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Assessment of thermal comfort in relation to applied low exergy systems

The design of a climate chamber and the use of a thermophysiological model

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ABSTRACT

Applying the low exergy (lowex) concept (i.e. low exergy HVAC systems) in the built environment allows reducing the use of high quality energy. However, application of lowex systems can result in global/local discomfort. Among others, discomfort is caused by combined non-uniform environmental conditions which can occur due to application of these systems. Satisfaction of the occupants with their thermal environment is one of the most important parameters to successfully apply lowex systems; therefore it is important to adequately assess thermal comfort under non-uniform and transient environmental conditions taking into account global and local effects and individual characteristics.

This paper describes the design of a climate chamber set-up which enables studying non-uniform environmental conditions. Furthermore, the use of a thermophysiological model to predict both global and local thermal comfort under non-uniform environmental conditions including individual characteristics will be discussed.

KEYWORDS
Thermal comfort, Physiological responses, Thermophysiological model, Thermo Physiological Test Room, CFD

INTRODUCTION

About one-third of the primary energy used in developed countries is consumed by heating, ventilating and air conditioning in residential, commercial and public buildings. The energy use in buildings represents a major contributor to fossil fuel use and carbon dioxide production. This reveals a high importance to reduce the energy use in buildings. In addition, focus is put on reducing the use of high quality energy sources. Exergy analysis is a relatively new concept in the built environment. Application of this concept allows assessment of energy sources on their quality.

In common building practice the term ‘energy use’ is used; the concept of exergy is rarely known. When trying to improve the energy supply systems of buildings in current practice, energy analyses are being used with the objective to minimize the energy “losses” and use the maximum of sustainable energy as possible. This resulted for example in well insulated dwellings equipped with heat recovery of ventilation air and a condensing boiler.
But energy analysis alone does not give enough insight to further improve our systems. Often energy efficiencies reveal that there are no further improvements possible, since many systems (such as the boiler and the heat exchanger of the given example) already have an energy efficiency of almost 100%. But even though the energy efficiency can be 100% or more, the quality of the energy is always degraded to some extent. So even though there are no energy losses, there are losses in the quality of the energy and therefore there is a need for improvement. Exergy analysis can identify and quantify these losses and is therefore a method to support the development of further improved systems.
According to this, thermal neutral building concepts which use low quality heat and cold sources (i.e. low temperature heating and high temperature cooling) obtain a higher rating than building concepts that use high quality gas or electricity for heating or cooling directly.

Thermal comfort is one of the main requirements for successful application of low-exergy (lowex) HVAC systems. The Annex 37 (Juusela, 2003) study revealed that an optimal energy/exergy use not always results in an increased comfort level. In some cases it proved to be more difficult to achieve thermal comfort, for example to compensate the slow response of floor and/or wall heating and/or cooling by means of ventilation. Application of lowex systems can result in local and/or global discomfort. For example through unintended flows in case of application of a natural ventilation system in combination with low temperature heating. Non-uniform thermal conditions, which may occur due to application of lowex systems, are often responsible for discomfort. More knowledge on the interaction between the system, indoor climate and the human body is indispensable to design optimal systems in the future.
For a comparison between different design variants in the design process of a building it is important to know how the building will perform in real-life. One of the most significant parameters is how satisfied the future occupants will be with the environmental conditions, which is highly dependent of their thermal comfort. Therefore, it is important to predict the thermal comfort which will be achieved by the designed indoor climate conditions.
Boerstra et al. (2000) have shown that low temperature floor heating systems (LTH) in combination with natural ventilation can result in more draught complaints near windows in comparison to a traditional heating system (radiators) or a high temperature floor heating system. Another case wherein problems can occur is in case of a well insulated room in combination with a LTH system. During winter time when the room starts to heat up due to direct solar radiation, often cooling occurs through natural ventilation, by for example opening a window, which can result in draught complaints. In this case cooling through the balanced ventilation system and switching off the heating system is not efficient because of the slow response time of the floor heating system.
However, in some cases the prevalence of local discomfort, for example draught under warm conditions, is not uncomfortable. Nevertheless, it is very important to

assess the thermal comfort adequately in the design phase, because otherwise expected comfortable conditions could turn out to be uncomfortable.
In general, the combined effects of convective flows and radiant asymmetries play an important role in the assessment of thermal comfort and are therefore important to study.

