# IMPACT OF INDIVIDUAL CHARACTERISTICS – SUCH AS AGE, GENDER, BMI, AND FITNESS – ON HUMAN THERMAL SENSATION

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## ABSTRACT

A new Human Thermal Model (HTM) has been developed at VTT Technical Research Centre of Finland (VTT) for predicting thermal behaviour of the human body. HTM is based on true anatomy and physiology of the human body, and it estimates human body tissue and skin temperature levels. HTM divides the body into sixteen different body parts each being further sub-divided in realistic tissue layers. The functional tissue layers are also connected to adjacent body parts by a blood circulation system, which has been used for physiological thermoregulation of the whole body. The thermal sensation and thermal comfort estimation methodology by Zhang Hui (2003) is integrated in HTM, allowing much more detailed thermal sensation and thermal comfort index estimations than traditional Fanger's methodology (Fanger 1970). HTM is a module of a non-commercial VTT House building simulation tool, also developed at VTT. VTT House is used for modeling thermal interactions between the human body and the surrounding space by means of finite difference heat balance method, including convective, radiation, and evaporative heat transfer. This integrated method enables the quantitative analysis of the significance of both external (air and surface temperatures, air velocity, and relative humidity) and internal (clothing and metabolic activity level) boundary conditions on thermal sensation and comfort. As a module of the VTT House building simulation tool, HTM can be used for estimating more accurately than before the thermal sensation and comfort of building occupants in transient and non-uniform conditions (Holopainen 2012). This paper aims to evaluate impacts of age, gender, BMI and fitness on human thermal sensation. These results can be utilised in updating design and dimensioning guidelines when balancing energy efficiency and occupant well-being in the future buildings.

## INTRODUCTION

Energy-efficiency seems to become a key-driver for whole building and construction industry in the near future. Therefore, new construction and building service concepts are obviously needed. Most likely better thermal insulation levels and at least partly new heating and cooling solutions will be adopted. To avoid unpleasant indoor environment outcomes in future buildings, a more holistic approach focusing on occupant aspects is therefore recommended. Since thermal issues seem to remain dominant cause of indoor environment complaints also in the future, it is very important to really understand true nature of both complex physical and physiological phenomena, influencing human thermal sensation and comfort.

When estimating human thermal comfort, influencing boundary conditions are most commonly divided into two categories: (1) external and (2) internal parameters. External (or environmental) parameters are related to surrounding space, and they are air temperature, surface temperatures, air velocity, and humidity. Internal (or personal) parameters are related to human herself/himself, being clothing and metabolic rate. Furthermore, the metabolic rate (i.e., internal heat generated by human body tissues) depends on individual anatomy and activity level.

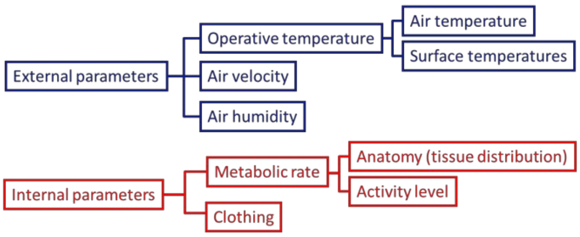


*Figure 1 External and internal parameters influencing on human thermal sensation.*

Human thermal comfort can be estimated with several alternative methods. The widely used international standards ISO 7730 (1984) and ASHRAE 55 (2003) use Fanger's PMV (Predicted Mean Vote) method for calculation of thermal comfort. This method is a good starting point for estimation of thermal comfort, and it has been widely utilised when predicting indoor environment conditions. However, the PMV method is applicable only to steady-state, uniform thermal environments. In order to estimate impact of individual characteristics – such as age, gender, body-mass-index (BMI), and fitness – on human thermal sensation, such human thermal models, which take into account the effect of human thermoregulation system and realistic transient heat transfer phenomena, need to be utilised.

## METHODS

### Human thermal model integrated in a building simulation environment

Human Thermal Model (HTM) is a module of a non-commercial VTT House building simulation tool developed at VTT Technical Research Centre of Finland (VTT). Both the human body and the surrounding space are described by an integrated thermal nodal network, which consists of node capacitances and inter-nodal conductances. This approach allows realistic estimations of thermal interactions between the human body and the surrounding space including convective, radiation, and evaporative heat transfer. Ultimately, the transient node temperatures of both human body tissues and building structures are solved using the finite-difference heat balance method (Tuomaala 2002).

