Analysis of Thermal Comfort and Microclimatic Conditions in Special Workplaces

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Abstract.

Microclimatic conditions and thermal comfort are important factors in the design of high quality buildings and the quality of working conditions for people in different operations. The importance of thermal comfort in the indoor environment can not be underestimated. A vast majority of complaints about indoor climate relate to poor thermal comfort. This paper presents an analysis of subjective thermal comfort measurement. The experiments were conducted to collect the data in the real conditions. ComfortSense system was used in these experiments. A Humidity and an Operative probe are available together with application software with graphical presentation of results including the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). The operating conditions are regulated by law in our country. The aim of the legislation is to protect people in the working environment and create appropriate health conditions for them. The goal of a thermal comfort analysis is finding an appropriate function of the physical parameters (background radiant temperature, air temperature, air humidity, wind speed, clothing, metabolic rate, and core temperature), which would yield the corresponding comfort/discomfort level.

Keywords: air, human, humidity, temperature, velocity

1. Introduction

There are many ways of creating indoor environments that provide thermal comfort and the factors involved are generally well understood. The reduction of air temperature in an office during a heat wave using air conditioning systems can provide thermal comfort for the people in that office. The increase in air movement using fans or natural air flows, however, can also provide comfort even if the air temperature is not reduced. The conditions that provide thermal comfort are well understood, from a century of systematic laboratory and field research, involving studies in psychology, psychophysics, biophysics and physiology (Hall, 2010). However, the relationships among designing for thermal comfort and energy use, human behaviour, and sustainability have not been studied extensively and are not well understood. The principles for creating thermal comfort are a prerequisite to sustainable design. Use of the principles to achieve requirements for energy and sustainability is a subject of on-going investigation (Parsons, 2003).

2. Thermal comfort

The condition of comfort of an environment depends on the interaction between multiple factors physical, physiological and psychological. The World Health Organisation (1999) defines the comfort such as Health is a state of complete physical, mental and social wellbeing and not merely the absence of disease or infirmity (Fabbri, 2015).

And the ASHRAE 55 standard defines comfort that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation. (ASHRAE 55, 2017).

The human heat balance equation describes how the body (homeotherm) can maintain an internal body temperature near to 37°C in terms of heat generation and heat exchange with the environment. In practice, what is achieved is not a steady state (constant temperatures) but a dynamic equilibrium: as external conditions continually change, so the body responds to ‘regulate’ internal body temperature. Metabolic heat is produced in the cells of the body, each of which must also maintain homeothermy. This heat is transferred from the cell to its surroundings mainly by conduction, due to thermal gradients between the cell and its surroundings, and by convection, due to movement of extracellular fluids, e.g. blood. There is therefore a dynamic and complex heat transfer between the cells of the human body that will depend upon the thermophysical and physiological properties of the cells, e.g. the thermal conductivity, density and specific heat of the cells and blood perfusion rates. If the body did not lose heat to the environment (i.e. if it were completely ‘lagged’) then, although there may be heat exchanges within the body, there would be no effective temperature gradient between the body and the environment. Heat would then be stored and body temperature would rise at about 1°C per hour for a resting person. For most cases, however, there is an effective temperature gradient between the internal body and the human skin. There is a net heat transfer from the cells of the body to the surface of the body where it can be lost to the environment by conduction, convection, radiation and evaporation at the skin surface and the lungs. The thermal properties of blood, muscle, fat, bone, etc. will therefore be important for internal heat transfer and hence body heat exchange. However, to regulate temperature in a changing environment, this ‘passive’ system must be controlled by a dynamic system of thermoregulation. Both of these systems are discussed separately below, however, it is important to remember that the body functions as a ‘whole’ and not as separate component parts (Parsons, 2003).

3. Human body

Responses to our thermal indoor environment have a considerable effect on health, comfort, and performance. There has been considerable scientific investigation into these responses and formal methods have been developed to design and to develop the interior environment.

