Monitoring results and analysis of thermal comfort conditions in experimental buildings for different heating systems and ventilation regimes during heating and cooling seasons

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Abstract. This paper focuses on the long-term monitoring of thermal comfort and discomfort parameters in five small test buildings equipped with different heating and cooling systems. Calculations of predicted percentage of dissatisfied people (PPD) index and discomfort factors are provided for the room in winter season running three different heating systems – electric heater, air-air heat pump and air-water heat pump, as well as for the summer cooling with split type air conditioning systems. It is shown that the type of heating/cooling system and its working regime has an important impact on thermal comfort conditions in observed room. Recommendations for the optimal operating regimes and choice of the heating system from the thermal comfort point of view are summarized.

1. Introduction

Five small experimental test buildings with internal dimensions 3×3×3 m have been built in Riga, Latvia (Figure 1). They have identical constructions of floor, ceiling, also the door and window. Only the walls have been built with different materials – aerated concrete, ceramic blocks, wooden logs, plywood frame and rock wool insulation (see [1]). The thickness of used wall materials is chosen according to the same calculated thermal transmittance (U-value) of 0.16 W/ (m^{2}K), the same as for floor and ceiling. U-value for window and door is 0.8 W/(m^{2}K). After 4 years of the project running, a large number of measured data points is collected and the results linked to the energy consumptions, mathematical modelling, humidity monitoring and mould growth risk analysis are published [1-5]. Similar studies were performed on a variety of building design solutions and material effect on energy consumption and indoor climate also in other countries and for other climatic zones, e.g., in Finland [6], Spain [7] and Italy [8].

   All the test buildings are equipped with identical air-air heat pumps used for the heating/cooling and electric convection heaters; two buildings are additionally equipped with air-water heat pumps. Three ventilation modes may be provided with the help of installed systems. Long-term measurement data for several heating and cooling seasons is used to evaluate and analyse the differences in thermal comfort conditions and local discomfort factors (vertical temperature difference and draught rate) for different types of heating and cooling systems under real operating conditions. Short-term specific measurements of thermal comfort conditions using special equipment are also available for several periods. The analysis of this data allows selection of the optimal heating system and its operating regimes not only for better energy efficiency, but also in terms of thermal comfort conditions.

Figure 1. Overview of the testing ground and cross-section of the building with the location of main temperature and air humidity sensors (marked as dots) and heat flux sensor (Q-WALL).

2. Experimental set-up and used evaluation methods

The measurement data is collected every minute from the weather station (air temperature, relative humidity, wind speed and solar irradiation), as well as from each building (temperature and humidity at heights of 0.1/0.6/1.1/1.7/2.9 m, air velocity, solar irradiation, electric powers and energy consumption for heating/cooling systems, CO_2 concentration, heat flux etc.). A placement of main temperature/humidity sensors is shown in Fig. 1. Additionally mean radiant temperature has been periodically evaluated using portable microclimate measuring device DeltaOHM HD 32.1 [9].

Identical split-type air conditioning systems with indoor unit placed above the door on the north facade are used for the cooling. The following four different types of heating are installed and used for the heating (Figure 2):

- an air-air heat pump with an indoor unit (same as for cooling) placed above the door on the north facade (A-A);
- an air-water heat pump with low-temperature large convectors placed on the floor near the outer wall (A-W.F);
- an air-water heat pump with heating capillary mats placed on the ceiling (A-W.C);
- a standard electric heater placed near the window on the south facade (EL)

The type of used heating system, the placement of heat exchanger and corresponding air movement regimes in a room influence the temperature stratification in the room, affecting also the thermal comfort conditions. The PMV/PPD model described in ISO 7730 standard [10] was developed by Fanger [11], it uses heat balance equations and empirical studies about skin temperature to define thermal comfort. Four environmental parameters – air temperature, mean radiant temperature, air velocity, and relative humidity – as well as two assumptive factors – human metabolic rate (*met*) and clothing insulation (*clo*) are used for the calculation of thermal sensation. The last two parameters used in calculations is chosen according to sedentary activities (*met*=1.2) during heating and cooling seasons (*clo*=1 and *clo*=0.5 accordingly) [10]. Predicted percentage of dissatisfied people (hereinafter PPD) quantifies the expected percentage of dissatisfied people in a given thermal environment.

