Proceedings of Conference: ***Adapting to Change: New Thinking on Comfort*** Cumberland Lodge, Windsor, UK, 9-11 April 2010. London: Network for Comfort and Energy Use in Buildings, http://nceub.org.uk

Thermal comfort and occupant satisfaction in residential buildings – Results of field study in residential buildings in Athens during the summer period

Agathi Sakka[a,b], Andreas Wagner[a], Mat Santamouris[b]

[a]Building Science Group, University of Karlsruhe, Englerstr. 7, Karlsruhe, Germany

[b]Group of Building Environmental Physics, University of Athens, Building Physics 5, University Campus, Athens, Greece

An extensive thermal comfort field study of ten residential buildings took place in Athens in both naturally and mechanically ventilated residential buildings, during the summer period, and obtained 1002 sets of data. Each of the 1002 questionnaire responses was made simultaneously with a detailed set of indoor climatic measurements, and estimates of clothing insulation and metabolic rate. These observations in naturally and mechanically ventilated buildings were broadly consistent with ISO 7730 Thermal Comfort Standard, ASHRAE Standard 55-92 and Greek indoor climate Standards. The research showed a strong relation between the prevailing mean outdoor temperature and indoor temperatures for comfort. The strong correlation between the mean temperature during each survey and that found to be thermally neutral by the residents has been analyzed. Additionally, the research showed that PMV often overestimated the subjective warm, especially in the case of the natural ventilated residential buildings.

Keywords: Thermal comfort, Thermal sensation, occupant satisfaction, adaptive algorithm

1. Introduction

The energy consumption in residential buildings is mainly used to create and maintain comfort conditions in the indoor environment, which also affect health of the residents. Overheating problems occurring during a warm period may cause dissatisfaction of the occupants and have a direct impact on the energy consumption of buildings for air-conditioning purposes. It has been reported that, due to the serious heat waves observed in Greece during 1987-1989, there was an increase of about 800% in annual purchases of air-conditioning units in the following years (1). This has been confirmed by the fact that the recent years have shown a rise in the number of air-conditioning systems which creates supplementary loads during the warm season.

With the urgent need to reduce the economic and environmental costs of energy consumption, the European committee gives top priority to the energy efficiency in the building sector. Hence, the latest revision of the Greek building regulation (2) aims to reduce the energy consumption due to air conditioning during the warm season and encourages passive cooling techniques, such as natural ventilation which increases indoor air speed and improves the thermal comfort. It also presents new building concepts and technologies as well as new energy strategies that appear into the market day by day. During the last years varieties of examples for low energy buildings in different use have been already constructed and are under operation with monitored results. However, energy saving measures should be done without having any negative consequences to the occupant's comfort. On the contrary, despite their energy benefits of better energy efficiency these new buildings and the existing stock have to meet the occupants' needs for comfort and life quality.

While the buildings differ in a number of ways in their geometrical form, they differ in their heating, cooling and control system and in other factors related to their occupants as the clothing and the human activity. Differences have been found by Humphreys (1978) (3), Busch (1992) and deDear and Brager (1998) (4) between the occupants of buildings which are being heated or cooled and those which are not. Several researches have shown that the natural ventilated buildings can be comfortable all over the year and they use less than half as much as energy than those with air conditioning and the occupants of naturally ventilated buildings were found to accept and prefer a significantly wider range of temperatures that fall out of the standard comfort zone defined by ISO 7730(5).

The purpose of this paper is to evaluate different algorithms in naturally and mechanically ventilated residential buildings for the Greek climatic context. Therefore a field survey has been conducted in eight naturally ventilated residential buildings and two mechanically ventilated residential buildings. First the paper presents the methodology, and the thermal comfort algorithms considered in this study. Then, results of application of different algorithms are provided with an analysis of the indoor climates in the surveyed buildings. Finally a comparative analysis is developed which allows us to evaluate the applied algorithms.

2. Methodology

2.1 Characteristics of surveyed buildings

In order to cover a wide interval of indoor conditions, a tested survey type was adopted with multiple visits in each of the surveyed buildings. In total ten buildings were surveyed. They are located in the west region of Athens in Greece.

The most of the buildings are built between 50s and 80s, with several of them are built around 1950s. These buildings are made of reinforced concrete, one to three floors height. Generally there are in good condition. The main problem is the deconstruction of coating in some parts of their facade. The maintenance of the building facades is not good in most cases. They were chosen for this study upon the following selection criteria: the use of natural or mechanical ventilation for cooling during hot period with an important thermal mass, their solar protection for exposed glazing and the availability of people to take part in the investigation. The surveyed buildings are presented in Figure 1.

In each building, apartments have been selected in order to have various orientations and conditions encountered within the building. In this research, the 90% of the participants that were applying the questionnaire were female between 30 and 40 years old.

Figure 1 Buildings R7, R8

2.2. Environmental measurements of indoor and outdoor climate

During the study, which was carried out during the summer period of 2009, over a period of approx. 20 weeks, short questionnaires had to be filled in by the residents once a day resulting in 1002 single surveys during this specific monitoring period. In the questionnaire, all aspects relevant to comfort, like room temperature, air velocity and humidity were addressed. All questions had to be answered within a 7-point-scale by the residents. Sections for free comments were also provided.

The mean participation rate was 89%, 1002 questionnaires in total were available for the statistical evaluation. The residents were asked to fill in the questionnaires at different hours of the day. The clo values determined from the questionnaire ranged from 0.33 to 0.5 and the measured air velocity ranged from 0.1 to 0.3m/sec inside the residential buildings.

The surveys were accompanied by measurements of the relevant thermal comfort parameters. Additionally, the indoor air temperatures and relative humidity were recorded continuously throughout the monitoring period in those rooms where the survey was carried out. Outdoor climate data for the site was also available for the whole period and additionally a temperature logger was situated on an urban station.

Figure 2 Measurement instruments

To achieve these measurements, proper equipment has been chosen that offers portable devices which measure air temperature, radiant temperature, relative humidity and air velocity in compliance to the specifications of the ISO 7726-30 standard. These devices have an important capacity of data storage up to 30,000 measurements. A battery ensures the energy autonomy for one day of full measurements. Figure 2 shows the measurement equipments.