Existing methods for the evaluation of the general thermal state of the body, both in comfort and under heat- or cold-stress considerations, are based on an analysis of the heat balance for the human body. Under cool to thermo-neutral conditions, heat gain is balanced by heat loss, no heat is stored, and body temperature equilibrates, that is:

$$S = M - W - C - R - E_{sk} - C_{res} - E_{res} - K \ (W/m^2) \tag{1}$$

S - Heat storage in the human body, M - Metabolic heat production, W – External work, C – Heat loss by convection, R – Heat loss by radiation, E_{sk} - Evaporative heat loss from skin, C_{res} - Convective heat loss from respiration, E_{res} - Evaporative heat loss from respiration, K - Heat loss by conduction.

The four environmental factors influencing this heat balance are: air and mean radiant temperature (°C), air speed (m/s), and partial water vapor pressure (Pa). The three personal variables are: metabolic heat production due to the activity level (W/m^2 or MET), the thermal resistance of clothing (clo or m^2K/W), and the evaporative resistance of clothing (m^2Pa/W). These parameters must be in balance so that the combined influence will result in a thermal storage equal to zero.

There are two categories of human responses to the thermal environment: voluntary or behavioral responses, and involuntary or physiological autonomic responses. Voluntary or behavioral responses generally consist of avoidance or reduction of thermal stress through modification of the body’s immediate environment or of clothing insulation. Physiological responses consist of peripheral vasoconstriction to reduce the body’s thermal conductance and increased heat production by involuntarily shivering in the cold, and of peripheral vasodilation to increase thermal conductance and secretion of sweat for evaporative cooling in hot environments. Autonomic responses are proportional to changes in internal and mean skin temperatures. Physiological responses also depend on the point in a diurnal cycle, on physical fitness, and on the sex of the individual. Behavioral responses rely on thermal sensations and discomfort. The latter appears to be closely related to the level of autonomic responses so that warm discomfort is closely related to skin wetness and cold discomfort similarly relates to cold extremities and shivering activity (Kalz and Pfafferott, 2014).

4. ASHRAE STANDARD 55

ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy) is a standard that provides minimum requirements for acceptable thermal indoor environments. It establishes the ranges of indoor environmental conditions that are acceptable to achieve thermal comfort for occupants. Percent dissatisfied (PD) represent percentage of people predicted to be dissatisfied due to local discomfort. Predicted mean vote (PMV) is an index that predicts the mean value of the votes of a large group of persons on the seven point thermal sensation scale.

Predicted percentage of dissatisfied (PPD) is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV (Fanger, 1989).

The PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. Fanger (1970) related PMV to the imbalance between actual heat flow from the body in a given environment and the heat flow required for optimum comfort at the specified activity by the following equation:

$$PMV = [0{,}303\ exp(-0{,}036\ .\ M) + 0{,}028).\ L] \tag{2}$$

L is the thermal load on the body, defined as the difference between internal heat production and heat loss to the actual environment for a person hypothetically kept at comfort values.

Predicted percentage of dissatisfied (PPD) is an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV. Index PPD is expressed according to the relation:

$$PPD = 100 - 95.\ e^{-(0{,}03353.PMV^4 + 0{,}2179.PMV^2)} \tag{3}$$

The PMV-PPD model is widely used and accepted for design and field assessment of comfort conditions. ISO Standard 7730 includes a short computer listing that facilitates computing PMV and PPD for a wide range of parameters (Ashrae, 2018).

Operative temperature, relative humidity and velocity of air are also evaluated. The ranges of these factors are defined by law 99/2016 on details of health protection against heat and cold load at work.

5. DANTEC ComfortSense system

ComfortSense is a multichannel system for measurement air velocity and air tem-perature, humidity and operative temperature. It calculates statistical values – Draught rate (DR), Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). ComfortSense can be used for many applications including HVAC research and development, testing of ventilation equipment, building research, passenger com-fort studies in the automotive and aviation industries. Thermal comfort measure-ments with ComfortSense comply with International Standards EN 13182, ISO 7726, 7730, ASHRAE standard 113 and ASHRAE standard 55. The ComfortSense system consists of a main frame with input channels for up to 16 probes. The omnidirectional probes measure both air velocity and temperature. The ruggedly designed probes and cables are perfectly suited for large test rooms. The draft probe is equipped with an omnidirectional thin-film sensor for measuring air velocity and a small fast-response thermistor for measuring air temperature (Fig. 1).