The overall objective of the research project is the development and verification of a tool to assess the thermal comfort of occupants under non-uniform and transient conditions. Current empirical models, for example the PMV/PPD model, are less well applicable for predicting thermal comfort under dynamic and/or non-uniform environmental conditions. For these conditions additional empirical models have been developed (ISO 7730, 2005; ASHRAE, 2004). By using ThermoSEM, a thermophysiological model, it is possible to predict physiological responses under combined asymmetric boundary conditions and in more detail including individual characteristics [van Marken Lichtenbelt, 2004 and 2007]. The coupling of physiological responses (i.e. local skin temperatures and core temperature) and thermal sensation/ thermal comfort, however, remains an important research issue.
To study the influences of non-uniform thermal conditions (combined radiant and convective) on human thermal comfort and physiological responses, a climate chamber set-up will be used.

This paper addresses the design of an experimental facility to support the research into non-uniform environmental conditions. First the design of the measurement facility will be discussed, which is going to be used to study the effects of non-uniform environmental conditions on test-subjects, temperature distribution, air flow and turbulence patterns. Secondly, the use of a thermophysiological model will be explained. At the end of the paper some questions will be addressed regarding the prediction of thermal comfort under non-uniform environmental conditions and future work.

THERMOPHYSIOLOGICAL TEST ROOM

To study the effects of thermal non-uniform environmental conditions a unique climate-chamber set-up facility was designed, the so-called thermophysiological test room (Figure 1).

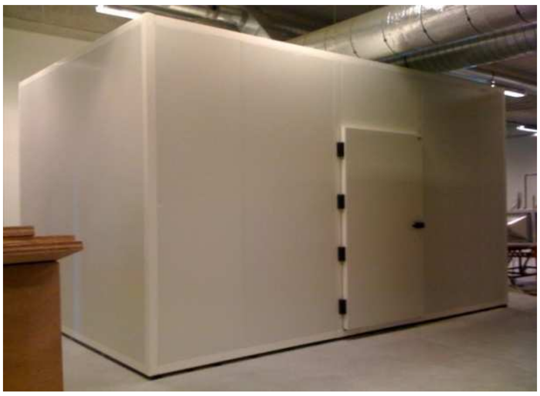

Figure 1: Impression of thermophysiological test room

The test room will be realized at the laboratory of the unit Building Physics and Systems of the department Architecture, Building and Planning at the Eindhoven University of Technology. The dimensions of the room are equal to a standard office room: 3.6x5.4x2.7m^3 (WxLxH). The door (1.22x2.21m^2, WxL) is situated in the

middle of the long edge, in this way the room is symmetrically which is an advantage for numerical modeling the room. Furthermore, this is an advantage in case of using a laser-doppler anemometer to measure the air flow pattern and turbulence in the room; the traverse system of the laser can be placed in front of the door opening, and as result the air flow pattern of the entire room can be mapped.
The test room is constructed of a well insulated cold-storage chamber (wall thickness is 100mm) [Gelderman, 2010]. In this chamber the temperature of each surface (walls, ceiling and floor) can be controlled individually in the range of 11-35°C, in order to study the effects of radiant asymmetries. To realize this, a water-based heating and cooling system will be implemented. For all surfaces a modular system composed of an extruded anodized aluminum profile (Figure 2), developed and produced by Triple Solar, will be installed [Triple Solar, 2010]. The main advantages are, among others: the system can be used for both heating and cooling (hot or cold water can be supplied trough the ducts), the system has a short response time, the system is relatively inexpensive and is suitable for dry-wall construction. The bearing power of the panels is sufficient to install the panels directly on a floor construction.

