Thermal comfort models for indoor spaces and vehicles - current capabilities and future perspectives

Cristiana Croitoru[1], Ilinca Nastase[1,*] , Florin Bode[1,2] , Amina Meslem[3], Angel Dogeanu[1]

[1] CAMBI, Technical University of Civil Engineering in Bucharest, Building Services Department, 66 Avenue Pache Protopopescu, 020396, Bucharest, Romania, ilinca.nastase@cambi.ro,

[2] Technical University of Cluj-Napoca, Mechanical Engineering Department, B-dul Muncii nr.103-105, D03, Cluj-Napoca, Romania, florin.bode@termo.utcluj.ro

[3]Université Européenne de Bretagne, Laboratoire de Génie Civil et Génie Mécanique, Equipe Matériaux Thermo Rhéologie, France, amina.meslem@univ-rennes1.fr

* corresponding author

This is the peer reviewed version of the article

Cristiana CROITORU, Ilinca NASTASE, Florin BODE, Amina MESLEM, Angel DOGEANU, Thermal comfort models for indoor spaces and vehicles - Current capabilities and future perspectives, Renewable and Sustainable Energy Reviews, 44 (2015) 304–318

which has been published in final form at

http://dx.doi.org/10.1016/j.rser.2014.10.105

Abstract

Throughout this paper, we reviewed the most popular thermal comfort models and methods of assessing thermal comfort in buildings and vehicular spaces. Most of them are limited to specific steady state, thermally homogenous environments and only a few of them address human responses to both non-uniform and transient conditions with a detailed thermo-regulation model. Some of them are defined by a series of international standards which stayed unchanged for more than a decade.
The article proposes a global approach, starting from the physiological reaction of the body in thermal stress conditions and ending with the model implementation. The physiological bases of thermal comfort are presented, followed by the main thermal comfort models and standards and finishing with the current methods of assessing thermal comfort in practice. Within the last part we will focus mainly on thermal manikin experimental studies, and on CFD (Computational Fluid Dynamics) numerical approach, as in our opinion these methods will be mostly considered for future development in this field of research.

Keywords: thermal comfort models, Fanger's models, Adaptive thermal comfort models, Physiological thermal comfort models, thermal comfort assessment

Introduction

Achieving thermal comfort for *occupants in buildings* in extreme conditioning requirements and irrespective of the environmental outside conditions has been the main focus for the Heating Ventilation and Air Conditioning (HVAC) design engineers and systems developers. We observe, however, that contemporary techniques of air flow diffusion are not optimized simultaneously for these two inseparable goals: thermal comfort and energy savings. This observation can be applied to both buildings and vehicles fields. This paradox is due on one hand to bad diffusion of cold air, and on the other hand, to weakness of the conception of these systems. Behind this, the use of air flow models that are not fully adapted to conditions in the buildings and all other interior spaces can be found. In our opinion, this issue finds a theoretical response to the adaptation of existing theoretical models for different indoor (building or other enclosures) conditions, in terms of human thermal comfort.

On the other hand, the thermal comfort of *vehicular occupants* is gaining more and more importance due to the rising attention towards comfortable mobility, in addition to the growing time that people spend in vehicles (private or public transport). Furthermore, comfortable vehicular climate control in many cases not only help to reduce the driver stress but also guarantee good visibility by avoiding the fogging phenomenon, and contributing to a more secure driving. In addition, today's demand for better vehicular energy utilization and more efficient performance have led to an increased interest in investigating and analyzing the system and design requirements for good indoor and vehicle environments. For example, the need to reduce the heat loads that enter passenger compartments has become an important issue in the early stages of vehicle design. Moreover, achieving an improved thermal comfort system will lead to substantial cost reductions. A quantitative example given in the literature shows that in the United States alone approximately 26 billion liters of fuel are consumed annually for cooling vehicle passenger compartments [1]. This cost can be reduced by improving HVAC systems design.

A technical answer may come from the conception of the air diffusion devices which have to be optimized for improving mixing between supplied flows and their ambient in order to improve thermal comfort. Nevertheless, *this technical direction of research has to be preceded by the theoretical advances* in improving the existing comfort models which seem to be inappropriate in many situations [2-4]. Indeed, nowadays, we have the possibility of using advanced methods and devices both in terms of computing capabilities and experimental techniques. The existing thermal comfort models are all built with simplified assumptions, often limited because of available resources when they were conceived – *over 30 years ago for the most used of them*. We have today the opportunity to validate these models by taking into account the variation of several parameters, and to correct them and to propose new better models.

There were many attempts during the three past decades of proposing different objective evaluation methods of this subjective matter which is thermal comfort, though without very much success. Indeed, several models and indexes are available and standardized nowadays, proposing a quantification of the thermal comfort for buildings and other indoor spaces such as vehicular cabins or other [2-5]. In the same time, the majority of these models or indexes usually lead to wrong results and incorrect assessment of a thermal ambiance when the depending parameters are not close to the ones for which they were proposed [6-8]. Fanger's

studies, for instance, are the basis for the two main standards [9, 10] that are currently used for assessing thermal comfort in all types of enclosures occupied by humans even if they were originally conceived to be applied to buildings. Fanger's studies, as well as many of the experimental investigations conducted afterwards, are based on real human participants dressed in standardized clothing and doing completed standardized activities, exposed to laboratory thermal environments. These investigations established specifying environmental parameter ranges (i.e. comfort zones) in which a large percentage of occupants with given personal parameters will regard the environment as acceptable. However, it is currently recognized that even in buildings pure steady-state conditions are rarely encountered in practice, given the interactions between building structure, occupancy, climate and HVAC systems (especially for new systems like displacement or personal ventilation). For strongly non-uniform and transient environments like vehicular cabins the previous cited standards are even more not applicable for obtaining reliable results. Moreover, there are several parameters, usually affecting the human perception of thermal comfort, that are not even taken into account in these models. In the same time the models used so far can be either too generalist or either too difficult to implement and judge [11]. Experimental campaigns show high discrepancies between numerical results and *in situ* evaluation and furthermore even higher discrepancies between human subjects' response and experiments using other methods of evaluation [12, 13].

Throughout this review we propose an attempt of answering to several questions, namely: *What are the limits of the mentioned above models in a CFD approach and which one gives the best results? Are these models adapted to nowadays indoor evaluation methods, since they have not been updated for decades? Which is the "best" thermal comfort model? Do we need extra evaluation or just a better implementation of existing models? What are the future perspectives for thermal comfort predicting?*

We decided to start our review by introducing the **physiological bases of thermal comfort**, followed by the main **thermal comfort models,** the discussion of **the main standards used for the thermal comfort assessment in occupied environments,** and finishing with the **current methods of assessing thermal comfort in practice**. Within the last part we will focus mainly on thermal manikin experimental studies, and on CFD numerical approach, as in our opinion these methods will be considered for future development.

1. Thermal comfort definition and physiological bases of thermal comfort

Thermal comfort is a subjective term defined by a plurality of sensations and is secured by all factors influencing the thermal condition experienced by the occupant, therefore is difficult to give a universal definition of this concept. Human thermal comfort is sometimes defined *as all conditions for which a person would not prefer a different environment* [14]. Another definition provided by American standard ASHRAE 55 [10] explains the thermal comfort *as a subjective concept related to physical and psychological well-being in agreement with the environment*. Because human beings are different, this term usually refers to a set of optimal parameters, for which the highest percentage possible of a group of people, feel comfortable about the environment [15].

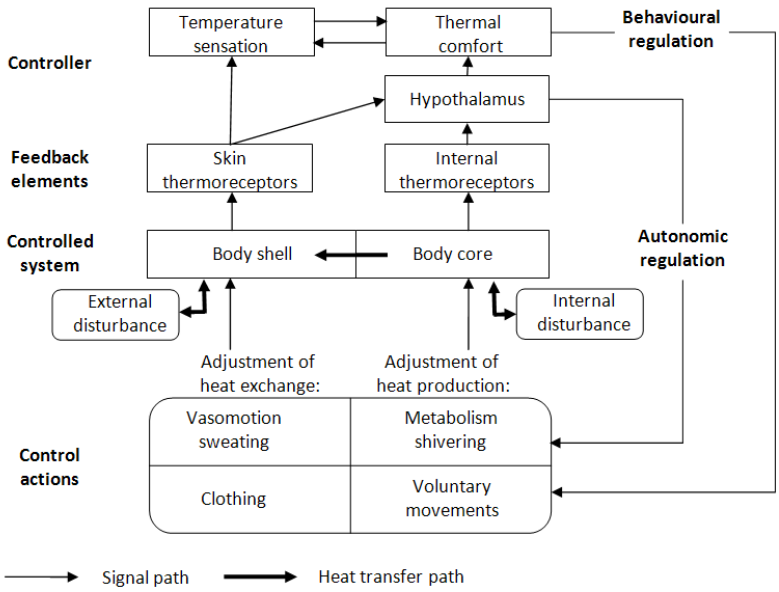


Figure 1: Schematic diagram of autonomic and behavioral temperature regulation in man from Hensen [16]

Thermal comfort is assured by all the factors that influence the exchange of heat between the human body and its environment. This way we can differentiate between factors connected with the human organism like the age, gender, weight, metabolic rate, type of activity, etc., factors connected with the clothing like thermal resistance, material structure, number of layers, and factors connected with the environment like air temperature, velocity, humidity, pressure and turbulence intensity and frequency [9, 15, 17, 18]. To achieve thermal equilibrium, the body continuously varies the ratio between the heat produced and transferred. Maintaining this balance is the first condition to achieve a feeling of thermal neutrality. Fanger [15] showed that "human thermoregulatory system is quite effective and tends first to make a heat balance without any real comfort and then to adjust his reaction to external stimuli".

As shown by Hensen [16] the *human thermoregulatory system is more complicated and incorporates more control principles than any actual technical control system.* It behaves mathematically in a strongly non-linear manner and contains multiple sensors, multiple feedback loops and multiple outputs. The Figure 1, from Hensen's paper [16] shows some basic features of the human thermoregulatory system. The controlled variable is an integrated value of internal temperatures - near the central nervous system and other deep body temperatures - and skin temperatures. The controlled system is influenced by internal heat generation by exercise and external thermal disturbances from the heat and cold environment. External thermal disturbances are rapidly detected by thermo-receptors in the skin. This enables the thermoregulatory system to act before the disturbances reach the body core. Important in this respect is that the thermo-receptors in the skin respond to temperature as well as to the rate of change of temperature. Autonomic thermoregulation is controlled by the hypothalamus. There are different autonomic control actions such as adjustment of: heat production by shivering, internal thermal resistance by vasodilatation or vasoconstriction, external thermal resistance by control of respiratory dry heat loss, water secretion and evaporation by sweating and respiratory evaporative heat loss. The associated temperatures for these autonomic control actions may not necessarily be identical nor constant or dependent on each other [19]. Besides autonomic thermoregulation, there is also behavioral

thermoregulation with control actions such as active movement and adjustment of clothing. Behavioral thermoregulation is associated with conscious temperature sensation as well as with thermal comfort or discomfort [15].

2. Thermal comfort models

During the past four decades, extensive investigations and experiments involving human subjects have resulted in methods for predicting the degree of thermal discomfort of people exposed to a certain environment. The most well-known and widely accepted methods are : Fanger's "Comfort Equation" and his practical concepts of "Predicted Mean Vote" and "Predicted Percentage of Dissatisfied" [15] and J.B. Pierce two-node model of human thermoregulation [20, 21]. The Fanger model is an empirical model that predicts a thermal vote, on the basis of several parameters and empirical equations of the heat transferred between human body and the environment, results that were obtained in strict laboratory steady-state conditions on human subjects. Since this model was widely criticized, other models have been proposed afterwards. The idea that the body reacts and tries in permanence to adapt leaded to the theory of "adaptive models". Thus, the human body can adapt from the *physiological, behavioral and psychological* point of view. The physiological models try to simulate the thermoregulatory system of the human body, the authors making several assumptions on how this regulation system works.

