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Characteristics of indoor temperatures over winter for Belgrade urban dwellings: Indications of thermal comfort and space heating energy demand

M. Kavgic[a,*], A. Summerfield[b], D. Mumovic[a], Z.M. Stevanovic[c], V. Turanjanin[c], Z.Z. Stevanovic[c]

[a] The Bartlett School of Graduate Studies, University College London, Gower Street, WC1E 6BT London, UK
[b] Energy Institute, University College London, Gower Street, WC1E 6BT London, UK
[c] Institute of Nuclear Sciences-Vinca, University of Belgrade, PO Box 522, 11001 Belgrade, Serbia

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ABSTRACT

A lack of empirical data for residential indoor temperature has important implications for policymakers in terms of energy performance objectives and the use of energy demand models for the building stock. This study investigates winter indoor temperatures, relative humidity and vapour pressure excess in 2009–2010 across various types and ages of buildings using half-hourly monitoring of 96 dwellings representative of residential buildings in Belgrade, including those with district heating (DH) with no direct occupant control in which heating is charged on a floor area basis. The average daily living room temperature of 22.8 °C (95%CI: 21.9–22.7) in DH dwellings was 2.3 °C higher than those with other heating types, including individual central heating (ICH) and non-central heating (non-CH), daily bedroom temperature of 22.3 °C (95%CI: 21.9–22.7) was 3.0 °C higher. Evening living room and night bedroom temperatures in ICH dwellings were 22% and 37% of the time respectively below 18 °C, and 10% and 27% of the time respectively in non-CH dwellings. The high degree of overheating in DH dwellings indicates the considerable potential to reduce energy consumption, if user controls and heating bills reflected household consumption were introduced.

1. Introduction

Indoor temperature and humidity in dwellings are key indicators of occupant thermal comfort, air quality and associated health issues, such as the prevalence of allergens and mould growth. Indoor temperature also drives energy consumption via the occupant demand for space heating and cooling relative to external conditions. In a recent study of centrally heated dwellings in the UK, it was found that a 10% rise in the heating demand temperature, for instance changing the thermostat setting from 20 to 22 °C, resulted in a 15% increase in energy consumption [1]. However the relationship is not straightforward as the temperatures demanded and attained by occupants are in turn influenced by building attributes, such as the thermal and air infiltration properties of the building envelope, the type of heating system and its control systems [2–4].

If from a technical perspective some of the physical determinants of indoor temperature appear well established, the empirical evidence from studies of occupied dwellings is relatively scarce. An early study of spot (daytime) temperatures from UK dwellings found that centrally heated dwellings were on average 3 °C warmer than dwellings without central heating [4]. A more recent study of low income homes found that under standardised external conditions of 5 °C median daytime living room and bedroom temperatures were 19.1 °C and 17.1 °C respectively, and these increased to 20.7 °C and 19.9 °C after energy efficiency measures and installation of central heating. Surveys of ‘low-energy’ homes in the UK (that have insulation and double glazing) have also found that these houses were heated to higher average temperatures and had less variation in temperature across the dwelling than expected from the earlier findings. While studies have found variations in mean temperature, in the diurnal range of temperatures, and temperatures across different parts of the dwelling, these findings are often from studies of a particular social group (such as low income households) [3,5] or dwellings built to special energy standards (such as passive and low-energy house) [6], or for a specific geographical location or climate [4,7,8]. Overall, there is scarce empirical evidence for indoor temperatures directly relevant to the characteristics of the central European building stock and climatic conditions.

Accurate information about indoor temperature has become increasingly important over the last decade as governments in Europe and elsewhere move to adopt policies aimed at reducing carbon emissions through improvements to the building stock. While many energy models are available to support policy development by predicting changes to energy consumption as a result of

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* Corresponding author.
E-mail address: miroslava.kavgic@gmail.com (M. Kavgic).

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energy efficiency measures it is often not clear what assumptions for consequent variations in indoor temperature are being made or their empirical basis. In some cases they are based on operating conditions that have been deemed as standard, rather than from field measurements. For instance British Research Establishment's Domestic Energy Model (BREDEM) assumes that the living room is heated to 21 °C and other premises to 18 °C for 9 h on weekdays and for 16 h on weekends [9]. Others have used novel indirect methods, such as occupancy pattern modelling from household employment data [10], to improve estimates of indoor temperature for the UK. Moreover the adaptive model for comfort temperature has highlighted the dynamic role of occupants in modifying indoor temperature settings as a response to changing external seasonal and climatic conditions [11].

Another issue that needs to be considered for effective policy formulation is the efficiency of the upgrade programmes as improvements to building fabric and/or changes in heating systems often result in higher thermal comfort levels rather lower energy use, termed as 'take back' or the 'rebound' effect. Although it is assumed that as building energy performance is increased the amount of 'take back' is limited to an upper level that corresponds with neutral temperature settings ∼21–22 [12], the extent this is supported by empirical measurement is unclear. District heating, whereby space heating is essentially unconstrained and without economic consequences, may provide the opportunity to estimate this neutral temperature that corresponds with an upper level of 'take back' temperature, by identifying the level that occupants reduce indoor temperature.