Figure 1: The draft probe, robust velocity temperature probe and manikin version

The manikin version of the draft probe is very compact, with a flexible cable connection to the probe tip, making it suitable for building into a manikin for passenger comfort applications. Velocity range is 0.05 to 5m/s, indicates up to 10 m/s and temperature is -20 to 80°C for both types. Robust velocity and temperature probe has velocity range 0.1 to 30m/s. Humidity range is 0-100%. Dantec has also operative temperature probe. The sensor element simulates a standing person when it is vertical, a sitting person when tilted 30°C from vertical and a reclining person when in the horizontal position. Temperature range is 0 – 45°C (Fig. 2)(www. hwww.dantecdynamics.com/comfortsense).

Figure 2: Humidity probe, operative temperature probe and main frame

6. Measurement of thermal comfort in special workplace

Thermal comfort measurements were made in the summer, when the outdoor temperature was above 30 °C. Thermal comfort was measured in the kitchen. This kitchen is situated in the basement of an industrial building. The kitchen has no windows, only one door. Here are prepared around 400 meals daily. Around 400 meals are prepared daily. Two large hoods are designed to remove vapors. The room is without fresh air supply. There are two workers in the room. Each worker has a role and a work position in the room. One provides food to customers and the other provides dishwashing. The first worker is affected by the heat from the food heaters and the second worker is affected by the heat from the dishwasher. Food is heated in water heaters and there is also a dishwasher in the room.

The clothing insulation was is 0.5 CLO, because workers had only underwear, short sleeve shirt, light pants, socks, shoes and work vest. The level of human activity is 2.5 MET depending on the calculation possibilities of the ComfortSense program and working activity.

The positions of the measuring probes are located in the living areas of the rooms where the workers work most often. These places are defined as workstations or seating positions depending on the function of the space. If operating conditions allow it, it shall be measured at the center of the room or 1 meter from the wall inwards from the center of the largest window. Measurements shall be made at locations where the extremely high values of thermal parameters are estimated or observed. Measurement of relative humidity requires that the measurement site be in one location within the zone in each room so as to exclude the effects of ventilation and air conditioning systems. The probe is located at the highest point of the measuring device above the other probes. Air temperature and air velocity are measured at 0.1 m, 0.6 m, and 1.1 m for seated persons and 0.1 m, 1.1 m and 1.7 m for standing persons. The operating temperature or PMV-PPD is measured or calculated at 0.6 meter for seated persons and for standing persons 1.1. We had standing persons setting.

7. Results

The graphs on the left (Figures 3, 4 and 5) show measurements of operating temperature, air velocity and humidity under real-world workplace conditions without adjusting the working environment. The positions of the measuring probes were placed with best way to simulate the workstations. The graphs on the right (Figures 3, 4 and 5) show measurement after the change of the working conditions.

