Occupant behaviour and thermal comfort in buildings: Monitoring the end user

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Abstract: Studies indicate that the energy performance gap between real and calculated energy use is for 80% caused by the occupant. This human factor may be composed of routine and thermoregulatory behaviour. When occupants do not feel comfortable due to high or low operative temperatures and resulting high or low skin temperatures, they are likely to exhibit thermoregulatory behaviour. The aim of this study is to understand and monitor this thermoregulatory behaviour of the occupant. This study presents a detailed monitoring study of two females living in a near Zero Energy Building (nZEB). During this study they were measured three weeks over a time span of three months to get insight in their preferred thermal environment and related thermoregulatory behaviour. During this study the following parameters were monitored: activity level, clothing worn, micro climate, skin temperatures, and thermal comfort and sensation. Micro climate to assess exposed conditions and skin temperature at five positions on the body were measured with wireless sensors. They wore an Actiwatch® to measure their activity level, and every two hours the subjects filled in a questionnaire regarding their thermal comfort and sensation vote (7-point scale), clothing, activities, and thermoregulatory behaviour. Both participants show a unique pattern when looked at the relationship between exposed- and skin temperatures. Three areas could be distinguished in the measuring data, one sleeping area and two living areas. All three areas are associated with maximum comfort. Thermal sensation was not significantly related to any of the single variables, e.g. (mean) skin temperatures, operative temperature, Clo-value, and activity level. Interestingly, combining the variables provided insight in the preferred thermal environment. The differences between the two living areas could be explained by differences in activity level, Clo-value, and ambient conditions. The first living area matches with standing activities with average Clo-values, the other area with sitting activities with lower Clo-values. In conclusion, the subjects acted on their thermal comfort and sensation vote by changing their clothing or their activity level.

Introduction

Studies indicate that a human factor is responsible for 80% of the performance gap between calculated and realized energy use (Tohoku University, 2013). Over the last couple of years, it has become easier to calculate building related energy performance with simulation programs. However, these calculations are focussed on energy use of buildings, based on fixed user behaviour conditions and reference climate years. Therefore, these calculations lack information about real life performances. In this way an energy performance gap is inevitable, a result of this gap are strong deviations in energy use between almost similar apartments. The human factor consist mainly of routine and thermoregulatory behaviour. Examples of thermoregulatory behaviour are moving from one environment to another, changing clothes, and adjusting the thermostat. These actions are taken to avoid discomfort and to seek comfort in the thermal environment (Jacquot, Schellen, Kingma, van Baak, & van Marken Lichtenbelt, 2013).

Fanger (1973) already concluded that there are a number of parameters that contribute to the thermal environment, such as air temperature, mean radiant temperature, relative air velocity, vapor pressure in ambient air, the activity level and the clothing worn. The PMV-model is based on the predicted mean vote of the general population. In this study the themoregulatory behaviour and thermal comfort of individuals is investigated. This is the first field study where the thermoneutral zone (TNZ) model is used to determine the comfort zone of occupants. The area in which people feel neutral in their environment is called the TNZ, wherein the comfort zone acts as centre. The TNZ is defined as ‘the range of ambient temperature at which temperature regulation is achieved only by control of sensible (dry) heat loss, i.e. without regulatory changes in metabolic heat production or evaporative heat loss.’ (IUPS Thermal Commission, 2001). This definition only includes biological mechanisms of the body, e.g. changing the skin temperature to maintain the body’s core temperature, and does not include the thermoregulatory behaviour of people. ASHRAE concluded that thermal behaviour is for people a major factor to come to satisfaction with the thermal environment (2004). Thermoregulatory behaviour will therefore probably occur when occupants experience discomfort.

Previous research has focused only on experiments in laboratories or artificial environments designed to reflect the real living or working space. There has been no experiments conducted with test-subjects in their own home or working space. This lack is caused by the difficulty to control all the physical parameters in a dwelling (e.g. temperature, relative humidity, ventilation, air velocity, CO2 concentration). However, during this study the test-subjects were living in a fully monitored dwelling where they could be closely observed and measured in their own home to show an insight in their thermoregulatory behaviour. The aim of this study was to provide an insight in the thermal environment of occupants in real life situations.

The thermoneutral zone model

The TNZ model includes fysiological differences between occupants. From a biological point of view the body wants to use as little energy as possible to ensure its core temperature, which is shown in Figure 1.