According to ISO 7730, the desired thermal environment for a room can be divided into 3 categories (Table 1). Each category prescribes two factors: a maximum percentage of PPD for the body as a whole and percentage dissatisfied (PD) for local discomfort. PPD index and two of local discomfort parameters – draught rate (DR) and PD caused by vertical temperature difference between the head (1.1 m) and ankles (0.1 m) for sitting person (Figure 3) will be calculated and analysed in this study. Another local discomfort parameter – radiant asymmetry was measured periodically with the help of portable microclimate measuring device DeltaOHM HD 32.1 (Figure 4). As it is shown in studies [12], the radiant asymmetry in a room is strongly affected by the window/door due to its large area and low temperatures

of inner surface, however, in our case energy efficient triple glazed window/door with U=0.8 W/(m²K) and solar heat gain coefficient (*g*-value) of 0.5 reduces the temperature difference on the inner surface and this impact may not be very essential.

Figure 2. Different heating systems used for heating and cooling: EL – electric heater, A-A – air-air heat pump (used also for cooling), A-W.F – air-water heat pump with convectors, A-W.C – air-water heat pump with capillary mats placed on the ceiling.
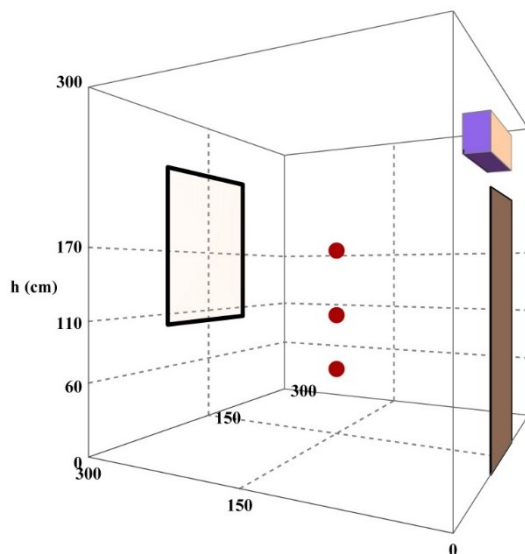

Figure 3. Placement of the temperature sensors used for the estimation of PPD index and local discomfort parameters.

Figure 4. Microclimate measuring device DeltaOHM HD 32.1 with radiant temperature asymmetry and globe temperature sensors.

Table 1. Categories of thermal environment according to ISO 7730 standard.

| Category | Thermal state of the body as a whole. PPD, % | Local discomfort | | | |
| | | Draught rate, % | PD, % caused by | | |
			vertical air temperature difference	warm/cool floor	radiant asymmetry
A	< 6	< 10	< 3	< 10	< 5
B	< 10	< 20	< 5	< 10	< 5
C	< 15	< 30	< 10	< 15	< 10

3. Results

The obtained results can be grouped into four following parts in order to analyse and easy interpret the direct impact of heating/cooling systems and ventilation regimes, as well as for the overview of local discomfort parameters:

- type of heating system – A-A, A-W.F, A-W.C, and EL with normal ventilation regime;
- type of cooling system – A-A, A-W.F, and A-W.C with normal ventilation regime;
- different ventilation regimes for A-A and A-W.C systems used for heating and cooling.
- local discomfort by vertical air temperature difference and by draught rate with and without ventilation.

