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Modelling study of the impact of thermal comfort criteria on housing energy use in Australia

Zhengen Ren*, Dong Chen

CSIRO Land and Water, Private Bag 10, Clayton South 3169, Victoria, Australia

HIGHLIGHTS

- Impact of thermal comfort acceptability limit on housing energy use.
- Relaxing the acceptability limits has minor impact in regions without hot summer.
- Decrease from 90% to 70% in the acceptability can save energy by 40% in Darwin.
- Cooling energy can be minimized in tropical regions for lightweight houses.

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ABSTRACT

It is an increasing challenge for building designers in the 21st century to provide for thermal comfort at minimum energy cost by taking into consideration both the current and the future warming climate. Most previous studies have focused on thermal comfort in non-residential buildings under current climatic conditions. This study evaluates the impact of thermal comfort criteria by lowering the acceptability limits on space cooling energy requirements for Australian residential buildings, under both the current and projected future climates (with an assumed global warming of 2 °C) through building simulations using three different types of typical building constructions – lightweight, heavyweight, and a combination. The results show that under both current and future climates, relaxing thermal comfort criteria by lowering the acceptability limits from 90% to 70%, has a small or minor impact on space cooling energy consumption for the heavyweight and combination type construction in the subtropics (Brisbane), warm temperate (Sydney), temperate (Melbourne) and cool temperate (Hobart) climate regions. However, it has significant impact on space cooling energy consumption (saving more than 40%) in tropical regions (e.g. Darwin) and regions with a hot summer climate (e.g. Alice Springs and Mildura). For the lightweight type construction under the current climate, relaxing the acceptability limits will increase the energy star rating by 3.6 stars in Darwin, 0.5 star in Mildura, 0.3 star in Alice Springs and 0.2 star in Brisbane. Under the projected future climate, relaxing the acceptability limits to 70% will increase the energy star rating by 1.6 stars in Darwin, 1.2 stars in Brisbane, 0.7 star in Alice Springs and 0.3 star in Mildura. It was also found that for all the climates, relaxing the acceptability limits from 90% to 80% has greater impact than that from 80% to 70%. By relaxing the acceptability limits, the space cooling energy consumption can be minimized in tropical and subtropical regions for high set lightweight houses.

1. Introduction

Globally, buildings consume around 70% of end-use energy for space heating, cooling, ventilation and artificial lighting [1]. As demonstrated in the literature [2], high energy consumption of air-conditioning is not necessarily required to achieve thermal comfort in many cases. Large amounts of energy can be saved by allowing air-conditioning systems to operate under a wider range of indoor temperature fluctuations. In recent years, thermal comfort in buildings has attracted the attention of many researchers worldwide, partly due to the increased public awareness of climate change [1]. Given the increasing costs of energy and the awareness of climate change, it is increasingly necessary to optimize thermal comfort settings to consider both energy use and climate change together.

In ASHRAE 55 [3], thermal comfort is defined as “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. Apart from cultural influences, thermal comfort depends upon environmental and personal factors. It is

* Corresponding author.
E-mail address: zhengen.ren@csiro.au (Z. Ren).

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complicated to predict the range of temperatures for this comfort condition. Thermal comfort has been discussed since 1930s. Climate chamber tests and field studies are two approaches used in the field of thermal comfort. Steady-state models were developed from climate chamber tests, which were based on heat exchange processes of the body, such as the widely used Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD) model [4]. Most of the steady-state models were developed prior to the field studies.

Field studies conducted in real buildings led to adaptive thermal comfort models, which were based on the adaptive principle that occupants are active and not passive (the PMV method) relating to their thermal environment, i.e., “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” [5]. To do that, occupants may change their clothing, posture, activity, etc. or change their surrounding environment using windows, blinds, fans and in certain conditions mechanical space heating or cooling. People may also move around to find a room with improved conditions. Under the hypothesis of adaptive thermal comfort where people gradually lessen the human response to repeated environmental stimulation through both behavioural and physiological as well as psychological adaptation, and the fact that past thermal history will modify the occupant’s thermal expectations and preferences, people in warm climates will prefer higher indoor temperatures than those living in cold climates [6]. A number of studies show that the range of comfort temperatures in naturally ventilated buildings or mixed-mode buildings is much wider than what PMV-PPD predict [7–10].

The adaptive method was developed from field studies in mainly naturally ventilated office buildings [6,11–16] by relating indoor operative temperatures (acceptable ranges) to prevailing outdoor temperatures. The acceptable range is the comfort temperature band within which the great majority of people, described by the percentage of acceptability, are adequately comfortable. This acceptable temperature range is wider than ‘ideal’ conditions and would encompass feeling such as ‘slightly cool’, ‘slightly warm’ and ‘neutral’. Thermal comfort is subjective and personal, and there may be no single condition that is comfortable for all the occupants at any given time. Furthermore, the heating and cooling capacities required would be prohibitive if the acceptable temperature range has to be met for 100% of the occupancy time, even during extreme weather conditions [17].