Many of residential buildings in Belgrade have high infiltration of outdoor air, moisture penetration into the walls, inadequate indoor temperatures and thus luck of thermal comfort [13,14]. Consequently, average household energy use of 240 kWh/m^2 per annum [15] is about 2.5 times greater in Belgrade than in the Northern European countries with more severe climate [16], and the largest share (∼70%) is spent on space heating [13]. While average household space heating energy use per square metre of living area in apartments is 124 kWh/m^{2}per annum in single-family houses it is 30–40% higher [13,17] Furthermore, old and poorly maintained buildings can consume 2–3 times more energy for space heating than the new buildings [13].

This paper aims: (a) to describe the variation in temperature, relative humidity (RH) and vapour pressure excess (VPX) across various types residential buildings, with a range of constructions dates corresponding to changes in building standards, and different heating systems; (b) to look for evidence of insufficient heating in dwellings without district heating or central heating; (c) to use district heated dwellings to identify a 'saturation' or maximum demand temperature set by occupants when heating is effectively unconstrained by costs; and (d) to provide insight into temperature, RH and VPX in households occupied by different age groups. The study has involved detailed temperature and humidity monitoring for over a year of a representative sample of dwellings of residential buildings in Belgrade.

2. Methodology

2.1. The Belgrade's residential temperature and relative humidity study

A modified multi-stage stratified sampling method was used to divide the Belgrade housing stock into homogenous groups 'strata' according to four building characteristics: location (urban, suburban), building type, year built, and space heating system. The number of housing units for monitoring in each stratum has been allocated proportionately, except for gas heated homes where oversampling was carried out to ensure sufficient numbers in the sample from this group, as they currently represents only 2% of the Belgrade's housing stock [15,18]. A convenience sample method was used to recruit 96 participants in the study from employees at the 'Vinca' Institute of Nuclear Sciences. Measurements of temperature and RH in living room and bedroom were obtained in the 92 households. Data from four dwellings were incomplete or omitted from the study due to the misplacement of data loggers, and sudden 'illness', and 'personal problems' of occupants. Information about household socio-demographic characteristics (i.e., type of municipality, occupant age and number of occupants), dwelling's characteristics (i.e., type of dwelling, year built, upgrade, and type of primary space heating system) and ownership and use of home appliances (i.e., frequency of cooking) were obtained from interview surveys conducted in the home.

Using HOBO data loggers (temperature range: −20 to 70 °C; RH range: 5–95%; temperature accuracy: ±0.35; RH accuracy ±2.5) measurements for temperature and RH were recorded the living room and bedroom of each dwelling at half-hourly intervals from 15 April 2009 to 15 April 2010. Loggers were placed by the surveyor at around a height of 1.5 m, away from direct solar radiation, external walls, air conditioning devices, and devices that generate heat. Hourly external temperature and RH were obtained from the Republic Hydro-meteorological Service of Serbia [19]. Belgrade is under the influence of the moderate continental climate with long and snowy cold winters, hot summers, often with heavy rain showers, short springs, and longer autumns characterised by frequent sunny and warm periods. The mean monthly temperature levels during the survey were within the 95% confidence interval of the 20 years average for the period November–April, and were on average 7.0 °C compared to 7.7 °C for the average for winter conditions in Belgrade in the last 20 years.

2.2. Outcome measures

For each dwelling mean daily (24 h) temperature, RH and VPX were calculated for the living room and bedroom as well as daily living room and bedroom standardised temperatures, RH and VPX. Mean temperature, RH and VPX were also calculated for different periods in the day: morning (06:00–09:00), daytime (09:00–16:00), evening (16:00–22:00), and night (22:00–06:00).

2.3. Covariates

District type: Each dwelling was categorised according to *urban* (i.e., inner city) or *sub-urban* districts.

Building type: Buildings have been divided into two categories, namely: apartments located in the multi-storey buildings and single-family houses. Apartments typically consist of a living room adjacent to the kitchen (often open space), two bedrooms and a bathroom. The single-family houses have one or predominantly two floors where the lower floor comprises of kitchens and living areas and the upper floors, bedrooms and bathrooms.

Year built: Periods were based on the timing of the Building Regulations that prescribed changes in the thermal characteristics of building envelopes. The four periods identified were: 1946–1970; 1971–1980; 1981–1997; and 1998–2006. The effect of year built on variation in indoor temperature has been tested only on non-upgraded dwellings. Buildings built after 2006 have not been included within the research project due to the non-existing data. The explanation for omitting building constructed prior-1946 is given elsewhere [20].

Heating system type: For assessing the effect of type of heating system upon measured temperatures and RH, the sample has been divided into three categories, namely: district heating (DH), individual central heating (ICH) and non-central heating (non-CH).