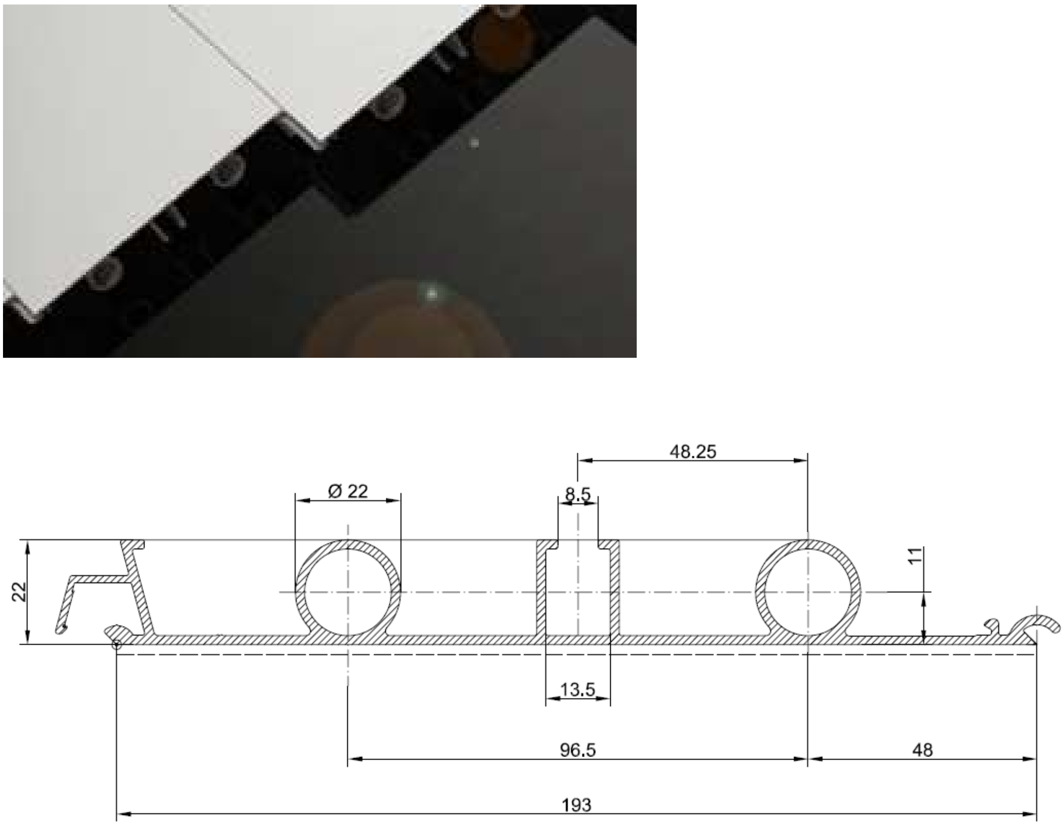

Figure 2: Impression of modular surface system [Triple Solar, 2010]

One total surface, for example a wall, consists of several combined elements (width 600mm). These elements are composed of three profiles (width 193mm), each fitted with one supply and one outlet duct, with a centre-to-centre distance of 96.5mm. The principle of one element is schematically given in Figure 3 (centre). In order to achieve an equal temperature distribution over the panel and to avoid a convective flow between the ducts, the space in between the ducts will be insulated.
The water cooling takes place through the aquifer system which is available on the campus and can be used within the range of 10 – 17°C. The heating of the water occurs through a boiler in combination with a supplementary electrical heater for fine-

tuning the supplied water temperature. The total temperature range of the supplied water is 10 – 35°C.

Before the climate chamber will be equipped, a test wall, composed of one element and three profiles (0.6x2.7m^2, WxL), was realized to examine the temperature deviation across the wall. In Figure 3 (left) an impression of the investigated test wall is given. The results show that the maximum temperature difference occurs from the middle of the left side of the element to the middle of the centre profile, the maximum temperature difference between these two positions was 1.1°C; note that the two warm spots on the infrared thermograph picture (Figure 3, right) represent temperature sensors which were covered by polystyrene foam to isolate them from the environmental temperature. Most probably the difference between the two positions is caused by an obstruction near the coupling (weld) of the main supply duct and the supply duct of the profile. During the realization of the test room it is very important to prevent these obstructions.
The tests were performed at an air temperature of 24°C, RH 40%, the supplied water temperature was 5.5°C at a water flow rate of ±8.5 l/min and the pressure difference between the inlet and the outlet duct was 0.012±0.002 bar.

