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CASE STUDY OF OCCUPANT'S PERCEPTION OF INDOOR THERMAL CONDITIONS UNDER DIFFERENT HEATING SYSTEMS

Alžběta Kohoutková, Jana Horváthová, Martin Kny and Ondřej Nehasil
[1]University Centre for Energy Efficient Buildings, CTU in Prague
Czech Republic, Europe
alzbeta.kohoutkova@cvut.cz, jana.horvathova@cvut.cz,
martin.kny@cvut.cz, ondrej.nehasil@fsv.cvut.cz

ABSTRACT

This study is focused on a human perception of a thermal environment. The human perception is influenced by many factors, for example activity, clothing, age, gender and psychological condition. In the laboratory thermal conditions of outdoor and indoor environment were artificially simulated. Experiments were repetitively held on the group of 24 occupants for different kinds of heating systems. These occupants were of same age and wore same kind of clothing. Half of them were male and half female. The aim of the sets of experiments was to assess a of occupants´ perception of the thermal conditions.

INTRODUCTION

Energy saving requirements nowadays lead to an effort to reduce energy consumption for heating, ventilation, cooling, lighting and other building services systems used in buildings. Energy consumption in buildings (in Europe and in the Czech Republic) comes to approximately 40 % of the total energy consumption. (Horváthová 2017)

The research hypothesis was based on the assumption that different heating systems use would require different temperature controls because occupants would sense heat differently under different thermal conditions created by different heating systems. These results could be beneficial for further research and development of optimal controls of heating systems in terms of thermal comfort.

To confirm this hypothesis, it was necessary to carry out the series of experiments for different temperatures and different heating systems. These experiments were carried out under the same conditions. The occupant sat at the same place in the lab and his/her clothing was kept the same for all temperature levels.

It is important to determine optimal indoor environmetal parametres (to reach thermal comfort) and to minimize energy demand of buildings and to create a healthy indoor environment. The data analysis presented in this paper is based on measured data and questionnaire survey collected data from a large experiment conducted with a group of 24 subjects. These occupants subjectively assessed the thermal comfort in laboratory test chamber under different heating systems conditions.

The subject of the study was the thermal comfort assessment perceived by an subject during different heating systems operation and different settings of the required temperature by a conventional controls. The heating systems were installed in a double test chamber. This chamber is able to provide the same boundary conditions repeatedly and is able to to identify small differences in the behavior of individual heating systems. Operation of individual heating systems was controlled by a PWM (Pulse Width Modulation) room thermostat based on room air temperature. Individual experiments were performed after the thermal environment had stabilized to the desired value. The thermal environment was investigated at three steady temperature levels, one of which was the optimum state for a given heating system, based on previous research.

The temperature values $T+$, $T-$ and T_{opt} were selected according to the previous laboratory experiments and the results obtained by the thermal manikin.

Since the experiments were held in Europe in the Czech Republic authors would like to shortly mention the country´s climate characteristics. The climate of the Czech Republic is moderately continental, with cold winters (during which the temperature is often below freezing) and warm summers, during which nights remain cool.

The temperature difference between summer and winter is relatively high, due to the landlocked geographical position. (Tolasz, 2007)

LITERATURE REVIEW OF PRECEDENT STUDIES

Ways of thermal comfort assessment were investigated by Houghton & Yaglou (1923) and by Bedford (1936) in the first half of the 20th century.

The Bedford scale is still in use today. Fanger (1970) has long been dealing with the thermal comfort issue and in 1970 has specified the basic and complementary factors that influence thermal comfort (defined by PMV and PPD indices).

Gagge et al. (1986) opted for a different approach to assessing thermal comfort. He used his physiological model to determine the standard effective temperature SET (recognized by ASHRAE in 1986). The SET calculation is similar to the calculation of the PMV index, as it is also based on the thermal balance equation, which includes occupant factors (clothing and metabolism).

The basic difference between the PMV index and the standard effective SET temperature is that SET is based on the prediction of the mean skin and skin moisture temperature (TSENS thermal sensitivity index and TDISC thermal discomfort index). Fiala (2003) defined the Dynamic Thermal Sensitivity Index (DTS) as an equivalent index to the PMV index. The DTS index can also be used for time-varying conditions and represents the overall thermal sensation of an occupant, which is dependent on the mean skin temperature, its time change and body core temperature.