3.1. Predicted percentage of dissatisfied people (PPD)

Calculations of PPD index have been made for all used heating systems (A-A, A-W.F, A-W.C and EL) during chosen 2-hour period with 20°C indoor temperature and normal ventilation regime (air exchange rate 0.45 1/h); results are visualized in Figure 5 (left). As it is seen, running of A-A and A-W.F heating systems meet the requirements only of C category of thermal environment in the room, often exceeding the 10% PPD limit value (Table 1). The operation of A-W.C system may provide the B category with the PPD index between 6 and 7%, while electric heater in the room satisfies the requirements of A category of thermal environment remaining below the level of 6% PPD. One of the reasons of this is difference in operation regimes – indoor temperature limits for the A-W.F system is set to 2°C meaning greater fluctuations but higher energy efficiency (less on/off cycles), while for electric heater switching takes place several times per minute, providing specified indoor temperature very accurately. Meanwhile, calculated PPD index for the A-A system is so high due to intensive airflow from the heat pump's indoor unit.

The analysis of PPD index for operation of three cooling systems during 2-hour period with 23°C indoor temperature (Figure 5, right) demonstrates very similar B category thermal environment conditions for both air-water heat pump A-W.F with chiller-type heat exchanger and for air-water heat pump with capillary heat exchanger map on the ceiling A-W.C (see Figure 2). At the same time, PPD index for the cooling period provided by the air-air heat pump with split-type air conditioner periodically exceeds the maximum acceptable limit of 10% and is even higher than 15% for a few minutes during its operating cycle. This is due to low initial temperature in the cycle start for this type of cooling (see Figure 5, right).

Outdoor air ventilation and corresponding air velocity variations are another factors affecting thermal comfort. Normal ventilation regime and switched off mechanical ventilation in the room are analysed for A-A and A-W.C heat pumps operating in heating and cooling modes; results for the same 17-hours long time periods are shown in Figure 6. Due to the specificity of air-air heat pump operation without energy accumulator, when the system is switched on and off very frequently according to set indoor temperature range settings, fluctuations of temperature-dependent PPD index are highly expressed.

During heating season, PPD index for A-A system is calculated between 5% and 8% with normal ventilation regime and up to 10% with switched off ventilation system (yellow and red lines in Figure 6, left), meaning B category of thermal environment. At the same time requirements even of C category cannot be met during cooling period mainly due to the larger temperature difference; the mechanical

ventilation regime for this case is more important, because of replacing of a hot indoor air, which decreases the PPD index (green and blue lines in Figure 6, left).

The use of water accumulator tank in the air-water heat pump system A-W.C reduces on-off cycles of heat pump's outdoor unit improving an energy efficiency; temperature fluctuations for both heating and cooling seasons in this case are small (Figure 6, right), while an absolute values of PPD index is in the same range as for A-A heat pump. It is seen, that thanks to smaller fluctuations, three of A-W.C modes satisfy B category requirements of thermal environment, and only in case of switched off ventilation in the room during the cooling PPD reaches maximum 13%.
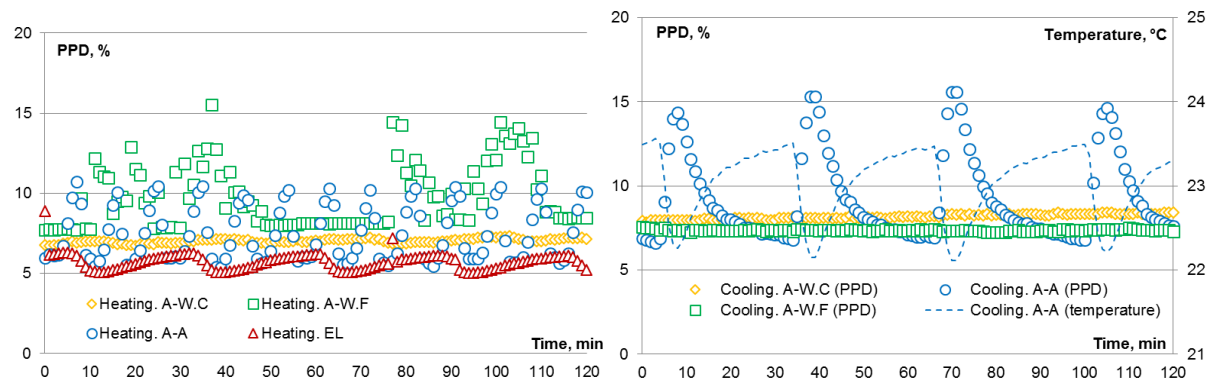

