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A field study of indoor thermal comfort in the subtropical highland climate of Bogota, Colombia

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ABSTRACT

This paper undertakes the first field study of indoor thermal comfort in Colombia. The objective of this study was to compare thermal comfort data gathered in office buildings in Bogota, Colombia with the predictions made by three well established standards: ISO 7730:2005 (PMV model), ANSI/ASHRAE Standard 55:2013 (adaptive model) and EN Standard 15251 (adaptive model). The study comprised the administration of a thermal assessment survey to 115 participants and the simultaneous measurement of indoor and outdoor physical variables in 3 offices having different ventilation regimes (natural ventilation, mechanical ventilation and mixed-mode i.e. both natural ventilation and air-conditioning). The findings show that the PMV model incorporated in the ISO 7730 as well as in the ASHRAE standard (which is the standard currently adopted in Colombia for regulating indoor environmental parameters) is able to describe comfort conditions in the mechanically ventilated (MV) office. In the case of the naturally ventilated office (NV), results indicate that the PMV model is not successful at estimating occupants' thermal sensations, and underestimates occupants' perception of discomfort. The EN 15251 adaptive model underestimates thermal discomfort in the NV and MM offices. The ASHRAE adaptive model shows similar patterns underestimating discomfort in the NV office. The findings provide robust evidence that the lack of perceived or actual control in low-energy naturally ventilated buildings strongly reduce occupants' thermal comfort and thus invalidate adaptive model predictions.

1. Introduction

Human thermal comfort has been a subject of research for more than a century, in parallel to the ever more prevalent role of air-conditioning in the market [1]. That research has produced significant findings and developments and has led to the advent of standardisation. Thermal comfort standards have been established in order to allow the measurement and evaluation of those thermal environments humans are usually exposed to [2].

In the late 1960s, P.O. Fanger, pioneer of the thermal comfort research, created a static heat-balance model with the aim of defining a referenced set of indoor environmental variables which were able to provide acceptable thermal conditions to the majority of the occupants [3,4]. Fanger's model led to the definition of the well known PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indices which were firstly incorporated into the ISO international standard in 1984.

However, Fanger's model was only intended for application in artificially controlled spaces; the problem of defining thermal comfort conditions in naturally ventilated environments has led to the conceptualization of the adaptive model of thermal comfort which was firstly introduced by Nicol and Humphreys in the 1970s [5] and, then, incorporated in 2004 into the ASHRAE Standard 55 thanks to the research of Brager and De dear [6].

The evidence underpinning those models has been obtained either in climate chambers (Fanger' conventional model) or in actual buildings (adaptive models). Fanger's model is based on experiments conducted in climate chambers in Denmark and the United States [4]. The adaptive model of the ASHRAE Standard 55 is based on data collected in the 1990s by de Dear and Brager as part of the ASHRAE Project RP-884 [6] involving field measurements in Thailand, Indonesia, Singapore, Pakistan, Greece, UK, USA, Canada and Australia. The adaptive model described by Nicol and Humphreys (EN Standard 15251) is based on data collected in the EU Project Smart Controls and Thermal Comfort (SCATs) [7] which involved a 3-years survey of 26 European buildings in France, Greece, Portugal, Sweden and the UK.

Therefore, despite being termed international standards, these standards are based on data from a limited number of geographical regions of the world focusing on Europe, North America, Asia and Australia.

Field studies are fundamental for assessing existing comfort

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Nomenclature

Cll 72-NV naturally ventilated office
Cll 93-MV mechanically ventilated office
Cll 100-MM mixed-mode office

standards in other regions of the world and for developing new algorithms defining comfort conditions in different climates and cultures. The assessment of the applicability of thermal comfort standards requires field data comprising both objective sensor data (air temperature, globe temperature, relative humidity and air speed) and subjective data (actual thermal sensations recorded at the same time as the objective data, thermal preferences etc.).

This paper intends to compare thermal comfort data gathered in a field study in Bogota, Colombia with the comfort predictions and temperature values recommended and regarded as universal by the international comfort standards ISO 7730:2005 [2], ASHRAE Standard 55-2013 [8] and EN Standard 15251 [9].

1.1. Bogota's climatic characteristics

Bogota's local climate is influenced by two key factors: its latitude and its elevation. Bogota's elevation is 2600 m above sea level. It is well known that there is a clear correlation between elevation and average annual temperatures. For this reason, although tropical latitudes are usually associated with tropical climates which are characterized by a lowest mean monthly air temperature never under 18 °C [10], the annual average temperature in Bogota is only 14.2 °C, between a mean minimum of 8.4 °C and a mean maximum of 19.7 °C [11]; the region has a subtropical highland climate which is oceanic rather than tropical. The Köppen–Geiger climate classification for Bogota is Cfb [10].

