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In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands

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ABSTRACT

Reducing energy consumption in the residential sector is an imperative EU goal until 2020. An important boundary condition in buildings is that energy savings shouldn't be achieved at the expense of thermal comfort. There is, however, little known about comfort perception in residential buildings and its relation to the PMV theory. In this research an in-situ method for real time measurements of the quantitative and qualitative parameters that affect thermal comfort as well as the reported thermal comfort perception was developed and applied in 30 residential dwellings in the Netherlands. Quantitative data (air temperature, relative humidity, presence) have been wirelessly gathered with 5 min interval for 6 months. The thermal sensation was gathered wirelessly as well, using a battery powered comfort dial. Other qualitative data (metabolic activity, clothing, actions related to thermal comfort) were collected twice a day using a diary. The data analysis showed that while the neutral temperatures are well predicted by the PMV method, the cold and warm sensations are not. It seems that people reported (on a statistically significant way) comfortable sensation while the PMV method doesn't predict it, indicating a certain level of psychological adaptation to expectations. Additionally it was found that, although clothing and metabolic activities were similar among tenants of houses with different thermal quality, the neutral temperature was different: in houses with a good energy rating, the neutral temperature was higher than in houses with a poor rating.

1. Introduction

The built environment is responsible for about 40% of total energy use in Europe. Of this 40%, 63% is related to residential energy consumption [1]. European and national regulations like the Energy Performance of Buildings Directive EPBD and specific parts of national building codes aim to reducing the energy consumption of buildings in order to achieve the goals set for emissions and resource consumption by 2020.

The prediction and assessment of the energy consumption of residential dwellings is an important means to this end. Building performance simulation is a widely accepted method for this purpose. Buildings are highly complex systems in their own right. Both new buildings and renovated ones that are equipped with new heating and ventilation systems have high performance requirements that are closely related to EU sustainability goals for 2020. Increasing the reliability of building performance simulations can make an important contribution to reduction of the energy consumption of residential building stock.

The need for increased reliability of building simulations is also closely related to the discrepancy between actual and predicted energy use in the residential building sector. Researchers in the Netherlands and elsewhere have found a substantial gap between actual and predicted energy use in residential dwellings, with the worst dwellings (those with an energy rating of F or G) consuming significantly less energy than expected while dwellings with a higher energy rating consume more [2]. One reason for this discrepancy could be limited information on the building's thermal envelope and installations (more obvious in older dwellings where no records are available on the materials used). Another important reason is related to a misunderstanding or underestimation of the role of the occupant's behaviour [3,4,5]. Simulation software in its current form has very limited capabilities for taking the energy-related behaviour of the occupant into account. There is a clear need to take this behaviour into account during the design phase of new residential buildings or the renovation phase of older ones [3,4,6,7].

An important requirement both for new dwellings and for the refurbishment of older ones is that thermal comfort should be maintained or improved. Many commercially available simulation

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packages for the calculation of the energy consumption of buildings such as ESP-r, TRNSYS and Energy+ use the ISO 7730 method [8] for the assessment of occupants' thermal comfort. This seems to work well for office buildings, but not for residential buildings [9]. The ISO 7730 method, developed by P.O. Fanger, predicts perceived thermal comfort as a function of metabolic activity, clothing level and the four classical environmental parameters air temperature, mean radiant temperature, air velocity and humidity. Although Fanger's formulations were based on a sound physical model, the general validity of the statistically derived parameters is doubtful [9]. The thermal responses of occupants of residential and office buildings recorded in various countries differ from the predicted values [10,11,12,13,14,15] though Humphreys showed, in a world-wide data set of 16,762 cases with various settings, that the perceived thermal comfort agreed quite well with the model's predictions [15]. This means that it is very difficult to draw general conclusions for specific local settings, despite the model's strong physical basis.

Residential dwellings, unlike office buildings, include zones with variable thermal comfort requirements, are characterised by less predictable activities and provide more ways for the tenant to adapt to his thermal environment in order to reach the desired comfort level [16]. These conditions in these residential settings differ greatly from those applying in the climate chamber Fanger used to develop the PMV thermal comfort index.

Temperature levels and profiles in dwellings are expected to have an important effect on the energy consumption for heating and tenants' thermal comfort [17,18,19]. Furthermore, the operative temperature is a critical component of the PMV comfort index.

