Circadian winter thermal profiles and thermal comfort in historical housing – field study

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Abstract. In winter thermally inefficient building envelopes of pre-retrofit historical housing allow for ca. sevenfold higher heat loss from heated apartments than the new built housing in Poland. As a result space heating in pre-retrofit tenements is regarded to be highly energy demanding and costly if the internal temperatures were to be kept on average at standard 20°C assumed in building regulations. In this field study, carried out in January-March 2020, we investigated circadian thermal profiles and the associated thermal comfort in historical tenements both pre- and post-retrofit. The 16 apartments participating in our research were equipped with heating systems prevalent in Polish urban historical buildings, i.e. solid fuel stoves, electric heating, district-supplied central heating, or individual gas boilers. The former systems provided intermittent local heating while the latter central heating with thermostats. Our research comprised spot check multi-parameter measurements and continuous monitoring of the thermal environment, together with a longitudinal thermal comfort questionnaire survey (N=2539), energy consumption analysis and semi-structured interviews with the residents. The differences detected in average (12.6°C) and range (up to 5.0°C) of diurnal temperatures did not explain the thermal comfort survey results on individual thermal sensations and preferences. What proved more important for the residents was the time of day when the maximum or minimum temperatures occurred and their perceived control over temperature and the cost associated with heating. Accordingly, we identified a need for further studies investigating the link between domestic thermal comfort and satisfaction with the usability of the heating system and control over the cost of heating.

1. Introduction
Most of the overall energy consumed in historic housing located in colder climates is related to space heating, addressing the residents’ need for thermal comfort [1][2]. Where solid fuel combustion is used for heating purposes striving for thermal comfort contributes also to air pollution [3]. In Poland, the thermally inefficient building envelopes of pre-retrofit historical housing allow for ca. sevenfold higher heat loss from heated apartments than the new built housing [4][5]. As a result space heating in pre-retrofit tenements is regarded to be highly energy demanding and costly if the internal temperatures were to be kept on average at standard 20°C assumed in building regulations [6]. A better understanding of the actual thermal conditions and the related perceptions is needed for the residents using different heating systems in buildings of pre- and post-energy retrofit historic housing. The key question related to different heating systems and building envelope standards explored here is their ability to deliver
thermal conditions matching the residents’ capabilities and expectations. In other words the link between the residents control over their thermal environment and the related thermal perceptions and preferences is sought.

Control over thermal environment is one of the drivers of the observed diversity in individual comfort votes [7]. Studies in the office environment suggest that control was one of the strongest predictors of thermal comfort [8][9]. Available, but not exercised control (adaptive opportunity) and perceived control (expectation) are categorised as psychological aspects in thermal comfort analysis [7]. The exercised control (behavioural adjustment) changes the thermal environment hence belongs to the contextual drivers of diversity of thermal perceptions. There is a lack of thermal comfort studies that analyse thermal comfort votes in the context of control over a thermal environment in a domestic environment.

This paper aims to contribute to filling this gap in knowledge by analysing circadian winter thermal profiles and the related thermal responses for known types of heating systems, building energy standards and occupancy profiles. These three categories define different levels of control over thermal environment for the residents of the 16 apartments in historic tenements covered by this study. First the methods and case study characteristics are briefly introduced. Next analysis and results are presented. The following discussion links the findings with the physiological contribution to understanding the expectations related to circadian thermal profiles. Conclusions indicate the need for further studies.

2. Method
All the thermal field data was collected across 6-8 weeks between January-March 2020 in nine historic tenements in 16 participating apartments privately owned (4) and social (12). The field study consisted of spot check multi-parameter measurements and continuous monitoring of the thermal environment, together with a longitudinal thermal comfort questionnaire survey, as well as the assessment of energy consumption [5][10].