Figure 5. Calculated PPD index for different heating (left) and cooling (right) systems with normal ventilation.
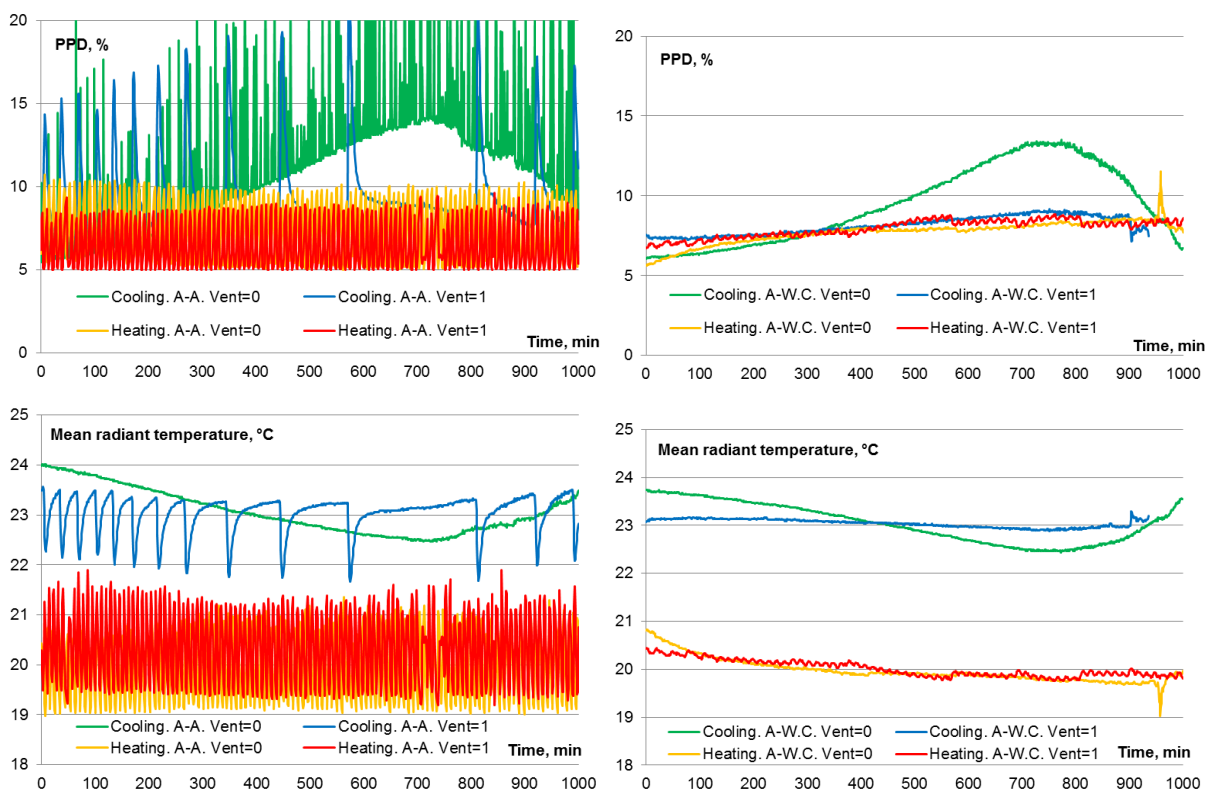

Figure 6. Long-term monitoring of PPD index (above) and mean radiant temperature (below) for A-A (left) and A-W.C (right) systems during heating and cooling with and without ventilation.

3.2. Percentage dissatisfied (PD) for local discomfort

Analysis of local discomfort for existing systems includes two continuously monitored parameters – discomfort due to vertical temperature difference for sitting person and due to draught rate (DR), as well as radiant asymmetry factor, which was measured periodically with the help of portable microclimate measuring device.