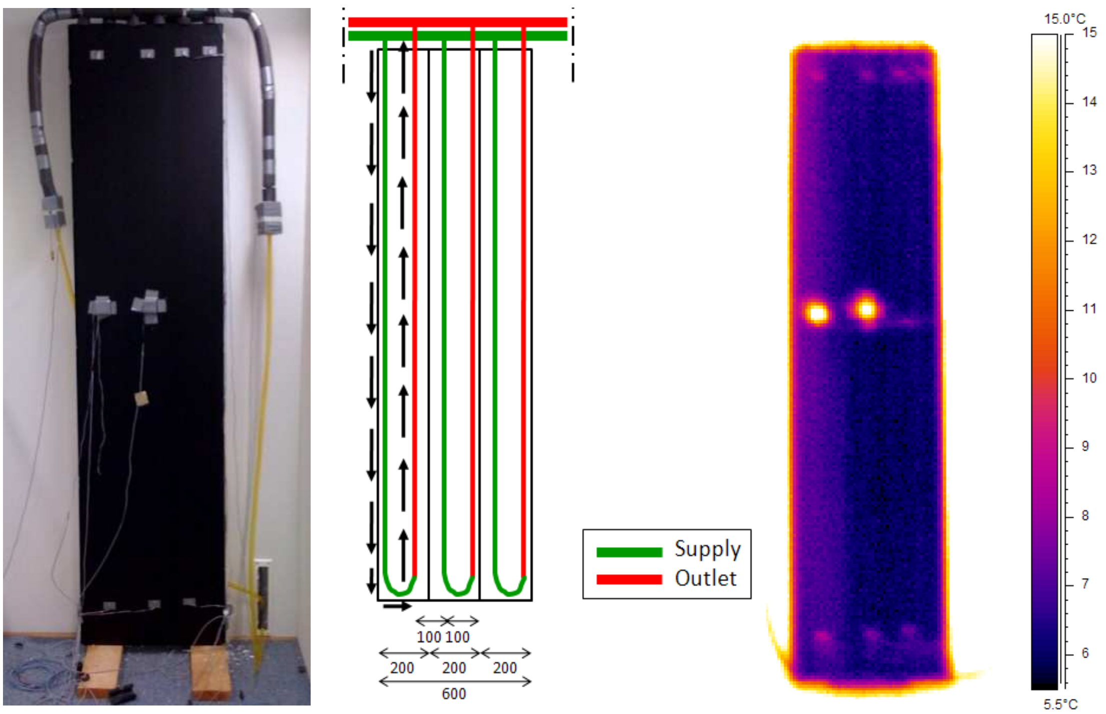

Figure 3: Impression of test wall (left), schematic system principle (centre) and picture of infrared thermography (right)

To study the effects of different ventilation principles and air velocities, two ventilation principles will be applied: mixing ventilation and displacement ventilation with a velocity range of 0.05-0.5 m/s. Plenum boxes will be used to supply the air to the test room, in order to achieve an equally distributed air flow over the short edge of the room. In total four boxes (100x3600x100mm^3 WxLxH) will be installed along the short edges in the top and the bottom of the room; note that they are not installed in the wall, ceiling or floor but that they are ‘free standing’. They can be used both as inlet and exhaust, and the direction of the flow can be sidewards or up-/ downwards

(bottom/top respectively). Additionally, also grilles can be installed in the boxes which enable simulating for example natural ventilation.
The volume flow rate can be adjusted continuously up to 170 l/s (612 m^3/h) and the ratio of outdoor air can be adjusted. Furthermore, the supplied air can be humidified through an ultrasonic humidifier up to10kg/h in order to achieve a relative humidity range from 30-80% over the entire temperature range. The temperature range of the selected air handling unit is 9 - 45°C [Verhulst, 2010].

THERMOPHYSIOLOGICAL MODEL

For the prediction of local skin temperatures and core temperature the dynamic thermophysiological model ThermoSEM will be used (Figure 4) [Van Marken Lichtenbelt, 2004 and 2007]. The dynamic model consists of passive and active components. The passive components model heat transfer phenomena and heat redistribution within the body, including the thermal effects of blood circulation, heat generation, accumulation and conduction in tissue layers. The human body is subdivided into cylinders and spheres representing the body elements (Figure 4, right). Every cylinder and sphere is built of several layers that represent different tissue materials. Furthermore, the cylinders are divided spatially into three sectors (anterior, posterior, and interior) by which asymmetric boundary conditions can be modeled. The model interacts with the environment by convection, radiation, respiration, skin evaporation and water vapor diffusion. The active component represents the actual thermoregulatory system. The body responds to temperatures and changes in temperature by extra heat production produced by shivering, sweating and vasomotion. The main advantage of this model is that asymmetric boundary conditions and individual body characteristics (height, weight and fat percentage) can be taken into account [van Marken Lichtenbelt, 2004 and 2007].