The meteorological data were obtained from the station that is located on the roof of the building R1 (Figure 3). Data included the records of air temperature, relative humidity, wind speed and direction. The solar radiation data has been collected by National the Observatory of Athens (lat 37.58°N, long 23.43°E, altitude 107m).

Figure 3 Instruments placed n the top of the roof of the building R1

All information is considered as fully confidential. A database has been created and the necessary quality control has been performed, while all extreme values have been excluded.

2.3. Description of the questionnaire

The environmental measurements were accompanied with questionnaires that are intended to evaluate thermal sensation and thermal preference (a five-point scale) of participants. The questionnaire is also used to collect data about the clothing and the activities of participants in order to calculate thermal comfort indices.

The questionnaire is divided in four sections. The first section asks the resident to evaluate the thermal environment at the moment of measurements using the perceptual scale Table 2 shows the wordings of the scale. The second section includes the clothing and activity checklists. The activity checklist is referred in the physical activity of the resident as well. In the third section, the resident has to evaluate the overall quality of the indoor environment at the moment of measurements on a five-point-scale. The last section includes a checklist on the use of different thermal environment control means: windows, local fans, shading devices.

Thermal Perception Scale	Thermal Preference scale
Cold	Much warmer
Cool	Warmer
Slightly cool	Slightly warmer
Neutral	Neither warmer nor cooler
Slightly warm	Slightly cooler
Warm	Cooler
Hot	Much cooler

Table 1 Thermal perception scale and Thermal preference scale

2.4 Data collection procedure

Each building was surveyed seven times during a week alternating the visits between the afternoons. Only one person was needed to accomplish the complete data collection.
The participants were surveyed in their homes according to the following steps. In the first step, the resident has to fill in the questionnaire. At the same time, the recording devices were placed on a surface by the researcher. The devices were set to make the thermal measurements during a period of approx.12 min. At the end of the l5min, the filled questionnaire and the devices are recovered.
The field study was conducted during May, June, July, August 2009, covering the warm conditions while data are being collected during the winter period as well.

3. Calculated thermal comfort indices and algorithms

The questionnaires and the environmental measurements data were applied to an excel file. Clothing and activity values were recorded for each resident. Then the environmental measurements and questionnaires data were merged on a single excel work sheet to facilitate the statistical analysis. From this database, different thermal comfort indices and algorithms could be calculated.

3.1. Rational comfort indices

The typical rational comfort indices are the PMV (Predicted Mean Vote) and PPD (predicted Percent of Dissatisfied people) ((Fanger 1970, 6) indices used by the ISO 7730 standard. To calculate them, the Comfort program has been used based on the algorithm proposed in the ISO 7730 standard.
The Effective Temperatures ET*(Effective Temperature) and SET (Standard Effective Temperature) used by the ASHRAE standard were also calculated with UCB Comfort calculator program. This program is based on the Gagge two-node model and calculates in dynamic conditions the physiological parameters of the human body centre and skin according to the model suggested by Gagge (7). The Pearson correlation coefficients of the rational comfort indices of the mechanical and natural ventilated buildings respectively were calculated and are shown on tables 2, 3 while each point of the calculated PMV compared with that of SET for the same thermal environment (Figure 4).

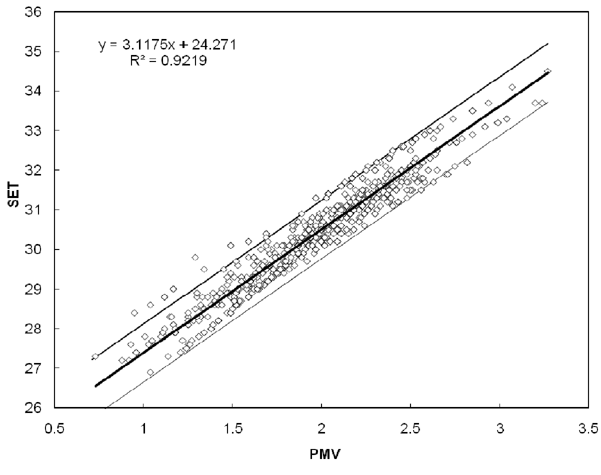


Figure 4 Scatter plot of PMV and SET

Table 2

Database_mv	Ta	Top	ET*	SET	PMV
Ta	1	0.82	0.83	0.82	0.83
Top	0.82	1	0.88	0.85	0.84
ET*	0.83	0.88	1	0.99	0.97
PMV	0.83	0.84	0.97	0.98	1

Database_nv	Ta	Top	ET*	SET	PMV
Ta	1	0.89	0.66	0.66	0.74
Top	0.89	1	0.78	0.78	0.83
ET*	0.66	0.75	1	1.00	0.98
SET	0.66	0.78	1.00	1	0.98
PMV	0.74	0.83	0.98	0.98	1

Table 3

Tables 2, 3 Pearson correlation coefficients of the rational comfort indices of the mechanical and natural ventilated buildings respectively

4. Results of questionnaires and measurements

4.1. Physical measurements of indoor and outdoor climate

Figure 5 shows the outdoor climate conditions during the whole study. They represent a typical but not very hot summer for Athens with the maximum temperature of 39.7° C.
Indoor air temperatures ranged from 23° C to as high as 38.9°C in the natural ventilated buildings sample during the monitoring period, making an average of 29.4°C. In the case of mechanical ventilated buildings, the indoor air temperatures ranged from 20°C to 35.5°C making an average of 27.95°C. The highest temperatures have recorded in the Residential buildings facing east and presenting a lack in the solar shading devices. Relative humidity