2.1 Thermal environment monitoring
The multi-parameter measurements were performed during two or three research visits. They were carried out using Testo 400 Universal IAQ Instrument measuring temperature (NTC ±0.5 °C), air velocity (hot wire ±(0.03 m/s + 4 % of mv)), air humidity (±2 %RH), absolute pressure (±3.0 hPa), ambient CO₂ concentration (±(50 ppm + 3 % of mv) from 0 to 5000 ppm) and radiant temperature (Class 1 according to standard EN 60584-2). The measurements were carried out usually in the main room in each apartment and with the long term measurements they were used to create long term comfort model (PMV, PPD, PMV’, PPD’).

The long term inside air parameters’ measurements were carried out using data loggers. The Comet System U3430 data logger for temperature (±0.4 °C), relative humidity (± 1.8 % RH ) and CO₂ concentration (±(50ppm +2% measured value)). Testo 174H - Mini temperature (±0.5 °C) and humidity (±3 %RH) data logger. Testo 175T2 – Temperature (±0.5 °C) data logger + measuring probe (surface temperature ±0.2 °C). The measurements were carried out in each room of the apartment.

2.2 Thermal comfort questionnaire survey
During the whole research period, the inhabitants were asked to fill in the thermal comfort questionnaire survey possibly a few times a day. The questions concerned Thermal Sensation Vote (from −3 to +3), Thermal Preference Vote (from −2 to +2), the worn clothing (used for CLO parameter estimation) and activity performed during last 15 minutes (used for MET parameter estimation). The participants were asked if the thermal conditions are acceptable or not and about the circumstances that might influence the thermal sensations (fatigue, hunger, illness, etc.).

2.3 Case study characteristics
The key characteristics of the 16 apartments and households participating in the study are presented in Table 1. All the apartments are located in close vicinity in tenements built at the beginning of the 20.
century. However current technical and energy standard of the buildings is varied, with some in pre- and post-thermal retrofit. The apartments are equipped with heating systems prevalent in Polish urban historical buildings, i.e. solid fuel stoves, electric heating, district-supplied central heating, or individual gas boilers. The former systems provide intermittent local heating while the latter central heating with thermostats or/and thermostatic valves.

### Table 1. Case study characteristics.

| Apt. no. | Floor area (m²) | Main heating system; additional heating | Building envelope standard | Surrounding internal spaces b | Residents gender & age | Employment status c | Available control: thermal environment |
|----------|----------------|----------------------------------------|---------------------------|-------------------------------|------------------------|-------------------|----------------------------------------|
| SF1      | 41.4           | SF; E: 5 heaters                        | Pre-retrofit              | MU                            | M59, F55               | W                 | low                                    |
| SF2      | 41.5           | SF; E: 1 heater                         | Pre-retrofit              | PU                            | F68                    | R                 | medium                                 |
| SF3      | 40.7           | SF; E: 1 heater                         | Pre-retrofit              | PU                            | F68                    | R                 | medium                                 |
| SF4      | 47.4           | SF; 2 stoves                            | Pre-retrofit              | H                             | F49                    | W + S             | low                                    |
| E1       | 34.5           | E: tiled stove (day-night tariff)       | Pre-retrofit              | MU                            | M66, F69               | R                 | low                                    |
| E2       | 54.5           | E: 3 portable heaters                   | Pre-retrofit              | H                             | F55                    | W                 | medium                                 |
| E3       | 62.9           | E: 1 portable heater                    | Pre-retrofit              | PU                            | F60                    | R                 | medium                                 |
| E4       | 50.0           | E: 1 storage heater (day-nigh tariff); E: 1 heater | Pre-retrofit              | H                             | F58                    | W                 | medium                                 |
| DH1      | 44.1           | DH                                      | Post-retrofit             | PU                            | M68, F33, F71          | R                 | high                                   |
| DH2      | 76.1           | DH                                      | Part. retrofitted         | H                             | M62, M63, F59          | W                 | high                                   |
| DH3      | 83.5           | DH                                      | Post-retrofit             | PU                            | M11, M13, M31, F36    | W                 | high                                   |
| DH4      | 59.8           | DH + E (bathroom)                       | Post-retrofit             | PU                            | M12, M42, F36          | W + S             | high                                   |
| G1       | 52.5           | G                                       | Part. retrofitted         | H                             | M26, F30               | W                 | medium                                 |
| G2       | 85.0           | G; SF: wood                             | Post-retrofit             | PU                            | M36, M70, F36, F70    | W + R             | high                                   |
| G3       | 55.9           | G                                       | Part. retrofitted         | PU                            | M4, M29, F27, F48     | W                 | high                                   |
| G4       | 128.5          | G                                       | Post-retrofit             | H                             | M26, F17, F54, F81    | W + R + S         | high                                   |

