VARIABILITY OF THERMAL STRATIFICATION IN NATURALLY VENTILATED RESIDENTIAL BUILDINGS

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ABSTRACT

Building energy simulation programs often use standard thermal comfort indices and thresholds as boundary conditions. However, most of them focus on comfortable indoor hydrothermal levels, rather than spatial distributions. This paper investigates internal temperature vertical stratification in naturally ventilated residential buildings. To evaluate this effect, a field study was carried out in Greater London during the winters of 2012 and 2013. This allowed the monitoring of indoor thermal stratification amplitude and frequency variability in real settings. To follow this investigation, CFD models simulating heat and mass transfer within the airflow are developed, and validated from the experimental results. To conclude, this paper reviews the potential for building-in greater thermal variability into existing comfort simulation tools.

INTRODUCTION

As described in ASHRAE 55, thermal stratification may cause local thermal discomfort when vertical air temperature difference (*ΔT*) between a person's feet and head is too great. Olesen et al. (1979) conducted a study in a control environment in which 16 subjects were exposed to 4-levels of stratification – from 0.4K to 7.5K; it concluded that 5 to 10% of people would feel uncomfortable if the difference was greater than 3 to 4K. The current standards are based on the result of this study, and set the following thresholds:

- ASHRAE 55-2013: ΔT < 3°C with thermal insulation of clothing set at *0.5 < Icl <0.7* and activity level set at *1.0 < M <1.3*.
- ISO 7730-2005: Category A: ΔT < 2°C, Category B: ΔT < 3°C, and Category C: ΔT < 4°C.

To date, research on thermal stratification in buildings and its effect on occupants' thermal comfort have largely focused on commercial buildings with forced-convection ventilation systems. This study investigates naturally ventilated dwellings and their performance during a typical winter week. First a field study was carried out during the winters of 2012 and 2013. Ten occupied houses were each monitored over a period of 10-consecutive days. This allowed the collection of empirical data on indoor thermal stratification amplitude and frequency variability in real settings. The cases-study building characteristics were then used as input in the modelling study. Finally a parametric modelling analysis reviewed the effects of airflow rates and adjacent surface temperatures on thermal stratification.

EMPIRICAL MONITORING

Method

Using a convenience sample, houses were selected in Greater London. Although this sample is not representative of the UK stock, it provides insights to answer the aim of this study. The sample characteristics are summarised in Table 1. All dwellings have central heating system with local gas boiler.

Table 1. Sample characteristics

House No.	No. Occupants	EPC rating	Position	Built Period
P01	4	55-68	Detached	1950-1966
P02	2	55-68	Terrace	Before 1900
P03	2	55-68	Terrace	Before 1900
P04	4	69-80	Semi	1930-1949
P05	4	81-91	End-Terrace	1967-1975
P06	2	55-68	End-Terrace	Before 1900
P07	2	39-54	Detached	1900-1929
P08	1	69-80	Terrace	1900-1929
P09	4	55-68	Terrace	Before 1900
P10	3	39-54	Terrace	1900-1929

The monitoring study followed ISO 7726 requirements in the estimation of T_a and *RH*. HOBO U12-012 dataloggers were placed at 4-standard heights (ISO 7726:2001, table 5), defined as ankle, abdomen and head levels, set at:

- Sitting position: 0.1m, 0.6m and 1.1m.
- Standing position: 0.1m, 0.6m and 1.7m.

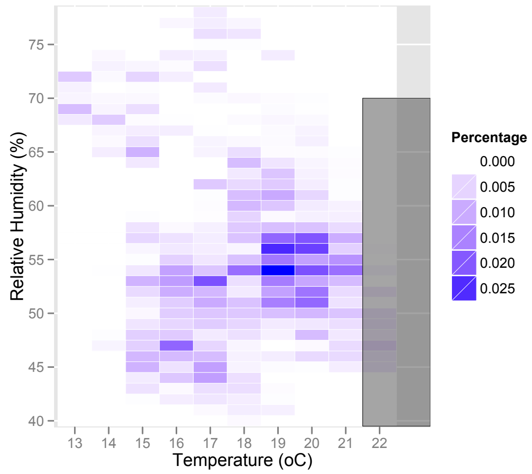

Figure 1. Internal monitored temperature and relative humidity in living rooms during occupied time with standard benchmark thresholds (grey box).