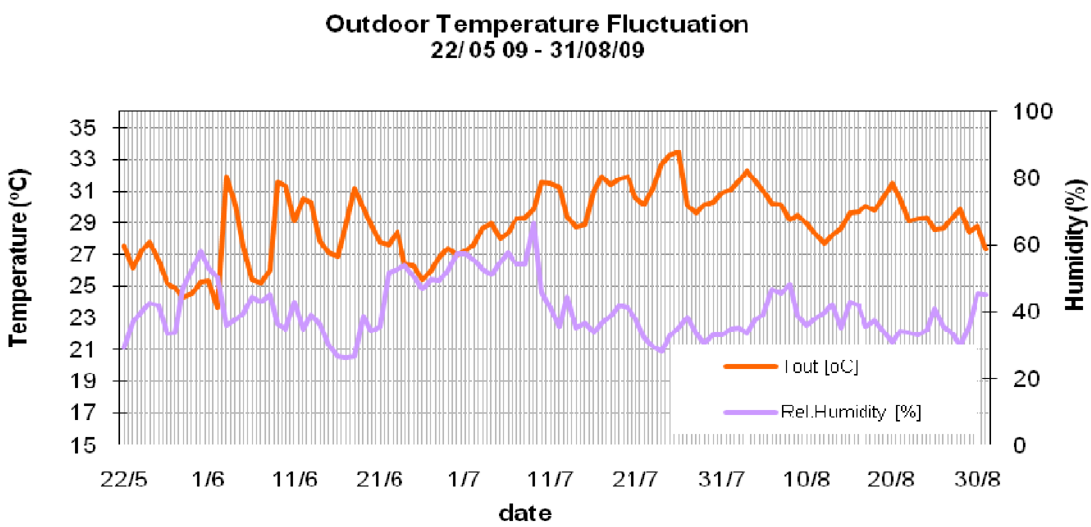


Figure 5 Outdoor climatic conditions during the monitoring period

showed high values during the hot season with a mean of 40.5%. There is also a big difference between the outdoor and the indoor temperatures in the most of the cases while the difference between the indoor temperatures compared to an urban station's temperature is very high, 3.3 °C to 5°C.

The chart of the cumulative percent (Figure 6) shows that over 40% of the maximum indoor temperatures are up to 35 °C, while 70% of the mean indoor temperatures are up to 30°C for the specific monitoring period.

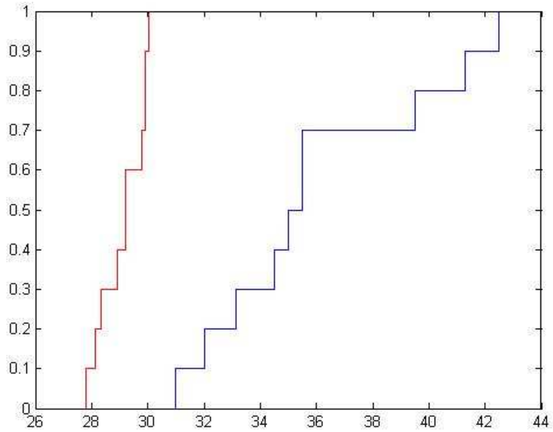
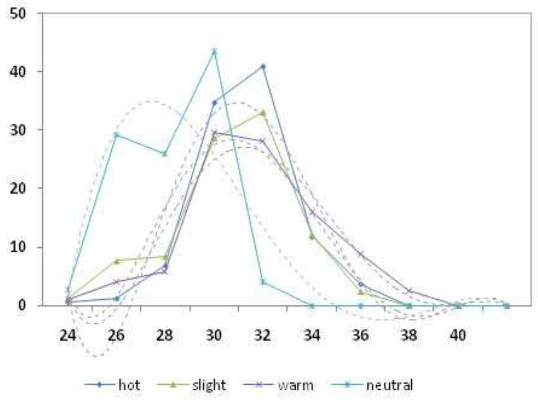


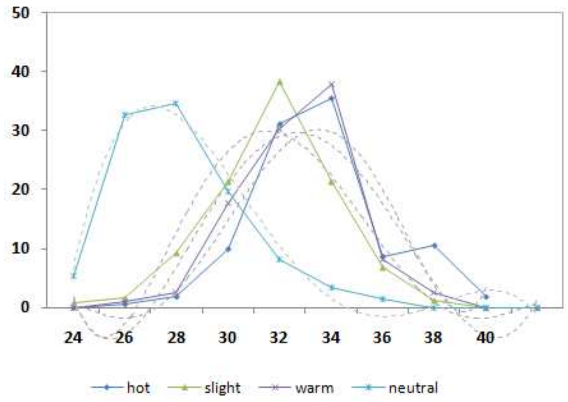
Figure 6 Chart of cumulative percent

The statistical T-tests of the differences of the means in the level of 0.05 do show a significant difference between the outdoor temperature and the indoor temperature of each residential building respectively during the specific monitoring period. The only exception is the case of the mechanically ventilated residential building R1.

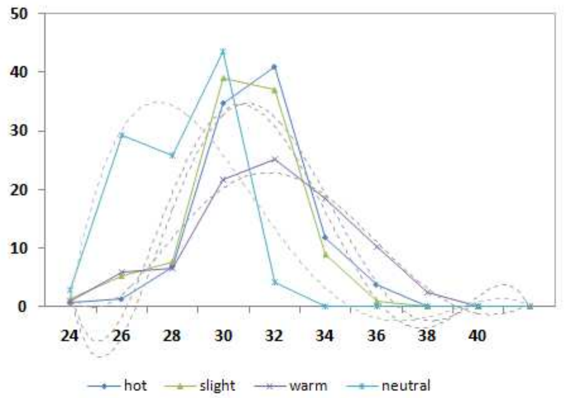
4.2. Thermal sensation and preference of participants

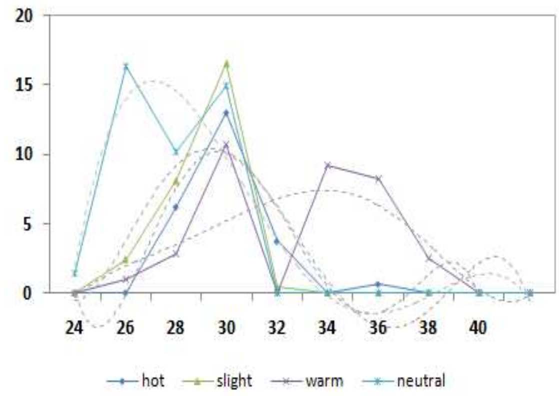
The surveyed participants emit their votes of the thermal sensation on evaluative and preference scales in response to the immediate conditions (Table 1).
The Figures 6, 7, 8, 9 show the cumulative distribution of indoor and outdoor temperatures of mechanical and natural ventilated residential buildings in relation with the thermal sensation votes of the residents. In the case of the mechanical ventilated buildings the aprox.45% of the neutrality votes are under the range of 30°C while the 43% feel 'hot' when the indoor temperature of their environment is 34°C. There is a small congestion between the votes of 'hot' sensation and 'warm' sensation but this can be because of 'behaviour' or 'psychological' reasons affect the residents. The biggest percent feel 'hot' on the outdoor conditions that up to 35°C high temperatures are preponderated.





