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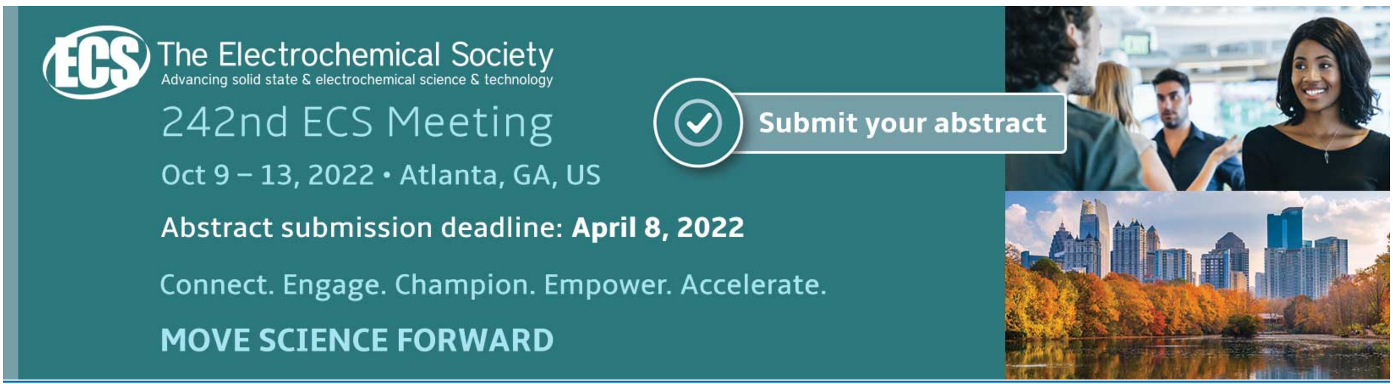

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A large field study of relationship between indoor and outdoor climate in residential buildings

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Abstract. High-quality data on indoor climate and energy collected in buildings is required to deepen our understanding of building performance. The aim of this work was to investigate the relationship between the indoor and outdoor climate in Danish residential buildings. Field data was collected in 45 apartments from April 2019 to November 2020. Internet of things (IoT) devices were installed to record the temperature, relative humidity and CO_2 concentration in the central corridor of each apartment. High CO_2 concentration (above 1,000ppm) and overheating were observed in the apartments. The changeover between the heating mode and the free running mode occurred between 11.1 to 13.6 ºC of outdoor air temperature. The temperature setpoints of the heating systems were around 20.6-22.3 ºC, which could be useful values to feed building simulations in order to achieve more realistic predictions of indoor climate and energy. The results of this study improve our understanding of indoor environmental quality in residential buildings at a national level.

1. Introduction

The indoor environment is known to be associated with occupants' comfort, health and performance and impacts building energy consumption. The building envelope and its systems regulate the indoor climate and should be designed and controlled following the outdoor climate. Findings from some studies [1,2] conducted in similar residential environments suggested differences in indoor climate and energy consumption depending on how the environments were operated. A better understanding of occupants' behaviour, setpoints, loads, etc. is therefore crucial to improve energy predictions using building simulation tools, for which high-quality data collected in actual buildings are necessary. A large field campaign in residential buildings in Denmark was performed to acquire information on indoor environmental quality. In this work, the aim was to investigate the relationship between indoor and outdoor climate in a multifamily residential building in Copenhagen.

2. Data and method

Field data collection was performed in a typical multifamily residential building in Copenhagen with brick wall façade and ceramic roof tiles, totalling 45 apartments. Most apartment units have a floor area of 66 m^2 with few larger units up to 93 m^2. All apartments are heated by radiators/convectors connected to a central water-based heating system and equipped with operable windows.

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2.1. Data collection
IoT devices were installed in a central corridor in each apartment to record the indoor air temperature, relative humidity and CO_2 concentration at 5-min intervals. Outdoor air temperature was also collected. Measurements were conducted from April 2019 to November 2020.

2.2. Data analysis
The measured indoor temperature was plotted against the running mean outdoor air temperature, which was calculated using the daily outdoor air temperature, and analyzed considering the 80 and 90% acceptability limits from ASHRAE 55 adaptive thermal comfort model [3]. The running mean outdoor air temperature is an exponentially weighted running mean of the daily mean outdoor air temperatures, as shown in ASHRAE 55 [3].

Piecewise regression analysis was conducted between the hourly indoor and the outdoor temperature for each apartment. The data is composed of temperature measurements during the heating and non-heating periods (where the apartments were free running). Compared to a linear regression model, piecewise regression has the advantage of accounting for the non-linear relationship between indoor and outdoor temperatures. During the heating period, the indoor temperatures are likely to be disconnected from outdoor temperatures, while during the free running mode the indoor temperatures tend to fluctuate according to the outdoor temperatures. This method allows multiple linear models to be fitted to the data for different ranges of the explanatory variable (in our empirical set up, the outdoor air temperature). Piecewise regression was applied by [4] to analyse the relationship between the indoor and outdoor air temperature in homes located in Boston, USA. The value of outdoor air temperature where a change in the slope of the linear models occurs is called a breakpoint. In this work, the breakpoint is an indication of the apartments' operation mode. The heating system was on at lower outdoor air temperatures (below the breakpoint). Above the breakpoint, the apartments' indoor temperature was affected by the outdoor temperature.