The latest models of thermal comfort include the Berkeley model (Zhang, 2003) which describes the psychological aspects of the thermal comfort perception.

METHODS

During the work on this project following methods were used: experimental measurement, calculations based on measured data collection, data collection of questionnaires filled by occupants and statistic analysis of these gained data.

Double test chamber description

The measurement, operation testing and assesment of heating systems was carried out in one of two test chambers in a double test chamber in a laboratory of a research centre (see *Figure 1* and *Figure 2*). This double test chamber consists of two test chambers, the corridors and an entrance hall. The adjacent test chambers are separated by inter partition. In these chambers and corridors one can simulate different indoor and outdoor conditions. Inner dimensions of each test chamber are 4,4 m x 3,1 m x 2,85 m. Thermal transmittance factor (U – values) of test chamber members are:

- Floor : U = 0,132 W/m^2.K
- Ceiling: U = 0,103 W/m^2.K
- Wall to corridor: U = 0,134 W/m^2.K
- Window: U = 1,200 W/m^2.K
- Door: U = 1,200 W/m^2.K

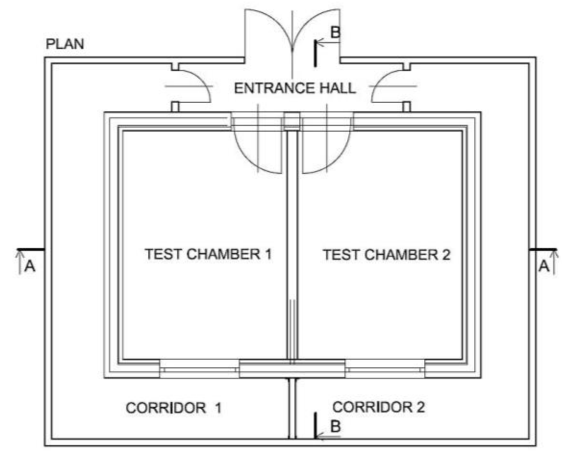

Figure 1 – Double test chamber – Plan

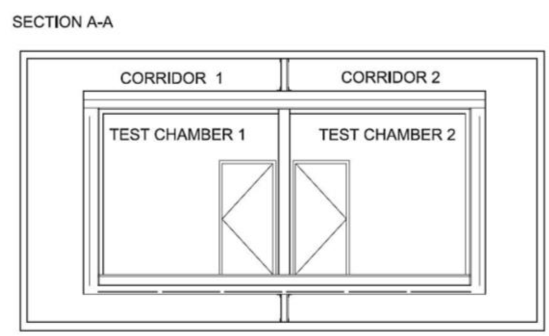

Figure 2 – Double test chamber – Section A-A

Experiments were held in the test chamber 1. Thermal environment in the adjacent test chamber 2 was kept similar to that one in the chamber 1. This arrangement was taken to prevent heat fluxes from occuring in between these test chambers.

In the corridor area the air temperature setpoint was -12 °C to simulate traditional outdoor winter conditions in the moderately continental climate. This is a traditional design value for heating systems design and testing in the Central Bohemian Region where the laboratory is located.

Measurement description

Four electrical heating systems were chosen to measure and assess thermal comfort on: convection heater, floor heating, ceramic heating panel, ceiling heating (ceiling foil). Experiments were carried out with different thermostat settings on each one of these systems.