Figures 6, 7 Cumulative percent of indoor and outdoor temperatures respectively of mechanical ventilated residential buildings in relation with the thermal sensation votes of the residents





Figures 8, 9 Cumulative percent of indoor and outdoor temperatures respectively of natural ventilated residential buildings in relation with the thermal sensation votes of the resident

The statistical Tests [T>1.96] show a significant decline on the distribution of the thermal sensation votes in the cases of correlation between the outdoor and indoor temperatures of natural and mechanically ventilated residential buildings. As it can be seen from the Figure 10, the votes for thermal sensation are given subject to the operative indoor temperature. The votes for 'neutral' and 'slightly warm' represent 56.5% of all votes and include temperatures above 25.5°C.

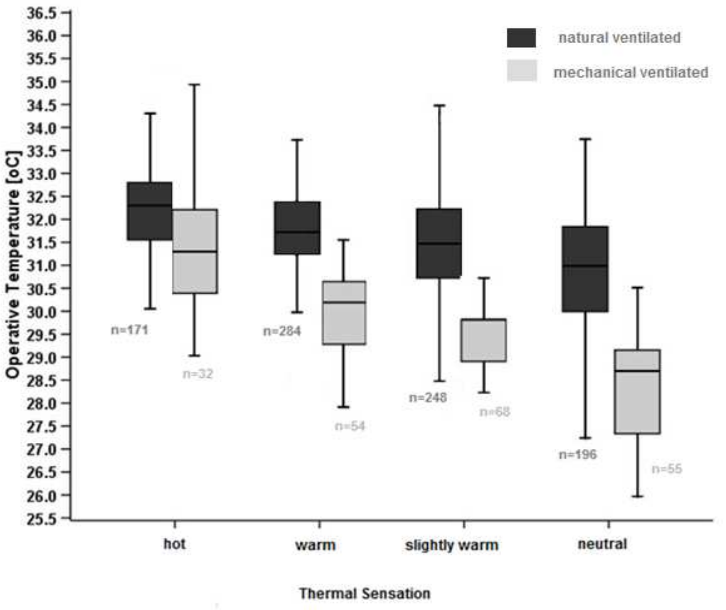


Figure 10 Box plots of votes of thermal sensation against operative temperature in the residential buildings

Figure 11 show that only 43 votes evaluated the indoor climate as "very unsatisfying" and 243 votes as "slightly unsatisfying". These votes correspond to a majority of votes of "very warm" and "slightly warm" for the thermal sensation. The neutral and positive votes on indoor climate coincide well with a large acceptance of the indoor temperature.

Though there was not a broad of air velocities measured in the residential buildings, the residents demanded stronger air movements particularly when the sensations ‘hot’ and ‘warm’ were chosen.

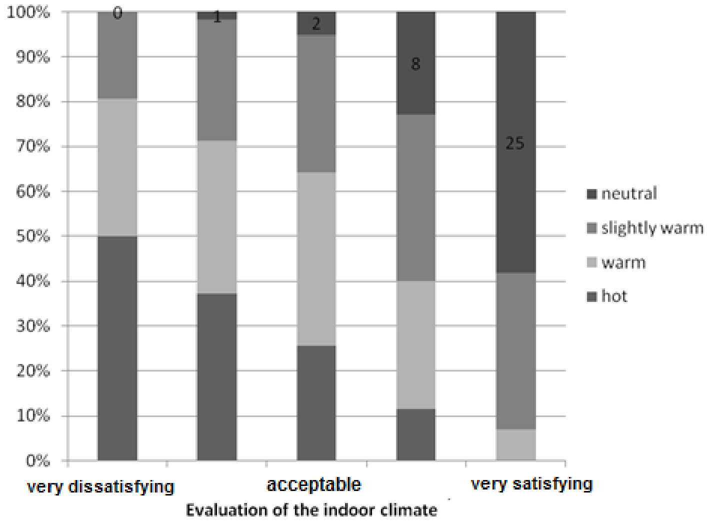


Figure 11 Thermal Evaluation of indoor climate

Surprisingly the PMV include negative values indicating a cool or even cold indoor environment.

Mean Responses

During this research, it was found that the mean warmth sensation of the residents was usually closer to the 'hot' sensation (Figure 12).

It is noted and fully agreed with previous researches of F. Nicol and Humphreys, 1973, that people felt hot if the indoor conditions were hotter than those to which they were currently adapted, rather than because of the conditions themselves (8).