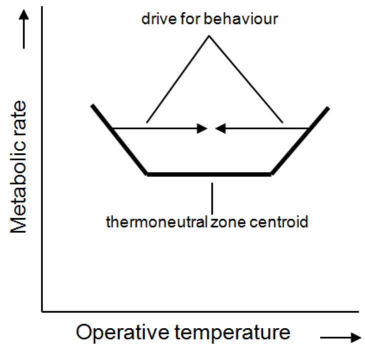

Figure 1, Increasing metabolism when the body has to regulate its heat loss

The core temperature of a body is very stable and around 37 degrees. The area in which the body is in neutral state is called the thermoneutral zone, wherein the comfort zone acts as centre. When the operative temperature increases or decreases the body has to work harder to maintain its core temperature by regulating its vains to increase or decrease the heat loss of the body. When regulating through dry heat loss is not sufficient enough, the temperature will be regulated by sweating or shivering.

By including the fysiological differences of occupants it is possible to calculate the skin temperature and thus the optimal indoor environment for individuals. The skin temperature can be determined by the amount of body fat and the amount of produced heat; known by the metabolism of a person. As a result, the optimal operative temperature can be determined by combining the thermal resistance of the clothing with the relative humidity and the air velocity of the environment. The influence of all these parameters can be derived from these calculations, this makes it possible to calculate the TNZ as a relation of the skin temperature and the operative temperature, see Figure 2.

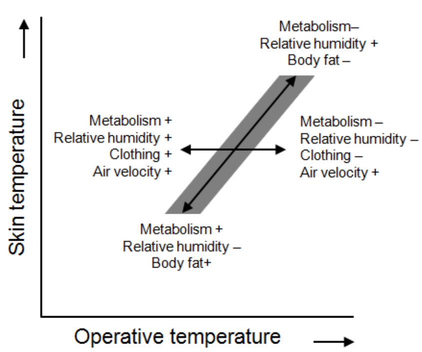

Figure 2, The thermoneutral zone as a result of the relation between skin temperature and operative temperature

As can be seen in Figure 2, the grey zone indicates the thermoneutral zone. The position of this zone in the graph depends on the characteristics of the person, like body fat and metabolism. In addition, the position depends on the clo-value, relative humidity and air velocity. Outside of this zone, the body will need to regulate his temperature more extensively trough sweating and shivering, which can be experienced as uncomfortable.

Methods

During this study the test-subjects lived in a fully monitored dwelling where they could closely be observed and measured in their own home to get an insight in the thermal environment of occupants in real life situations. Two females lived in a single family house which was recently renovated to a near zero energy building. There were three measuring weeks in total over a period of three months.

In the beginning of the experiments the test-subjects filled in a general questionnaire, regarding illnesses and medicine use. In addition, anthropometric data was collected, e.g. age, sex, height and weight. During this study the following parameters were monitored using a two hourly questionnaire: activity level, clothing worn, thermal comfort, and thermal sensation. Micro climate and skin temperatures, at the Four point ISO-defined skin sites, were measured with wireless sensors (iButtons®), shown in Figure 3. In addition an extra sensor was used to measure the skin temperature at the under arm.

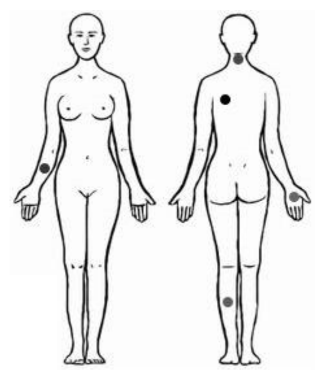

Figure 3, Four point ISO-defined skin sites to measure skin temperatures. An extra iButton was placed at the under arm.

To measure the micro climate, an iButton was placed with a brioche at the outer layer of the clothing. An Actiwatch® was used to measure their activity level, and every two hours the subjects filled in a questionnaire regarding their thermal comfort and sensation vote (7-point scale), clothing, activities, and thermoregulatory behavior. The corresponding clo-value were calculated using by the clothing choices in the questionnaire (McCullough, Jones, & Huck, 1985) (McCullough, Jones, & Tamura, 1989).

Results

During this study the sensation and comfort vote are handled separately. For both test-subjects no correlations could be found between skin temperatures and comfort or sensation vote (respectively $R^2 = 0.0087$, $p = 0.1947$ and $R^2 = 0.0007$, $p = 0.7212$). This is a contradiction with results from other studies (bron).