Various studies have derived indoor temperature profiles for the residential built environment but they differ in the methods used, the length of the monitoring period and the season when measurements were made. In many cases, temperature sensors with data recording intervals of 15, 30, 45 or 60 min were used [20–30]. The duration of the measurement campaign varied from 1 to 4 weeks [25,31] in some studies, while in others it covered the whole heating period (December to April in one northern European country (Belgium) [31]; a study in one southern Mediterranean country (Greece) [24] also covered the whole heating period –one that is much shorter than northern European countries like the Netherlands or Belgium. In one study the tenants were given the temperature sensor together with the operating manual and were invited to install it themselves [26], which could lower the accuracy of the measured data. In all these studies the data were collected locally in data loggers and had to be retrieved manually. Other studies used questionnaires or diaries for recording the temperatures where the tenants had to fill in the required information [32,33]. This probably led to large uncertainties, as no measurements were performed.

The aim of the present paper is to provide information on a kit for in-situ real-time measurement of the quantitative and qualitative parameters that affect thermal comfort on the reported tenant's thermal sensation and finally to present the resulting analysis of energy-related occupant behaviour (in particular the parameters that affect the PMV comfort index). This is important because thermal comfort may affect largely occupant behaviour, which relates to energy consumption and which in turn is an important factor for the discrepancy between actual and theoretical energy consumption in the residential dwellings.

The results presented here are taken from the Ecommon (Energy and Comfort Monitoring) campaign which took place in the Netherlands as part of the Monicair [34], SusLab [35] and Installaties 2020 [36] projects. Thirty-two residential dwellings (classified by energy rating and types of heating and ventilation system) were monitored for a 6-month period, from October 2014 to April 2015, which is the heating season for north Western Europe. Quantitative data (air temperature, relative humidity, CO_2 level and movement) for each room in the dwellings (living room, kitchen, bedroom 1 and bedroom 2 or study) were collected wirelessly at 5-min intervals. In addition, qualitative data (thermal sensation, metabolic activity, clothing, actions during the previous half hour related to thermal comfort) were collected over a 2-week period by two different methods, wirelessly and by entries in a manual log (see Section 2.3.2). The wireless device used to capture the thermal sensation of the tenants was time-coupled with the sensors for the quantitative data. This allowed the thermal sensation of the tenants at any given time to be time-coupled with the exact atmospheric conditions (temperature T, relative humidity RH and CO2 level), which could improve the reliability of the PMV calculations (see Section 2.3.1). All data (quantitative and qualitative) were available for inspection and analysis in real time throughout the whole campaign via a remote desktop application.

The next chapter describes the research questions, the design of this study, the way the campaign was set up, the data acquisition equipment and the data management system. The results follow in chapter 3 which first presents the neutral operative temperatures, per room type, derived from the PMV calculations and the recorded thermal sensation of the tenants. Further on, the relationship between the reported thermal sensation and the calculated PMV is explored in order to further validate the ability of the PMV index to predict the tenant's real thermal sensation. The next two sections (3.4 and 3.5) describe the clothing and metabolic activity of the tenants during the measurement campaign against the operative temperature and thermal sensation. Further, the clo and met values that correspond to the neutral thermal sensation of the tenants were calculated and the effect of the inaccuracy of these values was researched. Finally, a section with discussion, conclusions and recommendations conclude the present study.

2. Study design

Comfort has seldom been researched on site in actual conditions, and even more rarely has been measured in other ways than using surveys. The main research questions in this paper aim to determine whether it is possible to make such measurements and how the results of these measurements compete with already existing insights from PMV theory.

2.1. Research questions

The goals of this study are:

1) To perform in-situ real-time measurement of quantitative and qualitative data on comfort and occupant behaviour and their underlying parameters in an easy, unobtrusive way, in a residential environment.
2) To determine the tenants' temperature perception in relation to the energy rating and the ventilation and heating systems used in the dwellings.
3) To determine the type of clothing worn by the tenants and their activity levels in relation to the thermal sensation of the occupants.
4) To determine the neutral temperature levels calculated by the PMV method and to compare them to the neutral temperatures derived from the measurements thermal sensation.
5) To determine to what extent the PMV comfort index agrees with the thermal sensation reported by the tenants.
6) To determine if there is a relationship between the type of clothing and metabolic activity with thermal sensation and the indoor operative temperature.