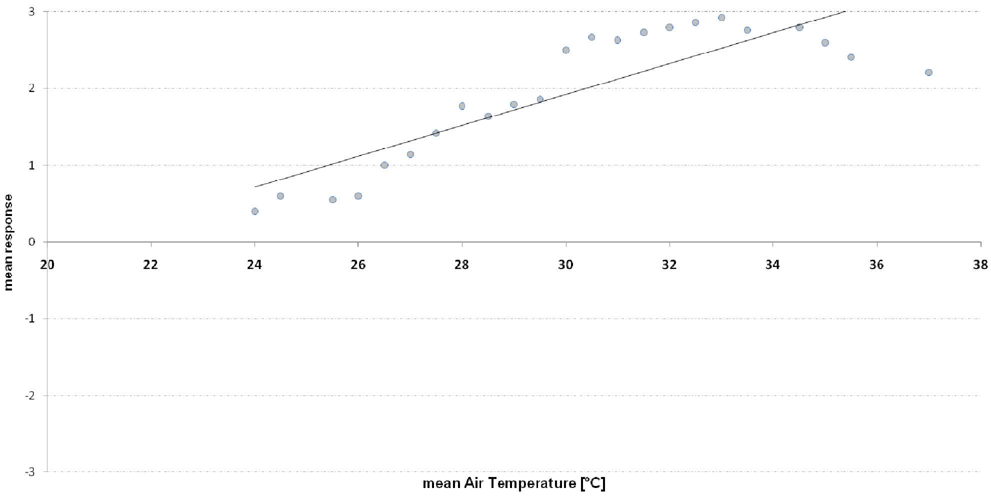


Figure 12 Scatter plot of the mean response and mean room temperature

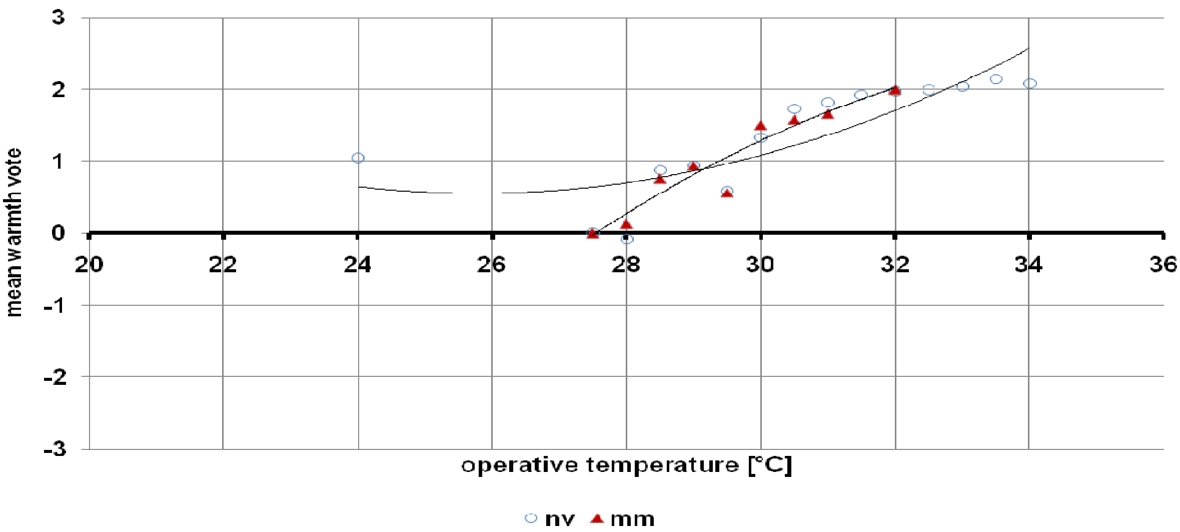


Figure 13 Scatter plot of the mean warmth vote against operative temperature of both natural and mechanical ventilated residential building

From the figure 13 it seems that the residents feel 'neutral' in their environment whether the indoor temperature is between 27°C and 28°C during the summer period (Figure 13).

Figure 13 also shows that a number of the mean responses lie quite far from thermal neutrality, and these occurred not only when the mean operative temperatures were extremely hot. This suggests both that probably the response of these residents had failed fully to operate.

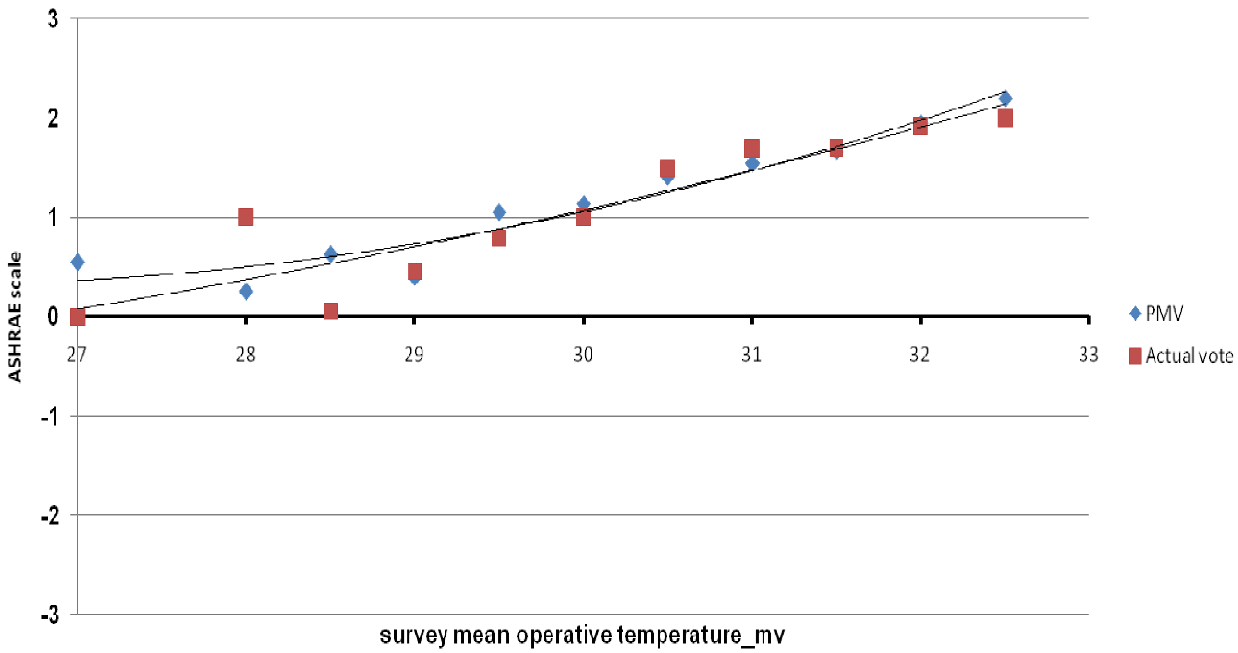


Figure 14 Scatter plot of the mean vote against operative temperature of mechanical ventilated residential buildings