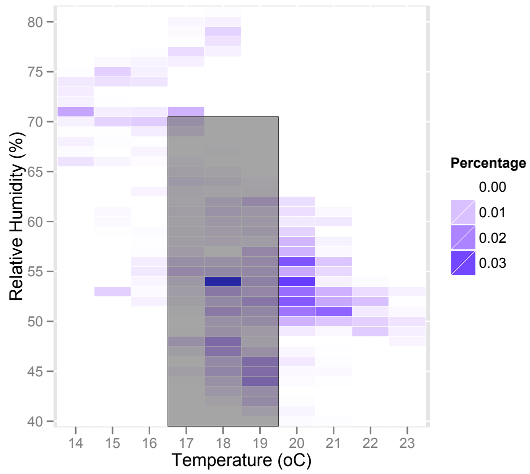

Figure 2. Internal monitored temperature and relative humidity in bedrooms during occupied time with standard benchmark thresholds (grey box).

The sensors were fastened to wooden-pole and positioned at 0.1m, 0.6m, 1.1m and 1.7m from the ground to comply with the requirement of ISO 7726. These were placed in the occupied zones of living rooms and bedrooms where the participants carried out their activities, and did not obstruct usual circulation. The effect of thermal radiation and incident solar gain were taken into account when locating the sensors. The measurement epoch was set at 5-minutes, and logging was continuous for a minimum period of 10-days. In conjunction occupants used wearable sensors, which established when dwellings were occupied. These schedules were then used to filter the monitoring data, and identify T_a and *RH* during occupied periods.

Results

Outdoor weather conditions were used as an indicator of whether the external temperatures were low enough to require space heating. As external temperatures were below the degree-day threshold of 15.5°C for 99.8% of the recording period, CIBSE (2006(a)) winter environmental design criteria were taken as benchmarks; these are as follow:

- Indoor temperature (CIBSE, 2006 (b), Table 1.5): living rooms [22 to 23°C], and bedrooms [17 to 19°C].
- Indoor relative humidity (CIBSE, 2006 (b), Section 1.3.1.3): 30 to 70%.

Indoor monitored temperatures and relative humidity were compared to these benchmarks, the results are summarised in Figure 1 and 2.

We can observe that in living room 99.5% of the recordings fall outside the recommended ranges; with 99.5% of recorded T_a outside the benchmarks, but 95.5% of recorded *RH* within the benchmarks. These results are surprisingly high; in contrast bedroom data shows only 64.4% of the recordings outside the recommended ranges for T_a and *RH*.

To follow this analysis, temperature stratification in living rooms and bedrooms were reviewed, see table 2, Figure 3 and 4. In living room, the amplitude of the mean temperature variation in height may reach 5.3°C, which is greater than the 3°C limit prescribed for a category B acceptability by the current standard.

Table 2. Internal monitored temperature during occupied time.

House No.	Living Room Temperature (°C)			Bedroom Temperature (°C)		
	%>3°C	ΔT	Mean	%>3°C	ΔT	Mean
P01	**98.8**	**5.3**	**16.2**	0.0	0.8	18.5
P02	12.0	1.9	18.6	1.6	0.9	18.0
P03	14.8	2.5	19.1	0.0	0.2	19.8
P04	**64.3**	**3.0**	**18.2**	0.0	1.7	18.6
P05	7.8	1.7	16.2	0.0	0.4	16.5
P06	30.7	2.6	20.4	0.0	0.9	21.7
P07	0.0	0.9	16.0	0.0	0.7	15.4
P08	**54.2**	**3.1**	**20.1**	0.0	1.6	19.9
P09	**63.3**	**3.4**	**17.4**	0.0	0.2	17.3
P10	**100**	**3.9**	**20.2**	0.0	0.4	18.5
Mean	**44.6**	**2.8**	**18.2**	**0.16**	**0.8**	**18.4**

note: **%>3°C**: percentage of time (T_a at 1.7m) - (T_a at 0.1m) greater than 3°C; **ΔT**: difference between mean T_a at 0.1m and 1.7m (°C); **Mean**: mean temperature standing position.