2.1 Fanger's models and other heat balance models and indexes

The earliest studies were performed by Professor Ole Fanger, convinced that only a trans-disciplinary approach- heat and mass transfer, thermal physiology, psychophysics, ergonomics, biometeorology, architecture and textile engineering- can lead to satisfactory results concerning thermal comfort of inhabitants [15]. This vast research work had as a goal to predict the conditions necessary for optimal indoor thermal environments. This way, Fanger's studies and many of the experimental investigations conducted after were based on real human participants dressed in standardized clothing and doing completed standardized activities, exposed to laboratory thermal environments.

Fanger started form the hypothesis that at thermal comfort state, the human body balance between the heat produced, consumed and transferred to the environment. Analyzing the most important variables that can influence the thermal comfort state and introducing them in the equation of thermal balance of the human body (*heat exchanged with the environment by radiation, convection, conduction, respiration and perspiration*) the result was an index that can predict a thermal vote of the occupants in certain indoor conditions, which is the *Predicted Mean Vote* (PMV) index [15], in accordance with the seven-point thermal sensation scale:

$$PMV = (0.303e^{0.303} + 0.028)\{(M - W) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) - 0{,}0014M(34 - t_a) - 3{,}96 \cdot 10^{-8} f_{cl} [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] - f_{cl} h_c (t_{cl} - t_a)\} \quad (1)$$

Where:

$$t_{cl} = 35.7 - 0.0275(M - W) - I_{cl}\{(M - W) - 3.05[5.73 - 0.007(M - W) - p_a] - 0.42[(M - W) - 58.15] - 0.0173M(5.87 - p_a) - 0.0014M(34 - t_a)\} \quad (2)$$

And:

M: metabolic heat rate (W/m^2);
W: activity level (W/m^2);
t_{cl}: temperature at clothes level (°C);
p_a: water vapor pressure (Pa);
t_a: air temperature (°C);
I_{cl}: thermal insulation of clothes (Clo);
f_{cl}: clothing factor;
t_{mr}: mean radiant temperature (°C);
h_c: convective heat transfer (Wm²/°C);

When the heat balance equation proposed by Fanger is satisfied, the heat generated by the human body is dissipated without having an increase or a decrease in body [15]. PMV index values are between -3 and 3. These values quantify the average opinion of a group of subjects on the state of comfort.

Associated with this parameter, is the index *Predicted Percent of Dissatisfaction* (PPD), indicating the percentage of occupants in thermal discomfort. A value of 10% of the PPD index corresponds to a range between -0.5 and +0.5 for PMV. Even for the PMV = 0, about 5% of occupants are in discomfort. The PPD index is expressed as:

$$PPD = 100 - 95\exp[-(0.03353PMV^4 + 0.2179PMV^4)] \quad (3)$$

These relationships were drawn from experimental investigations on human subjects, which showed that the mean skin temperature and the sweat secretion are closely related with the thermal comfort state [15]. A single equation was thus resulted, which assumes that all generated sweat is evaporated, for normal indoor clothes worn in regular indoor environments with low to moderate activity levels.

An early study of Fanger and Pedersen [22] displayed the effect of the air velocity fluctuations on the sensation of discomfort and then later Fanger and Christensen [23] correlated local turbulence intensity of the indoor air flow with thermal discomfort sensation in an index called "*Draft Rate*" (DR). Their studies investigated the effect of air turbulence intensity on the sensation of humans. This sensation was translated in a local thermal comfort model, opening the local investigation series. The draft charts can evidence the problem zones in a case of a bad air distribution system. The Draft Rate is an index that depends on the mean velocity, temperature but also on the air turbulence intensity value. More consideration about the DR index is presented in paragraph 4.1.

$$DR = (34 - t_a) \times (v_a - 0.05)^{0.62} \times (0.37 \cdot Tu \cdot v_a + 3.14) \quad (4)$$

Where:
t_a- mean air temperature (°C);
v_a - mean air velocity (m/s);
Tu- air turbulence intensity (%);

Thermal comfort models proposed by Fanger have been used for more than forty years, being able to predict a general comfort state. We have to note that most work related to thermal comfort has concentrated *on steady state conditions*. These are the most common models used so far for indoor building environment thermal comfort assessment [17, 24] *and are the basis*

for the two main standards [9, 10] *that are currently used for assessing thermal comfort in all types of enclosures occupied by humans even if they were originally conceived to be applied to buildings.*

They have been extensively applied to the vehicular in-cabin environments even if their main characteristics complicate the human thermal comfort determination and predictions are due to its *thermal transient values and time gradients*. Additionally, *the non-uniform thermal environment associated with the high localized air velocity, the in-cabin air temperature distribution, the solar heat flux, and the radiative heat flux from surrounding interior surface, all further complicate such predictions*[3, 25]. Furthermore, unlike air conditioned buildings, the vehicle in-cabin climate is dominated by thermal transient conditions rather than steady-state conditions. Other challenges include the psychological as well as physiological differences among the passengers. Finally, the vehicular in-cabin environments is affected by a large number of parameters that include the different interior surfaces and air temperatures, the air velocity distribution over the interior complex geometries, the relative humidity, the solar intensity and its scattering over the different material types and surface niches in the cabin, the angles of incidence, the type of clothes, etc. Also many of these parameters are dependent with unknown relationships [6].

Historically, Fanger's model was preceded with almost five decades by the concept of *Effective Temperature* (ET) [26] based on three comfort parameters, i.e., the air temperature, the relative humidity and the air velocity. Later, the influence of the metabolic rate and of clothing was integrated in a similar manner as the one of Fanger, by Gagge in a corrected *Effective Temperature* (ET*) and in a corresponding *Effective Temperature Scale* (SET*), which are based as the PMV, on the heat balance of the human body. SET* is integrating the two node model [21], and is standardized by ASHRAE. *As in the case of the PMV, these models are the equivalent characteristics of certain fictive environments, with fixed factors taken into consideration as derived from empirical models.*

The equivalent temperature model is standardized in both ASHRAE and ISO standards [10],[27]. The equivalent temperature is a pure physical quantity and represents the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment [10]. For given values of humidity, air speed, metabolic rate, and clothing insulation, a comfort zone may be determined, in terms of a range of operative temperature that people find thermally acceptable.

Equivalent temperature use the same method of calculation as the operative temperature for ambient air velocities less than 0.1m/s, which is the average of the air temperature and the mean radiant temperature weighted respectively by the convection heat transfer coefficient and the radiation heat transfer coefficient for the occupant [10].

For ambient air velocities values greater than 0.1m/s, the equivalent temperature is expressed as[28]:

$$t_{eq} = 0.55 \cdot t_a + 0.45 \cdot t_{mr} + \frac{0.24 - 0.75\sqrt{v_a}}{1 + I_{cl}} (36.5 - t_a) \quad (5)$$

Where:

t_a: air temperature (°C);

v_a: air velocity (m/s);
I_{cl}: thermal insulation of clothes (Clo);
t_{mr}: mean radiant temperature (°C);

While the operative temperature is given as only one global quantity, we can make distinction between several equivalent temperatures as: the *directional equivalent temperature* – referring to the heat exchange within the half-space in front of the infinitesimal plane and described as a normal vector to the measuring plane in every point, defined by magnitude and direction; the *omni-directional equivalent temperature* which is all around a body part or the whole body, measured generally with an ellipsoid sensor; the *whole body equivalent temperature* related to the whole body of a human being and which is the standardized quantity; and the *local equivalent temperature* related to a number of or one single body part. All these equivalent temperatures might by determined using one or several, hot-film or ellipsoid sensors as described in the EN ISO 14505/2 [27]. However another method using a thermal manikin is providing also the equivalent temperature for asymmetrical environments such as vehicles is also described in EN ISO 14505/2 [27].We will come back later to these practical experimental methods used for evaluating thermal comfort.

Also before Fanger's studies, in order to evaluate the uniformity of air velocity and temperature, Koestel and Tuve [29] studied the effect of air motion on comfort and defined draft as any localized feeling of coolness or warmth of any portion of the body due to both air movement and air temperature, with humidity and radiation considered constant. They defined the *Effective Draft Temperature* (EDT) [30] as the difference in temperature between any point in the occupied zone and the control condition, by using a relation originally proposed by Rydberg and Norback [31] and later modified by Straub et al. [32]:

$$EDT = (T_i - T_{a\,mean}) - 8(v_{ai} - 0.15) \quad (6)$$

Where

T_i: local air temperature (°K);
T_{amean}: mean air temperature of the room (°K);
$v_{a\,i}$: local air velocity (m/s);

Values obtained by calculations of EDT index should be between 1.1 K (indicates a feeling warm sensation) and -1.7 (indicating a feeling of cold) for a comfortable environment and a limit of minimum 80% of satisfied occupants [30, 33]. These values are considered for a sedentary activity. The number of points where the EDT is calculated between the limits specified above reported to the total number of points is defined as *Air Diffusion Performance Index* (ADPI).

A new thermal comfort model is making place recently combining the EDT index with the Fiala model concept [34-37]. The *Universal Thermal Climate Index* (UTCI), based on this new model, was documented in a number of papers during the last years [37-39]. The index itself was then derived conceptually as an equivalent temperature: for any combination of air temperature, air velocity, radiation, and humidity, UTCI is defined as the isothermal air temperature of the reference condition that would draw out the same dynamic response of the physiological model.

2.2 Human thermo-physiological models

The validity of PMV Fanger's model was questioned by many researchers, for cases where the tested parameters were strongly different compared to the conditions used for conceiving the model, particularly in real field studies or in strongly non-homogenous and transitional vehicular environment. Discrepancies between actual and predicted neutral temperatures reflect the difficulties inherent in obtaining accurate measures of *clothing insulation* and *metabolic rate*. In most practical settings, poor estimations of these two variables are likely to reduce the accuracy of PMV predictions. The DR Fanger's model was less discussed and corrected, anyway, the issue of how to interpret and compare results *between local cooling and whole-body cooling* experiments is probably the major problem when interpreting the influence of air velocity [12, 13].

Closely related to Fanger's models, *nodal thermo-physiological* models were intended to put in the same balance equation, the heat and mass production of the human body and its transfer with the environment. Instead of correlating the empirical thermal sensation scale based on a panel evaluation with heat transfer, they provide the local skin temperature variation as a result of simulated physiological reactions. This way, the main difference with Fanger's models is this possibility of simulating transient capabilities of adaptation of the human body to the external stimuli. The more factors are taken into consideration, the more nodes are in the model. Physiological reactions that occur in the thermoregulatory process are representing the adaptive characteristic of the human body for different conditions, by changing the heat flux ratios (shivering leads to a higher metabolic rate, vasoconstriction leads to lower radiation and convection heat flux rate, sweating leads to a higher evaporation heat flux rate etc.)[40].

Historically, thermo-physiological models were connected to the military research applied to clothing improvement. In 1972, Givoni and Goldman [41] developed an empirical model to predict the human body core temperature. They stated that for any given combinations of metabolic rate, environment, and clothing a theoretically determined equilibrium core temperature and a matching skin temperature would be generated, and unified biophysical formulas could be constructed to adequately predict that response. The so called "Pierce two-node model" was first proposed by Gagge et al. [42], considering the body consisting in two layers: the core and the skin. The model takes into account the modification of the temperature of the core and skin weighted by the percentage of each. Thermoregulatory mechanisms (sweating, skin blood flow, shivering) are defined in terms of thermal signals from the core, skin and body, for moderate activity levels and uniform ambiances.