Figure 3: Operative temperature measurements at the workplace

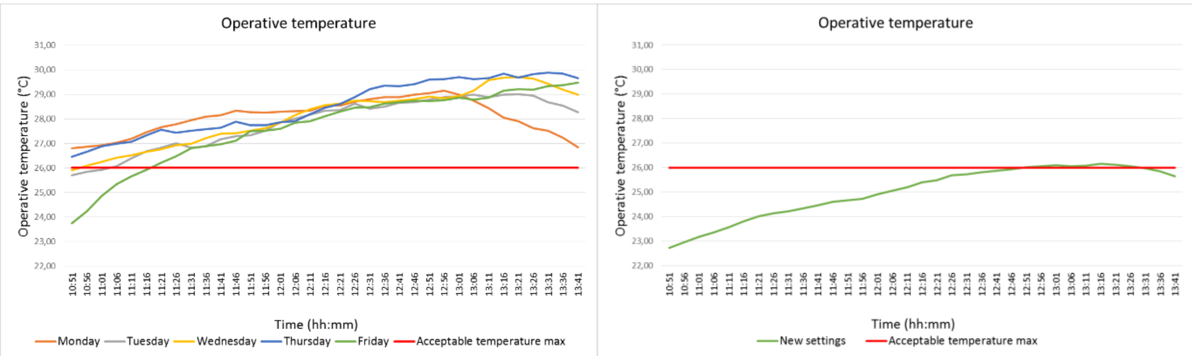


Figure 4: Relative humidity measurements at the workplace

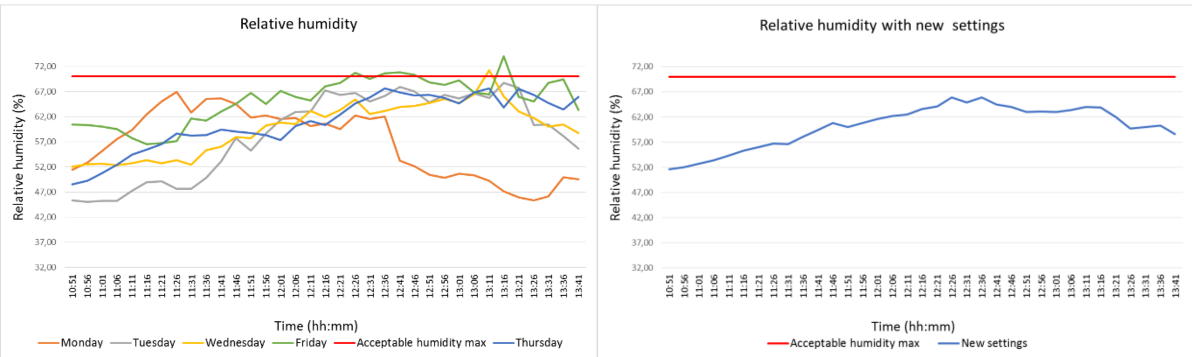


Figure 5: Air velocity measurements at the workplace

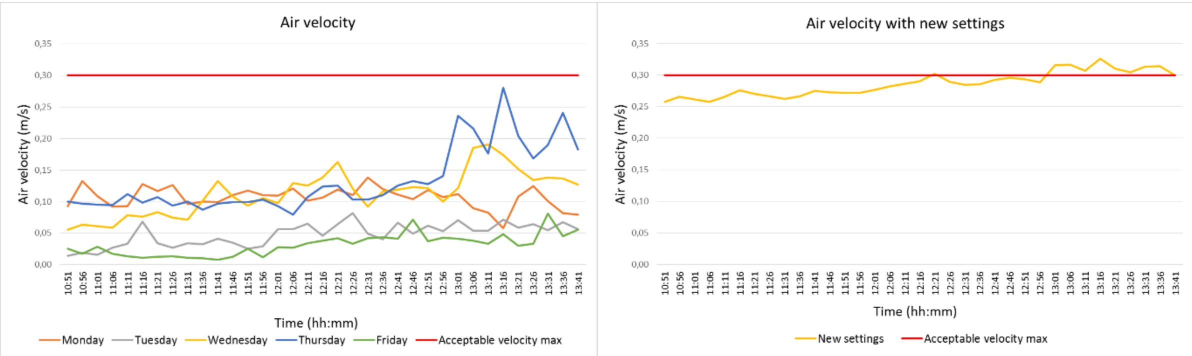
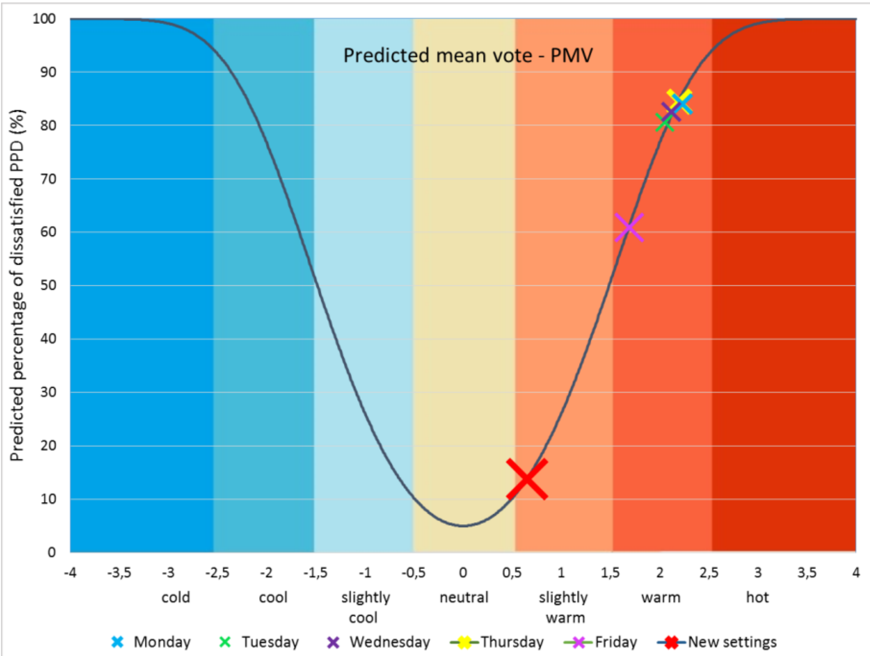