However in bedrooms, thermal stratification ranges from 0.2 to 1.7°C, which remains within the benchmarks. Then in living room, we can observe that half of the sample experienced temperature difference greater than 3°C for 54% of the time or more. It is also interesting to note that large stratification occurs in relatively cold environments (P01) and warmer ones (P10). One conjecture might be that larger vertical thermal stratification is not only the effect of natural convection but of other factors such as air infiltration through the floor or adjacent surface temperature.

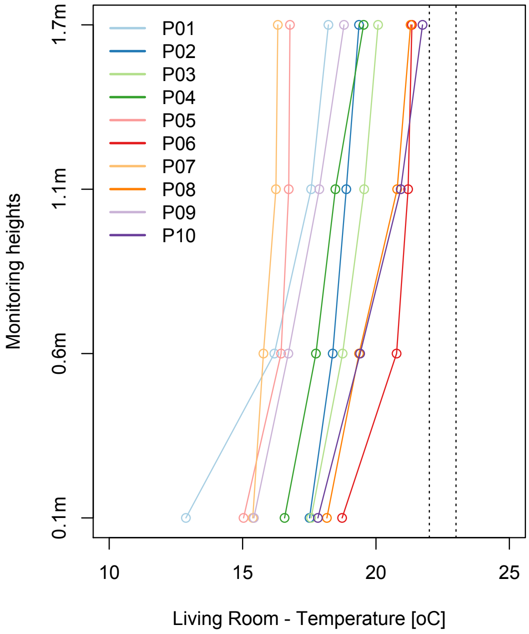

Figure 3. Air temperature profiles in living room, vertical distribution comparison between the 10 cases-studied with standard benchmark thresholds (vertical dotted lines).

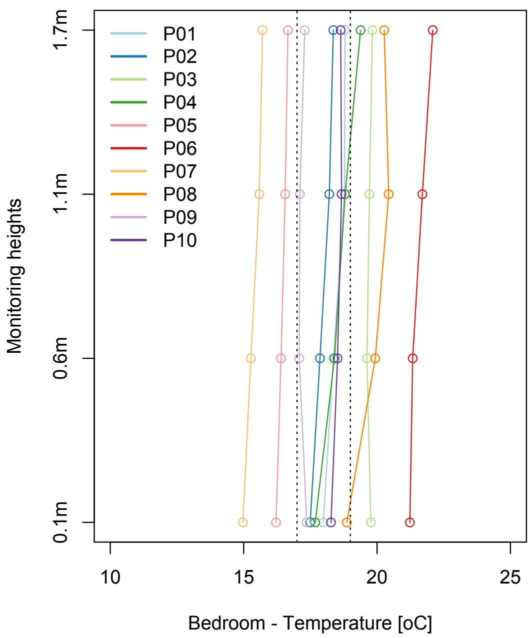

Figure 4. Air temperature profiles in bedroom, vertical distribution comparison between the 10 cases-studied with standard benchmark thresholds (vertical dotted lines).