HTM is based on true anatomy and physiology of the human body, and it estimates human body tissue and skin temperature levels. The human body is divided into sixteen different body parts: head, neck, upper arms, lower arms, hands, chest and back, pelvis, thighs, lower legs and feet. Each body part is further sub-divided typically in four realistic tissue layers (bone, muscle, fat, and skin) by concentric cylinders. The functional tissue layers are also connected to adjacent body parts by a blood circulation system, which has been used for physiological thermoregulation of the whole body. (Holopainen 2012).

Simulated human body (transient) tissue temperature values offer general level information about thermal indoor environment. In order to obtain more valuable information, the thermal sensation and thermal comfort estimation methodology by Zhang (2003) has been integrated in HTM, allowing much more detailed thermal sensation and thermal comfort index estimations than e.g. traditional Fanger's commonly utilized methodology. This integrated HTM method enables the quantitative analysis of the significance of both external (air and surface temperatures, air velocity, and humidity) and internal (clothing, metabolic rate) boundary conditions on thermal sensation and comfort.

### Individual characteristics for human thermal model

When evaluating impact of individual characteristics (i.e., age, gender, BMI, and fitness in this study) on human thermal sensation, the influencing internal parameters need to be varied and selected systematically. Table 1 shows the adopted constant clothing parameters (corresponding to an overall insulation of 0.86 clo) based on thermal and evaporative resistances of different garments defined by Fu (1995). Metabolic rate is depending on individual tissue distribution and activity level. In order to evaluate impact of the individual characteristics, activity level was assumed to be constant 1.2 MET (being 70 W/m$^2$ and corresponding to sedentary office work). Air velocity is assumed to be <0.10 m/s corresponding to body part convective heat transfer coefficient values defined for a seated person by deDear et al. (1997) with values ranging from 2.8 W/(m$^2$ K) to 4.5 W/(m$^2$ K).

*Table 1*
*Adopted thermal and evaporative resistances of garments used in simulations (Fu 1995).*

| GARMENT | THERMAL RESISTANCE, m$^2$K/W | EVAPORATIVE RESISTANCE, m$^2$kPa/W |
|---|---|---|
| Short-sleeve shirt | 0.041 | 0.0041 |
| t-shirt | 0.030 | 0.0032 |
| long-sleeve turtleneck sweater | 0.112 | 0.0105 |
| briefs | 0.030 | 0.0037 |
| shorts | 0.030 | 0.0037 |
| jeans | 0.037 | 0.0066 |
| calf-length socks | 0.054 | 0.0104 |
| soft-soled shoes | 0.108 | 0.0208 |

Individual metabolic rate depends not only on activity level but also on individual tissue distribution. This is because the basal heat generation varies quite a bit between different tissue types. Basal heat generated in rest by brain, viscera, muscle, fat, and skin tissue are 12.7W/kg, 3.83W/kg, 0.67W/kg, 0.004W/kg, and 1.01W/kg, respectively (Smith 1991). The specific heat generated by muscle tissue varies according to activity level being 1.38W/kg for seated, 2.02W/kg for sedentary activity, 3.55W/kg for light activity, and 5.07W/kg for medium activity (Holopainen 2012).

Proportion of bone tissue has been reported to be 18.8% for a typical male (Smith 1991), and on average 3% less for females. Based on this indicative information, bone weight has been estimated by equation

$$weight_{bone} = weight\,[0.158 + (0.03 Gender)\,], \quad (1)$$

where *weight* is total weight of a person, and *Gender* is 1 for male and 0 for female.

Similarly, weight of skin tissue (Smith 1991) is estimated by equation

$$weight_{skin} = weight\,[0.0374 + (0.01 Gender)\,]. \quad (2)$$

During the last two decades, there has been going on several studies describing relation between human body-mass-index (BMI) and percentage body fat. Results of one such study are illustrated in Figure 2, in which percentage body fat distribution depending on BMI for females and males is presented. Firstly, these results indicate that the absolute percent body fat of females are on average 10.75% higher than males with same BMI values. Secondly, average deviations between the minimum and the maximum percent body fat values seems to be 22.0% with same BMI – depending most likely on individual body fitness (i.e., a ratio between body fat and muscle tissue). In addition, age of a person has also noticed to be a significant parameter in percentage body fat, and an annual increase of 0.13-0.23% in body fat has been reported (Deurenberg et al. 1991).