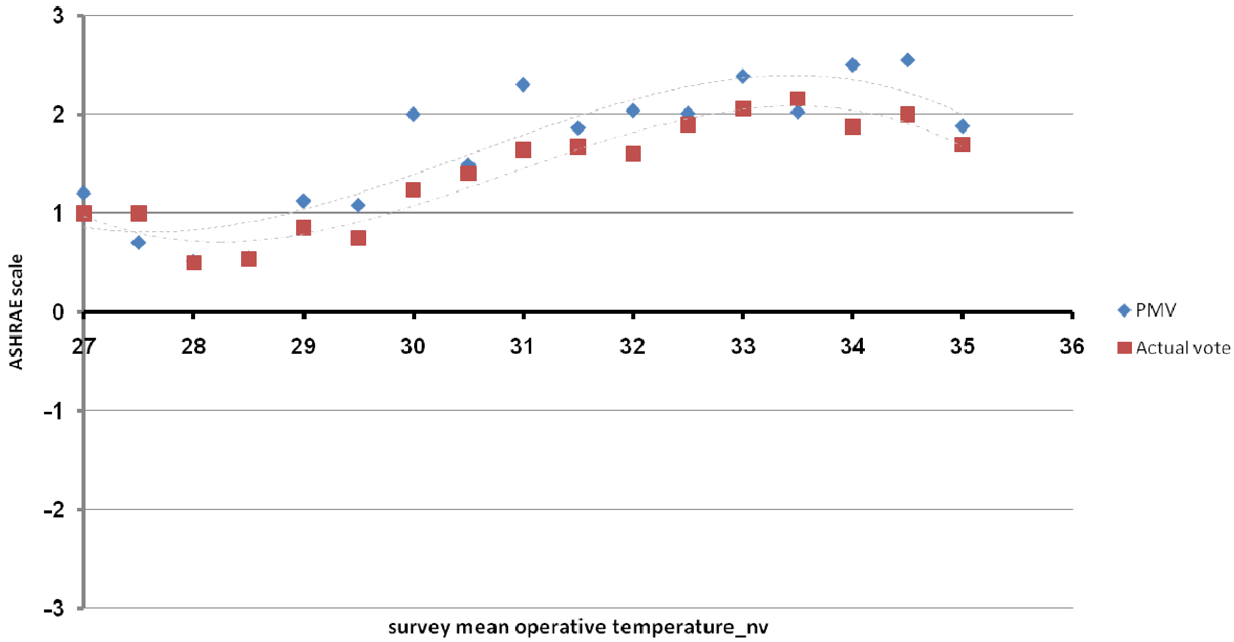


Figure 15 Scatter plot of the mean vote against operative temperature of natural ventilated residential buildings

Figures 14, 15 show the mean votes given by the residents in relation with the predicted values using the PMV equation. The curves show that PMV deviates substantially from the residents' mean thermal sensations at indoor temperatures especially in the cases of the natural ventilated buildings. This shows that PMV overestimates the subjective warmth. PMV was at its best when the mean indoor temperature was in the region of 30 - 31oC.

Regression coefficient

The mean regression coefficient of the research for the specific period was 0.26 scale units/K for the naturally ventilated buildings and 0.32 for the case of mechanical ventilated buildings. We can extract a regression coefficient for each naturally ventilated building but the difference among them is not significant.

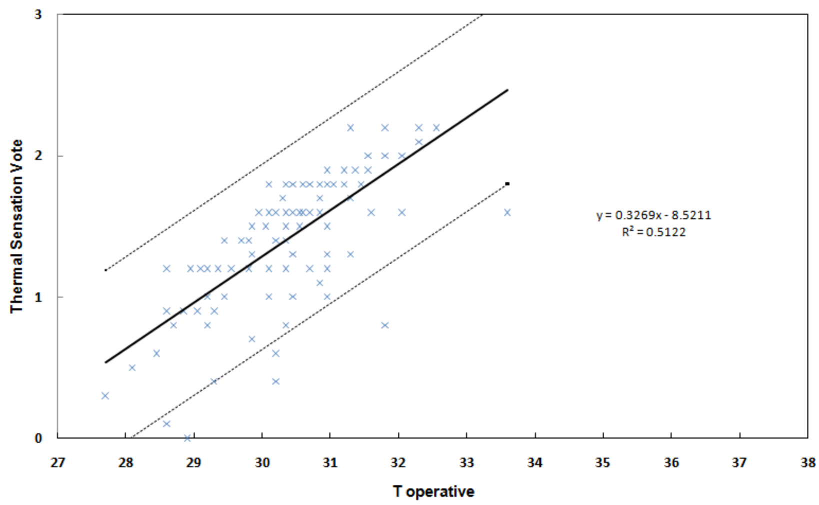


Figure 16 Scatter plot of warmth vote and operative temperature of mechanical ventilated residential buildings

The research showed that the regression gradient decreases as the standard deviation of the operative temperature increases and that in the cases of the mechanical ventilated buildings the regression gradient is significantly higher (Figure 17). That can be this can be because of ‘behaviour’ or ‘psychological’ reasons affect the residents (9).

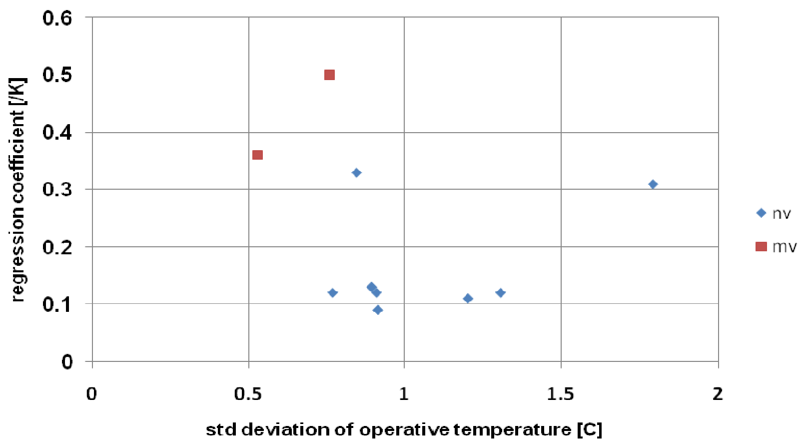
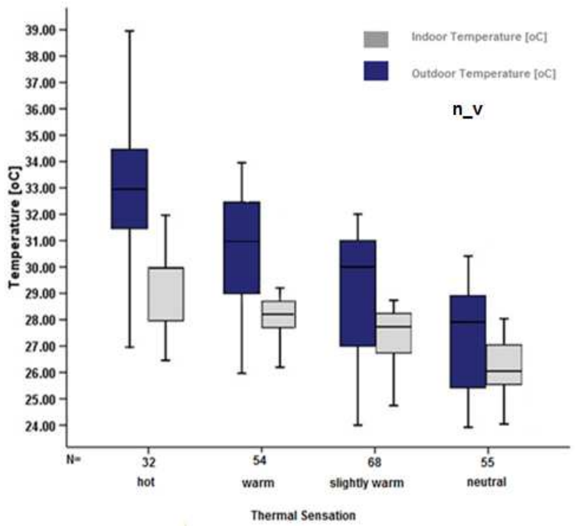