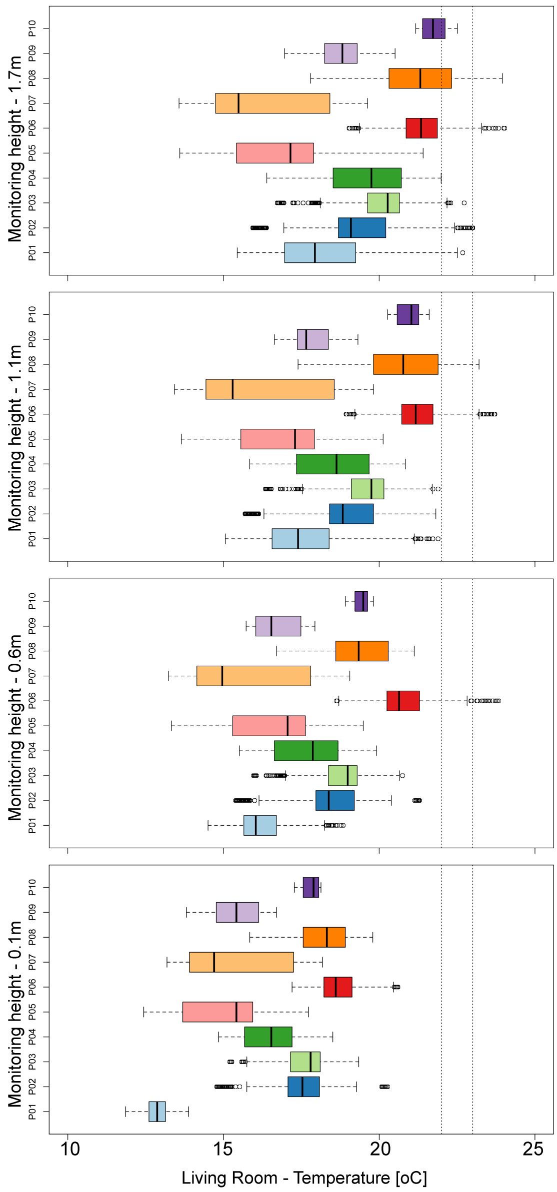

Figure 5. Air temperature in living room, vertical distribution comparison between the 10 cases-studied with standard benchmark thresholds (vertical dotted lines).

As greater thermal stratification was observed in living rooms, further analysis was carried-out to investigate T_a distributions at the 4-monitoring heights, Figure 5. Results show that temperature ranges fluctuate between 0.9 and 7.8°C; and the amplitude of the variations is greater at head height than at feet height, for example:

- P01, temperature range at 0.1m=2.0°C and at 1.7m=7.2°C.
- P07, temperature range at 0.1m=5.0°C and at 1.7m=6.1°C.

This is an interesting finding and may be explained by a range of factors such as localised heat gains i.e. the occupants or equipment (luminaires, etc.).

SIMULATED RESULTS

Method

Most existing building energy simulation (BES) programs aim to solve conditions of a volume given a set of input and output, using volume control analysis (i.e. EnergyPlus software). The intent is often to minimise energy demand while keeping occupants comfortable. With regards to thermal comfort, hydrothermal set-points and/or comfort indices levels are assigned as boundary conditions to the models. The fundamental structure of this type of software limits the level of analysis, as thermal distribution can only be studied by setting multiple volumes within one room. Therefore to investigate thermal stratification in a room, discrete analysis should be used. This method solves a grid of points within a volume using the principles of fluid dynamics (i.e. OpenFOAM software). As an analysis method, computational fluid dynamics (CFD) is used in this paper to provide a detailed analysis of the thermal environment within the dwellings' living rooms. The study focuses on the variability of thermal stratification in particular 2-variables T_a and v_a. Other thermal-comfort-indices' variables including T_r, *RH, Met* and I_{cl}, are not assessed in this analysis.

Webb (2012 and 2013) developed a software, cMap, written in Python and using input data files from EnergyPlus for the room geometry, thermal properties and external weather conditions. After selecting the thermal comfort index and timeframe output, cMap produces contour heat-map as 2D slices through the space in any direction and at any location. One of the drawbacks of this software is in EnergyPlus input, which assumes that T_a, v_a, *RH, Met* and I_{cl} are constant across a room, only T_r and the comfort indices are discrete outputs. However the coupling of BES and CFD allows the analysis of stratification in heights and levels with realistic boundary conditions from the BES input (Mirsadeghi et al., 2008). Using another coupling method, this paper applies DesignBuilder CFD software, to simulate heat and mass transfers within the case-studies' living room, and validates the output with the experimental results. The simulations are based on 10-case studies; which have been rationalised to 5-models using the features of the case studies including location, orientation, fabric, ventilation and heating system characteristics. These define the geometry and boundary conditions of the models. The EnergyPlus model was then set to run for hourly intervals during 1-week period, matching the empirical monitoring dates, and using London-Gatwick weather file. CFD boundary conditions were extracted from the BES model for a weekday at 12pm. DesignBuilder CFD generated automatically a uniform rectilinear Cartesian gird with a default spacing of 0.3m and merging tolerance of 0.03m. The final structure of the living room CFD grid comprised of 6,776 cells with 28 cells on the X-axis, 22 cells on the Y-axis and 11 cells on the Z-axis – the maximum aspect ratio was 11.33 which is an acceptable ratio for modelling a room (Baharvand et al., 2013). The study uses Reynolds-averaged Navier-Stokes (RANS) equation simulation with standard k-ε turbulence model. The Upwind discretisation scheme was chosen, and the models were run until converged solutions were achieved, this point was reached at about 1,000 to 4,000 iterations.