3. Results and final remarks
Table 1 presents a summary of the indoor climate in all surveyed apartments. The hourly indoor air temperature ranged from 16.7 ºC in winter to 28.8 ºC in summer and the hourly indoor air relative humidity varied from 17.1% to 74.7%. The indoor air temperature and relative humidity distribution were marked by the heating period and the free running mode. Overall, the mean CO_2 concentration levels were high, especially in winter where in several occasions the threshold of 1,000ppm adopted by Danish building regulations was exceeded. This is concerning since such values are the mean of the hour and indicate an insufficient removal of pollutants through ventilation.

Table 1. Summary of hourly indoor climate condition in the apartments.

Parameters	N	Mean	S.D.
Indoor air temperature (ºC)	14,044	22.7	1.9
Relative humidity (%)	14,044	45	9
CO_2 concentration (ppm)	14,044	838	453

3.1. Analysing the relationship between indoor and outdoor climate
Figure 1 presents the hourly indoor air temperature plotted against the running mean outdoor air temperature considering all 45 apartments. The adaptive thermal comfort model from ASHRAE 55 and the percentage of time outside the 80 and 90% acceptability limits are also shown in Figure 1 -the model is applicable between 10.0 and 33.5ºC of running mean outdoor air temperature. Overall, thermal conditions were within the acceptability limits, except for few overheating hours.

Overall, results from the piecewise regression analysis indicated a weak association between the indoor and the outdoor air temperature during the heating period (low values of the correlation coefficient, *r*), and the slopes of the linear models were close to zero (0). In contrast, indoor temperatures increased with increasing outdoor air temperature during the free running mode (slopes of the linear models varied between 0.32-0.38), as predicted by the adaptive model, and both variables were highly correlated (r > 0.7). Figure 2 shows the results for an apartment. In this case, the breakpoint was 11.1ºC (but it varied from this value up to 13.6ºC when considering all apartments). The mean indoor temperature for the heating mode (i.e. values below the breakpoint) was 20.6ºC (up to 22.3 ºC when considering the whole sample). This exemplifies the different behaviors with regard to the heating system. The mean indoor air temperatures may be used as an example of heating setpoint for building simulations and the breakpoints as an example of the transition between heating period and free running mode in Danish apartments.

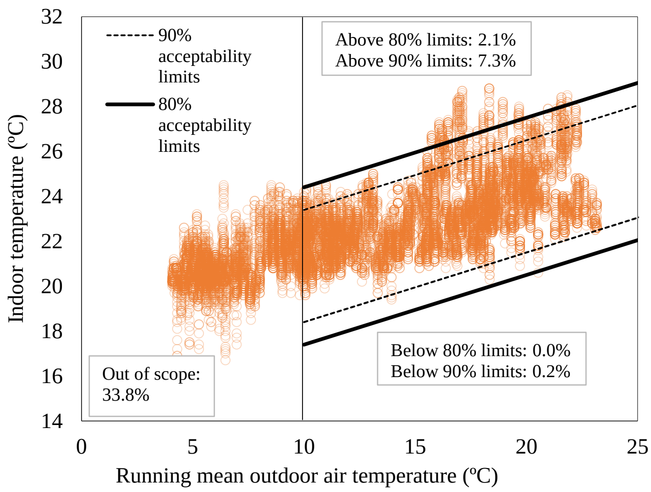

Figure 1. Indoor temperature plotted against the running mean outdoor air temperature. ASHRAE 55 adaptive model limits indicated in the figure along with percentage of time outside the 80 and 90% limits.

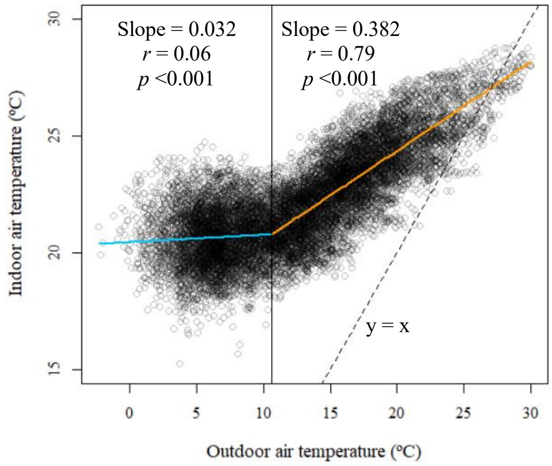

Figure 2. Piecewise regression between hourly indoor and outdoor air temperature for an apartment. Model intercept=20.44, R^2=0.65, N=13,992.

3.2. *Final comments*

The work presented herein is part of a larger project where more than 1,000 apartments are being investigated across Denmark, involving indoor environment and energy measurements. To our knowledge, the database is the most comprehensive sample of indoor environmental parameters in residential buildings. Future research will contribute to a better understanding of the indoor climate and energy in multifamily residential buildings at a national level.

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