Another two-node model that can be taken into discussion is KSU- two- node model developed at Kansas State University in 1977 [43]. This model is similar to Gagge model but, the index resulted is a thermal sensation that is calculated differently for warm or cold environments. A complex multi-node model published in 1970, Stolwijk's 25-node model [44], was used in aerospace applications, where non-uniform conditions were to be assessed. In this model, the body is divided into six parts, each part being composed by 4 layers, the 25^{th} node being the central blood compartment. Because of the division in six body parts, the model is more dynamic, being able to predict the thermal sensation for each part. The environment is still considered as with steady state conditions, but this model was the beginning of a suite of more adaptive thermoregulatory models. A representative one is IESD – Fiala thermo-regulation model [35, 36], which involves a controlled passive system and an active controlling system. The active system is a numerical model that predicts the thermo-

regulatory reactions (vasoconstriction, vasodilatation, shivering and sweating), while the passive system simulates the physical body and the dynamic heat-transfer that occurs inside the body and at its surface. The model was validated with experimental studies, both transient and steady conditions, and showed good agreement with experimental data. Another model based on the Stolwijk model, the 65-node thermoregulation model [45] proposed by Tanabe et al. was published in 2002. The model has 16 body segments corresponding to the thermal manikin, each divided in four layers: core, muscle, fat and skin. The 65th node is the central blood compartment, which exchanges convective heat with all other nodes via the blood flow. Heat transfer coefficients and clothing insulation were derived from the thermal manikin experiments. The study even proposes a CFD coupling, showing satisfactory results.

The Berkeley Model [46] uses an unlimited number of sequential sets of environmental and physiological input conditions, called phases. Each phase consists of the following data: Duration, Metabolic rate, Physiological constants, Clothing (insulation level and moisture permeability), air temperature, mean radiant temperature (or a list of surface temperatures, emissivity and angle factors), air velocity, relative humidity, contact surface thermal properties. Phases are most commonly used to represent segments of time where environmental conditions are constant or vary linearly with time. Since the length of the phase is arbitrary, non-linear transients can be simulated by short, linear approximations. All of the physiological constants embedded in the model can also be changed through the input data. Several objects are needed to represent each element of the physical model (see Figure 2). The node object is the basic unit in this object structure. All the actual simulation procedures like heat production, heat transfer and regulating control mechanism are done within node objects. Multiple nodes are organized into a tree-like structure that is maintained by a higher level object, the segment object. A segment also has a blood object which contains an artery and a vein. The body consists of several segments that are connected with each other via blood. Nodes exchange heat with their adjacent nodes via conduction as well as with blood.
The practical five steps in using the Berkeley model for predicting local thermal sensation are the following [25]: (i) importing a human geometry into a finite differencing platform that includes the Berkeley sub-routine; (ii) meshing the human geometry depending on the resolution needed; (iii) setting the biological material properties and the thickness values to each individual part; (iv) setting the environmental boundary conditions, including the environmental variables, the clothing properties, the surface conditions, and the convection settings; (v) solving the heat transfer balance equations using a finite differencing approach.

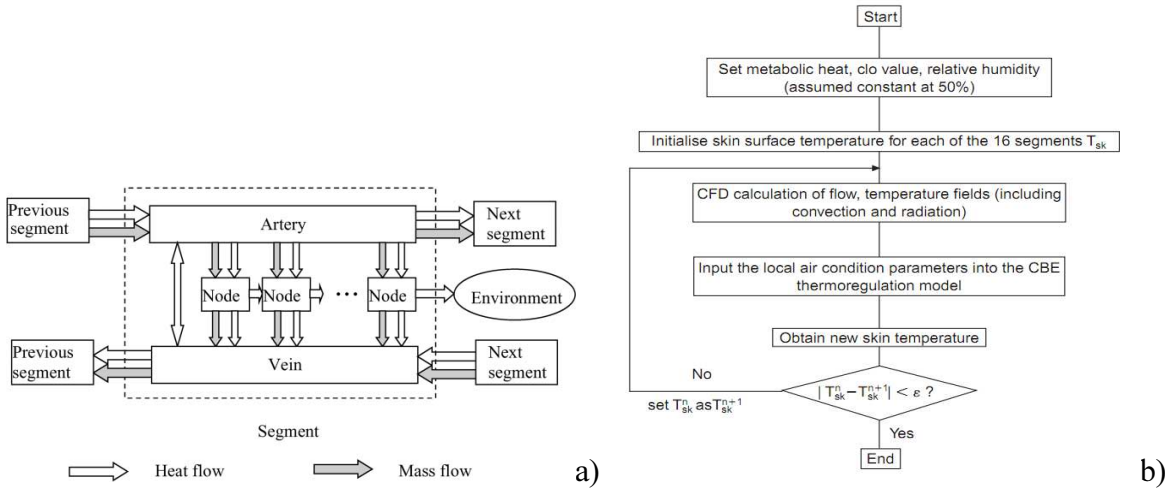


Figure 2: a) Berkley model [46], b) Example of a first coupling attempt between the Berkley model and CFD [47]

Another physiological adapting model is the multi-elements model, the improvement being the clothes layer model [48]: the Stolwijk's multi-node model was modified considering the sweat accumulation on the skin surface and applied to simulate the physiological response of the human body. This human model is connected with a heat/moisture model of clothing materials that takes into consideration the adsorption of water vapor in the fibers. Furthermore, a multi-layer clothes system is developed and integrated with the human model. The result agrees well with the published experimental data. Practically, the number of nodes integrated in the models is unlimited, depending of course on the computational resources. Other multi-node models are improvements of the old ones [49].

We have to note however that the application of all these nodal thermo-physiological models has not yet been adopted by any of the international standards and guidelines as a possible prediction method for evaluating the local and overall thermal sensations.

2.3 Adaptive models – Psychological and postural adapting models

The documented research literature and standards dedicated to thermal comfort might be divided in two main categories: the ones dedicated to the classical physiological models (including Fanger's approach and nodal evaluation of local thermal sensation) on one hand, and the ones dedicated to the *adaptive approach* on the other hand.

In 1994, de Dear [50] expressed a number of reservations about the validity of the climatic 'chamber' approach of Fanger and on the subsequent models. The first reservation related to the unnatural way of judging the thermal sensation through unnatural laboratory-type research. "*There are persistent doubts about the experiential realism of the chamber methodology*" de Dear argued. Another concern with Fanger's models and all the other related indexes was that they do not seem to take into account the cultural, climate and social contextual dimension of the comfort [51]. Based on field studies among the acclimatized population, the adaptive approach, is supposed to represent better people's responses to thermal stimuli encountered typically in normal buildings. It has the purpose of analyzing the real acceptability of thermal environment, which strongly depends on the context, on the behavior of occupants and their expectations (Figure 3). The adjustments have been summarized by de Dear [51] in three categories: behavior adaptation, physiological adaptation and psychological adaptation. In recent years, different authors have encouraged field studies in addition to laboratory experiments, in order to get more reliable information about the actual workplace comfort and the relevant (interacting) parameters.

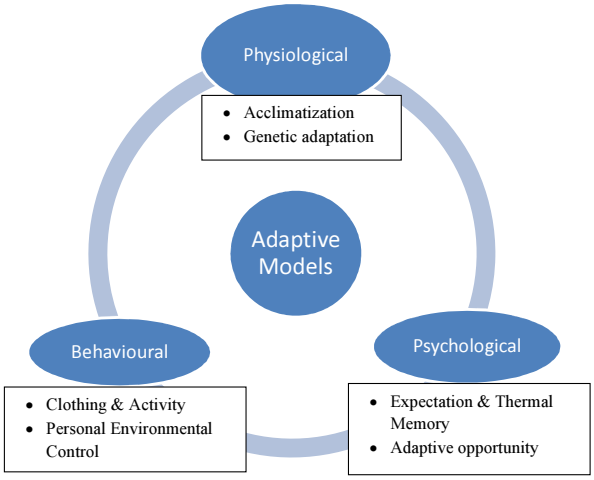


Figure 3: Schematic diagram of the holistic principle of the Adaptive Models

Field studies also allow for analyses of other factors than those that can be simulated in laboratory climatic chambers, as the subjects provide responses in their natural environment, wearing normal clothing and behaving without any additional restrictions [52]. The subjectivity in thermal experience and the interpretations flowing from a very complex interaction between the occupants and their environment has been the focus of a great deal of study and provides the theoretical foundation to the adaptive approach to thermal comfort studies [34]. As shown by Nicol and Humphreys [53], *„the adaptive method, unlike the heat-exchange method, does not require knowledge of the clothing insulation and the metabolic rate in order to establish the temperature required for thermal comfort. Rather it is a behavioral approach, and rests on the observation that people in daily life are not passive in relation to their environment, but tend to make themselves comfortable, given time and opportunity. They do this by making adjustments (adaptations) to their clothing, activity and posture, as well as to their thermal environment."*The fundamental principle of adaptive thermal comfort is that: "*If a change that occurs induces discomfort, the occupants' body reacts to restore comfort*." [53]. The comfort temperature is a result of the interaction between occupants and the building. This adaptation is a two-way process [54]. Either the occupants have to adapt to the environment either to adapt the environment to meet their needs, so they feel less discomfort. There are three variable contexts: the climate, the building and the time. The internal heat is determined depending on the climate conditions. The second context is the building, especially the features and the services it offers to its occupants. The third context is the time, the human activity taking place in the time unit and comfort temperature being variable in time.

The results from the field studies of Humphreys [55-57] suggest that the average vote of comfort varies less than we would expect, for a wide range of interior climate conditions. This way, the author concluded that the comfort temperature is closely related to the average temperature measured on the inside. Further studies were made [58, 59], showing that adaptive actions are needed to achieve comfort. For example, in [58] is shown that the most important ways for the occupants to reach the comfort level were clothes changing and the air movement improvement. Humphreys proposed a correlation between the interior comfort temperature and the outer average temperature through several experimental field campaigns in different locations in the world [60]. He found a major difference between comfort temperature variations of naturally ventilated buildings and heated or cooled buildings. In the first case this was found to be a linear function, while in the second a rather more complex relation was established. The indoor comfort temperature depends in this case on the variations of the outdoor temperature and the operation of the building: for free running buildings, the daily and seasonal changes of the outdoor temperature will dictate the indoor thermal conditions, while for heated and cooled buildings (systems functioning when heating and cooling are required) this dependence will be weaker [61]. Moreover, the same authors argue that these empirical correlations have to be reconsidered since the human body is able to adapt to external temperature variations and the mean outdoor temperature of a certain month can dramatically change from a year to another. It is considered that the use of records of monthly mean of the outdoor temperature should be replaced with more dynamic measures, like exponentially weighted running mean temperature [62].

De Dear and Brager [63] classified building's occupants in two categories: those from naturally ventilated buildings and those from buildings heated or cooled, as having different expectations (expectations not in the interaction with the building services but related to the

expected temperature in a particular situation).The occupants that have control on the characteristics of the building climate are much less demanding about the convenience gained. The feeling of being in control psychologically leads to faster adaptation to different conditions. The opening of a window, switching on a fan and changing clothes, posture, and activity lead to a more extended range of the comfort temperature. They also found that adaptive actions need time to show their effect. Their rate of change is smaller than the changes undergone by the weather from a season into another, but higher than the variations which take place every minute. Therefore, it requires a time step for climate change but adaptive actions are obvious. The study underlines the formula for the comfortable temperature as a linear function of the exterior temperature, in a naturally ventilated building. The relation for heated or cooled buildings is much more complex and less stable. Even if we talk about naturally ventilated buildings or buildings heated or cooled, this approach promotes indoor variable climate control to dynamically provide comfort to their occupants.

The adaptive theory has to be applied with regard to climatic zone differences since the results showed the adaptive equation for moderate climate cannot be applied to hot climates [64]. Moreover, people in hot climates adapt to higher neutral operative temperatures, being necessary an bespoke adaptive thermal model. Indeed as displayed by Indagrandi et al. [65], comfortable condition can be reached at temperatures different from those suggested by the current local and international standards, and the air movement which is widely used in this area is not taken into consideration.