Results

Having monitored each case study, the first dwelling (P01) shows the greatest vertical stratification (refer to Table 2). In this instance the modelling study was used as a tool to explore this result. First, BES simulations for the whole building were completed to determine the zones' boundary conditions; then focusing on the living room, a CFD analysis was carried out. As illustrated in Figure 6, the living room was adjacent to the entrance lobby and separated by a partition containing an internal window. As the entrance lobby's T_a was significantly warmer, warm air was introduced at high level in the living room, and therefore increased the vertical stratification in the room.

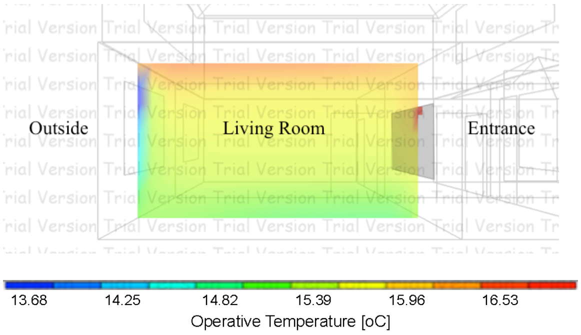

Figure 6. P01 living room- modelled T_a stratification.

Following this short study, CFD may also be used to investigate other aspects that influence spatial variation of temperature. The cases-study's HVAC systems consisted of hot-water radiators and natural ventilation; therefore only natural convection is reviewed in this paper. The development of natural convection flow depends partly on the difference between ambient air temperature (T_a) and surface temperature (T_s). Warm air rises and spread over the ceiling, while cold air descends and spreads over the floor – as illustrated in Figure 6. Another factor to consider is air velocity (v_a) in the zone, as higher velocity instigates larger temperature gradient.

To investigate these two factors, a BES was carried out for the last dwelling (P10). As BES assumes that T_a is the same within a given volume, the resultant T_a was uniform within each zone; this differs greatly from the monitored results where the mean recorded temperature stratification was 3.9°C in living room. To follow this study, BES results were used as input boundary conditions to a CFD analysis.

As shown in Figure 7, the modelled results underestimate the stratification effect; for example in living room modelled ΔT (difference between mean T_a at 0.1m and 1.7m) was lower than 0.75°C.

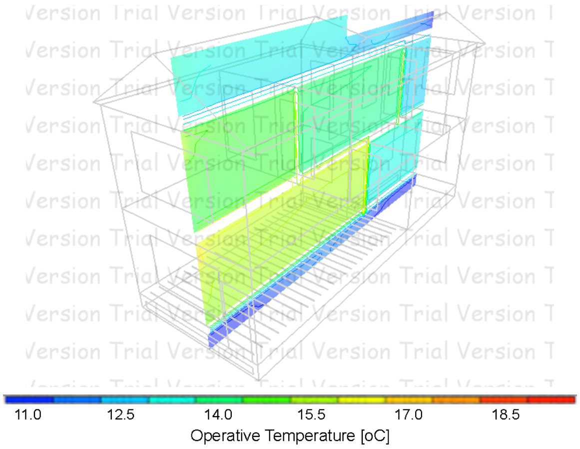

Figure 7. P10 – whole building modeled operative temperature stratification.

This observed difference between monitored and modelled results might be caused by the difference between monitored and modelled boundary conditions, rather than the validation of the CFD program. Therefore boundary conditions to the CFD analysis, in particular airflow in/out, air temperature (T_a) and surface temperature (T_s), were inputted manually and iteratively to match the monitored results. Then each one of these three variables was changed on-at-a-time to investigate different scenarios – see input boundary values in Table 3.

