Variable Thermal Comfort Index for Indoor Work Space in Office Buildings. A Study in Germany

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ABSTRACT: International standards state the thermal comfort requirements that office spaces must comply with. These are based on a model developed by Prof. Paul Ole Fanger of the Centre for Indoor Environment and Energy, Denmark. Today, forty years of research show an evolution in these experiences. The work presented here is to develop a tool to evaluate the thermal comfort of working environments of office buildings. A methodology is devised on the basis of on-site measurements and questionnaire responses. For measurements, a mobile unit equipped with sensors is used, whereas the questionnaire obtains user responses on thermal quality of the work space. The thermal conditions of thirty office buildings presenting different acclimatization systems have been surveyed. The correlation between objective and subjective data allows developing a formula that shows the thermal comfort level for a given environment as a function of local aspects. For the surveyed buildings, the resulting comfortable temperature was 23.3°C, and the minimum percentage of user individuals experiencing discomfort with such temperature was 7%.

Keywords: field work, PPD-index, neutral temperature, thermal sensation, thermal preference

INTRODUCTION

The definition of thermal comfort for any given space can be stated by applying the PPD Index, (Predicted Percentage of Dissatisfied) as proposed by the standard [1]. This index is built upon a mathematical model developed by Fanger using data from experiences made with humans in a controlled climatic chamber. The model responds on a small sample of people sharing a pre-defined thermal environment [2]. Research results from [3] and [4] have shown that the user's behaviour indicates that even in spaces having constant thermal conditions; they are capable of experiencing adaptation processes which allow them to accept thermal conditions imposed by the building manager controlling the HVAC system. Other authors [5], [6], [7] and [8], state that personal factors and close vicinity parameters, such as the external climate, affect the thermal perceptions of persons. Several authors [9], [10], [11], [12] and [13] state that the use of standards, such as [1], based on Fager's model, evince deviations stemming from causes inherent to the very method used to attain it. They show, moreover, that the adaptation capability of users to the various thermal environments is not considered in the experiments made in climatic chambers.

As a contribution criteria on thermal neutrality (thermal satisfaction) are defined. Results evaluations show strong correlations between the mean vote on thermal sensation, the mean vote on thermal preference and the operative measured temperature readings. Besides, a model is developed to predict the variable thermal comfort in office buildings and a methodology is devised to elaborate computational tools for professionals working in this disciplinary area. These tools should help address the monitoring and evaluation of thermal parameters of real work spaces that may lead to establish indicators on the environmental quality of buildings.

DEVELOPMENT

The method presented here is based on making measurements and having the space users fill questionnaires simultaneously to the measuring sessions carried out as a field work in 30 building offices in Germany [3], [4] and [5]. Measurements are made with a mobile unit equipped with high-precision sensors, and the questionnaire contains questions on thermal aspects of their work space. Through the user vote, these results are translated into a value scale.

Office Buildings: The data base for the analysis is made up with information collected in 30 office buildings being not older than 10 years or renewed on the basis of international standards on energy efficiency. The buildings are subject to the Central European climate and are located in several German cities (see [3]). They are located between 48° and 53°N latitude. Some of these buildings are shown in Figure 1. The research work aims at stating that it is possible to discern about differences from among the strategies used for ventilation and acclimatization. To this purpose, the buildings have been discriminated into three categories or types: Type 1, T1 (non-acclimatized buildings), Type 2, T2 (partially
acclimatized buildings) and Type 3, T3 (acclimatized buildings). According to [14], [15] and [16], the building variant type T3 with manually-operated windows presents no significant difference with those of type T2. If they have no manually operated windows, these buildings are known as “air conditioning building” [17] and [15].

Questionnaire: The questionnaire is a subjective-type measurement that gathers diagnosis information given by the ordinary user. It contains questions on psychological, physiological and physical aspects linked to the user and the surrounding environment [3]. From the questionnaire, the CV “Comfort Vote”, namely, the user’s vote on thermal sensation, is issued on a 7 point scale. Along this scale having two dissatisfaction poles, the user places his thermal sensation by choosing from a range that starts from -3 (cold), -2 (cool), -1 (slightly cool), 0 (neutral), +1 (slightly warm), +2 (warm) and ends at +3 (hot), with the possibility to choose intermediate ratings (see Figure 3). The CV allows, therefore, finding a thermally acceptable rage of temperature.