Thermal comfort studies in buildings have been recently reviewed [1,18–21]. These studies discussed the research on steady-state and adaptive thermal comfort, as well as thermal comfort standards for naturally ventilated, air-conditioned and mixed buildings. Field studies in educational, office, residential and other building types were also examined. A number of other studies [22–28], have focused on the investigation of thermal comfort and energy efficiency. As mentioned in [20], in general, these studies of the energy use implications of thermal comfort in built environment can be grouped into two areas: case studies (HVAC, heated or cooled buildings) and implications for thermal comfort standards.

Most of the case studies for heating and cooling of buildings focused on increasing the summer set point temperature (SST) or setting a variable indoor set point temperatures for different times of the day and different outdoor conditions. Two major types of control strategies were proposed. The first type involved diverse thermostat techniques through changing the setback period, set point temperature, and setback temperature [29]. To have a better understanding the trade-off between thermal comfort and energy consumption, attempts have also been made [30,31] to correlate cooling energy consumption with corresponding thermostat operational mode. The second type of control strategy covered deals with the dynamic control of the set point temperature based on adaptive thermal comfort models [32,33]. Case studies summarized in [20] show that substantial energy can be saved for both office and residential buildings, ranging from 6% reduction in HVAC electricity usage in Australian office buildings (by increasing 1 °C in the SST) [34] up to a 33.6% reduction in total energy cost in hot desert region in Riyadh [35].

To offer a uniform method for the building industry and the general public, many studies have been undertaken on the implications of thermal comfort standards since early 2000s, including the works by de Dear and Brager [10] for global general buildings; Van der Linder et al. [36] for office buildings in Netherlands; Ogbonna and Harris [37] for classroom, studio and residential buildings in Nigeria; Nicol and Humphreys [38] for global general buildings; Nicol and Humphreys [13] for office building in Europe; Roaf et al. [39] for global general buildings; Yao, Liu and Li [40] for university classroom buildings in China; Indraganti [41] for residential buildings in India; Panao, Camelo and Goncalves [42] for residential and “small service” buildings in Portugal; Cândido et al. [43] for non-domestic buildings in Brazil; Yun, Kong and Kim [44] for office buildings in South Korea; Liang, Lin and Hwang [45] for school buildings in Taiwan; and Li et al. [46] for two types of buildings (heated/cooled or free-running mode) in China.

Nowadays the international standards commonly used to evaluate the thermal environments are ISO 7730-2005 [47], ASHRAE 55-2013 [3] and EN 15251-2007 [48]. The Predicted Mean Vote-Predicted Percentage Dissatisfied (PMV-PPD) method, which was based on Fanger’s theory [4], is the basis of ISO 7730-2005 and the Graphic and Analytical Comfort Zone methods in the ASHRAE 55-2013 standards. Both EN 15251-2007 and ASHRAE 55-2013 standards adopted the adaptive thermal comfort method for the evaluation of the indoor environment of naturally ventilated buildings. The ISO 7730-2005 standard does not incorporate the adaptive thermal comfort method, but specifies the thermal indoor environment to be within 70% of the acceptability limit for naturally ventilated buildings [17]. For naturally conditioned spaces, ASHRAE 55-2013 specifies the acceptability limit to be 80%. To meet high occupant expectations of thermal environments, the acceptability limit of 90% is specified in ASHRAE55-2013. The PPD is the complement of the thermal acceptability. For the three acceptability limits mentioned above the PPD are 30%, 20% and 10% respectively.

Most previous studies have been concentrated on non-residential buildings. Compared to non-residential buildings, occupants of residential houses generally have greater opportunities (subject to the capabilities of the building and its systems) to decide and create thermal comfort conditions themselves. Given the large overall energy consumption from the residential sector, increasing energy prices, and changing climate, there is an increasing interest in the study of impact of different thermal comfort models (standards) on residential energy consumption. For instance, Attia and Carlucci [49] conducted a simulation study to compare the impact of four models (Fanger’s model in ISO 7730, the ASHRAE55 adaptive comfort model, the EN15251 adaptive model and Givoni’s model) on energy consumption and thermal performance for a zero energy multi-residential building in hot climates. This study shows, that to meet the thermal comfort criteria according to ISO 7730 in comparison to EN1521, ASHRAE 55 or Givoni’s model, the percentage of energy consumption difference varied up to 16%, 21% and 24.7%, respectively. Kim et al. [50] carried out a field study of air conditioning and thermal comfort in residential buildings in Sydney and Wollongong, Australia. They found that the comfort zone widths for 80% acceptability were 9 K in residential settings, which is 2 K wider than that expected by the adaptive model. Shiel et al. [51] presented a simulation case study to estimate the space heating and cooling energy of a one-bedroom residential building in a warm temperate climate (Adelaide, South Australia) with global warming using alternative Standard Effective Temperature (SET*) comfort approaches. For the SET* comfort approaches, the acceptability limits of 90% and 80% were also evaluated. The results from their study showed that the SET*80% approach with air movement, changed clothing and occupant acclimatization can save over 95% of the Nationwide House Energy Rating Scheme (NatHERS) residential heating and cooling energy. Shiel et al. [51] suggested that more research is needed for the inclusion in NatHERS.