Table 3. Input boundary conditions to the base case and each scenarios

	Base Case	S1	S2
Infiltration (l/s)			
Floor	0.05	0.0	0.0
Int. doors	0.25	0.5	0.5
Ext. door	0.9	0.5	0.5
Windows	0.4	0.25	0.25
Surface temp. (°C)			
Floor	15.8	15.8	20.0
Partitions	16.3	16.3	16.3
Ext. walls	13.6-15.1	13.6-15.1	13.6-15.1
Ceiling	17.1	17.1	17.1
Average zone operative temp. (°C)	17.1	17.1	17.1
Ext. air temp. (°C)	5.0	5.0	5.0

Scenario 1 (S1) focused on reducing airflow in/out by introducing a floor covering onto the un-insulated timber floor. As shown in figure 8, this intervention reduced the stratification gradient in the occupied zone from 2.25 to 0.75°C. Scenario 2 (S2) focused on increasing the surface temperature by introducing underfloor heating. As shown in figure 8, this intervention increased the stratification gradient in the lower part of the occupied zone (0.1m to 0.6m) from 0.75 to 1.5°C, but then the gradiant descreased in the mid-and-upper-part of the occupeid zone (0.6m to 1.7m) from 1.5 to 0.4°C.

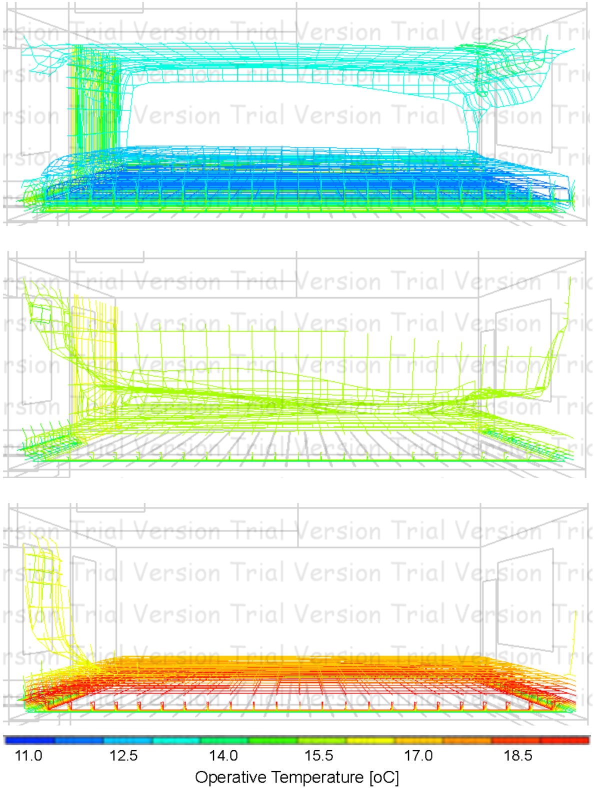

Figure 8. P10 living room – longitudinal section with operative temperature 3-D contours for the base case, scenario 1 and scenario 2 (top to bottom).

To follow this analysis, thermal comfort index (PMV) was computed using DesignBuilder CFD comfort calculations. This tool takes into account variations in air velocity, ambiant temperature, and radiant temperature of the surrounding surfaces from the CFD output; while metabolic rate (1.32 met) and clothing level (0.82 clo) are assumed to be constant for the entire zone (Gauthier and Shipworth, 2014). As illustrated in Figure 9, in all three cases, the variations in PMV within the occupied zone are small; with a maximum difference of 0.2 PMV score between 0.1m and 1.7m. However the overall PMV score is higher after both interventions; in (S1) PMV increased from -1.7 to -1.3, while in (S2) PMV increased from -1.7 to -1.1. It is important to note that resultant PMV values remain negative as operative temperature in both scenarios remains relatively low.

To conclude, simulated thermal stratifications were reviewed using different scenarios, and showed significant difference when amending airflow in/out and surface temperature. However there was little thermal comfort variability in the zone when applying the same scenarios.

