponding mean outdoor air temperatures, acquired through field studies. The neutral temperature is defined as the indoor temperature which an average occupant finds neither warm nor cool, hence *neutral* [24]. This has historically been determined using two methods:

- By regressing the Thermal Sensation Vote (*TSV*) against the indoor temperature, with the neutral temperature corresponding to a $TSV = 0$ [25]. Three different types of linear regression are used in the literature: simple, binned (*i.e.* binning the *TSV* in 0.5 °C or 1 °C intervals) and weighted binned, where the weights are the number of votes in each interval. The gradient of the linear regression fitted between the *TSV* and the indoor temperature indicates the temperature perturbation needed for a change of 1 unit in *TSV*. It is therefore a measure of occupant sensitivity to indoor temperature changes and gives the degree to which a population can adapt to variations in the thermal environment. Lower gradients can be associated with more effectively adapted and less sensitive occupants [26]. A lower slope is also indicative of a larger comfort band which means that occupants can tolerate exposure to a wider range of indoor temperatures [22,25,27].
- By using the Griffiths method. Here, the neutral temperature T_n is derived through the following equation:

$$T_n = T_m - TSV_m / G \qquad (1)$$

Where TSV_m is the mean Thermal Sensation Vote, T_m is the mean

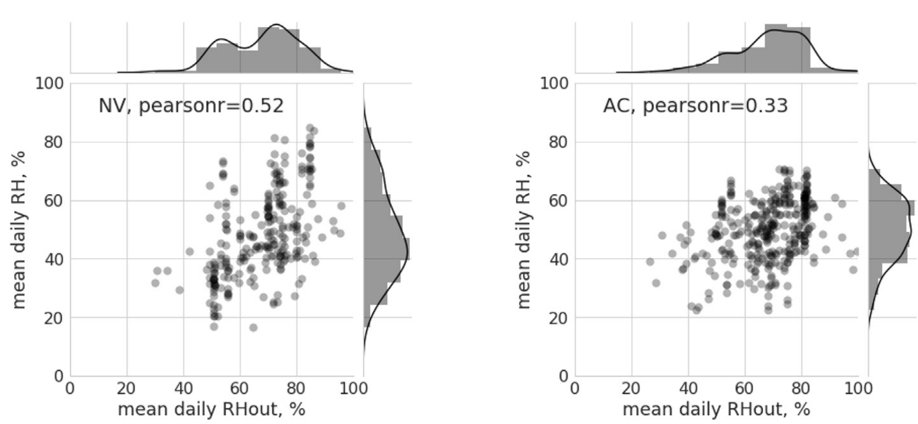

Fig. 1. Scatterplot and histograms with kernel density estimates (derived using a Gaussian characteristic function) of mean daily indoor (*RH*) and outdoor (*RHout*) relative humidity for the ASHRAE RP-884 naturally ventilated (NV, left) and air-conditioned (AC, right) buildings. The number 'pearsonr' is the Pearson correlation coefficient.