Figure 6 shows the measurement results for the parameters PMV and PPD according to the standard Ashrae and our STN 7730 EN.

Figure 6: PMV and PPD parameters



8. Conclusion

Employers are obliged to ensure technical and organizational measures that eliminate or reduce the adverse effects of thermal-moisture microclimate factors on employees' health to the minimum possible and achievable. Furthermore, it is stipulated that employers are obliged to provide a drinking regime and appropriate protective clothing and personal protective equipment in case of increased heat or cold load. Measurements show that working conditions are not ensured. Our law defines three main parameters – operative temperature, air velocity and relative humidity. The law sets their maximum permissible values. All employers are obliged to ensure these values in the workplace. The law also provides for possible measures and maximum working time in this conditions. We measured one week exactly at the time when the workers were working. Interviewing workers is an important step in understanding issues at a particular location. The results of relative humidity and air velocity are normal except for minor changes. The results for operative temperature are well above the allowed value. The feeling of heat is very pronounced at this temperature and workers sweat. After this measurement we made a change in working conditions (results on the right side of figures). Portable air conditioning was placed in the kitchen. Operative temperature is now in the standard but air velocity is not good. Despite good measurement results worker feel excessive drafts. The correct setting of the air conditioner will be investigated in the future. PPD and PMV parameters were also evaluated in the evaluation of the impact of the working environment on the thermal comfort of workers. These parameters determine the mean warmth of a group of people and the predicted percentage of dissatisfaction with the operating conditions. They are designed for each measurement day with respect to the setting.

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References

[1] Ashrae Staff (2018) *ASHRAE GreenGuide Design, Construction, and Operation of Sustainable Buildings*. Published by W. Stephen Comstock, Fifth edition, ISBN 978-1939200-80-8

[2] Ashrae (2017): *Ashrae Handbook Fundamentals 2017*. Publisher: American Society of Heating and Air-Conditioning Engineers, ISBN 978-1-939200-59-4, ISSN 1930-8043. pp 1013.

[3] Fabbri, Kristian (2015) *Indoor Thermal Comfort Perception. A Questionnaire Approach Focusing on Children*. Springer International Publishing Switzerland, ISBN 978-3-31918650-4, pp. 304.

[4] Fanger P O (1970*),* Thermal Comfort, Copenhagen, Danish Technical Press. *Journal of Building Construction and Planning Research*, Vol.2 No.1, March 18, 2014.

[5] Fanger P O, Melikov A K, Hanzawa H and Ring J (1989), Turbulence and draught, *Energy and Buildings*, 12(1): 21-39.

[6] Hall, R (2010) *Materials for energy efficiency and thermal comfort in buildings*. Woodhead Publishing Limited, ISBN 978-1-84569-526-2. pp 755.

[7] Kalz E. Doreen and Pfafferott Jens (2014*) Thermal Comfort and Energy-Efficient Cooling of Nonresidential Buildings*. Springer briefs in applied sciences and technology, ISBN 9783-319-04581-8, pp 138.

[8] Parsons, K.C. (2003) *Human Thermal Environments*. Published by Taylor and Francis, London and New York. ISBN 0-203-30262-1, pp 560.

[9] www. hwww.dantecdynamics.com/comfortsense