From the questionnaire, the PV “Preference Vote” (vote on thermal preference) allows finding a user preference and defining an index as a percentage of dissatisfied. The user chooses his/her thermal preference in a 3 point scale, verified with standardized scales of [19]. The thermal preference index works as a complement to the CV, (see Figure 4).

RESULTS

Regardless the ventilation and acclimatization factors, the Figure 5 shows the spread of the operative temperature in winter (number of measurements, n=345), in the transient period (n=457) and in summer (n=546). In addition, the average value and the standard deviation for each period are presented as well. The indoor climatic conditions vary upon seasons.

The largest oscillations of top in summer arise basically in spaces of the type T1 buildings, with ample chances of affecting the thermal comfort of these work spaces. This situation and, moreover, the noticeable oscillations on operative temperature observed during the transient period and summer time call for a detailed analysis of the
thermal sensation vote, as a function of the ventilation and acclimatization variants, so as to be able to know the meaning these temperatures imply for the workspace users. In this field work a total of 1100 questionnaires (votes) on thermal sensation for the sample of 30 office buildings have been collected. The observation on the measured operative temperature and the comfort vote attained from the questionnaire is the starting point for evaluating the thermal comfort of real work space environments. The users' subjective rating allows finding the ranges where the operative temperature can be perceived as comfortable (neutral thermal sensation), high (warmth sensation) and low (cold sensation). For the analysis, the changes on the thermal conditions in the variants for ventilation and acclimatization are observed as well, as a function of the seasons. Figure 6 show that spaces in type T1 buildings undergo the greatest thermal annual oscillations of operative temperatures and thermal sensation. In summer, the mean comfort vote falls within the hot zone in the ASHRAE scale. As a contrast, types T2 and T3 buildings show relatively constant thermal conditions, and the thermal comfort vote evolves around the neutral zone, very slightly offset towards the warm zone in the ASHRAE scale. This slight increment in operative temperature in these two building types in summer lies much below the values found for type T1. The small fluctuations found in types T2 and T3 buildings turn it difficult to determine the level at which the users accept the thermal conditions, or whether they prefer a cooler or a warmer setting that what currently is set. This calls for considering the relationship existing between the thermal preference vote and the measured operative temperature. In all cases, the statistical significance rises above 99%, with the exception of type T3 in winter, which reaches only an 85% of confidence (p<0.14).

![Figure 6: Comparison between CV-vote and operative temperature, as function of the year's seasons and the ventilation and acclimatization variants](image)

The information rendered by the PV, Preference Vote (n=528 questionnaires) is complementary to the obtained through the CV, because it allows viewing defined the thermal acceptance profile [20]. The thermal acceptance range could be estimated from deductions on the comfort model proposed by Fanger [2], who has defined that the users pleased by the thermal environment would vote CV = ±1, and those preferring a cooler space, or a warmer one than the one they are experiencing, would vote above +1 and below -1, respectively, over the 7 point ASHRAE scale. This criterion is adopted by the norm [1] and by other standards that base their selection upon this latter norm [17] and [21]. In order to set a parallel comparison with Fanger's research [2], the thermal comfort/discomfort is expressed as a percentage value for the studied sample. Figure 7 shows that the percent spread of preference votes issued by users that only during the measurements have shown thermal discomfort (PV ≠ 0), and that they would rather have a warmer setting (decreasing curve) or a cooler one (rising curve) that what currently was set. On the x-axis of Figure 7, the measured operative temperature are expressed every 2 °F (Fahrenheit) and in their Celcius equivalent. Figure 7 shows that the minimal percentage margin of users displeased with the thermal setting, either because of sensation cold or warm, is achieved at top = 23.3°C. The intersecting point between both regression straight lines is a signal on the condition for maximum thermal comfort sensation.

