DTU Library

Operative temperature drifts and occupant satisfaction with thermal environment in three office buildings using radiant heating/ cooling system

Kolarik, Jakub; Toftum, Jørn; Olesen, Bjarne W.

Published in:
Proceedings of Healthy Buildings Europe 2015

Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

F: Physical responses & physiology
F.2. Health assessment (incl. Thermal comfort)

OPERATIVE TEMPERATURE DRIFTS AND OCCUPANT SATISFACTION WITH THERMAL ENVIRONMENT IN THREE OFFICE BUILDINGS USING RADIANT HEATING/ COOLING SYSTEM

Jakub Kolarik[1,*], Jørn Toftum [2] and Bjarne W. Olesen[2]

[1]Department of Civil Engineering, Section for Building Energy, Technical University of Denmark, Kgs. Lyngby, Denmark
[2]Department of Civil Engineering, International Centre for Indoor Environment and Energy, Technical University of Denmark, Kgs. Lyngby, Denmark

[*]Corresponding email: jakol@byg.dtu.dk

Keywords: Operative temperature drift, Thermal comfort, Radiant heating/cooling

SUMMARY

The objective of this study was to analyse operative temperature drifts and occupant satisfaction with thermal environment in office buildings utilizing embedded radiant heating/cooling systems. Three office buildings were investigated: Town Hall in Viborg, Denmark (floor area 19400 m^2), IDOM, Madrid, Spain (16000 m^2), TiFS, Padua, Italy (2200 m^2). Continuous measurements of operative temperature were conducted at four workplaces in each building for one year. Occupants' satisfaction was assessed by internet based questionnaire. Results showed that mostly exceeded limits were those for 4-hour drift (0.8 K/h), which were exceeded at least in 2% and up to 52% of occupied time in investigated buildings. Limits for hourly and 2-hour drifts were exceeded in max. 2% of occupied time. Median values were in ranges of 0.12-0.29 K/h, 0.18-0.52 K/h and 0.27-0.84 K/h for 1, 2 and 4-hour drifts respectively. Occupants' in all buildings were rather satisfied with temperature conditions. Median temperature satisfaction (0="Clearly satisfied" - 5="Clearly dissatisfied") was 2, 1 and 1 for Viborg, Madrid and Padua respectively. Temperature satisfaction slightly decreased when rate of temperature change increased, thus higher temperature drifts seemed to lead to higher dissatisfaction, however the collected data did not allow for robust statistical analysis.

INTRODUCTION

Radiant heating/cooling systems have become a natural part of sustainable high performing building concepts Olesen (2012). Due to the principle of their operation, utilization of such systems is associated with drifts of operative temperature. Occupants are therefore exposed to non-steady thermal conditions, which may influence their thermal comfort and productivity (Kolarik et al. 2009 and 2010). International Standard ISO/EN 7730 (2005) allows maximum drift of 2 K/h. American standard ASHRAE Standard 55 (2013) allows for 2.2 K/h for drift duration of 1 hour, but only 0.8 K/h for drift lasting 4 hours. Scientific literature reporting temperature drifts in real buildings is limited. De Carli and Olesen (2002) focused on measurements of operative temperatures four buildings with the following systems:

(a) wall-floor-ceiling heating-cooling system (light structure building), (b) floor heating-cooling system, and, (c) active thermal slab system with pipes embedded in the deck (TABS). Results showed operative temperature in the occupied spaces varied between 21°C and 24ºC during most of the working hours. This resulted in a temperature drift from 0.2 to 0.4 K/h. Daily temperature increase was up to 3.2 K. The study did not include either subjective assessments of the thermal environment by the building occupants. On the contrary the study of Tian and Love (2008) offers a comprehensive field study on occupant thermal comfort and thermal environments with radiant slab cooling. The authors conclude that main advantage of radiant cooling for thermal comfort was reduced local thermal discomfort with reduced vertical air temperature difference as well as reduced draft rate. The objective of the present study was to analyse operative temperature drifts and occupant satisfaction with thermal environment in office buildings utilizing embedded radiant heating/cooling systems.