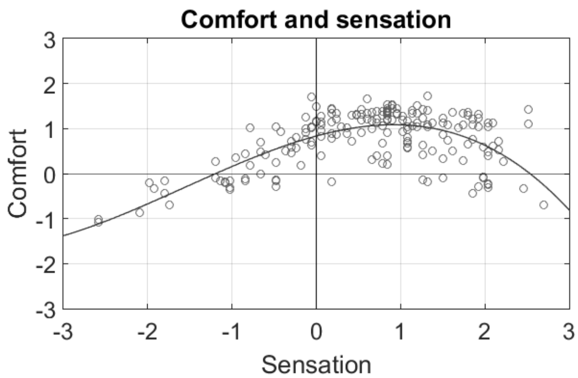

Figure 4, Comfort vote against sensation vote

In the PMV-model of Fanger, sensation and comfort are identified as one and the same. Figure 4 shows the comfort vote against the sensation vote. A significant correlation can be found ($R^2 = 0.5000$, $p = 0.0279$). As can be derived through the trend line, this test-subject is most comfortable at the top of the trendline, which represents a sensation vote of 1, 'slightly warm'. The other test-subject showed the same trend.

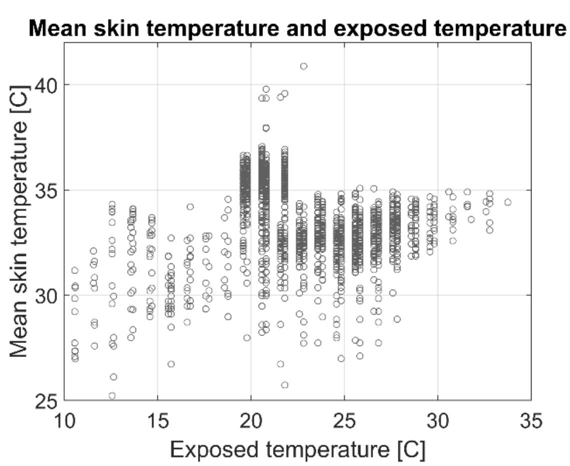

Figure 5, Mean skin temperature against exposed temperature ($R^2 = 0.0100$, $p = 0.1177$)

Figure 5 shows the exposed temperature, the temperature on the outer layer of the clothes, against the mean skin temperature. These are more than 2000 measuring points, because every 10 minutes data was logged. No real correlations can be found ($R^2 = 0.0100$, $p = 0.1177$). Although, the density of the measuring points indicate that the skin temperature and exposed temperature combinations were frequently measured.

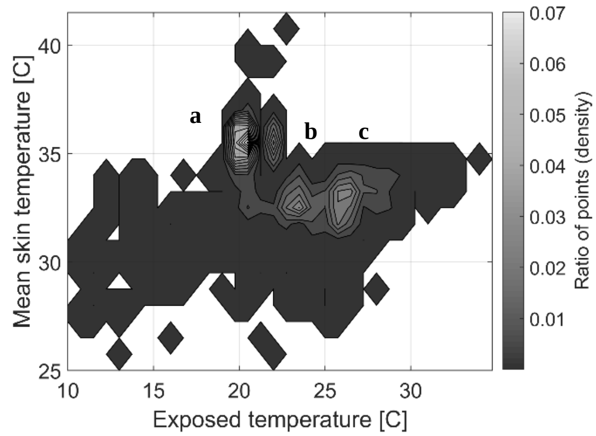

Figure 6, Contourplot of the data in Figure 5 with three centers (a, b, c)

Figure 6 shows a contourplot of the data in Figure 5. This contourplot shows three different centers (a, b, c). These three centers represent the thermal environment of this test-subject in real life. After combining the parameters filled in in the questionnaires, center a. corresponds with the measurements during the night. The test-subject wore the sensors continuously, this means that there are many measuring points during the night. Center b. corresponds with standing activities in an indoor environment with regular winter clothing (e.g. jeans and sweater, clo-value ±0.8). Center c. corresponds with sitting/resting activities and lower clo-values (<0.6).