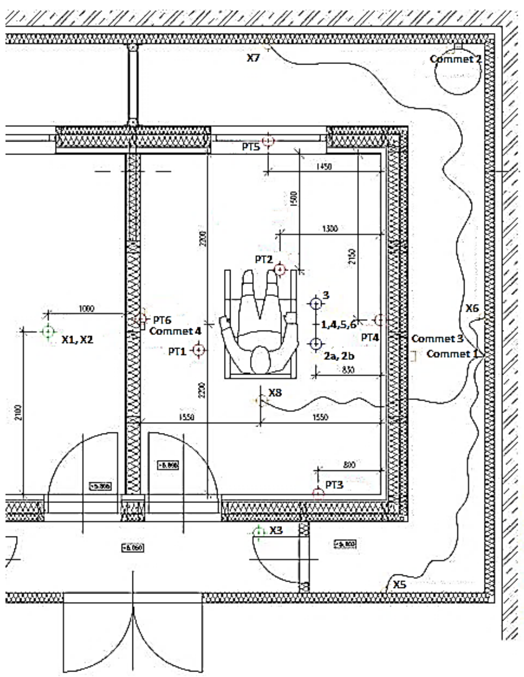

Figure 3 –Detail view of Test chamber 1 with sensors (for mark meaning see the parameters listing on the right side of this page)

A chamber PWM thermostat was situated on the wall of test chamber 1. It controlled the heating systems based on air temperature in the investigated test chamber 1.

Single experiments were carried out after the thermal environment became stable on the required temperature value. Thermal environment was investigated on three steady-state temperature levels. One of these levels was the optimal level for the chosen heating system. This optimal level was a result of previous experiments held in the laboratory which was also confirmed by the thermal manikin themal conditions assessment. Thermostat settings for particular measurements are listed in the *Table 1*.

Thermal sensation of indoor environment (by a subject) is influenced by a few factors especially subject´s physical activity, garment, age, gender and momentary psychological state.

The experiments were carried out repeatedly on 24 subjects of similar age, clothing and physical activity with respect to the nature of the experiment. There were 12 females and 12 males present. The main experimental focus was on detection of the differences in the thermal environment perception.

Table 1 Thermostat settings – particular measurements

THERMOSTAT SETTINGS T_{SET}	**T-**	**T_{OPT}**	**T+**
Convection heater	20,0 °C	22,5 °C	24,0 °C
Ceramic heating panel	20,0 °C	22,0 °C	24,0 °C
Floor heating	20,0 °C	22,0 °C	24,0 °C
Ceiling foil	20,0 °C	22,5 °C	24,0 °C

The thermal comfort questionnaire was filled for 3 times during each experiment by each subject. The chosen number of subjects, three-times during experiment questionnaire survey data collection and momentary health state data collection were settled to eliminate influence of momentary of mind and momentary psychological state.

The combination of 4 heating systems, 3 temperature setpoints, three-times questionnaire survey data collection made by 24 subjects lead to 288 experiments in total and 864 data sentences collection in total. This collection consists of all investigated and measured parametres and questionnaire survey entries. (Kabele, Horváthová et al. 2017)

Each experiment took 90 minutes and the continuous measurement of following parametres was carried out in the double test chamber during each experiment (For sensors location see *Figure 3*):

- Air temperatures $t_{a,1\text{-}4}$ in the double test chamber (at 4 height levels – 1; 3; 4; 5; 6 marks on the *Figure 3*);
- Globe temperature t_g in the middle of the test chamber 1 at the height of stomach of a sitting subject (at a height of 0.6 m above the floor – 2a, 2b marks on the *Figure 3*);
- Relative humidity *RH* (1; X1 marks on the *Figure 3)*;
- Atmospheric pressure p_a (X3 mark on the *Figure 3*);
- Surface temperatures of the double test chamber structures t_p (PT1; PT2; PT3; PT4; PT5, PT6 marks on the *Figure 3*)
- Air speed in the double test chamber v_a (3 mark on the *Figure 3*);
- Measurement of the sound pressure level in the double test chamber;

- Measurement of the illumination level (illumination intensity) in the double test chamber;
- CO_2 concentration measurement in the double test chamber;
- Outdoor air temperature t_e in the corridor 1 (X5, X6, X7, X8 marks on the *Figure 3*);
- Questionnaire survey data collection on the thermal sensation of subjects (three-times per experiment);
- Heart rate and body surface temperatures monitoring (on 5 body parts) of subject´s bodies;
- Collection of images of subjects garment;
- Record of On-line video/audio stream of experiment course made for measurement assistant – subjects communication and subjects light-intensity activity control

ASSESMENT

The thermal comfort assessment can be simply divided into two basic groups, namely the objective and subjective thermal comfort assesment. Objective methods are based on the results of measurements of physical quantities which determine the state of the indoor environment. Subjective methods are based on the subjective sensations of subjects in the investigated environment (questionnaire survey). (Horváthová 2017)

Data analysis is focused on the results which describe the correlation of the objective and subjective thermal comfort assesment of the investigated test chamber 1.