METHODOLOGIES

The Table 1 summarizes the three investigated office buildings. In each building continuous measurements of indoor environmental parameters were conducted at several workplaces. For the purpose of the present analysis, two representative measurement points were chosen in south and north part of the office space each building. Measurements comprised air and operative temperatures (measurement accuracy: ± 0.4 ºC at 25 ºC), relative humidity (measurement accuracy: ± 2.5% from 10% to 90%). For the operative temperature, grey sphere-shaped sensors (Simone et al. 2007) were used. Two types of Onset HOBO data loggers U12-012 and U12-013 were used to store the measured quantities in 10 minutes intervals. Figure 1 illustrate placement of operative temperature sensor at workstations. Data sets collected in all buildings were further processed to exclude weekends and holidays (official national holidays for particular country were considered) as well as periods when particular building was not occupied. Occupancy periods for studied buildings as well as whole measurement periods are shown in Table 1. Hourly mean operative temperatures calculated for all data-points were used to determine average temperature drifts for 1, 2 and 4 hours period.

Figure 1. (Left) Placement of the operative temperature sensor at workplace, (Right) A set of grey sphere-shaped sensor and data logger

Average drift for respective time periods were determine for each day (occupied hours) in the data set. Determined average drifts were analysed with respect to requirements of ASHRAE (2013) (see Table 3). Average operative temperature drift *r* that would be experienced by occupants for respective periods was calculated using expression (1) (modified from Kolarik et al. (2011)).

$$r_k = \frac{\sum_{i=1}^{n-1} \left| \theta_{o,i+k} - \theta_{o,i} \right|}{n-1} \quad [K/h] \tag{1}$$

where θ_o is hourly mean operative temperature at analysed workplace, *i* is an ordinal number of the hours during the period of occupancy, *n* is the number of hours the building is occupied and *k* is the length of analysed time periods (*k* = 1, 2 and 4; see Table 3).

In order to evaluate occupants' satisfaction with indoor environment internet based questionnaire survey was distributed among employees in investigated buildings. The employees were requested to answer a questionnaire consisting of 23 questions within a week, referring to one month period prior to the survey. In the survey, occupants were asked to assess their satisfaction with temperature conditions at their workplace, air quality, acoustic and lighting conditions as well as local thermal discomfort, building related health symptoms etc. Data regarding satisfaction with thermal environment will be presented in the paper. 6 point category scales coded from 0 to 5 (0 = "Clearly satisfied", 1 = "Satisfied", 2 = "Just satisfied", 3 = "Just dissatisfied", 4 = "Dissatisfied", 5 = "Clearly dissatisfied") were used for questions dealing with satisfaction. Questions with possibility of multiple answers (using check boxes) or dichotomic answers (using radio buttons) were used for detailed investigations of sources of thermal discomfort and local thermal comfort evaluation.

The statistical software R version 2.15.3 (R Development Core Team 2014) was used to analyse the data.

RESULTS AND DISCUSSION

Table 2 summarizes general analysis of the measured data. Highest mean operative temperature was measured in Madrid while the lowest in Viborg. The values for all buildings are close to the middle of the range recommended by EN 15 251 (EN 2007) for thermal environment at normal level of expectations in new and renovated buildings (so called Category II). Duration curves for hourly mean operative temperatures at workplaces situated towards south are presented in Figure 1. Operative temperature limits for the category II for indoor environment according to EN 15 251 (2007) are indicated by grey vertical lines. It is clear from the figures that none of the buildings had problems with too low operative temperatures. On the other hand, slight tendency for overheating can be seen for every building. Percentage of occupied hours in southern space with $\theta_o > 26$ °C was 9.8%, 5.5% and 3.6% for IDOM Madrid, TiFS Padua and Viborg Town Hall respectively. For workstations in northern parts of the buildings percentage of occupied hours with $\theta_o > 26$ °C was 8.3%, 7.2% and 2.3% for IDOM Madrid, TiFS Padua and Viborg Town Hall respectively. According to EN 15 251 (2007) the recommended upper temperature limit can be exceeded in maximum 5% of occupancy time. Table 2 also shows that median values of r_k calculated for whole investigated period in particular buildings were far below 2 K/h. Highest median values were observed for southern space in Viborg Town Hall. This is most probably caused by the lack of external solar shading on the building, thus the solar heat gains play the most significant role. Table 3 summarizes percentage of occupied hours during which r_k limits according to ASHRAE (2013) were exceeded. The limit value for r_4 (4-hour drift; max. 0.8 K/h), was exceeded in all studied buildings. The highest percentage of occupied hours with r_4 > 0.8 K/h was observed in southern space of Viborg Town Hall (52.4%), the lowest in north oriented space of IDOM Madrid (1.9%). Exceedance of temperature drift rates for shorter time periods was not that prevalent. This is consistent with nature of TABS systems installed in the buildings, which are known to impose slow but steady temperature drifts while eliminating more rapid temperature fluctuations.