McCarthney and Nicol [59] underlined the idea that an adaptive model assumes a non-technical measure of cost optimization and the reduction of the unwanted effects, while maintaining the occupants comfort. More, it is mentioned that the adaptive comfort means 10% energy savings estimated for a 1 K change in the value of the comfortable temperature, but with the remark that it is easier to achieve these numbers for naturally ventilated buildings than air-conditioned ones. This approach was later transformed in ASHRAE Standard 55/2004 [10]which involves the calculation for the internal temperature of thermal comfort. The adaptive approach is also found in EN 15251 [66] for indoor environment comfort assessment.

Various adaptive studies are found in the literature, these include: comparative studies between traditional and modern living spaces [67], building performance assessing methods [68, 69], low energy consumption systems [70-72], comparative studies with regard to sex [73], effects of indoor climates on thermal perceptions [74], thermal comfort in classrooms [75, 76], patients' thermal comfort in hospitals [77, 78], and thermal comfort in outdoor environments [79-82] etc. No adaptive thermal comfort approach for vehicular cabins is available in the literature.

As in the case of the PMV/PPD approach, the adaptive approach has been criticized in the literature, especially the use of the adaptive comfort chart in the ASHRAE Standard 55, which promotes an acceptable indoor temperature range as a linear function of the mean monthly outdoor temperature only. As shown in a recent paper by Halawa and van Hoof [83] *the vulnerability of this much simplified approach is that all the assumptions applied when developing the adaptive comfort chart are hidden from the user of this chart, which is creating confusion.*

2.4 Main Standards related to the thermal comfort assessement

The EN ISO 7730 standard [9] is relying on Fanger's approach and on the confort equation previously described. The standard addresses the evaluation of moderate thermal environments, an referes to other ISO documents specifying methods of measurement and evaluation of moderate and extreme thermal environments (ISO 7243 [84], ISO 7933 [85] and ISO 11079 [86]). Being up-dated in parallel with the ASHRAE 55 standard [10], the latest version of the EN ISO 7730 standard [9] includes also a minor, not very specific, section about adaptive comfort which specifies that thermal conditions can be imposed for different values of PMV than those from the standard.

The new version of ASHRAE 55 standard [10] dating from 2013 specifies methods for the evaluation of the thermal environment of buildings through several parameters in order to obtain a certain degree of global and local comfort for the occupants, at a certain level of activity and clothing. ASHARE 55 [10] either uses the PMV-PPD approach or Standard Effective Temperature (SET) comfort zones for conditioned spaces either an adaptive approach for determination of acceptable thermal conditions in naturally ventilated spaces, using operative temperature contours as a function of mean outdoor air temperatures. The conditions which influence the thermal comfort are more detailed in comparison with ISO 7730 [9].

Indoor parameters which need to be considered in order to conceive a building are mentioned in EN 15251[66], a standard which has a global approach on indoor comfort with regards to energy performance of buildings. Besides thermal comfort, air quality and acoustic and visual comfort are taken into consideration for design and assessment of the built environment. For each component of indoor evaluation a certain standard is indicated, as in the case of the thermal comfort the ISO 7730 standard. In function of PMV-PPD values, four categories of ambiences are established. Nicol and Wilson consider in [87] that these categories of building ambiances and the corresponding expectations of the occupants, can be mistakenly interpreted as indicators of 'quality', especially as the phrase 'high expectation' is associated with a category of environment leading to higher energy consumption when not necessary. The adaptive approach from this standard was compared with the adaptive approach from ASHRAE 55 and the results showed higher temperatures resulted from the first.

When assessing vehicles environment, the standard ISO 14505 is used with its three parts [88-90], since in this environment the convective, radiative and conductive heat exchange is very complex and the loads can vary intensively in time and space. Part 2 of the standard proposes a different method of evaluation: equivalent temperature, since the classical PMV- PPD method applies for uniform conditions. This temperature can be calculated, according to different measuring principles, for the whole body, for each segment, or directional or either omnidirectional. The instruments employed can be either thermal manikins either omnidirectional sensors for integration of discrete measurements.

3. Thermal comfort assessment in practice

In the following part of the manuscript, the main methods used in practice to evaluate the quality of a given real or virtual thermal environment are passed in review.

3.1 Human subjects response

Before Fanger's studies, many campaigns involving tests on human subjects' thermal response have been made. These studies were intended to document thermal sensation recorded by different people in various environments, especially work places, e.g. [91-94]. Fanger himself couldn't use the reported results from most of these studies, since one or more of the six main variables in comfort equation were not measured or reported [15], but some of them were valuable as they offered all needed data for comparison and good agreements in results. For example, the experiments realized by Nevins et al. [95] and McNall et al. [96] permitted, a comparison with Fanger's work, because large numbers of college-age persons have been used as subjects and all the variables mentioned above were monitored during the tests.
Fanger conducted his tests on college-age or elderly human subjects, from United States or Denmark, exposed to different thermal conditions, and activities etc. [15, 97], mainly in laboratory conditions. Most of the experimental studies have been carried out in an "environmental chamber" at Technical University of Denmark, a 2.8m x 5.6m x 2.8m chamber, where different steady state conditions were tested. This limitation to steady-state conditions was discussed by many scientists, Fanger admitting that minor fluctuations may occur. *The Professor explained that people will be more disturbed by the fluctuations in temperature, than a constant environment, so steady state conditions are suitable for thermal comfort vote* [15].

In parallel of this steady state approach, different studies appeared, demonstrating the influence of transient conditions. The difference between thermal comfort and temperature sensation during changing environmental conditions was demonstrated by experiments of Gagge et al. in 1967 [98]. The subjects were exposed for one hour to neutral thermal conditions, then a step change to a much colder or warmer environment for a two hour exposure, which was followed by a step change back to neutral conditions. Re-entering to the neutral conditions from hot environments, discomfort disappeared rapidly however more slowly than in the case of re-entering from cold to neutral step.

Experimental campaigns focusing on transient conditions have gained territory, even if Fanger's model was widely adopted. Changes in transient conditions experiments can be categorized as cyclical [16], ramps or drifts and steps. The same author mentions some difficulties reached during experimental studies: the results were in fact subjective responses of a highly complex system; the usage of different semantic voting scales (with words like acceptable and unacceptable or scales of 2, 7 or 9 points); differences in acceptability criteria; differences in testing conditions; differences in subject's nature (age, nationality, sex etc.). *Fanger's special experimental conditions like using a climatic chamber lead to the idea that human subjects must be tested from field-studies of people in daily life and not rigid laboratory conditions* [99]*, idea underlined also by de Dear in* [100]*. They got to the belief that field studies have a more immediate relevance to usual living conditions* [63, 101, 102].

Another category of field studies concern the local sensation effect on overall thermal sensation. This approach has been intensively studied at Berkeley University [103-106] and other laboratories [107-111], results that help validating thermal comfort models for non-uniform environments evaluation.

3.2 Sensors

Since Fanger's first studies and the development of the PMV and PPD indexes, an instrument which measures simultaneously these indexes was proposed at Danish Technical University by Korsgaard and Madsen [112, 113]. It was equipped with an omni-directional air velocity sensor, a relative humidity sensor and an operative temperature sensor with an ellipsoidal shape with a diameter of 56 mm and a length of 160 mm (Figure 4a). For this last sensor the measurement element is a nickel wire coil, measuring the average surface temperature of the ellipsoid. The form and size of the measuring element facilitate direct measurement of the operative temperature. Its size was chosen so the heat loss ratio between radiation and convection is similar to that of the human body. The shape of the measuring element is chosen so that hot or cold surfaces have a similar influence on the sensors on the human body. 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. The color and surface structure of the measuring element is chosen to simulate an average dressed person as closely as possible. Nowadays, modern similar equipment is largely used and it usually proposes local measurements of the Draft Rate also (Figure 4b). The standard EN ISO 14505/2[27] for thermal comfort in vehicles prescribes the size of the ellipsoid of 50mm in diameter and 200mm in length. It recommends using several sensors mounted on a man-shaped rig in order to have access to the local and whole body values of the equivalent temperature.

Another method of evaluating the equivalent temperature is using flat surface sensors – for instance a small platinum electrically heated surface to different settings according to the activity level of the person (in general at a constant rate of 85 W/m². the sensors may be placed on the surface of a human body shaped dummy or on a real person. In order to provide a single value for the overall equivalent temperature, individual values obtained from each sensor are added and area weighted in a representative way [27].

A local discomfort meter proposed by Nilsson [114], also for assessing thermal comfort in vehicular cabins consists in a double sided heated skin element. The difference in mean heat flux (MHF) from the two opposite elements can directly be transformed to a thermal asymmetry. The electrical signals received from the skin element are transformed by a microprocessor into a value called Perceived Heat Flux (PHF) which is equivalent to the sensation of local thermal discomfort.

3.3 Thermal manikins

Another type of experimental investigations in assessing thermal comfort are based on thermal manikins – electrically heated dummies - which are either body segment skin temperature controlled, either body segment power controlled. They provide an equivalent temperature based upon a whole body PMV value but using a lot of simplifying assumptions. Over time various materials were used for manufacturing thermal manikins, models eventually being made of aluminum or plastic, so handling them would involve no problems related to user safety. Another significant step was the introduction of regulation and control techniques, leading to more precise measurements.

Because a thermal mannequin, that is standing only, is limited to certain limited experimental situations, there were made models with joint that allowed the exploitation of various positions of the human body. Then, these joints have led to mobile thermal manikins, the simulated human body in motion. Most of these models are used to test the clothes. Thermal mannequins began to be increasingly widely used, being constantly improved, reaching to act as "human", integrated with a system of breathing or even perspiration on the skin.

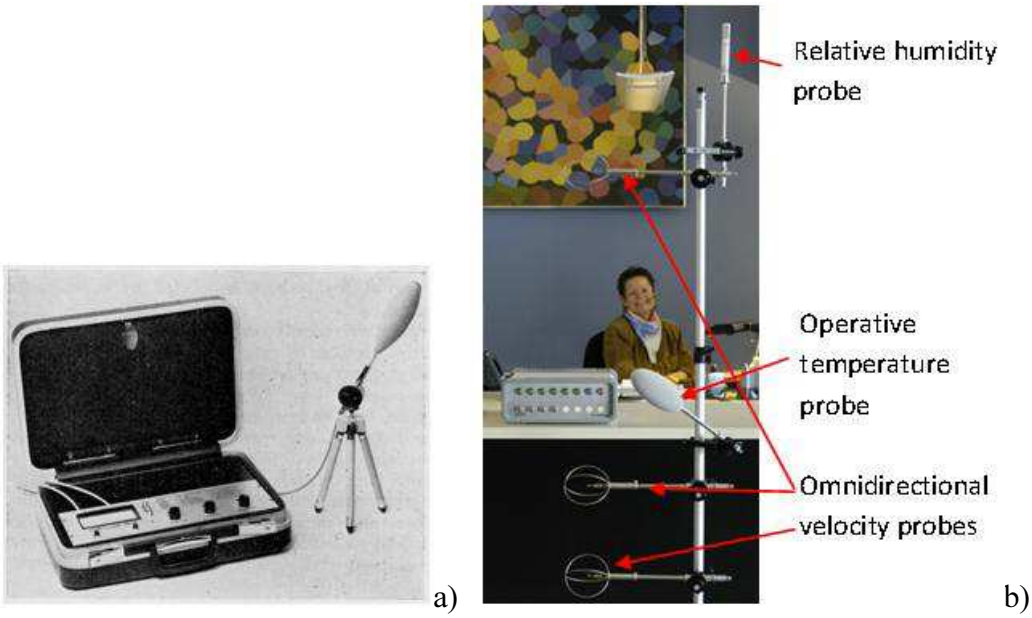


Figure 4: **a) Comfort-meter developed by Korsgaard and Madsen [112, 113], b) Modern measurement system with omni-directional velocity probes, operative temperature probe, relative humidity probe [115]**

Manikins used in sophisticated thermal comfort studies are expensive and delicate instruments as well, but also have many advantages, such as accurate simulation of human body, measurements of heat transfer, methods for measuring the thermal resistance of clothing, fast, repeatable and accurate measurements etc. An efficient thermal manikin can measure heat transfer through convection, radiation and conduction all over the surface, whether it receives or releases heat. Heat transfer coefficients are calculated for several conditions, particularly when air velocity or motion are taken into consideration [116].