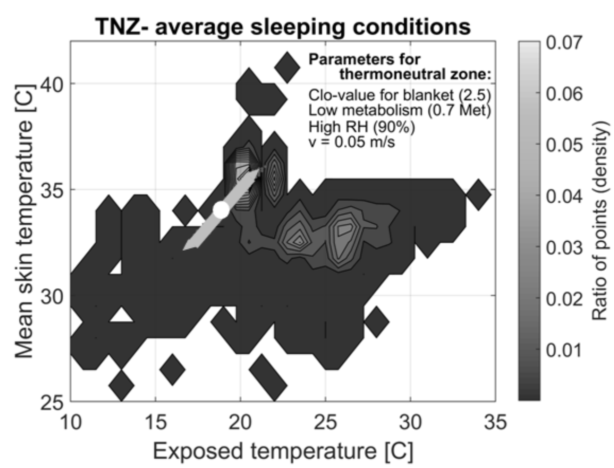

Figure 7, Contourplot of measurements including the calculated TNZ for this test-subject with parameters that should represent the micro climate in bed

Figure 7 shows the thermoneutral zone with the characteristics for this test-subject with parameters that should represents the micro climate in bed, e.g. a low air velocity, a high relative humidity, a low metabolism and a high clo-value for the blanket. As can be seen in the figure, this calculated TNZ corresponds with the measured data.

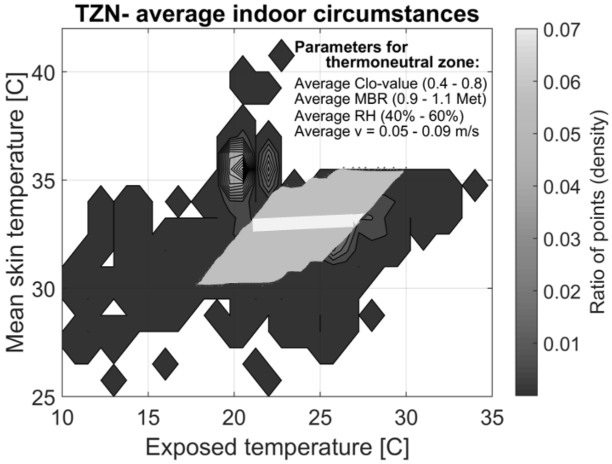

Figure 8, Contourplot of measurements including a range of calculated TNZ's for this test-subject with parameters that should represent the indoor environment

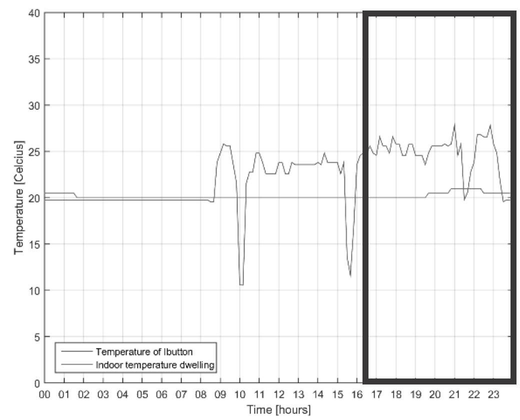

Figure 9 Temperature logged by the iButton on the outer side of the clothes versus the temperature logged by the dwelling. The orange window indicate the moment when the test-subject was present

Figure 8 shows a range of calculated thermoneutral zones with the characteristics for this test-subject with parameters that should represents deviations for a normal indoor climate during the day. A range of TNZ's is calculated because the relative humidity, air velocity and metabolism can change every hour. As can be seen in the figure, the calculated thermoneutral zones correspond with the measured data.

Discussion

For both test-subjects no correlations were found between skin temperatures and comfort or sensation vote. Further research is necessary to determine if this lack is due to the measuring interval of the sensors or if these relations cannot be found in real life because variations in parameters. If the measuring interval is too large, this will result in less measuring points during short moments of high metabolism. Furthermore, the thermoneutral zone is very sensitive for changes in clothing or activity level. Therefore, when these variables change multiple times during a day, the thermoneutral zone will vary frequently as well.

In addition, further research is necessary to assess the influence of the radiation by the human body on the iButton worn on the outer side of the clothing. The radiation of the human body might influence the measured exposed temperature, see Figure 9.

Finally, although this field study was very extensive and over a longer period of time with only two test-subjects, these results are only based on one field study. More research is necessary to validate the TNZ model.

Conclusion

The gap between measured and calculated energy use will probably not completely be explained by using the TNZ model. Although, this model can explain the differences in indoor temperature preferences, which might contribute for a large part to the gap.

Furthermore, with the new technologies in smart buildings and demotics it might be interesting to implement the TNZ model in the HVAC systems of dwellings and office buildings. A temperature sensor could be implemented in a watch, which could communicate with the HVAC system. By using the TNZ model, it might be possible to calculate the optimal indoor air temperature for an individual and adjust the set points when this person enters the dwelling or the office. This might decrease energy use and will increase the comfort levels in buildings.

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