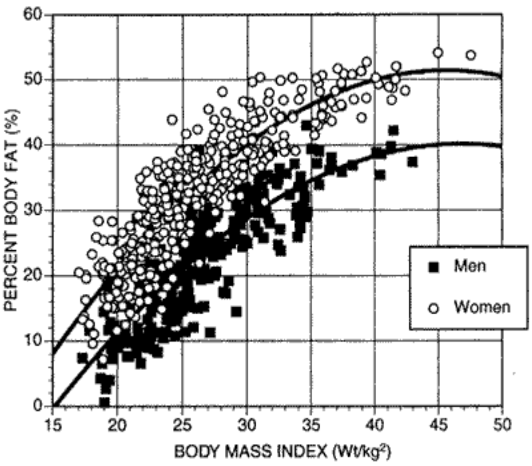


*Figure 2 Body fat percentage versus body-mass-index. (Jackson et al. 2002)*

Based on the data presented by Jackson et al (2002) in Figure 2, weight of fat tissue is estimated in this study by the following equation

$$weigh_{fat} = weight\,[-0.0438\,BMI^2 + 4.014\,BMI - 10.75\,Gender + 0.23\,Age - 51.81 - 22.0\,(ToneIndex - 0.5)]/100, \quad (3)$$

where *ToneIndex* describes individual fitness of a person (the maximum value of 1 corresponds to a body with low percentage body fat, value of 0.5 refers to average percents of fat drawn in Figure 2, and the minimum value of 0 corresponds to a body with high percentage of fat).

For an average male adult, Smith (1991) has given weights of 1.4 kg for brain, 11.6 kg for viscera, and 3.0 kg for lung. In addition to these, we have assumed 4.1 kg of blood for an average adult. Finally, after these amounts of different tissues and blood are estimated, all the rest of the given body weight will be muscle tissue.

**Test case definitions**

From the HTM point of view, all external parameters were fixed by definition of a test room. For simplicity reasons, steady-state space conditions were assumed, and both indoor air and all surface had constant temperature values of 22 ºC. Indoor air humidity was 40% RH, and emissivity of all surfaces was assumed to be equal to 0.9.

When estimating impact of individual body characteristics on thermal sensation, fixed male height of 175 cm and female height of 162 cm were assumed. For both genders, the following parameter intervals were adopted

- *BMI*: min 20 – max 30
- *Age*: min 20 years – max 80 years
- *ToneIndex*: min 0 – max 1

The minimum *BMI* index value 20 means weights of 52.5 kg and 61.3 kg and the maximum *BMI* value 30 corresponds to weights of 78.7 kg and 91.9 kg for the assumed average heights of females and males, respectively.

**Thermal Sensation Model by Zhang**

Zhang (2003) has developed a new thermal sensation model to predict local and overall thermal sensation in non-uniform transient thermal environments. The overall thermal sensation (TS) is calculated as a function of the local skin temperatures and the core temperature, and their change in time. The sensation scale by Zhang is presented in Figure 3. When the local skin temperature differs from the local skin temperature set point, the sensation reaches the sensation scale limits between +4 (very hot) and -4 (very cold). Positive index values indicate various degrees of "hot" sensation and negative values indicate "cold" sensation. The index value equal to zero indicates thermal neutrality. The index values between -3 and +3 are comparable to the ASHRAE thermal sensation scale (ASHRAE 1993).

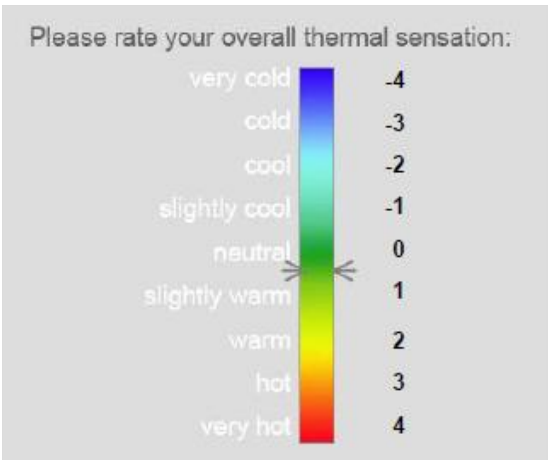


*Figure 3 Thermal sensation scale by Zhang (2003).*

## SIMULATION RESULTS

Impact of Body-mass-index (*BMI*) and *Tone Index* on thermal sensation of females from 20 years to 80 years are presented in Figures 4, 5, and 6.