a SF: solid fuel tiled stove, E: electric heaters, DH: district heating, G: gas boiler central heating, b MU: mostly unheated, PU: partially unheated, H: heated, c W: working full time, R: retired, S: student

### 3. Key results

### Table 2. Internal parameters and questionnaire survey results.

| Case | Ti in the main room (°C) | Ti daily mean (°C) | Ti daily range (°C) | Daily mean Top 30-minutes average | TSV average | TPV average |
|------|--------------------------|--------------------|---------------------|----------------------------------|-------------|-------------|
|      | max  | min  | med  | max  | min  | max  | min  | max  | min  | max  | min  | female | male | female | male |
| SF1  | 25.0 | 18.7 | 21.6 | 22.6 | 19.8 | 3.8  | 1.5  | 22.2 | 18.1 | 0.01 | -0.10 | 1.16   | 1.72   |
| SF2  | 21.4 | 14.0 | 17.6 | 17.8 | 17.2 | 4.6  | 0.2  | 19.1 | 17.2 | 0.76 | 0.23  | 0.91 |
| SF3  | 20.6 | 10.7 | 17.5 | 17.8 | 17.3 | 3.4  | 0.6  | 18.7 | 16.7 | 0.02 | -0.02 | 0.00   | 0.23   |
| SF4  | 24.1 | 18.3 | 19.8 | 20.1 | 19.7 | 3.6  | 0.2  | 18.5 | 17.9 | -0.73 | 0.90  | 0.00   |
| E1   | 23.8 | 11.8 | 17.4 | 19.7 | 12.3 | 2.5  | 0.4  | 18.4 | 16.7 | 0.00 | 0.22  | 0.00   | 0.23   |
| E2   | 20.5 | 16.9 | 18.8 | 19.2 | 18.8 | 2.6  | 0.5  | 19.5 | 19.0 | 0.00 | 0.00  | 0.00   |
| E3   | 25.3 | 17.7 | 22.2 | 22.5 | 21.8 | 5.0  | 0.1  | 22.2 | 21.0 | 0.57 | 0.39  | 0.07   |
| E4   | 28.0 | 21.0 | 22.0 | 25.0 | 22.2 | 1.5  | 0.0  | 22.9 | 20.7 | 0.33 | 0.07  | 0.16   | 0.03   |
| DH1  | 20.3 | 17.3 | 19.3 | 19.3 | 19.2 | 0.9  | 0.0  | 20.0 | 19.3 | -0.05 | 0.00  | 1.16   | 0.03   |
| DH2  | 23.0 | 20.3 | 21.6 | 20.9 | 20.0 | 2.9  | 0.0  | 21.3 | 20.5 | 0.16 | 0.05  | 0.05   |
| DH3  | 21.0 | 16.1 | 18.1 | 22.6 | 19.5 | 3.1  | 0.0  | 22.2 | 20.9 | -0.21 | -0.44 | 0.05   | 0.19   |
| DH4  | 21.5 | 13.8 | 18.2 | 19.6 | 18.9 | 4.1  | 0.2  | 20.4 | 20.0 | 0.38 | -0.25 | 0.50   | 0.19   |
| G1   | 25.5 | 18.3 | 21.9 | 24.9 | 18.7 | 4.2  | 0.8  | 22.7 | 20.9 | 0.51 | 0.95  | 0.00   | -0.53  |
| G2   | 27.5 | 18.5 | 20.5 | 21.5 | 20.1 | 2.3  | 0.5  | 20.9 | 20.2 | -0.09 | -0.24 | 0.08   | 0.24   |
| G3   | 24.6 | 20.3 | 22.7 | 23.4 | 20.4 | 3.1  | 0.3  | 23.9 | 22.1 | 0.79 | 0.27  | 0.27   |
| G4   | 23.8 | 19.5 | 21.5 | 23.0 | 21.1 | 3.7  | 1.2  | 22.8 | 21.2 | 1.15 | 0.40  | 0.03   | -0.25  |
3.1 Thermal conditions and key survey results (TSV and TPV)