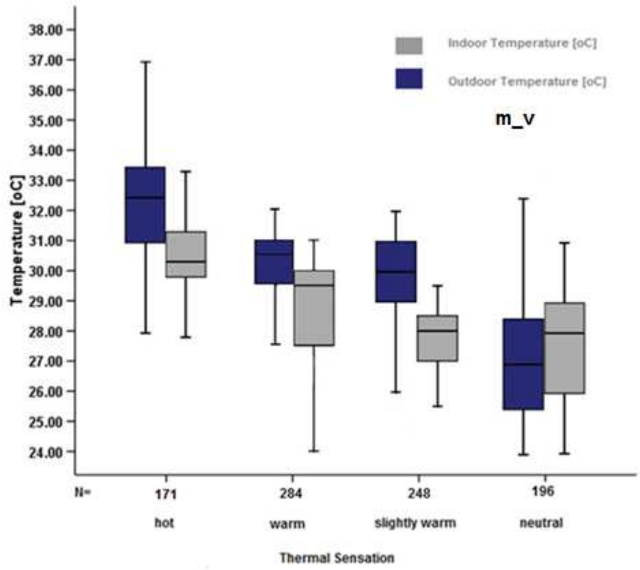
Figure 17 Scatter plot of regression coefficients of warmth vote on operative temperature vs the std deviation of the operative temperature

Temperatures for thermal neutrality

The vote for 'neutral' covers a significant temperature range. There is a difference of 6.5°C between the mean value of the outdoor temperature which corresponds to the votes for 'hot' and the mean value of the outdoor temperature which corresponds to the votes for 'neutral' while there is a difference of 2°C between the mean value of the indoor temperature which corresponds to the votes for 'hot' and the mean value of the indoor temperature which corresponds to the votes for 'neutral' (Figure 18).

From the Figure 19 it can been seen a difference of 5°C between the mean value of the outdoor temperature which corresponds to the votes for 'hot' and the mean value of the outdoor temperature which corresponds to the votes for 'neutral' while there is a difference of 4°C between the mean value of the indoor temperature which corresponds to the votes for 'hot' and the mean value of the indoor temperature which corresponds to the votes for 'neutral'.





Figures 18, 19 Box plot of vote of thermal sensation against indoor and outdoor temperatures in naturally and mechanically ventilated buildings respectively

Simple linear regression was performed between thermal sensation and operative temperature to determine the strength of the relationship between them in the case of natural ventilated buildings. Figure 20 shows the regressions obtained in the monitoring period. The thermal sensation votes correlated strongly with the operative temperature. In the case of the naturally ventilated monitoring buildings the variations of the indoor temperature is more important compared to the case of the mechanically ventilated buildings and the residents became less sensitive to the temperature rise. This can be explained by the diversification of thermal experiences of occupants and the interactions between occupants and their environments as suggested by F.Nicol (10).

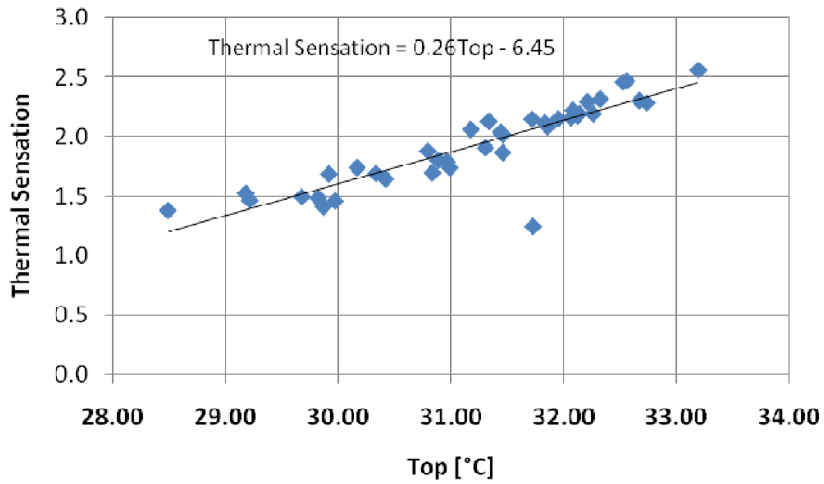


Figure 20 Linear regressions of thermal sensation votes vs. operative temperature

While the mean thermal sensation vote -TSV(mean)-, the mean operative temperature - Top(mean)- and the regression gradient-b-were known, the operative temperature-Top(n)- has been calculated at which the residents have average reported being thermally neutral by the calculation (9)

Top(n) = Top(mean) –TSV(mean)/b

Figure 21 shows the neutral temperatures against the mean of the operative temperature at the times when their comfort votes were obtained. It is obvious that there is not a strong correlation of the neutral temperature with the mean operative temperature. The curve suggests that adaptation of the temperatures is less effective when the room temperatures

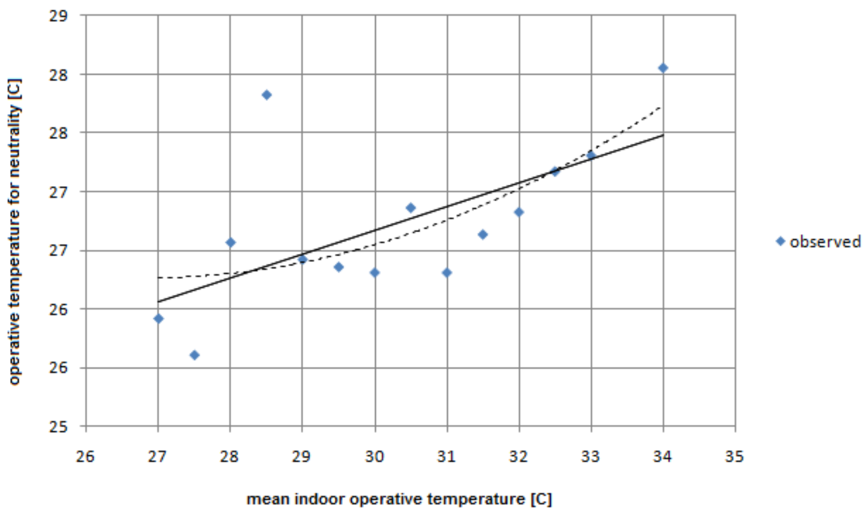


Figure 21 Scatter plots of neutral temperatures against the mean operative temperature

are below 28°C and up to 33°C. This can be resulted because the monitoring sample of residential buildings was small.