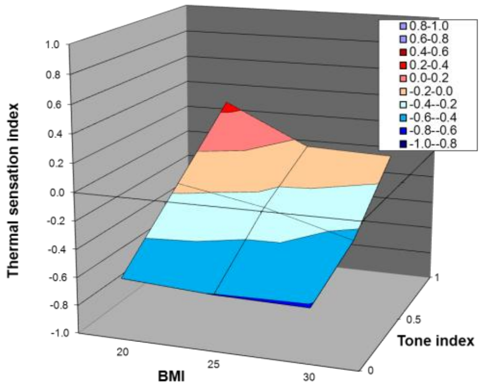


*Figure 4 Impact of BMI and Tone Index on thermal sensation of females (age 20 years).*

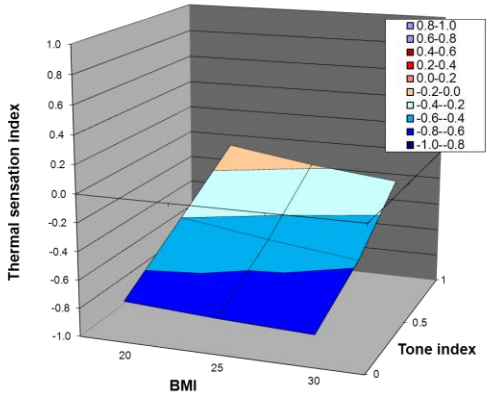


*Figure 5 Impact of BMI and Tone Index on thermal sensation of females (age 50 years).*

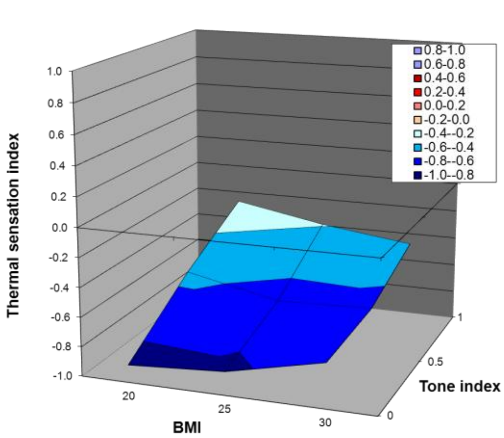


*Figure 6 Impact of BMI and Tone Index on thermal sensation of females (age 80 years).*

Figures 7, 8, and 9 show the impact of Body-mass-index (*BMI*) and *Tone Index* on thermal sensation of males from 20 years to 80 years.

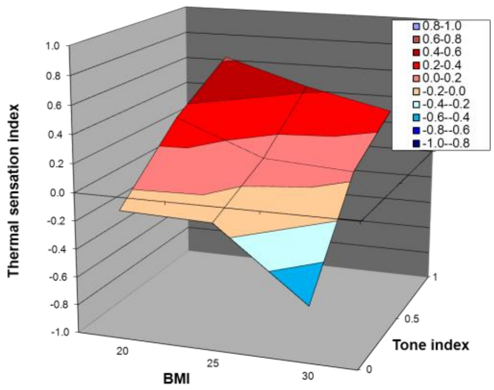


*Figure 7 Impact of BMI and Tone Index on thermal sensation of males (age 20 years).*

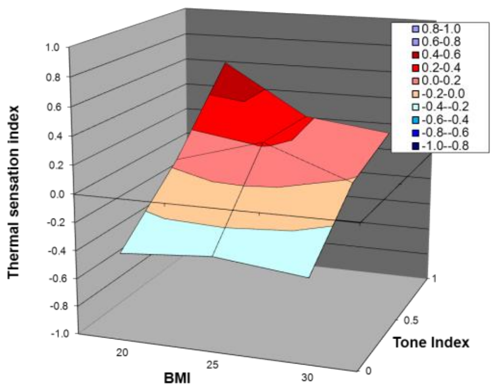


*Figure 8 Impact of BMI and Tone Index on thermal sensation of males (age 50 years).*

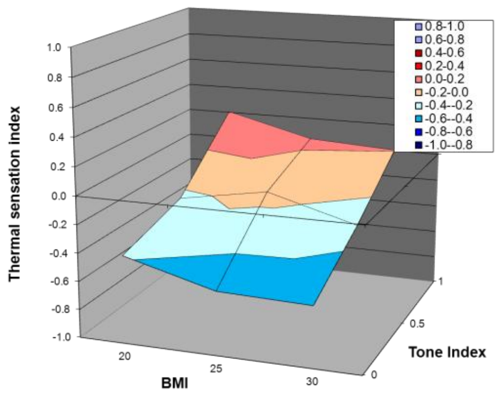


*Figure 9 Impact of BMI and Tone Index on thermal sensation of males (age 80 years).*

## RESULT ANASYSIS AND DISCUSSION

In this study, when estimating human thermal sensation, all *external* boundary conditions (i.e., operative temperature, air velocity, and humidity) are assumed to be constants. In addition, activity level, clothing, and heights of both females and males are kept constants. Furthermore, the results presented are valid for steady-state conditions without asymmetry in external boundary conditions. These assumptions were made to investigate significance of individual characteristics on thermal sensation under typical office working conditions.