Depending on the number of segments, spatial resolution may increase, the models of last generation having more than 100 individual segments. A thermal manikin may be subject to long-term tests, repeatable, under extreme or even dangerous situations for the body, conditions that could subjectively influence the results. Manikins can simulate any temperature and its distribution on the skin surface or the heat release (nature and intensity). This can be tested in various environments, and the results are interpreted in terms of thermal comfort. In addition to these results, the manikins can also evaluate heat, indoor air quality, air flow, clothing, the distribution of pollutants etc.

An important step for simulating a real human body is the breathing process on the manikin [117, 118]. The thermal manikin named „Walter" [119], improved by a system of "sweat" production with a cloth moistened with the help of pumps, controls the temperature by releasing the heat through evaporation. Another device, the Thermal Observation Manikin, or

TOM [120], was designed to measure heat gain in terms of exposure to heat sources in the automotive industry. These manikins incorporate a thermo-physiological response model that takes into account the heat flux transducers, temperature sensors and power sources, being translated into a thermal vote sensation. Growing interest on thermal comfort has led to the development of a new type of thermal model as part of a suite of equipment for evaluating ambiances of car cabins [121]. ADAM manikin (ADvanced Automotive Manikin) has 126 metallic segments covered with composite material that can be independently controlled for temperature, humidity and heat flow released. The manikin is controlled by cables or wireless with a transmitter for the output and input. An internal fan realistically simulates the breathing process.

3.3 Prediction of the vehicular comfort state using Infrared thermography

The Infrared thermography is non-invasive, non contact imaging approach that has been proposed by certain authors to measure the temperature variation on the human skin temperature [25, 122, 123]. As shown by Alahmer et al. [3], using infrared thermography is possible to achieve real-time measurements of solid surfaces temperature fields within the vehicular cabin in addition to clothes and visible body parts of the human subjects. This experimental approach overcomes the limitation of conventional one point temperature measurement techniques and of the visual observation methods.

There is a limited number of papers in the literature discussing the use of infrared thermography to measure and evaluate the thermal conditions inside the cabin, even though this optical technique seems to be a promising tool in the assessment of the comfort state in vehicular cabins, given that the surface's temperature is one of the most influencing parameters in this case. An early study of Burch et al. [122] displays several automotive applications of infrared thermography with focus on its use for automotive climatic control analysis. The author proposes a method for measuring ambient air temperature by using a thin (0.15 mm) layer of polyethylene plastic mounted perpendicular to the air stream.

Korukçu and Kilic [123] reported the use of the infrared thermography to measure the temperature of the front panel and that of the facial skin during the heating and the cooling cycles. The authors validated the proposed method by thermocouples junctions placed on the measured surfaces. It was found that the acquired temperature profiles (spatial and temporal) from the thermal cameras and the thermocouples were in agreement.

A practical example of how this technique can be used is given in the recent study of Alahmer et al. [25]. The article investigates the analysis and modeling of vehicular thermal comfort parameters using a set of designed experiments aided by thermography measurements in both steady and transient state of the test vehicle cabin. In this case, the temporal variation of temperatures especially for driver's skin, for different body segments mainly the forehead, the hands and the feet were recorded to be used as boundary conditions in numerical simulations. The authors used a 3-D Berkeley model that is set to be fully transient to account for the interactions in the velocity and temperature fields in the passenger compartment, which included interactions from turbulent flow, thermal buoyancy and the three modes of heat transfer conduction, convection and radiation. The analysis of the experimental and simulation results showed that controlling the relative humidity levels during the heating and

the cooling processes achieved the thermal comfort state faster than if this parameter was not controlled.

3.5 CFD models and thermal comfort assessment

The experimental approaches, using thermal manikins or human subjects, must take into account dependence of the response of the human body and the multitude of independent variation of parameters outlined above. Therefore, to establish reliable conclusions, they require a large number of experiments. This leads to high costs of experimental studies in terms of material resources and time. In this context, CFD (Computational Fluid Dynamics) numerical simulations have gained increased popularity in study of quality and thermal comfort inside ambiances during the past decades, especially those using RANS (Reynolds Averaged Navier Stokes) models. Indeed, starting with the first CFD studies for indoor airflow research, in 1973, Nielsen [124] presented an attractive alternative to pure experimental investigations, showing the great advantage of flexibility in choosing the configuration and boundary conditions. *Interactions between air flows involved in rooms or vehicular cabins are crucial for the study of the thermal comfort.* Information on thermal comfort parameters, air quality, and effectiveness of the ventilation/air conditioning systems can be extracted from the velocity, temperature and mass concentration distributions offered by the CFD models. This paragraph is dedicated to the problems involved in numerical modeling and limitations imposed by this approach which are specific to the thermal comfort field.

Along a large number of numerical studies from the literature, one could come across different geometrical from definitions of the human body from simple models to very complex shapes [125-127]. The documented results show that the realistic shapes of the virtual manikin lead to accurate results and predictions of the thermal comfort. In the same time, results obtained from CFD studies need to be validated with experimental data from real scale measurements before using CFD for larger parametric investigation. Other extensive studies tried to evaluate which would be the correct choice of turbulence model as a function of the appropriate geometry, for different ventilation strategies [128]. Murakami et al. and Sorensen and Voigt [125-127], focused on the study of velocity fields and radiative and convective heat flux released by the body. Sorensen [129] was the first to calculate the view-factors for the radiation heat flux between a human body and surrounding surfaces, while Bjorn and Nielsen [117], and Hayashi et al. [130] simulated pollutants distribution around the human and the impact on inhaled air quality.

Developing models for the human body and its interaction with the indoor environment was made step by step, starting from 2D simulations for air flow around simplified geometries for isothermal conditions. Transition to three-dimensional geometries allowed more realistic air flows and considering radiation between surfaces. The level of detail in reproducing the geometry of the human body was of course dependent of the available computer resources. In his study, Dunnett [131] used a cylinder with elliptical section to simulate a standing person while Niwa et al. [132] simulated a seated body by a cube. Other researchers have used more developed three-dimensional rectangular shapes to model airflow around a seated [133] or standing person [134-137].With increasing computing power, forms and complex geometries more close to the real shape of the human body were introduced, virtual thermal manikins being sometimes equipped with an air flow simulating human breath, or a generation of

moisture in the skin. Complex geometries of the human body can be generated using specialized CAD software or with a laser scanner usually used for geodetic studies.

Topp and Nielsen [128, 138] have investigated by numerical simulations the influence of the modeled body shape in the sitting position placed in an unidirectional flow field (Figure 6). Researchers have found that geometry has influence only in the region very close to the body, which is important for studies involving breath or air flows oriented to the face. However, a realistic geometry of the modeled body shape is necessary in studies that are looking closely to the convective flow around persons for assessing local thermal comfort for instance. This need is met for instances in the automotive field or for personalized ventilation studies, in which the investigated flow coincides with the boundary layer around the body. Because of the difficulty of meshing the domain which includes humanoid forms, beside laser scanned manikins mentioned above, very few studies have introduced true realistic models of the human body [139, 140].

Choosing turbulence model involves an algorithm that takes into account many considerations such as: the flow, the accuracy pursued, the available computational resources, the considered physical phenomenon etc. The most used turbulence models for the numerical simulation of the air flow around a human body are k-epsilon type models. Murakami et al. [127] points out that the only way to calculate the convection heat transfer in critical area is to use a fine mesh of MTV. However, in simulations using k-epsilon turbulence model for small Reynolds numbers, for a fine mesh of complex geometries, it is difficult to achieve convergence [141].
In the past, several turbulence models were used, either based on the case study or the involved resources. The study of Chen and Xu [142] demonstrated the applicability of zero equation turbulence model, for the air flow prediction for the general purpose spaces, without special conditions, with the advantage of low computing resource needs. Another model which involves a short computing time, the Spalart-Allmaras turbulence model, was tested by Torano et al. [143], and compared with standard k-epsilon and experimental data. Both turbulence models were found to provide satisfactory results.

For special environments like vehicular spaces, the k-epsilon and Low-Reynolds-Number realizable k-epsilon models were found to be better adapted, like in the study of Bosbacha et al. [144]: the numerical simulations were validated by PIV measurements inside an airplane cabin. Other models such as k-omega SST [145] were found to bring additional accuracy in reproducing velocity and temperature distributions for a an office [146]. It has been recently shown [147], by PIV measurements around a thermal manikin ventilated by a system of personal ventilation, that the flow around the breathing zone is very complex and is characterized by a strongly anisotropic turbulence, fact that could question the accuracy of the numerical simulations for a microenvironment performed by the models of isotropic turbulence. The LES (Large Eddy Simulation) approach compared to the RANS models offers the possibility to characterize the dynamic details of the flows and heat and mass transfer [148] but the involved computational resources make this approach still not adapted to the human body scale studies.



Figure 5:Detail of the virtual thermal manikin, 500000 cells [125]

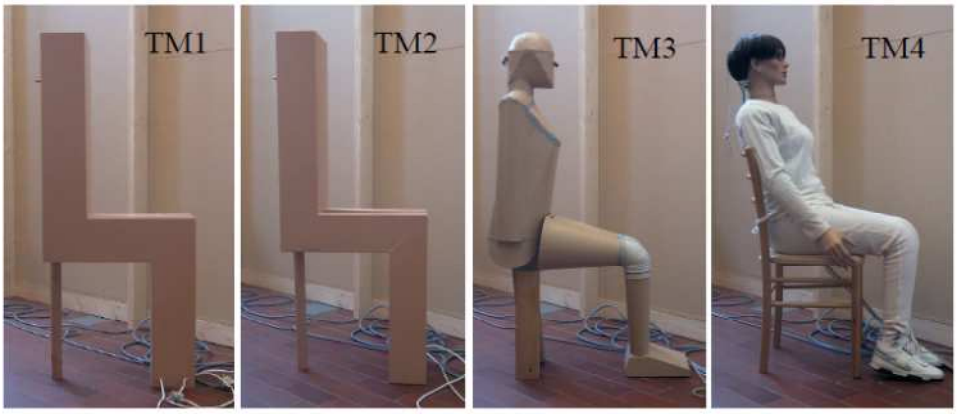


Figure 6: Different shapes of thermal manikins used for the experimental validation in the CFD studies of Topp and Nielsen [128, 138]

The boundary conditions used for simulating the human body are also extremely important. The first approach that integrated a humanoid form only took into account the convective transfer between the body and the environment[149]. The boundary conditions considered a constant flux of 20 W/m^{2}on the surface of the modeled body for a case with no other air flow than the convective one. Computational domain contained 125000 cells. A mean velocity of 0.26 m/s in the plume generated by the body was obtained, a value which was in good agreement with experimental data [149]. Distribution of body temperatures, the convection coefficient values on the skin surface are also in agreement with experimental data. In the same study, a case considering a uniform velocity flow of 0.25m/s was also treated. In the second case the values of local convective fluxes, and consequently the convective flow behavior couldn't be validated with the experimental data. Later, Murakami et al. [126] introduced a radiation model coupled with convection and the transport of moisture for a simple geometry body. The boundary conditions on the surface of the body were injected from a two nodes thermo-physiological model [42] imposing a uniformly distributed heat transfer between the body and the environment, which, through an iterative process controls the temperature at the skin surface. The results were found to be quite satisfactory, with a maximum velocity of the convective flow of 0.23m/s and a global heat flux of 100.4 W/m². The resulting skin temperature was found to be 33.3 ° C and the body core temperature, was respectively found to be 36.8 °C. Another attempt of coupling thermo-physiological models with CFD was proposed by Tanabe [45]. The nodal model had 16 segments, each with 4 layers: bone, muscle, fat and skin layer and a central system representing the circulatory system. Because heat transferred by radiation and convection was calculated using transfer

coefficients empirically determined, the CFD code was used only for calculating air flow around the virtual body. Other studies in the same direction are available in the literature [47, 139, 150, 151].