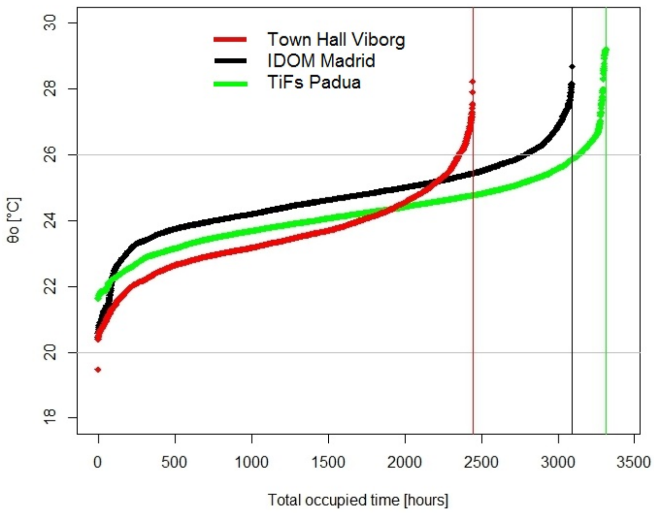

Figure 1. Duration curves for hourly mean operative temperatures (θ_o) measured in southern spaces of the investigated buildings; amount of hours in the data-set was not equal for all buildings – end of the data-set for particular building is indicated by a vertical line at corresponding colour.

Obtained results are in agreement with previous work of De Carli and Olesen (2002). They analysed daily operative temperature increase ("ramp") in four buildings. The results of their field study showed that most prevalent drift were in a range 0.1 - 0.4 K/h. This is consistent with interquartile ranges for r_1 presented in Table 3. However, the daily operative temperature increase was not considered in the present study, because preliminary analyses revealed that occupants were often not exposed to continuous temperature increased during the day. Thus detailed analysis of drifts for 1, 2 and 4-hour (r_1, r_2 and r_4) periods seemed more representative than using of simple afternoon-morning operative temperature difference. International standard EN/ISO 7730 (EN/ISO 2005) recommends maximum operative temperature drift 2 K/h. Considering the fact that limit 2.2 K/h by ASHRAE (2013) was almost never not exceeded in the present study(see Table 3), no further analyses regarding EN/ISO (2005) limit were conducted.

Table 3. Percentage of occupied time with drifts exceeding limits by ASHRAE 55 (2013)

Building	Time period, k [h]	1	2	4
	Max. $\Delta\ \theta_o$ [K]	2.2	2.8	3.3
	Max. r_k [K/h]	2.2	1.4	0.8
IDOM Madrid	South	0.0%	0.0%	31.8%
	North	0.4%	0.8%	1.9%
TiFS Padua	South	0.0%	0.3%	10.9%
	North	0.0%	0.0%	9.3%
Town Hall Viborg	South	0.0%	2.2%	52.4%
	North	0.0%	0.0%	12.9%

Figure 2 shows the median satisfaction with temperature conditions in all buildings corresponding to so-called recall period for the questionnaire survey (see Table 1). Median temperature satisfaction was in the range of the scale expressing overall satisfaction with the conditions (0="Clearly satisfied"; 2="Just satisfied"). When considering whole interquartile range, the highest satisfaction was expressed by respondents in IDOM Madrid. Viborg Town hall had the lowest satisfaction rate with median of 2 and interquartile range of (1, 3). Figure 3 (Left) represents relation between daily temperature drifts and temperature satisfaction data. Clear tendency for higher dissatisfaction at higher rates of temperature change can be observed for regardless the time period for which the drifts had been evaluated (1, 2 or 4 hours). Figure 3 (Left) indicates that operative temperature level per se did not influence thermal satisfaction.

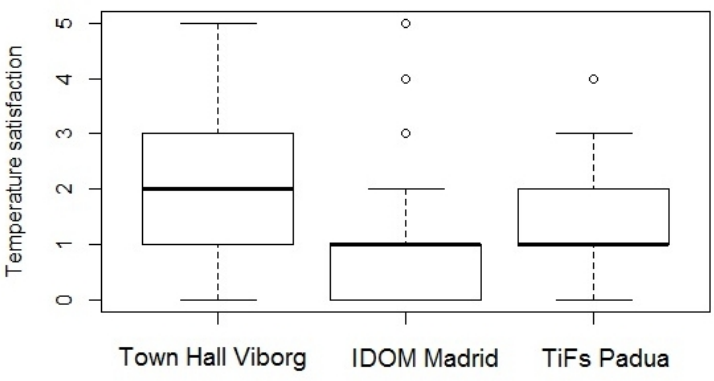

Figure 2. Box plot of temperature satisfaction for all surveyed buildings (on vertical axis: 0 = "Clearly satisfied", 1 = "Satisfied", 2 = "Just satisfied", 3 = "Just dissatisfied", 4 = "Dissatisfied", 5 = "Clearly dissatisfied")