Internal parameters of the investigated rooms and the results of the questionnaire survey are presented in Table 2.

3.2 Circadian analyses: thermal profiles and TSV, TPV

![Figure 1. Circadian operative temp. profiles in the main room: 30-min mean temp. for weekdays for the whole measuring period.](image)

Circadian profiles of operative 30-minutes mean temperatures for the main room of each apartment for weekdays of the monitoring period is presented (Figure 1). The weekends are excluded from this analysis, as they offer higher control opportunities for solid fuel heated households than during weekdays, when full time working adults are away for most of the day and cannot attend to the stoves in the morning. The thermal profiles between the apartments are contrasting not only in terms of the range of circadian operative 30-min mean (0°C for SF4, i.e. stable 24-hours profile up to 2.7°C for SF1, i.e. fluctuating 24-hours profile) but also time of day when peak or minimum temperatures occur. In some the temperatures are highest in the middle of the night and coldest in the afternoon and in others the opposite. Interestingly the 30-min. mean temperature minimum for SF1 (19.1°C) is slightly higher than the peak for SF3 (18.7°C) but they both occur in the afternoon between 4 - 5p.m. Analysis of thermal sensation and preference votes reveal that the latter is much better received by the residents (Figure 3). Overall the coolest apartments are heated with solid fuel, namely: SF2, SF3, SF4 and electricity (day-night tariff): EL1. All of these, as well as the remaining electrically heated apartments in pre-retrofit buildings with low radiant temperature of internal surfaces, often adjacent to under heated or unheated apartments further adding to heating load for those striving for thermal comfort. In such context the residents of SF1 are able to maintain an average daily operative temperature of up to 22.2°C, however to do so, they keep the indoor temperature on a very high level – even up to 28°C with the median Ti equal 21.6°C during measuring period (Table 2). With the high heat losses the residents struggle to maintain comfort conditions as revealed by the highest range of daily 30-min mean operative
temperature. Fuel poor E1[3] is the coldest in our sample with the mean temperatures (median = 17.4°C) close to the SF ranges. However thermal sensation and preference votes for E1 suggest relative satisfaction with thermal conditions despite low temperatures (Table 2, Figure 3). The key hypothesis to explain this is that the satisfaction of keeping the cost of energy at an affordable level, thus being in control over spending on heating leads to accepting the associated thermal conditions. Centrally heated apartments with district heating or gas boilers, mostly in post-retrofit buildings, have higher and more stable temperatures.

**Figure 2** Operative temperature distribution (navy-blue points) and 30 minutes mean (orange points) for pre-retrofit solid heating system (S3) and post-retrofit district heating central system (DH3).

Circadian scatter plot diagram shows operative temperatures for two apartments with contrasting thermal profiles characteristic for the different heating systems examined in our sample: SF3 in pre-retrofit building with local solid fuel and DH3 in post-retrofit condition equipped with district central heating and radiators with thermostatic valves (Figure 2). Broad range of temperatures and circadian fluctuation in SF3 contrasts with a narrow 2K range of higher and more stable temperatures across the 24 hours for the whole monitoring period in DH3. Flats with solid fuels are heated intermittently and with limited control over the heating pattern. Indoor temperature profile depends on the occupant’s direct sustained involvement. Here peak temperatures are related to the highest stove temperature in the afternoon hours and drop down in the evening when the resident goes to sleep.