Usual comfort prediction indexes such as PMV and DR can be easily extracted from CFD data, but still there are not many studies in the literature exploiting this great advantage. The paper of Catalina et al. [152] presents an example of using CFD for assessing thermal comfort in the presence of a radiant cooling system Unfortunately this study like so many others does not consider the presence of the human body itself and the interactions between the convective plume and the other flows in the room. A typical problem regarding this kind of numerical approach is that for the conception of building systems and simulation of the resulting indoor environment, it is still not acknowledged that convection flows caused by heat sources like the human body plume may significantly affect the flow distribution in rooms [153]. Generally, attention is given only on the flow generated by the air diffusion terminal devices or other HVAC systems. As shown by Kosonen et al [153] the point of occurrence of the maximum air velocity in the occupied zone depends on the heat source strength and its distribution in the room. Thus, the air flows interaction itself is of great importance when estimating occupants' comfort. An example in this way is the study of Omori et al. [154] CFD data and resulting values of the thermal comfort indexes are validated with experimental data obtained using a thermal mannequin. In the same time studies like the very recent article of Martinho et al. [155] propose a detailed geometrical model, a careful experimental validation using a sophisticated experimental thermal manikin but no thermal comfort assessment, except local body segments heat fluxes.

4 Discussion about limitations of the current models and methods and conclusions

Throughout this paper, we reviewed the most popular thermal comfort models and methods of assessing thermal comfort in buildings and vehicular spaces. In our opinion, most of them are not comprehensive enough or they are limited to specific environments and only a few of them address human responses to both non-uniform and transient conditions with a detailed thermoregulation model. Some of them are defined by a series of international standards which stayed unchanged for more than a decade. In an article from 2001 [156], noted that these standards are outdated and following their prescriptions cannot lead to acceptable conditions for most users: *"We need to reconsider the concept related to our comfort to achieve excellence in environmental quality. Our goal should be essential to provide fresh air, accompanied by a pleasant feeling, refreshing, without any adverse health effect and a comfortable thermal environment for all users"* said the Professor in [156]. At the same time if we consider two bibliographic articles at a distance of 20 years - [157] and [17] – we can see that nothing has changed in definition and use of Fanger's based heat balance approach models and subsequent evaluation indexes.

As previously explained, one of the problems of these standards is that extrapolation of results from the proposed models is used for a variety of situations (i.e parameters regarding the environment or the occupants) for which are not necessary adapted. If previously we cited the case of the strong anisotropy of the thermal environment, we could also evoke the case of the special requirements categories of people. Children, for instance, might be more sensible to indoor parameters. The question is if the previously cited methods and standards are still valid in these cases. Children, for instance, might be more sensible to indoor parameters, but the

question is if the previously cited methods and standards are still valid in this case. With adapted questionnaires, the researchers find that their TSV is higher than measured PMV [158]. Elderly people were found to be more sensitive to the change in indoor thermal conditions during the summer comparing to winter, fact which may be attributed to a superior level of clothing. In comparison to younger adults, elderly people response differently for the same environmental conditions, fact interpreted by the authors as depending on individual thermal adjustment particular to this category of age [159]. Other authors [160] show for instance that thermal sensation of the elderly is, in general, lower in comparison with the younger category, confirming that the evaluation method of the thermal comfort should be further adapted.

As pragmatic particular characteristics like shape, size, metabolic-rate, clothing-level or activity-level would have a major influence on the estimated thermal perception of the indoor environment [161], the most advantageous case would be a numerical tool allowing a CFD model to be coupled with a thermoregulatory model of the human body (see Figure 2b). From our point of view, the thermoregulatory Berkeley thermal comfort model [46] which considers the physiological interactions between the local body parts and the whole body thermal sensation, and local and whole body thermal sensation and comfort for asymmetrical conditions is the most fitted model to real situations in buildings or vehicles. The existing thermal comfort models that address the asymmetry environments need further development and improvement. For example, the Fiala [35] model seems mainly to address transient conditions while the Berkeley model focuses on the cooling effects in warm environments. Furthermore, it is envisaged that in the long run, practical reliable prediction of heat transfer between the human body and environment can be obtained with CFD methods, which can be fed back directly to the human body thermal regulation model so that the thermal sensation and comfort of different body segments can be evaluated more accurately. This coupling still needs to be done.

The equivalent temperature method from ISO14505/3 [89] using both sensors and thermal manikin based methods, to evaluate the thermal sensations in vehicles, still suffers from the fact that thermal sensation, primarily due to local sensible heat variations, is evaluated by using the clothing-independent thermal comfort diagrams and the reliability of the method would be treated with caution when evaporation from skin is involved. Additionally, the ISO 14505 [89] standard seems more sensitive to the warm environments, while less sensitive to cold environments, compared with the Berkeley thermal comfort model. This may imply that the ISO 14505 [89] Standard is just suitable for thermal neutral situation, where the latent heat of evaporation constitutes a very small part of the total heat transfer of human body. The model well predicts that reasonable design of personalized ventilation can also improve human's thermal comfort to a certain extent in agreement with experimental studies and the Berkley model predictions.

Additionally, in the case of the vehicular enclosure thermal comfort, other design parameters of the cabin are influencing thermal comfort sensation in an unpredictable relationship. An example is given by the thermal sensation offered by the car seats in term of seat cover materials for instance [25, 162, 163]. The thermal sensation of the surface itself is strongly influenced by the fabric properties, but once again, it is dependent on a very large number of interrelating factors which merge to provide an overall largely subjective assessment of comfort in the vehicle. Textiles for instance allow the production of overall mentally relaxing interiors by fabric design and color [164].

However, *modeling the comfort response itself* is the ultimate goal in using heat balance models. Indeed, all of the rational models make the inherent assumption that there is some predictable comfort response for a given physiological state of the body. Still, it is not clear if there is such a relationship and how it could be expressed in a universal, applicable way. It is obvious that, the state of comfort is inherently a psychological response, not a physiological response and we have to note that *there is absolutely no consensus amongst the models as how comfort should be related to the physiological variables or even which are the variables that have to be considered as important parameters*.

In the adaptive thermal comfort approach, there are not such parameters as *set point* as the comfort level of the occupants is dictated by the occupants themselves, or by "*changing the conditions to accord with comfort and changing comfort temperature to accord with the prevailing conditions*" [99]. The adaptive comfort approach may take credit for widening the range of acceptable comfort temperature, which makes it possible to claim more energy savings in buildings designed using this approach than those design using Fanger's approach. However, in long term run, this may found to be unsustainable. Some results from adopting the adaptive approach to the design of a number of buildings have shown that some green buildings are quite uncomfortable [19]. In fact, Nicol and Humphreys [99] have warned that "*a low energy standard which increases discomfort may be no more sustainable than one which encourages energy use"* because of the adaptive principle that "*occupants may well use energy to alleviate their discomfort*".

Acknowledgments

This work was supported by Grant of the Romanian National Authority for Scientific Research, CNCS, UEFISCDI, Project number: PN-II-ID-PCE-2011-3-0835 and PN-II-PT-PCCA-2011-3.2-1212

References

1. Rugh, J. and V. Hovland. *National and world fuel savings and CO2 emission reductions by increasing vehicle air conditioning COP*. in *Proceedings from the 2003 Alternate Refrigerant Systems Symposium in Phoenix*. 2003.
2. Croitoru, C., et al. *Numerical and experimental modeling of airflow and heat transfer of a human body*. in *Roomvent 2011*. 2011. Trondheim, Norway.
3. Alahmer, A., et al., *Vehicular thermal comfort models; a comprehensive review.* Applied Thermal Engineering, 2011. **31**(6–7): p. 995-1002.
4. Cheng, Y., J. Niu, and N. Gao, *Thermal comfort models: A review and numerical investigation.* Building and Environment, 2012. **47**(0): p. 13-22.
5. Wyon, D., et al., *Standard procedures for assessing vehicle climate with a thermal manikin.* SAE-Technical Paper Series, 1989.
6. Jones, B.W., *Capabilities and limitations of thermal models for use in thermal comfort standards.* Energy and Buildings, 2002. **34**(6): p. 653-659.
7. Humphreys, M.A. and J.F. Nicol, *The validity of ISO-PMV for predicting comfort votes in every-day thermal environments.* Energy and Buildings, 2002. **34**(6): p. 667-684.

8. Humphreys, M.A. and M. Hancock, *Do people like to feel 'neutral'?: Exploring the variation of the desired thermal sensation on the ASHRAE scale.* Energy and Buildings, 2007. **39**(7): p. 867-874.
9. *ISO 7730 - Ergonomics of the thermal environment —Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.* 2005.
10. ASHRAE, *''Thermal environmental conditions for human occupancy,'' ANSI/ASHRAE Standard 55-2013, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA*. 2013.
11. Arens, E., et al., *Are 'class A' temperature requirements realistic or desirable?* Building and Environment, 2010. **45**(1): p. 4-10.
12. Fountain, M.E., *Laboratory studies of the effect of air movement on thermal comfort: A comparison and discussion of methods.* ASHRAE Transactions, 1991. **97**(1): p. 863-873.
13. Charles, K.E., *Fanger's Thermal Comfort and Draught Models, IRC-RR-162* 2003 Institute for Research in Construction, National Research Council of Canada, Ottawa, K1A 0R6, Canada.
14. Santamouris, M. and D. Asimakopoulos, *Passive Cooling of Buildings*, ed. L. James & James Science Publishers. 1996.
15. Fanger, P.O., ed. *Thermal Comfort-Analysis and Applications in Environmental Engineering*. ed. C.D.T. Press. 1970.
16. Hensen, J.L.M., *Literature review on thermal comfort in transient conditions.* Building and Environment, 1990. **25**(4): p. 309-316.
17. Djongyang, N., R. Tchinda, and D. Njomo, *Thermal comfort : A review paper.* Renewable and Sustainable Energy REviews, 2010. **14**: p. 2626-2640.
18. Nilsson, H.O., *Thermal comfort evaluation with virtual manikin methods.* Building and Environment, 2007. **42**(12): p. 4000-4005.
19. Leaman, A., L. Thomas, and M. Vandenberg, *Green buildings: what Australian users are saying?* EcoLibrium, 2007. **6**(10): p. 22-30.
20. Gagge, A.P., *Rational temperature indices of man's thermal environment and their use with a 2-node model of his temperature regulation*, in *Federation of American Societies for Experimental Biology*. 1973, Federation Proceedings. p. 1572-1582.
21. Gagge, A.P., A.P. Fobelets, and L.G. Berglund, *A standard predictive index of human response to the thermal environment.* ASHRAE Transactions, 1986. **92**(2B): p. pp. 709-731.
22. Fanger, P.O.a.P., C.J.K. . *Discomfort due to air velocities in spaces*. in *Proceedings of the Meeting of Commissions B1, B2, E1 and the IIR, 4, Belgrade*. 1977.
23. Fanger, P.O. and N.K. Christensen, *Perception of draught in ventilated spaces.* Ergonomics, 1986. **29**(2): p. 215 - 235.
24. Van Hoof, J., *Forty years of Fanger's model of thermal comfort: comfort for all?* Indoor Air, 2008. **18**(3): p. 182-201.
25. Alahmer, A., M. Abdelhamid, and M. Omar, *Design for thermal sensation and comfort states in vehicles cabins.* Applied Thermal Engineering, 2012. **36**(0): p. 126-140.
26. F.C. Houghten, C.P.Y., *Determining lines of equal comfort.* ASHVE. Transactions, 1923. **29**: p. 163-175.
27. ISO, *Ergonomics of the thermal environment -Evaluation of thermal environments in vehicles Part 2: Determination of Equivalent Temperature, in ISO 14505-3:2006.* 2006.