When evaluating impacts of individual characteristics on thermal sensation by HTM methodology, it could be noticed that

1. Increase in age clearly seems to decrease thermal sensation values.
2. Lower thermal sensation index values were obtained for females when compared to males with corresponding *BMI* and *Tone Index* parameters.
3. In general, *BMI* seems to have minor impact on thermal sensation.
4. High *Tone Index* values (individual fitness) seems to cause the most significant increase in thermal sensation index values.

A standard EN 15251 (2007) defines thermal comfort categories based on Fanger's PMV index values:

- I -0.2 < PMV < +0.2 (PPD < 11.7%)
- II -0.5 < PMV < +0.5 (PPD < 20.5%)
- III -0.7 < PMV < +0.7 (PPD < 30.6%)
- IV PMV<-0.7; PMV>+0.7 (PPD > 30.6%)

Since PMV scale is similar to Thermal Sensation (TS) scale, at least rough quantitative estimations of impacts of individual characteristics on predicted percentage of dissatisfied can be presented.

Average differences between males with 20 years and 50 years, when comparing corresponding thermal sensation index values having same *BMI* and *Tone Index* values is 0.11, and same difference between males with 50 years and 80 years is 0.22. For females, the corresponding differences are 0.19 and 0.14, respectively. When combining results for both females and males, the average thermal sensation index difference for 30 years age difference of 0.16 was obtained. This phenomena, decreasing of thermal sensation index value along increase of age, might be one reason for elderly people being more sensitive to draught problems.

Average differences between females and males (by comparing corresponding thermal sensation index values of females and males) are 0.39, 0.48, and 0.39, for ages 20, 50, and 80 years, respectively. This is a significant difference being a potential candidate when trying to explain reported thermal sensation differences between males and females (i.e. females having higher sensitivity to variations in thermal environment).

According to the results presented in Figures 4-9, *BMI* value increase from 20 to 25 will decrease Thermal Sensation index by 0.09 for males and by 0.10 for females (average value 0.10). This reduction might be caused by increase in skin and heat loss area, but this phenomena obviously needs more detailed analysis in the future.

Different *Tone Index* values (i.e., individual fitness) seems to have the most significant impact on thermal sensation index values. An average increase of 0.60 in TS index was obtained in case *Tone Index* values were increased from 0.0 to 1.0. Some variations in increase was noticed for different ages and gender. For ages 20, 50, and 80 years, 0.68, 0.62, and 0.50 average increases of TS index values were obtained, respectively. For males 0.66 average increase, and for females 0.54 average increase in TS index value were obtained.

All the main observations presented above are closely linked to human body fat and muscle tissue ratios. This is most likely due to the fact that whenever proportion of body fat is increased (and proportions of muscle tissue decreased), metabolic rate with same activity level will decrease. The logic behind this observation is the fact that there exist three orders of magnitude difference between heat generation of muscle and fat tissues (2.02 W/kg vs 0.004 W/kg). This phenomena also seems to be supported by controlled laboratory measurements of several young male subjects, where individual rectal, tympanic, and skin temperatures were obtained (e.g., Takada et al. 2009).

This paper is focused to evaluate impacts of individual characteristics (i.e., age, gender, BMI and fitness) on human thermal sensation. The study has been conducted by utilizing a recently developed and validated Human Thermal Model, which takes into account both true anatomy (body part level tissue distributions) and physiology (thermoregulation) models (Holopainen 2012). There has also been scientifically documented results implying differences in thermoregulation processes for example between females and males as well as between different age groups, but no such differences in thermoregulation processes are included in the current version of HTM. Nevertheless, differences in tissue distributions (espacially muscle to fat ratios) seem to have major impact on individual thermal sensation. This observation seems to be a potential candidate when trying to explain documented different thermal sensations between different age groups as well as between females and males

(Karjalainen 2007, Indraganti and Rao 2010, Karjalainen 2011) under similar boundary conditions.

## CONCLUSION

Based on the result obtained in this study, it seems obvious that individual characteristics have clear impacts on thermal sensation. This is most likely due to individual body fat and muscle tissue ratios. Especially gender and individual fitness seem to have strong impact on different tissue type distribution – and ultimately on thermal sensation. This is most likely due to the fact that there exists three orders of magnitude difference between heat generation of muscle and fat tissues. However, more systematic laboratory and field measurements with different individual boundary condition parameter combinations are needed in order to present final conclusions.

In the future, impacts of individual characteristics on thermal sensation ought to have influence on design and dimensioning guideline development for different types of buildings. This is because different user groups (e.g., children, pupils with different ages, health care patients, and occupants of old-age homes) most likely have different expectations regarding to indoor thermal conditions.

## ACKNOWLEDGEMENT

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