**Figure 3** and **Figure 4** present the circadian relationship between TSV and TPV and the operative temperature for points at the time of the survey responses for apartments with different heat sources. Only selected cases are shown representing all the key trends observed in our sample. The analysis reveals major differences in satisfaction with thermal environment between apartments (e.g. SF1 and SF2) that cannot be explained by the operative temperatures. Lower temperatures do not necessarily mean unsatisfied residents. Rather lack of control over circadian thermal profiles. The most unsatisfied solid fuel users (SF1) during weekdays (a) have the highest operative temperatures, however at the wrong time of day (i.e. around 3 a.m.). Weekend analysis (b) shows much higher TSV results, with the majority of votes for “slightly warm”. The key difference between the week and weekend is the capacity to control when peak temperatures occur: the highest temperatures in the afternoon instead of in the night. SF4 is another apartment where lack of control seems to explain clear dissatisfaction with the thermal environment. The apartment is almost free-running, as the resident works daily in 12-hours shifts and has no time to use the solid fuel stove during weekdays. The adjacent apartments provide enough heat to keep the apartment warmer than most other solid fuel apartments in our sample. However the resident knows she cannot use the stove and perceives her apartment as cold (e). Analysis of CLO and MET factors is beyond the scope of this paper due to limited space.

In the apartments with solid fuels and electric heating, the residents prefer warmer conditions, even when the thermal sensations are above neutral. This may indicate that neutral conditions for the respondents were moved into warmer conditions, not to TSV = 0, as defined in European standards. The other aspect is that some of the respondents already got used to lower temperatures (they voted TSV=0 when Top = 17 or 18°C) as the comfort is defined by an energy bills aspect.
Figure 3. Thermal Sensation Votes and Thermal Preference Votes for different times of the day for selected inhabitants of apartments heated with solid fuels and electric heating.

The residents of the centrally heated post-retrofit apartments are used to higher and more stable temperatures. Within our sample all households exercised available control over heating. The least stable environment is in an apartment with dysfunctional thermostatic valves and room thermostat (b, c). Only for this apartment TSV and TPV revealed gender related differences in thermal. The man feels too hot, when the woman prefers warmer conditions.
Figure 4. Thermal Sensation Votes and Thermal Preference Votes for different times of the day for selected inhabitants of apartments with central district heating or individual gas boiler central heating.

4. Discussion

Mathematical models aim to predict the relationship between operative temperatures and thermal comfort vote results. When seeking thermal comfort votes personal factors such as clothing insulation and metabolic rate are assessed, the latter understood as activity level. However metabolic rate is linked not only to activity but also to core body temperature. Studies have shown that there is a circadian variation of core body temperature and related pattern of 1K range for centroid operative temperature calculated according to probability density function for thermoneutral zone (TNZ) model [7][11]. The minimum centroid operative temperature is in early morning hours (ca. 5 a.m.) and the maximum in the afternoon (ca.5 p.m.) [12]. Our findings seem to confirm the residents’ expectations for higher afternoon and evening temperatures, and when not met due to lack of available control a tendency for dissatisfaction with thermal environment despite relatively high operative temperatures (see SF1 vs. SF3).