5. Comparison between perceived votes and PMV predicted votes

The votes on thermal sensation do not correspond to the predicted mean votes, which were calculated with the data measured during the surveys. The range of PMV is very wide and only changes very slightly depended on the class of the subjective votes ('slightly warm', 'neutral') in both natural and mechanical ventilated buildings. The table 4 shows the statistical tests between frequencies of PMV values and the Thermal Sensation votes of each Residential building. The red numbers are presenting the cases where there is a significant difference between the PMV field of values and the Thermal Sensation votes. At the same time, it has been concluded that the best correlation among PMV values and the Thermal sensation votes is the class of the subjective votes 'slightly warm' (Table 5).

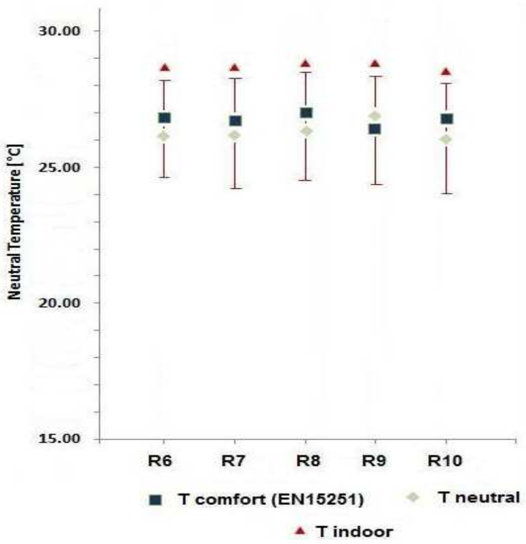
	neutral	Slightly warm	warm	hot		neutral	slightly warm	warm	hot
R1	6.18	1.10	8.30	4.06	R6	3.60	2.02	2.60	2.14
R2	3.73	5.89	6.77	2.08	R7	5.65	3.52	2.46	2.65
R3	3.88	4.80	5.71	3.88	R8	3.60	2.82	0.01	1.80
R4	4.88	3.30	2.93	4.09	R9	2.50	0.34	0.36	1.41
R5	5.26	3.14	0.95	5.59	R10	3.74	5.19	5.53	2.22

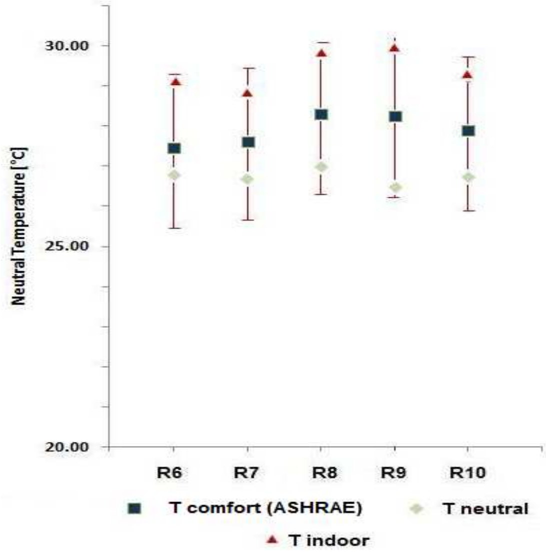
Table 4 Statistical Tests between Frequencies of PMV values of each Residential building

	R1	R2	R3	R4	R5
Neutral	0.03	0.00	0.00	0.00	0.00
Slightly warm	0.81	0.79	1.00	0.62	0.51
Warm	0.37	0.02	0.00	0.30	0.14
Hot	0.08	0.08	0.00	0.17	0.29
	R6	R7	R8	R9	R10
Neutral	0.00	0.00	0.00	0.00	0.00
Slightly warm	0.60	0.57	0.48	0.70	0.92
Warm	0.10	0.00	0.07	0.00	0.03
Hot	0.74	0.39	0.46	0.26	0.09

Tables 5 Percentage of the PMV values with the coincident Thermal comfort values

Figures 22, 23 compare the neutral temperatures in the five buildings with the comfort limits of EN1 and ASHRAE standards, respectively. The neutral temperatures are closer to the centre range of the EN1comfort limits, while they are closer to the lowest range of the ASHRAE comfort limits. However, they are all within the comfort limits of both standards for the five buildings. The comfort limits of both methods correspond well to the neutral temperatures found in this study except of some case that the PMV often overestimated the subjective warm in the case of the natural ventilated buildings.





Figures 22, 23 Measured neutral temperatures compared to the ASHRAE and the EN1 adaptive comfort zone respectively

Short Discussion

A field study has been conducted in eight naturally ventilated and two mechanical ventilated residential buildings in West part of Athens during the summer period. Findings from analysing the data gathered are as follows:

- There is a weaker relation between the mean outdoor temperature and the indoor neutral temperature in the case of mechanical ventilated buildings.
- The residents feel 'neutral' in their environment whether the indoor temperature is between 27°C and 28°C during the summer period.
- The thermal indoor climate was in general warm during the monitoring period, and more than the half of the participants were dissatisfied from the indoor thermal conditions and want to have more air movement.
- There is not a strong correlation of the neutral temperature with the mean operative temperature. This can be resulted because the monitoring sample of residential buildings was small.
- In the cases of the natural ventilated buildings, the thermal sensations are well correlated with the operative temperature compared to the cases of the mechanical ventilated buildings.
- In the same time the research showed that PMV often overestimated the subjective warm, especially in the case of the natural ventilated residential buildings. This statement reinforces the doubt of the ability of the thermal comfort indices to predict the thermal sensation of the occupants for residents in warm accommodations.

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