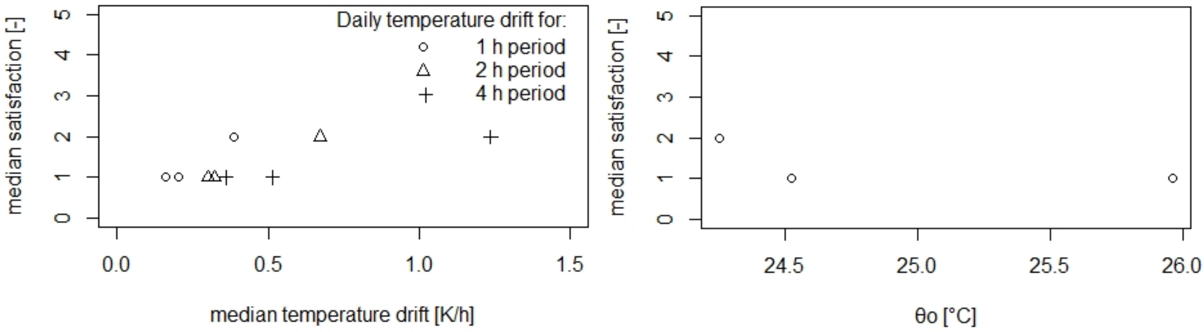

Figure 3. (Left) Relation between daily temperature drift and temperature satisfaction from all investigated buildings, (Right) Relation between daily mean operative temperature and temperature satisfaction from all investigated buildings

Questionnaire survey also showed that radiation from warm or cold surfaces was mentioned as a source of discomfort by less than 15% of thermally dissatisfied respondents in every building. The most prevalent sources of discomfort were: draught from natural ventilation system in Town Hall Viborg (58%); solar radiation (22%) and draught form corridors (22%) in IDOM Madrid; too little air movement (56%) and high relative humidity (44%) in TiFS Padua.

CONCLUSIONS

- The limit for 4-hour operative temperature drift (0.8 K/h) was exceeded in all studied buildings. Lowest percentage of occupied time with exceeded limit was observed in northern space of IDOM Madrid (2%), highest percentage of hours above limit was observed in southern space of Town Hall Viborg (52%).
- The limits for 1 (2.2) and 2-hour (1.4) drifts were not exceeded in more than 1% of occupied time in any building but Town Hall Viborg (2.2% of occupied time with drift > 1.4 K/h).
- Results show that slow drifts up to about 1 K/h were mostly prevalent in studied buildings.
- Median values corresponding to whole measurement period calculated for all types of studied drifts do not exceed 1 K/h.
- Maximum observed temperature drift was 3.2 K/h.
- Median (1st Qu., 3rd Qu.) values of temperature satisfaction were 2 (0, 5), 1 (0, 1) and 1 (0, 3) for Viborg, Madrid and Padua respectively.
- Temperature satisfaction slightly decreased when rate of temperature change increased, thus higher temperature drifts seemed to lead to higher dissatisfaction, however the collected data did not allow for robust statistical analysis.

ACKNOWLEDGEMENT

The study was conducted as a part of research project "Thermo Active Building Systems (TABS) – Performance in practice and possibilities for optimization" supported by Bjarne Saxhofs Fond til Støtte for Dansk Forskning, Denmark in the period 1.9.2012 – 31.12.2014. Following M.Sc. students should be acknowledged for their help during data collection: Mathias Hansen, Libor Gazovic, Kleanthis Chasapis, and Christoffer Rasmussen.