Average value of temperature difference for a selected 2-hour time period and calculated instantaneous PD value caused by this factor in the middle of a room is shown in Figure 7. Temperature difference for all the systems excluding air-air heat pump is below 1°C and PD is close to the zero. The requirements of A category thermal environment (Table 1) are fulfilled for all the cases. Warm air flow from the splitter in case the air-air heat pump is directed to the middle or part of the room, causing the highest air temperature values in this part, therefore larger temperature difference exist in the room between analysed heights of 0.1 and 1.1 m (Figure 3). However, also in this case, PD value is below 10% (Figure 7, right) meeting the needs of A category level.

The percentage of PD owing to draft rate is calculated using local turbulence intensity value of 40% [10] for selected 2-hour periods; results are visualized in Figure 8. As it is seen, all the data points for both – heating and cooling seasons is below 8%, which corresponds to A category of thermal environment (see Table 1).
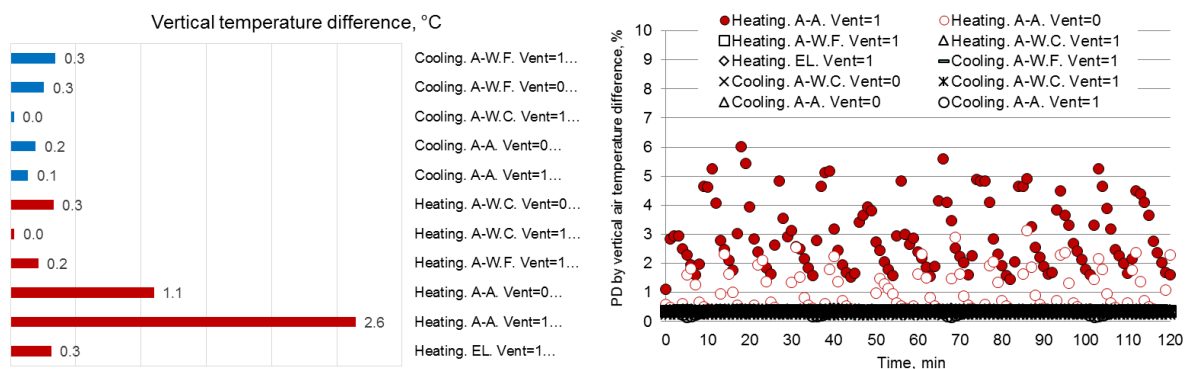

Figure 7. Average vertical temperature difference (left) and calculated local discomfort PD by this factor (right) for sitting person during heating and cooling with and without ventilation.
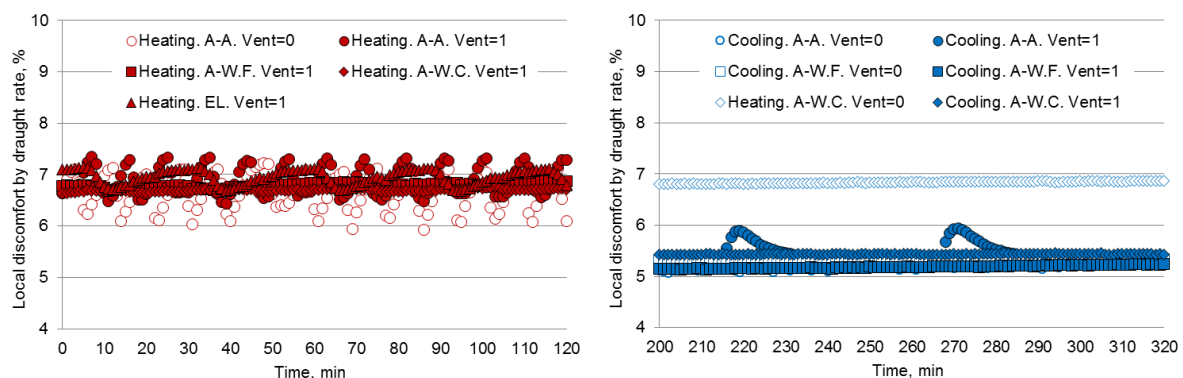

Figure 8. Calculated local discomfort by draught rate during heating (left) and cooling (right) with and without ventilation.