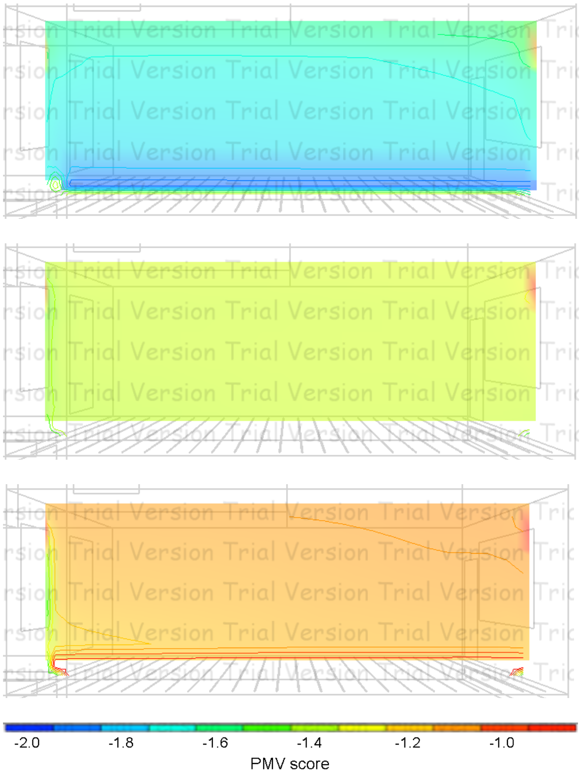

Figure 9. P10 living room – longitudinal section with filled PMV contours for the base case, scenario 1 and scenario 2 (top to bottom).

CONCLUSION

This paper explored variations in monitored and simulated thermal stratification in naturally ventilated residential buildings. Results show that monitored thermal gradients are larger than the current standard recommendations for 50% of the sample. Concurrently simulations were carried out to explore the potential causes of this effect, and included changes in surface temperature (T_s), and in airflow. One of the limitations of the simulation was the requirement for balanced airflow within the zone; as the case studies were naturally ventilated this may not be the case in real environments. Moreover BES models assume that air temperature is the same within a given volume. However thermal diversity in building is one of the solutions put forward in the quest to reduce energy demand. Therefore it may be interesting to use heuristic methods or monitored stratification profiles as input to BES models. Alternatively CFD results may be fed back to the BES model. The resultant output will be an estimation of temperature at different heights within the studied volume; this could then be taken as an input to predict thermal comfort level. In turn, this may lead to a new technique to infer predicted thermal comfort levels due to stratification effect in a room. In conclusion this coupling method has the potential for building-in greater thermal variability into existing simulation tools and making thermal comfort analysis more robust.

NOMENCLATURE

I_{cl}, clothing insulation (*clo*);
M, metabolic rate (*met*);
RH, relative humidity (*%*);
T_a, air dry bulb temperature (*°C*);
T_r, mean radiant temperature (*°C*);
v_a, relative air velocity (*m/s*).

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REFERENCES

ASHRAE. 2013. Standard 55-2013 - Thermal Environmental Conditions for Human Occupancy (ANSI approved), American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

Baharvand et al. 2013. DesignBuilder Verification and Validation for Indoor Natural Ventilation. J. Basic. Appl. Sci. Res., 3(4)182-189.

DesignBuilder Software Ltd. (2013) DesignBuilder, Version 3.4. UK. Availible at: www.designbuilder.co.uk

The Chartered Institute of Building Services Engineers (CIBSE), 2006 (a). Degree days: theory and application, TM41, London, UK.

The Chartered Institute of Building Services Engineers (CIBSE), 2006 (b). Environmental Design Guide A, London, UK.

Climate Change Act 2008 (c.27), London, UK.

Gauthier, S., Shipwoth, D. 2014. Generating empirical probabilities of metabolic rate and clothing insulation values in field studies using wearable sensors. In: conference proceedings: 13th International Conference of Indoor Air 2014, July 7-12, Hong Kong, China.

ISO 2001. Ergonomics of the thermal environment - Instruments for measuring physical quantities. BS EN ISO 7726:2001.

ISO 2005. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. BS EN ISO 7730:2005.

Mirsadeghi, M., Blocken, B., Hensen, J.L. 2008. Validation of external BES-CFD coupling by inter-model comparison. In Murakami, S. (Ed.), 29th AIVC Conference, 14-16 October 2008, (3, pp. 193-198). Kyoto, Japan.

Olesen, B.W., Scholer, M., Fanger, P.O. 1979. Discomfort caused by vertical air temperature differences. Indoor Climate, Fanger P.O. and Valbjorn O. eds., Danish Building Institute, Copenhagen, Danemark.

Webb, A.L. 2012. Mapping comfort: an analysis method for understanding diversity in the thermal envirnoment. Master Dissertation. Massachusetts Institute of Technology, USA.

Webb, A.L. 2013. Mapping comfort: an analysis method for understanding diversity in the thermal envirnoment. Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, Chambéry, France.