Table 1. Overview of investigated buildings

Building name (year of construction)	Location: Town, Country	Floor area [m^2]	Radiant heating/cooling system	Ventilation system	Solar shading system	Measurement period	Survey (recall period)	Survey – number of respondents	Occupied hours
Viborg Town Hall (2011)	Viborg, Denmark	19400	Floor heating/cooling	Natural-aut. control	No external solar shading	Feb. 2013[(2)] – Feb. 2014	May 2013 (April 2013)	533	8:00-19:00
IDOM (2010) headquarters	Madrid, Spain	16000	TABS[(1)]	Mechanical	South/west double façade with vegetation	Dec. 2012 – Jan. 2014	May 2013 (April 2013)	154	9:00-20:00
TiFS (2004) headquarters	Padova, Italy	2200	TABS	Mechanical	South-double façade with hori-zontal blinds	Jul. 2013 – Sept. 2014	Sept. 2013 (Aug. 2013)	60	9:00-19:00

[(1)] TABS – Thermo active building system – pipes embedded in storey construction, [(2)] Data from north part of the building available form from May 2013

Table 2. Summary of results regarding operative temperature, relative humidity and temperature drifts

Building	Work-place	θ_o (SD) [°C]	*rh* (SD) [%]	Med.[(1)] *r1* [K/h]	Min./Max. r_1 [K/h]	Med.[(1)] r_2 [K/h]	Min./Max. r_2 [K/h]	Med.[(1)] r_4 [K/h]	Min./Max. r_4 [K/h]
IDOM Madrid	South	24.6 (1.1)	38 (8)	0.26 (0.20,0.36)	0.03/0.76	0.39 (0.30,0.58)	0.06/1.38	0.55 (0.40, 0.86)	0.12/2.29
	North	24.7(1.1)	26 (7)	0.12 (0.10, 0.14)	0.02/3.18	0.18 (0.16, 0.23)	0.05/3.54	0.27 (0.20, 0.37)	0.06/4.44
TiFS Padua	South	24.2 (1.1)	50 (12)	0.20 (0.16, 0.25)	0.01/1.33	0.34 (0.27, 0.42)	0.01/2.00	0.54 (0.38, 0.65)	0.01/2.44
	North	24.3 (1.2)	49 (11)	0.22 (0.16, 0.27)	0.01/0.84	0.37 (0.28, 0.46)	0.01/1.20	0.54 (0.38, 0.66)	0.01/1.40
Town Hall Viborg	South	23.5 (1.2)	N/A[(2)]	0.29 (0.20, 0.42)	0.02/1.00	0.52 (0.33, 0.74)	0.03/1.68	0.84 (0.51, 1.30)	0.04/3.07
	North	23.9 (1.2)	41 (7)	0.22 (0.16, 0.27)	0.02/0.83	0.36 (0.27, 0.45)	0.04/1.27	0.55 (0.41, 0.69)	0.06/1.67

[(1)] Median value of r_k for whole period of measurements (1st Qu., 3rd Qu.), [(2)] Data not available due to technical problems

REFERENCES

ASHRAE (2003) Handbook–HVAC Applications, American Society of Heating, Refrigerating and Air–Conditioning Engineers, Inc., Atlanta, GA.

De Carli M, Olesen BW (2002) Field measurements of operative temperatures in buildings heated or cooled by embedded water-based radiant systems. *ASHRAE Transactions*, Vol.108 PART 2, 714-725, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.

EN (2007) EN 15 251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. European Committee for Standardization, Brussels, Belgium.

EN/ISO (2005) EN/ISO 7730: International standard: Ergonomics of the Thermal Environment-Analytical Determination of Thermal Comfort by Using Calculations of the PMV and PPD Indices and Local Thermal Comfort Criteria, ISO, Geneva, Switzerland.

Kolarik J, Toftum J, Olesen BW, Shitzer A (2009). Occupant Responses and Office Work Performance in Environments with Moderately Drifting Operative Temperatures (RP-1269). *HVAC&R Research*, Vol. 15 (5), pp. 931-960.

Olesen BW (2012) Thermo Active Building Systems Using Building Mass To Heat and Cool. *ASHRAE Journal*, Vol. 54 (2), pp. 44-52, ISSN: 0001-2491.

R Development Core Team (2014) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, http://www.Rproject.org.

Simone A, Babiak J, Bullo M, Landkilde G and Olesen BW (2007) Operative temperature control of radiant surface heating and cooling systems. In: Proceedings of Clima 2007 wellbeing indoors, the 9th REHVA World Congress, Helsinki, Finland.

Tian Z, Love JA (2008) A field study of occupant thermal comfort and thermal environments with radiant slab cooling. *Building and Environment,* Vol. 43 (10), pp. 1658-1670.

Toftum J, Kolarik J, Belkowska D, Olesen BW (2010) Influence on Occupant Responses of Behavioral Modification of Clothing Insulation in Nonsteady Thermal Environments (RP-1269). *HVAC&R Research*, Vol. 16(1), pp. 59-74.