In the domestic environment long term residents accumulate household specific knowledge about managing their thermal environment. They not merely react to the perceived lack of comfort, as suggested in classic thermal comfort theory [13] but develop practices aimed at preventing discomfort when possible. Indeed significant differences in domestic heating patterns have been observed linked with different thermal preferences [14][15] or fuel poverty [1]. Old solid fuel stoves lack automation and require direct involvement lasting 2-3 hours to activate heating and then provide limited opportunity to regulate temperature. Therefore their use and the related thermal profiles depend on occupancy patterns. Heating activated in the morning offers best match with the above predicted expectation for higher temperatures in the afternoon, however this pattern is only available to residents who stay at home in the morning hours, e.g. pensioners. Those most dissatisfied in our study are not those with the lowest temperatures but rather those working full time and having to rely on solid fuel combustion. Both such households, living in the studied apartments for more than 20 years, expressed their frustration with the lack of ability to match their heating patterns with their expectations. For one of them the key
issues were the circadian fluctuations of temperature due to significant thermal losses and importantly the peak temperatures at night-time contributing to perceived sleep deprivation and the minimum in the afternoon, when warmth would be welcome. Central heating systems with programmable thermostats in good working condition enable residents a significant level of control. In our sample all households exercised the control offered and introduced timeframes for specific temperatures. Interestingly as one thermal pattern was set for a household individual preferences came forward and variation in thermal sensation votes and preferences within the shared spaces were still observed. However intensity of thermal dissatisfaction was much lower than in households with low ability to control the overall thermal profiles.

5. Conclusions
The results of a winter thermal comfort study comprising of thermal monitoring and thermal comfort survey in historic tenements in Poland are presented through the lens of circadian profiles of operative temperatures as well as circadian residents’ thermal sensation and preference analyses. The results suggest a link between the level of satisfaction with the thermal environment and the ability to control it. Household capacity to control the thermal environment depended on the heating system used, level of heat losses and occupancy pattern. Further analyses are needed to untangle the role of different variables of thermal comfort in the studied sample.

References
[1] Rudge J. 2012 Energy Policy. 49 p 6–11
[2] Peffer T, Pritoni M, Meier A, Aragon C, Perry D. Build Environ. 46(12) p 2529–41
[3] Baborska-Narożny M, Szulgowska-Zgrzywa M, Mokrzecka M, Chmielewska A, Fidorów-Kaprawy N, Stefanowicz E, et al. 2020 Build. Cities vol. 1 no. 1 pp. 120–140
[4] Baborska-Narożny M, Szulgowska-Zgrzywa M, Stefanowicz E, Piechurski K, Fidorów-Kaprawy N, Laska M, et al. 2020 Komponent badawczy Inicjatywy DiverCITY4. Raport z badań.
[5] Baborska-Narożny M, Stefanowicz E, Piechurski K, Fidorów-Kaprawy N, Laska M, Mokrzecka M, et al. 2020 Węglem i nie węglem. Ogrzewanie kamienic: perspektywa mieszkańców i scenariusze zmian. (Politechnika Wrocławska, Oficyna Wydawnicza)
[6] PN-EN 12831:2006 Instalacje ogrzewcze w budynkach - Metoda obliczania projektowego obciążenia cieplnego.
[7] Schweiker M, Huebner GM, Kingma BRM, Kramer R, Pallubinsky H 2018 Temperature vol. 5 no. 4 pp. 308–342
[8] Brager GS, De Dear RJ. 1998 Energy Build. vol. 2 no. 1 pp. 83–96
[9] Paciuk M. 1990 The role of personal control of the environment in thermal comfort and satisfaction at the workplace
[10] Baborska-Narożny M, Laska M, Fidorów-Kaprawy N, Mokrzecka M, Małyszek M, Smektal M, et al. Energy Build, Thermal comfort and transition from solid fuel heating in historic multifamily buildings - a real world study in Poland – accepted for publication
[11] Kingma BRM, Schellen AJH, Lichtenbelt M, Van WD. 2014 Beyond the classic thermoneutral zone: including thermal comfort
[12] Lericollais R, Gauthier A, Bessot N, Zouabi A, et al. Morning 2013 PLoS One vol. 8 no. 3
[13] Fanger P 1974 Komfort cieplny
[14] Janda KB 2011 Archit. Sci. Rev. vol. 54 no. 1 pp. 15–22
[15] Gram-Hanssen K. 2010 Build. Res. Inf. vol. 38, no. 2 pp. 175–186