Statistics - hypothesis testing

Our hypotheses were statistically tested to allow us make a judgement whether or not the experimentally obtained data (subjective assesment) by males and females were statistically significant or not (if the data could be used in one set of 24 subjects or if it would be necessary to sort out this data by gender to two sets).

To find out an evaluation was performed using the so-called two-sample unpaired F-test and a two-sample unpaired T-test. It can be concluded that the probability of a null hypothesis on the median of the two subject sets is high, which is based on the results of these unpaired tests. It was examined that the difference between the medians for the subject sets is statistically insignificant therefore the differences in groups do not have a significant effect on the results of conducted experiment.

Subjective thermal comfort perception vs. objectively calculated PMV index

The aim of this data analysis part was the results comparison of the calculated value of the average predicted mean vote index (PMV) and the subjective thermal comfort perception value gained in the questionnaire survey.

Objectively calculated PMV index

PMV is an index which predicts a mean value of the subjective ratings of thermal sensation based on a large group of subjects in a an investigated indoor environment. These occupants can assess their sensation using a seven-point scale (created by Bedford) of thermal sensations (scale values were defined as: +3 hot; +2 warm; +1 slightly warm; 0 neutral; -1 slightly cool; - 2 cool, -3 cold). This scale of the predicted mean vote (PMV) was taken from the standard EN ISO 7730. The defined word assessment was taken from ASHRAE-55. This scale was based on the thermal balance of the human body with the environment.

The PMV index calculation can be performed on different value combinations of human metabolic rate, clothing insulation (insulation provided by garment), air temperature, mean radiant temperature, air speed and relative humidity under steady state conditions. In order to compare the results of the objective PMV and the subjective perception, it was necessary to determine an uniform metabolic rate value of the subjects and to calculate the thermal resistance value of their garment.

Metabolic rate value

Metabolic rate value was chosen for sedentary (little or no exercise) level of activity (office work, dwelling and school). The value was taken as 70 W/m^2 (which corresponds to the output of 130 W for an average subject area of 1.8 m^2) according to European standard EN ISO 7730. (ČSN EN ISO 7730, 2006)

Thermal resistance of clothing

The thermal resistance of the garment (thermal insulation of the garment) I_{cl} can be estimated according to the information given in the European standard EN ISO 9920 Ergonomics of the thermal environment - Estimation of thermal insulation and water vapour resistance of a clothing ensemble. or can be approximately calculated based on the empirical formula given in the same standard. The clothing of the subjects was following: underwear, trousers, a T-shirt and a slight sweater or sweatshirt. The thermal resistance value was calculated in the range of I_{cl} = 0.6 to 0.8 clo which is equal to interval of 0.093 $m^2.K / W$ to 0.124 $m^2.K / W$.

DISCUSSION AND RESULT ANALYSIS

On the horizontal axis of *Figure 4* chart the calculated PMV value can be seen. It is based on the measured parametres: measured air temperatures, air velocities, etc., and on the calculated parametres: the thermal resistance of the garment, and the metabolic rate value of the particular experiments. The vertical axis represents a subjective expression of the thermal sensation. The subjects marked a value in the range of 1 to 100 as they chose how to answer the question *"I'm very cold (1) / I'm very warm (100).* Each colouring symbolizes different thermostat temperature setpoint (blue marking = T-; green marking = T_{opt}; red marking = T+).

The calculated PMV index value coincides with the subjective heat perception in the investigated chamber (see the *Figure 4*). The trendline acquires the value of subjective sensitivity at level of 50 (neutral state = thermal comfort) at PMV = -0.0495. This value is very close to the predicted value of 0.