Studies have shown that cognitive and affective expectations-as identified by de Dear [1] -are not take into account in chamber studies [3]. For that reason, field studies of the same populations have shown consistent differences in relation to the comfort temperatures predicted by Fanger's heat-balance model [1,12–14]. It has been even suggested that the tropics might require a different level of comfort consideration from that currently provided in the standards [15]. In consequence, existing literature not only indicates that there is room for expanding the study of thermal comfort in tropical regions, but also highlights the fact that not enough internationally-recognised research has been done in the tropical zone of the Americas [16].

Furthermore, the particular climatic conditions of Bogota (which belongs to a tropical area but experiences a subtropical highland climate) are very different than those usually experienced in tropical latitudes. Bogota's climate is characterized by narrow variations of annual temperatures and precipitations distributed all year around, which are typical features of oceanic climates [10]. Therefore, the study of thermal comfort conditions in Bogota is of particular interest for three main reasons:

- to the authors' knowledge, no previous thermal comfort study has been carried out for this type of climate;
- the similarity with an oceanic climate makes extremely interesting to assess if international standards can be applied;
- the benefits of the knowledge that a study on this matter could bring, are not circumscribed to the particular interest of Bogota, but would suit also other cities under the same climatic conditions (subtropical highland climate); for example Pasto and Tunja (regional capitals in Colombia), Quito and Cuenca (national and regional capital respectively, in Ecuador), and Cajamarca (regional capital in Peru). This could potentially help to inform building codes in these countries.

1.2. Colombia's background

The existing building code in Colombia mainly deals with the suitability of the structural response of a building to seismic forces and incorporates some regulations related to fire protection [17]. Thermal comfort in buildings is only regulated by the Standard NTC 5316 [18] which is a Spanish translation of the ANSI/ASHRAE Standard 55. As outlined before, the ANSI/ASHRAE Standard 55 is based on studies from a limited number of geographical regions of the world focusing on Europe, North America, Asia and Australia and, therefore, could fail in predicting neutral temperatures in Colombia; this could consequently affect the need and the design of AC systems leading to higher energy consumptions and obvious environmental issues. Furthermore, the ANSI/ASHRAE Standard 55 categorizes mixed-mode buildings into the air-conditioned group (i.e. under the PMV model) and limits the applicability of the adaptive model to strictly naturally ventilated buildings without mechanical cooling system installed, therefore it is interesting to verify if the adaptive model is also applicable for these "special" mixed-mode buildings which have the potential to reduce energy consumption for cooling [19].

From the adaptive model proposed by ASHRAE, the acceptable operative temperature range for a naturally conditioned space under a mean monthly outdoor temperature of 14.2 °C (which is the annual average temperature in Bogota) would be between 18.7 °C and 25.7 °C for a 80% acceptability (see Fig. 1) [8]. Since the temperature in Bogota varies between a mean minimum of 8.4 °C and a mean maximum of 19.7 °C, the temperature range 18.7–25.7 °C is easily maintainable inside buildings. This could partially explain the absence of widespread heating or cooling systems in buildings in Bogota. Consequently, it could be argued that a sensible approach to passive design has the potential to produce a thermally comfortable indoor environment without the need of additional conditioning.

Concerns about climate change are also important drivers in relation to research in thermal comfort. Models presented by the Government of Colombia show that temperatures in Bogota could increase between 2 °C and 4 °C by the end of the century [20], which would be directly linked to conditions inside buildings and therefore to potential increases in energy consumption.

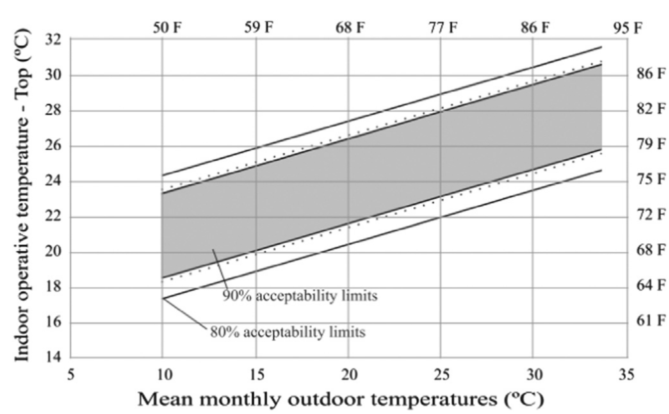

Fig. 1. Acceptable operative temperature ranges for naturally conditioned spaces according to the adaptive model proposed by ANSI/ASHRAE Standard 55:2013.