The last analysed local discomfort parameter – radiant temperature asymmetry was periodically measured at different location points using portable measuring device (Figure 4). Obtained results show that PD caused by radiant asymmetry not exceeds 5% practically for all the room (see example in Figure 9) for both heating and cooling seasons and different ventilation regimes, thus satisfying the

requirements of A category of thermal environment (Table 1). The exceptions are some points very close to the window (Figure 9, right), where highest temperature asymmetry up to 8% is observed in sunny days due to direct solar radiation during the measurement.
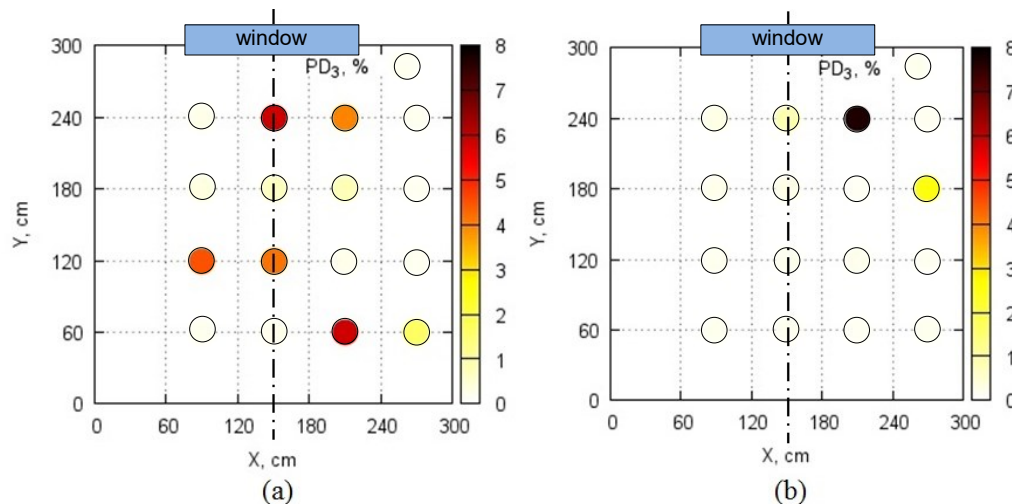

Figure 9. An examples of calculated percentage dissatisfied due to measured radiant temperature asymmetry for A-A during heating in horizontal plane at heights of 1.1 m (a) and 1.7 m (b).

4. Conclusions

Long-term monitoring of thermal comfort conditions in the similar test buildings equipped with different heating and cooling systems makes it possible to analyse the impact of their properties and settings on thermal comfort conditions. It helps to find possible causes of the local discomfort and experimentally estimate the category of provided thermal environment according to international standards; and to develop specific recommendations for producers, installers, and architects based on experimental measurements to get the best thermal comfort conditions in the room. As the determination of thermal comfort conditions and discomfort parameters are locally measured and calculated indicators, the results described in this paper cannot be applied or scaled to any room overall – they characterize conditions relatively close (1.5 m and more) to the heating/cooling or ventilation devices.

Our study shows that different heating systems with standard settings may provide a different level of thermal comfort and it is dependent also on environmental parameters (inside/outside temperature, solar irradiation etc.). Lower category of the thermal environment is observed when the heating system is adjusted to allow a wide range of heat carrier's temperature or without any heat accumulator meaning more frequent and larger fluctuations in temperature. The use of split-type air conditioners means high vertical temperature difference and high air velocity, especially near the indoor unit, as well as lower temperatures in the beginning of cooling cycle, which lowers the category of thermal environment. The use of mechanical ventilation system has a remarkable influence on PPD index especially for air-air heat pump system during cooling.

Analysed local percentage dissatisfied for local discomfort showed that heating and cooling systems used in test buildings mostly satisfy the requirements of highest thermal comfort category, but some factors like large indoor temperature corridor or location of indoor AC units with intensive airflows need to be optimized to ensure highest category of thermal comfort.

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