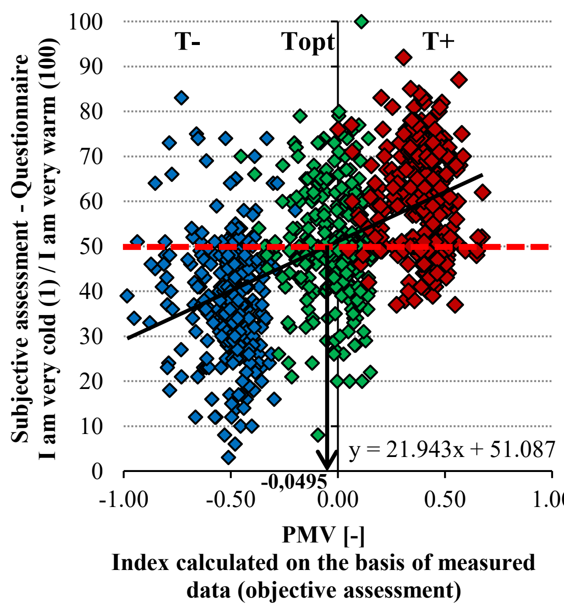

Figure 4 Objective vs. subjective thermal comfort perception

It arises from this graphical method solution that the subjective assessment made by subjects really corresponds with the objective assessment of the investigated chamber by using the traditional thermal comfort model expressed by the PMV index. This analysis confirmed the conformity of the subjective thermal comfort perception with the PMV index calculation with incredible accuracy. (Kabele, Horváthová et al. 2017)

Subjective assessment according to optimal air temperature

The real optimal air temperature appropriate for particular heating systems was determined by the dependence of the subjective thermal comfort sensation (gained in the questionnaire survey during the experiment) and the objectively measured air temperature $T_{a,\ opt}$ (measured air temperature at a height of 0.6 m above the floor) during the experiment.

Each assessed heating body has a different share of radiant heat and convective heat therefore different air temperatures are required to achieve the same globe temperature. (Horváthová 2017) On the horizontal axis of the *Figure 4* chart a subjective questionnaire survey question: I'm very cold (1) / I'm very warm (100) is displayed. On the vertical axis there is the measured air temperature $T_{a,\ opt}$ which was measured at the level of the human abdomen (at the height of 0.6 m above the floor). The real optimum temperatures for each system were derived from the chart and their values are: Floor heating = 22.74 ° C; Convector = 22.67 ° C; Ceramic panel = 22.24 ° C; Ceiling foil = 22.34 ° C.

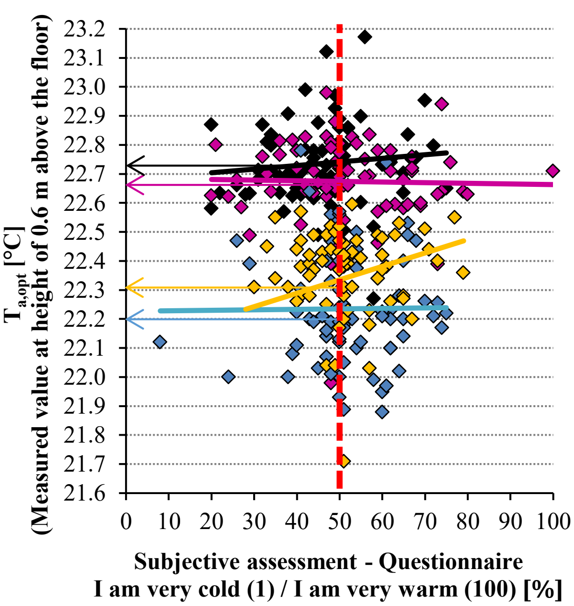

Figure 5 Subjective assessment comparison of the different heating systems adjusted to the optimal air temperature set point $T_{a,opt}$ (Horváthová et al. 2017)

When the results of the real optimal temperature were taken into account, it was obvious that the subjects perceived the coldest sensation during the floor heating operation. The assumption that the warm floor would have had a favorable warm floor effect on the overall subjects thermal comfort had not been confirmed. An interesting result is the correlation (and equality relation) between the neutral state (50% on the horizontal axis is equal to neutral state which is equal to thermal comfort) and the resulting optimum air temperature for individual heating systems. This equation depicts higher effect of the radiant heat transfer during the ceramic heating panel operation and the ceiling foil operation. It is also evident from the chart (see *Figure 5*) that the radiant heating surfaces, which operate with higher surface temperatures, influence the thermal comfort positively (except from floor heating). These higher temperature surfaces systems achieved thermal comfort at a lower air temperature than the others.