28. Madsen, T.O.B.K.N., *Comparison between operative and equivalent temperature under typical indoor conditions.* ASHRAE Transactions, 1984. **90**(1): p. 1077-1090.
29. Koestel, A. and G.L. Tuve, *Performance and evaluation of room air distribution systems.* ASHRAE Transactions, 1955. **61**: p. 533.
30. Organisation, I.S., *ISO 7243 Hot environments – estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)*. 1989: Geneva.
31. Rydberg, J. and P. Norback, *Air distribution and draft.* ASHVE Transactions, 1949. **55** p. 225.
32. Straub, H.E. and M.M. Chen, *Distribution of air within a room for year-round air conditioning-Part II. .* University of Illinois Engineering Experiment Station Bulletin, 1957: p. 442.
33. Madsen, T.L., *Thermal comfort measurements.* ASHRAE Trans., 1976. **82**(1).
34. Fiala, D., *Ph.D dissertation: Dynamic simulation of human heat transfer and thermal comfort*. 1998, De Montfort University: England.
35. Fiala, D., K.J. Lomas, and M. Stohrer, *A computer model of human thermoregulation for a wide range of environmental conditions: The passive system.* Journal of Applied Physiology, 1999. **87**(5): p. 1957-1972.
36. Fiala, D., K.J. Lomas, and M. Stohrer, *Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions.* International Journal of Biometeorology, 2001. **45**(3): p. 143-159.
37. Fiala, D., et al., *UTCI-Fiala multi-node model of human heat transfer and temperature regulation.* International Journal of Biometeorology, 2012. **56**(3): p. 429-441.
38. Nagano, K. and T. Horikoshi, *New index indicating the universal and separate effects on human comfort under outdoor and non-uniform thermal conditions.* Energy and Buildings, 2011. **43**(7): p. 1694-1701.
39. Jendritzky, G., R. de Dear, and G. Havenith, *UTCI-Why another thermal index?* International Journal of Biometeorology, 2012. **56**(3): p. 421-428.
40. Taleghani, M., et al., *A review into thermal comfort in buildings.* Renewable and Sustainable Energy Reviews, 2013. **26**(0): p. 201-215.
41. Givoni B., G.R.F., *Predicting rectal temperature response to work, environment, and clothing.* J. Appl. Physiol, 1972. **32**: p. 812-821.
42. Gagge, A.P., J.A.J. Stolwijk, and Y. Nishi, *An effective temperature scale based on a simple model of human physiological regulatory response.* ASHRAE Transactions, 1970. **77**(1): p. 247-262.
43. Azer, N.Z., Hsu, S., *The prediction of Thermal Sensation from Simple model of Human Physiological Regulatory Response.* ASHRAE Trans., 1977. **83**(1).
44. Stolwijk, J.A.J., *A mathematical model of physiological temperature regulation in man.* NASA CR-1855,Washington DC, 1971.
45. Tanabe, S., et al., *Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD).* Energy and Buildings, 2002. **34**: p. 637-646.
46. Huizenga, C., Z. Hui, and E. Arens, *A model of human physiology and comfort for assessing complex thermal environments.* Building and Environment 2001. **36**: p. 691-699.
47. Gao, N.P., H. Zhang, and J.L. Niu, *Investigating indoor air quality and thermal comfort using a numerical thermal manikin.* Indoor and Built Environment 2007
48. Yi, L., et al., *An integrated model for simulating interactive thermal processes in human–clothing system.* Journal of Thermal Biology, 2004. **29**(7–8): p. 567-575.

49. Dongmei, P., et al., *A four-node thermoregulation model for predicting the thermal physiological responses of a sleeping person.* Building and Environment, 2012. **52**(0): p. 88-97.
50. de Dear, R.J. and M.E. Fountain, *Field investigations on occupant comfort and office thermal environments in a hot-humid climate.* ASHRAE Transactions, 1994.
51. de Dear, R.J., G.S. Brager, *Towards an adaptive model of thermal comfort and preference.* ASHRAE Transactions, 1998. **104**(1): p. 145-167.
52. de Dear, R.J., J.W. Ring, *Human subjective experience of ambient temperature step-changes: experimental results compared to the predictions of a numerical model.* Indoor Air, 1990.
53. Nicol, F. and M. Humphreys, *Maximum temperatures in European office buildings to avoid heat discomfort.* Solar Energy, 2007. **81**(3): p. 295-304.
54. Veselý, M. and W. Zeiler, *Personalized conditioning and its impact on thermal comfort and energy performance – A review.* Renewable and Sustainable Energy Reviews, 2014. **34**(0): p. 401-408.
55. Humphreys, M.A., *Field studies of thermal comfort compared and applied.* Build Serv Eng, 1976. **44**(1): p. 5-23, 27.
56. Humphreys, M., *Outdoor temperatures and comfort indoors.* Batim Int Build Res Pract, 1978. **6**(2): p. 92-105.
57. Humphreys, M.A., *Variation of comfortable temperatures.* International Journal of Energy Research, 1979. **3**(1): p. 13-18.
58. Nicol, J.F. and I.A. Raja, *Indoor thermal comfort: the Pakistan study.* Energy for Sustainable Development, 1997. **3**(5): p. 50-60.
59. McCartney, K.J. and J. Fergus Nicol, *Developing an adaptive control algorithm for Europe.* Energy and Buildings, 2002. **34**(6): p. 623-635.
60. Humphreys, M.A. and J.F. Nicol. *Understanding the adaptive approach to thermal comfort*. 1998.
61. Humphreys, M.A., J.F. Nicol, and I.A. Raja, *Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach.* Advances in Building Energy Research, 2007. **1**(1): p. 55-88.
62. Santamouris, M., *Advances in Passive Cooling*. 2012: Routledge. 284.
63. de Dear, R.J., G.S. Brager, and D.J. Cooper. *Developing an adaptive model of thermal comfort and preference*. 1997.
64. Toe, D.H.C. and T. Kubota, *Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot–humid climates using ASHRAE RP-884 database.* Frontiers of Architectural Research, 2013. **2**(3): p. 278-291.
65. Indraganti, M., et al., *Adaptive model of thermal comfort for offices in hot and humid climates of India.* Building and Environment, 2014. **74**(0): p. 39-53.
66. Standardization, E.C.f., *CEN EN 15251*, in *Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*. 2007: Brussels, Belgium.
67. Ealiwa, M.A., Taki A. H., Howarth A.T., Seden M.R. , *An investigation into thermal comfort in the summer season of Ghadames, Libya.* Building and Environment, 2001. **36**: p. 231-237.
68. Wagner, A., et al., *Thermal comfort and workplace occupant satisfaction-results of field studies in German low energy office buildings.* Energy and Buildings, 2007. **39**: p. 758-769.
69. Freire, R.Z., G.H.C. Oliveira, and N. Mendes, *Predictive controllers for thermal comfort optimization and energy savings.* Energy and Buildings, 2008. **40**(7): p. 1353-1365.

70. Mui, K.W.H. and W.T.D. Chan, *Adaptive comfort temperature model of air-conditioned building in Hong Kong.* Building and Environment, 2003. **38**: p. 837-52.
71. Han, J., et al., *Field study on occupants' thermal comfort and residential thermal environment in a hot-humid climate of China.* Building and Environment, 2007. **42**: p. 4043-4050.
72. Schiavon, S., A.K. Melikov, and C. Sekhar, *Energy analysis of the personalized ventilation system in hot and humid climates.* Energy and Buildings, 2010. **42**(5): p. 699-707.
73. Wang, Z., *A field study of the thermal comfort in residential buildings in Harbin.* Building and Environment, 2006. **43**: p. 1034-1039.
74. Cena, K. and R. De Dear, *Thermal comfortandbehavioural strategies inoffice buildings located in a hot-arid climate.* Journal of Thermal Biology, 2001. **26**: p. 409-414.
75. Corgnati, S.P., R. Ansaldi, and M. Filippi, *Thermal comfort in Italian classrooms under free running conditions during mid-seasons: assessment through objective and subjective approaches.* Building and Environment, 2009. **44**: p. 785-792.
76. Mumovic, D., et al., *Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in EnglanD.* Building and Environment, 2009. **44**(7): p. 1466-1477.
77. Hwang, R.L., et al., *Patient thermal comfort requirement for hospital environments in Taiwan.* Building and Environment, 2007. **42**: p. 2980-2987.
78. Verheyen, J., et al., *Thermal comfort of patients: Objective and subjective measurements in patient rooms of a Belgian healthcare facility.* Building and Environment, 2012. **46**(5): p. 1195-1204.
79. de Dear, R.J., et al., *Thermal comfort in outdoor and semi-outdoor environments*, in *Elsevier Ergonomics Book Series*. 2005, Elsevier. p. 269-276.
80. Happe, P., *Different aspects of assessing indoor and outdoor thermal comfort.* Energy and Buildings, 2002. **34**(6): p. 661-665.
81. Hwang, R.-L., T.-P. Lin, and A. Matzarakis, *Seasonal effects of urban street shading on long-term outdoor thermal comfort.* Building and Environment, 2007. **46**(4): p. 863-870.
82. Zhu, Y., et al., *Evaluation of coupled outdoor and indoor thermal comfort environment and anthropogenic heat.* Building and Environment, 2007. **42**(2): p. 1018-1025.
83. Halawa, E. and J. van Hoof, *The adaptive approach to thermal comfort: A critical overview.* Energy and Buildings. **51**(0): p. 101-110.
84. Organisation, I.S., *ISO 7243 Hot environments – estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)*. 1989: Geneva.
85. ISO, *ISO 7933 Ergonomics of the thermal environment -- Analytical determination and interpretation of heat stress using calculation of the predicted heat strain*

2004.
86. ISO, *ISO 11079 Ergonomics of the thermal environment -- Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects*

2007.
87. Nicol, J.F. and M. Wilson, *A critique of European Standard EN 15251: strengths, weaknesses and lessons for future standards.* Building Research & Information, 2011. **39**(2): p. 183-193.