![Figure 7: Dissatisfied users because of cooler/warmer thermal preference respecting the operative temperature](image)

**DEBATES**

**Thermal acceptance and neutrality:** In order to evaluate the thermal comfort, the measurement results are compared with those of the questionnaire by resorting to a regression analysis. This allows defining an objective function and describing the behavior and interrelationship of variables. From the contrasting analysis between operative temperature and the mean thermal sensation vote, it is possible to observe differences between the analyzed ventilation and acclimatization variants that deserve to be highlighted (see synthesis in Table 2). In Figure 8, the slope b of the regression lines found for analyzed types and their intersection with the values on the ASHRAE scale along the y-axis, allow finding operative temperature ranges bounded by “slightly cool” and “slightly warm” thermal sensation (CV = ±1). They are an evidence on the thermal acceptance and adaptation degree of users.
A temperature value does not have the same meaning for each of the analyzed variants. The larger amplitude of the acceptance of top is noted for spaces of T1 buildings, with a minimum of 21.4ºC and a maximum of 25.3ºC, which is a good signal that these users are more capable of adapting themselves to more ample thermal amplitudes.

The concept of thermal neutrality is useful to express the physical, physiological and psychological state with which the user experiences a pleasant thermal environment, i.e., s/he feels neither cold nor hot, and issues a CV = 0 (cero) on the 7-point ASHRAE scale. If it takes into account Griffith's statement indicating that when CV = 0, then top = tn (see [26]), it is then possible to compute a neutrality temperature value (tn) for each study case. The values for operative temperature read on the intersection of the regression line with the y-axis = 0 in Figure 8 (thermal sensation vote, CV = 0) reach a reading of top = 23.2ºC for spaces of variant T1 and T2, and 23.3ºC in T3. The concept of neutrality is directly related with that of thermal preference. From comparing Figure 7 with Figure 8, it can be suggested the existence of an operative temperature range where the thermal dissatisfaction becomes minimal.

**Variable thermal comfort model:** The development of a model for thermal comfort implies making a probability analysis between the thermal preference and the measured operative temperature readings and requires establishing a parallelism with Fanger's studies (see [2]). Figure 7 shows the regression line obtained in this work by relating the thermal discomfort by preferring either cool or warmer condition respecting the measured operative temperature. Figure 9 shows the plots obtained by Fanger [2] in his experiments in a controlled climatic chamber. In order to make a comparison with Fanger's model, it is plotted a regression resembling an inverted Gaussian distribution curve whose minimum value or the apex of the curve coincides with the minimum percentage of dissatisfied respecting the indoor thermal ambient, and with the neutral temperature value.

In Figure 10, the model developed here is superposed with Fanger's curve (broken line curve). Fanger found the neutrality temperature to be 25.6ºC and a minimum percentage of dissatisfied of 5% [2]. In this work, it is found a neutrality temperature that is 2.3K lower than Fanger's and a minimum percentage of dissatisfied users of 7%, with top = 23.3ºC.
In this way, it is possible to consider the influencing factors on the degree of thermal adaptation of users, altogether with the seasonal climatic differences, the geographical, cultural and other factors. This integration, leads to a better optimization of climate management in buildings in operation, with variations in the ventilation and acclimatization systems.

**CONCLUSIONS**

The evaluation of thermal comfort shows clear differences arising in thermal acceptance expressed by user of different variant spaces as regards ventilation and acclimatization strategies.

Although Fanger warns on the possibility of users' thermal adaptation and the influence of climatic, geographical, cultural and other factors on thermal comfort, the comfort formula that he has developed does not allow those kind of variation. The study presented here lets conclude that the comfort model has to introduce the variables pertaining to the local surroundings.

The slope b of the regression analysis is an indicator of the adaptation of users to the local climate. The users of spaces having natural ventilation experience a more frequent contact with the outdoor surroundings and, therefore, are more tolerant to wider operative temperature ranges and swings, whereas the users of acclimatized spaces experience just minimal temperature variations and consequently, are more sensitive to temperature changes.

The different adaptation levels expressed by users can not be evaluated under a single criterion; actually, they rather constitute a potential challenge for reaching at a more efficient level in buildings in operation with different ventilation and acclimatization systems.

On the basis of the model developed in this work, it is worth noting the importance of surveying the comfort vote, and the need that both the questionnaire and measurement tasks are made simultaneously, so as to be able to compute the neutral temperature and to describe the thermal comfort zone. A similar result is obtained for the preference temperature which, in addition, is useful to show the thermal discomfort in percentage values.

Equation (1) and Figure 10 allows knowing the thermal comfort of a group of users, incorporating top and tn as variables. This allows expounding the user’s response on thermal comfort of real spaces, and to develop the strategies for a more convenient energy optimization of buildings in operation.

**REFERENCES**