Thermal comfort assessment according to subjective perception

This thermal comfort assessment is based on comparison of two following questions: *I'm very cold (1) / I'm very warm (100)* and at the same time I feel like: *I'm sated with food (1) / I'm hungry (100).*

The results shown in the *Figure 5* chart represent all experiments summary during continuous measurement of different heating systems and different overall assessments made by males and females. Each colouring symbolizes different thermostat temperature set point (blue marking = T-; green marking = T_{opt}; red marking = T+). It is clear that thermal comfort is also highly dependent on subjective sensations such as hunger; thirst etc. (see *Figure 6*). If subjects feel comfortable (they do not feel hungry), they are willing to tolerate a slight thermal discomfort and they assess it as thermal comfort. However, if they begin to feel hungry then they will sense more thermal discomfort (on the other hand when they were sated with food, they sensed rather slightly warm).

How do subjects perceive the temperature subjectively in the investigated environment?

The subjective perception of the set temperature was assessed on the basis of subjective sensation (questionnaire survey during the experiment) and objectively measured room air temperature.

On the horizontal axis on the *Figure 7* chart, the measured air temperature Ta is displayed during the individual experiments. On the vertical axis the answers are displayed for following question: At this time the room temperature seems to be (on the scale 0 to 100): *Comfortable (1) / Uncomfortable (100).*

It is clear (*Figure 7*) that subjects were less satisfied with the room temperature when it was lower (T-). The higher room temperature was the lower number of uncomfortable answers was.

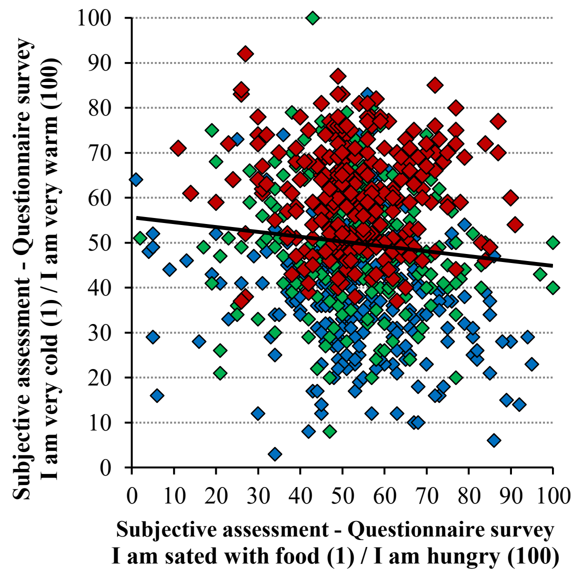

Figure 6 Subjective thermal comfort perceptions (Horváthová et al. 2017)

On the following *Figure 8* chart the results were summarized which represent the subjective of thermal

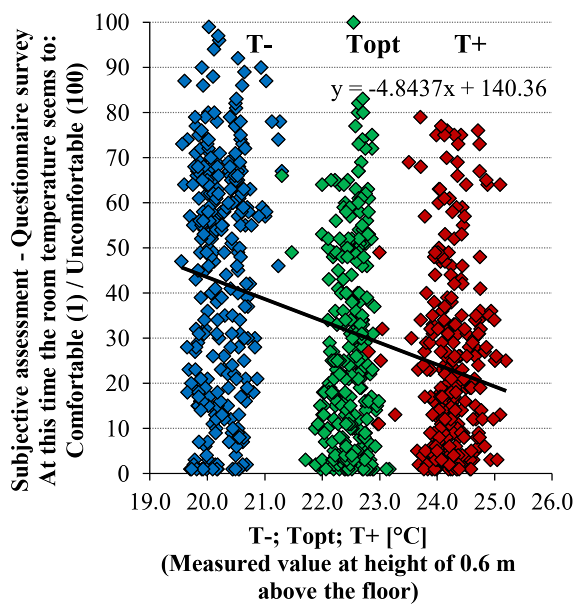

Figure 7 Subjective assessment of the room set temperature t_{set} in the investigated chamber (Kabele, Horváthová et al. 2017)

comfort perception at the set air temperature T_a *(T-; T_{opt}; T+)*. This chart displays the percentage of satisfied / dissatisfied subjects with the temperature in the investigated environment (subjective assessment - PPD index).