88. ISO, *Ergonomics of the thermal environment - Evaluation of thermal environments in vehicles Part 1: Principles and methods for assessment of thermal stress*, in *ISO 14505-1:2007*. 2007.
89. ISO, *Ergonomics of the thermal environment -Evaluation of thermal environments in vehicles Part 3: Evaluation of thermal comfort using human subjects*, in *ISO 14505-3:2006*. 2006.
90. ISO, *Ergonomics of the thermal environment -Evaluation of thermal environments in vehicles Part 2: Determination of Equivalent Temperature*, in *ISO 14505-3:2006*. 2006, ISO.
91. W. J. McConnell, F.C.H., F. M. Phillips *Further Study of Physiological Reactions.* ASHVE Transactions, 1923. **29**.
92. Bedford, T., *The warmth factor in comfort at work*, in *Rep. industr. Hlth. Res. Bd.* 1933: London.
93. F. C. Houghten, M.B.F., C. Gutberlet, *Local Cooling of Workers in Hot Industry.* ASHVE Transactions, 1941. **47**.
94. Rowley, F.B., Jordan, R. C. , Snyder, W.E., *Comfort reactions of workers during occupancy of air conditioned offices.* ASHVE Transactions, 1947. **53**: p. 357-368.
95. Nevins, R.G., Rohles, F. H., Springer, W., Feyerherm, A. M., *A temperature-humidity chart for thermal comfort of seated persons.* ASHRAE Transactions, 1966. **72**(1): p. 283-291.
96. McNall, J., P. E., Jaax, J., Rohles, F. H., Nevins, R. G., Springer, W. , *Thermal comfort (and thermally neutral) conditions for three levels of activity.* ASHRAE Transactions, 1967. **73**(1).
97. Fanger, P.O., *Thermal comfort*. 1982, Malabar, FL.: Robert E. Krieger Publishing Company.
98. Gagge, A.P., J.A.J. Stolwijk, and J.D. Hardy, *Comfort and thermal sensations and associated physiological responses at various ambient temperatures.* Environmental Research, 1967. **1**(1): p. 1-20.
99. Nicol, J.F. and M.A. Humphreys, *Adaptive thermal comfort and sustainable thermal standards for buildings.* Energy and Buildings, 2002. **34**(6): p. 563-572.
100. de Dear, R., *Thermal comfort in practice.* Indoor Air, Supplement, 2004. **14**(SUPPL. 7): p. 32-39.
101. Auliciems, A., *Towards a psycho-physiological model of thermal perception.* International Journal of Biometeorology, 1981. **25**(2): p. 109-122.
102. de Dear, R.J. *Global database of thermal comfort field experiments*. 1998.
103. Zhang, Y. and R. Zhao, *Effect of local exposure on human responses.* Building and Environment, 2007. **42**(7): p. 2737-2745.
104. Zhang, H., et al., *Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts.* Building and Environment, 2010. **45**(2): p. 389-398.
105. Zhang, H., et al., *Thermal sensation and comfort models for non-uniform and transient environments, part III: Whole-body sensation and comfort.* Building and Environment, 2010. **45**(2): p. 399-410.
106. Zhang, H., et al., *Thermal sensation and comfort models for non-uniform and transient environments: Part I: Local sensation of individual body parts.* Building and Environment, 2010. **45**(2): p. 380-388.
107. Chen, C.-P., et al., *Effects of temperature steps on human skin physiology and thermal sensation response.* Building and Environment, 2011. **46**(11): p. 2387-2397.

108. Choi, J.-H., V. Loftness, and D.-W. Lee, *Investigation of the possibility of the use of heart rate as a human factor for thermal sensation models.* Building and Environment, 2012. **50**(0): p. 165-175.
109. Foda, E., et al., *Models of human thermoregulation and the prediction of local and overall thermal sensations.* Building and Environment, 2011. **46**(10): p. 2023-2032.
110. Park, S., et al., *Local and overall thermal comfort in an aircraft cabin and their interrelations.* Building and Environment, 2011. **46**(5): p. 1056-1064.
111. Ghaddar, N., K. Ghali, and S. Chehaitly, *Assessing thermal comfort of active people in transitional spaces in presence of air movement.* Energy and Buildings, 2011. **43**(10): p. 2832-2842.
112. Korsgaard, V. and T.L. Madsen. *New instruments for measuring thermal comfort*. in *Proceedings of the 13th International Congress of Refrigeration* 1971.
113. Korsgaard, V. and T.L. Madsen, *Neue Geräte zur Behaglichkeitsmessung.* Klima und Kälte Ingenieur, 1973. **August**.
114. Nilsson, H.O. and I. Holmér, *Definitions and Measurements of Equivalent Temperature, European commission cost contract no smt4-ct95-2017 Development of standard test methods for evaluation of thermal climate in vehicles*. 2002.
115. Dantec Dynamics, S.A.S., *Comfort Sense system brochure, available on http://www.dantecdynamics.com/*.
116. Oliveira M., A.V., et al., *Analysis of natural and forced convection heat losses from a thermal manikin: Comparative assessment of the static and dynamic postures.* Journal of wind engineering and industrial aerodynamics, 2014. **132**: p. 66.
117. Bjorn, E. and P.V. Nielsen, *Dispersal of exhaled air and personal exposure in displacement ventilated rooms.* Indoor Air, 2002. **12**(2): p. 147-164.
118. Melikov, A.K., et al. *Impact of airflow interaction on inhaled air quality and transport of contaminants in rooms with personalized and total volume ventilation.* in *Healthy Buildings*. 2003. Singapore.
119. Fan, J. *New Functions and Applications of "Walter"-Sweating Fabric Manikin.* . in *International meeting on thermal manikins and modelling*. 2003. Strasbourg, France.
120. Lebbin, P., M. Hosni, and T. Gielda. *Design and manufacturing of two thermal observation manikins for automobile applications*. in *International meeting on thermal manikins and modelling*. 2003. Strasbourg, France.
121. Burke, R., J. Rugh, and R. Farrington. *ADAM - The Advanced Automotive Manikin.* in *International meeting on thermal manikins and modelling*. 2003. Strasbourg, France.
122. Burch, S.D., V. Hassani, and T.F. Penney. *Use of infra-red thermography for automotive climate control analysis*. in *Proceedings of the SAEWorld Congress*. 1993.
123. Korukçu, M.Ö. and M. Kilic, *The usage of IR thermography for the temperature measurements inside an automobile cabin.* International Communications in Heat and Mass Transfer 2009. **36**(8): p. 872-877.
124. Nielsen, P.V., *Berechnung der Luftbewegung in einem zwangsbelüfteten Raum.* Gesundheits-Ingenieur, 1973. **94**: p. 299-302.
125. Sorensen, D.N. and L.K. Voigt, *Modeling airflow and heat transfer around a seated human body by computational dynamics.* Building and Environment 2003. **38**(6): p. 753-762.
126. Murakami, S., S. Kato, and J. Zeng, *Combined simulation of airflow, radiation and moisture transport for heat release from a human body.* Building Environment, 2000. **35**: p. 489-500.
127. Murakami, S., S. Kato, and J. Zeng, *CFD analysis of thermal environment around human body.* 1996. **2**: p. 479-484.

128. Nielsen, P.V., et al., *Benchmarks test for a computer simulated person* Indoor Air, 2003. **14**(7): p. 144-156.
129. Sorensen, D.N., *Radiation between segments of the seated human body* in *ROOMVENT*. 2002. p. 317-320.
130. Hayashi, T., et al., *CFD analysis on rising stream araound a human body and its effect on inhalation air quality.* ASHRAE Transactions, 2002. **108**(2): p. 1173-1178.
131. Dunnett, S.J., *A numerical study of the factors affecting worker exposure to contaminant.* Aerosol Science and Technology, 1994. **25**(1): p. 481-482.
132. Niwa, K., et al. *Numerical analysis of flow and temperature field with local air conditioning by supply jets from the seats in hall*. in *ROOMVENT*. 1996.
133. Iwamoto, S. *A study on numerical perdiction methods of thermal environmnent around occupants*. in *INDOOR AIR*. 1996.
134. Bluyssen, P.M. and T. Lemaire. *The distribution of percieved air quality in an office space- computer simulations and sensory evaluations*. in *ROOMVENT*. 1992.
135. Gan, G., *Numerical method for full assessment of indoor thermal comfort.* Indoor Air 1994. **4**: p. 154-168.
136. Brohus, H. and P.V. Nielsen. *Personal exposure to contaminant sources in uniform velocity field* in *Healthy Buildings*. 1995.
137. Brohus, H. and P.V. Nielsen. *CFD models of persons evaluated by full-scale wind channel experiments*. in *ROOMVENT*. 1996.
138. Topp, C., P.V. Nielsen, and D.N. Sorensen, *Application of computer simulated persons in indoor environmental modeling.* ASHRAE Transactions 2002. **108**(2): p. 1084-1089.
139. Yang, T., et al. *A new simulation system to predict human-environment thermal interactions in naturally ventilated buildings*. in *Building Simulation*. 2007. Beijing, China.
140. Zhang, Y. and T. Yang. *Simulation of human thermal responses in a confined space*. in *INDOOR AIR*. 2008. Copnhagen, Denmark.
141. Voigt, L.K., *Navier-Stokes simulations of airflow in rooms and around a human body*. 2001, Technical University of Denmark.
142. Chen, Q. and W. Xu, *A zero-equation turbulence model for indoor airflow simulation.* Energy and Buildings, 1998. **28**(2): p. 137-144.
143. Torano, J., R. Rodríguez, and I. Diego, *Computational Fluid Dynamics (CFD) use in the simulation of the death end ventilation in tunnels and galleries.* WIT Transactions on Engineering Sciences, 2006. **52**.
144. Bosbacha, J., et al. *Experimental and numerical simulations of turbulent ventilation in aircraft cabins*. in *The Second ASME-ZSIS International Thermal Science Seminar (ITSS II)*. 2006.
145. Wilcox, D.C., *Reassessment of the scale-determining equation for advanced turbulence models.* AIAA Journal, 1988. **26**: p. 1299-1310.
146. Stamou, A. and I. Katsiris, *Verification of a CFD model for indoor airflow and heat transfer.* Building and Environment, 2006. **41**(9): p. 2171-1181.
147. Marr D. R., S.I.M., Glauser M. N., *Anisotropy in the breathing zone of a thermal manikin.* Experiments in Fluids, 2008. **44**(4): p. 661-673.
148. Musser, A. and K. McGrattan, *Evaluation of a fast Large-Eddy-Simulation model for indoor airflows.* J. Arch. Engrg, 2002. **8**(1): p. 10-18.
149. Homma, H. and M. Yakiama, *Examination of free convection around occupant's body caused by metabolic heat.* ASHRAE Transactions, 1988. **94**(1): p. 104-124.

150. Sevilgen, G. and M. Kilic, *Numerical analysis of airflow, heat transfer, moisture transport and thermal comfort in a room heated by two-panel radiators.* Energy and Buildings, 2011. **43**(1): p. 137-146.
151. Kilic, M. and G. Sevilgen, *Modelling airflow, heat transfer and moisture transport around a standing human body by computationla fluid dynamics.* Int. Journal Heat Mass Transfer, 2008. **33**(2008): p. 1159-1164.
152. Catalina, T., J. Virgone, and F. Kuznik, *Evaluation of thermal comfort using combined CFD and experimentation study in a test room equipped with a cooling ceiling.* Building and Environment, 2009. **44**(8): p. 1740-1750.
153. Kosonen, R., et al., *Impact of heat load location and strength on air flow pattern with a passive chilled beam system* Energy and Buildings, 2010. **42**(1): p. 34-42.
154. Omori, T., et al. *Coupled simulation of convection and radiation on thermal environment around an accurately shaped human body*. in *ROOMVENT*. 2004. Portugal.
155. Martinho, N., A. Lopes, and M. Gameiro da Silva, *Evaluation of errors on the CFD computation of air flow and heat transfer around the human body.* Building and Environment. **58**(0): p. 58-69.
156. Fanger, P.O., *Human requirements in future air conditioned environments* International Journal of Refrigeration, 2001. **24**: p. 148-153.
157. Fountain, M.E., *Laboratory studies of the effect of air movement on thermal comfort: a comparison and discussion of methods.* ASHRAE Transactions, 1991. **97**(1): p. 863-873.
158. Fabbri, K., *Thermal comfort evaluation in kindergarten: PMV and PPD measurement through datalogger and questionnaire.* Building and Environment, 2013. **68**(0): p. 202-214.
159. Hwang, R.L. and C.P. Chen, *Field study on behaviors and adaptation of elderly people and their thermal comfort requirements in residential environments.* Indoor Air, 2010. **20**(3): p. 235-245.
160. Schellen, L., et al., *Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition.* Indoor Air, 2010. **20**(4): p. 273-283.
161. Gao, N.P. and J.L. Niu, *Indoor and Built Environment.* CFD study of thermal environment around a human body: A review, 2005. **14**: p. 5-16.
162. Cengiz, T.G. and F.C. Babalık, *An on-the-road experiment into the thermal comfort of car seats.* Applied Ergonomics, 2007. **38**(3): p. 337-347.
163. Oi, H., et al., *Effects of heated seats in vehicles on thermal comfort during the initial warm-up period.* Applied Ergonomics, 2012. **43**(2): p. 360-367.
164. *Textiles in Automotive Engineering*, ed. W. Fung and M. Hardcastle. 2001: Woodhead Publishing. iii.