The human body has 250.000 thermoreceptors to recognize cold but only 30.000 thermoreceptors to recognize heat. That's the reason why the body recognizes sooner the ambient temperature decrease than the ambient temperature increase. (Horváthová 2017) *Figure 7 and Figure 8* showed the subjects satisfaction with the environment increased as the temperature increased. The higher the temperature in the room, the more people are satisfied in the given environment. The results prove that subjects were more dissatisfied in cooler environment than in warmer one for the data of 3 specific set-point temperatures and 4 heating modes.

Authors would like to say, that the results are valid for occupants who live in a moderate climate. Occupant's adaptation to the outdoor environment in which they spend some time is not negligible. The experiments were held in Europe in the Czech Republic in moderately continental climate with cold winters and warm summers.

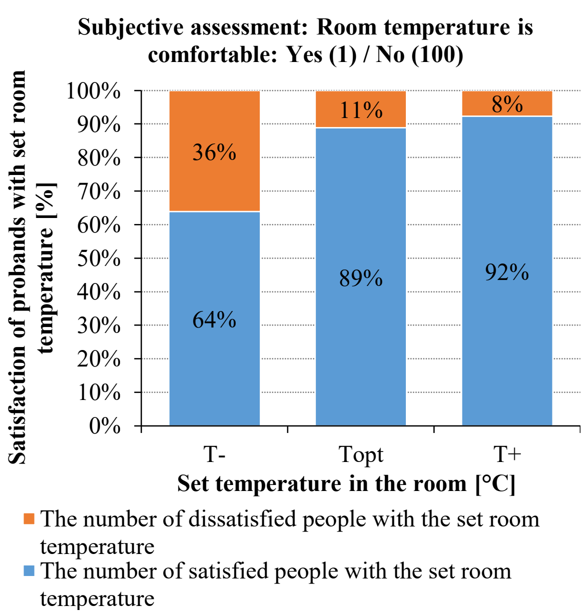

Figure 8 Number of satisfied / dissatisfied subjects with the set room temperature (Kabele, Horváthová et al. 2017)

CONCLUSION

The paper dealt with human perception to the given thermal environment and also dealt with the influence of the environmental state (temperature) on the subject´s state (subjective perception). The subjects psychological and physiological perception only were monitored to the given thermal environment during the particular experiments. The most common type of adaptation (change of clothes, change of physical activity etc.) was not considered because of the constant boundary conditions need of all experiments. The paper assessed human thermal perception under 3 specific set-point temperatures and 4 heating methods.

According to the experiment chart results subjects were more satisfied in a warmer environment. Optimal air temperature T_{opt} was assessed as a decent thermal comfort (neutral thermal sensation).

According to charts which displayed subjective assessment of thermal comfort for different heating systems operation, low energy consumption buildings behave differently in terms of thermal indoor environment than the traditionally built dwellings. Required lower heat outputs cause the surface temperature decrease for floor heating during the use of high-quality heating controls. This decrease is so rapid that subjects stopped sensing the radiation heat part of heat transfer when they assessed thermal conditions created by floor heating. That´s the reason why the floor heating systems need the highest air temperature of all tested systems to achieve thermal comfort.

The study results showed that the subjective thermal comfort sensation was influenced by various individual factors such as fatigue, state of mind, mood etc. The subjective thermal comfort perception was also influenced by other indoor environmental factors (air speed, air flows, relative humidity, etc.).

The temperature perception is an individual matter that depends on many factors – on the age of subject, on the sex of subject, on the momentary health and mental state of subject and many others. There will always be some occupants in an indoor environment who will not be satisfied with the thermal conditions.

ACKNOWLEDGMENT

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