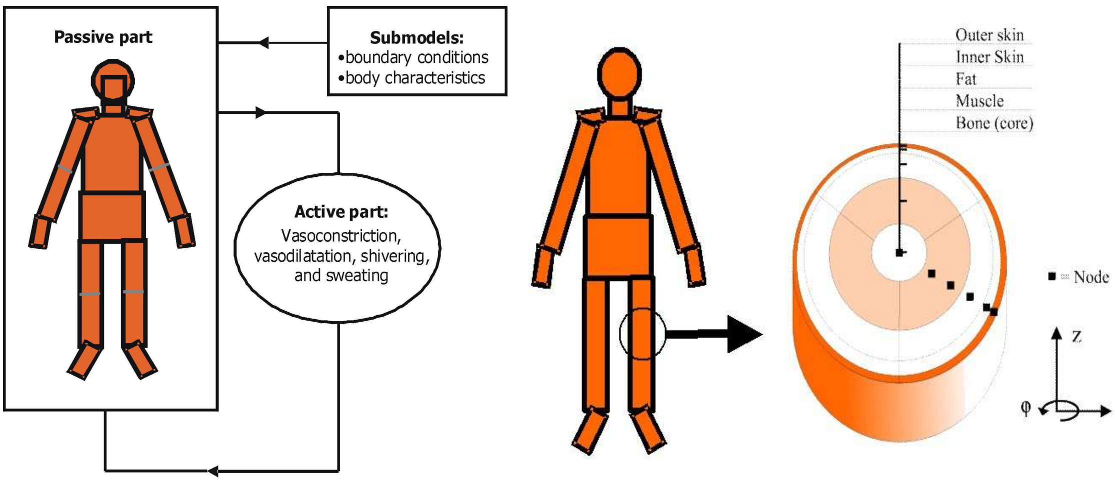

Figure 4: Schematic representation of the thermophysiological model ThermoSEM, left: thermoregulation scheme; right: passive part of the model.

In previous studies by Van Oeffelen et al. (2008) and Schellen et al. (2008) the model is tested for moderate non-uniform and transient environmental conditions through laboratory experiments with test subjects. The results of these studies showed that the model has a large potential for application in the built environment regarding the prediction of thermal comfort under uniform, non-uniform and transient environmental conditions. However, some improvements need to be implemented.

An important aspect which needs to be included is an appropriate definition of the boundary conditions. The model proved to be highly sensitive for air velocity and turbulence intensity (both global and local) [Van Oeffelen et al., 2008; Schellen et al. 2008; Timmers, 2008]. Therefore, Computational Fluid Dynamics (CFD) will be used to determine the boundary conditions near the person and to examine the level of detail which is necessary to model the physiological responses correctly.
On a physiological level improvements are made by, among others, Severens et al. (2010) and Kingma et al. (2010) with respect to a physiologically based active system (e.g. for vasoconstriction). Further developments can be made by adapting the scaling of the metabolic rate and probably a distinction should be made between genders.

PREDICTION OF THERMAL COMFORT

In the building design phase it is useful to predict thermal comfort of the occupants; often the PMV/PPD (Fanger, 1970) model is used for this. However, many researchers showed the limitations of the PMV/PPD model. The optimal thermal condition is not necessarily equal to thermal neutrality since preferences for non-neutral thermal sensation are common. At the same time, low and high PMV values do not always represent discomfort [Croome et al., 1993; Nicol and Humphreys, 2002; van Hoof, 2008].
Moreover, several studies indicate that optimum thermal conditions for the elderly differ from those of young adults (Collins et al., 1981; Natsume et al., 1992; Hashiguchi et al., 2004; van Hoof and Hensen, 2006; DeGroot and Kenny, 2007, Schellen et al., 2009).
Also gender plays a role in perceiving the indoor climate, in general females are more sensitive for cold conditions and deviations from the optimum conditions than males. Furthermore, females frequently prefer higher temperatures [Nakano, 2002; Parsons, 2002; Karjalainen, 2007]. This, however, is contrary to results from studies reported in ASHRAE (2009). These reveal that the thermal conditions preferred by the elderly and females do not differ from those preferred by younger adults and males.
Due to the characteristics of the input variables, the model is not capable to predict thermal comfort under non-uniform environmental parameters (i.e. a vertical air temperature stratification cannot be modeled because air temperature is defined as mean air temperature). To solve this latter problem, standards have been developed regarding local discomfort caused by draught, asymmetrical radiation and/or vertical temperature differences. However, in some cases these standards might be conservative and the prevalence of local discomfort, for example draught under warm conditions, is not uncomfortable. Furthermore, these standards focus at individual non-uniform conditions (e.g. only a vertical temperature gradient), however the combination of non-uniform conditions can result in discomfort while the individual conditions are within the comfort range.
In general, based on the references summarized, the model is suitable in situations where the indoor climate conditions are uniform, close to neutral and where the individual occupants do not differ too much from each other.

However, how should thermal comfort be handled in conditions which are non-uniform (combined effects), non-neutral, or in buildings where the occupants significantly vary in age, gender or body composition?

VALIDATION

For the validation of the methodology and the models five test cases have been defined, which will be studied under laboratory conditions. The non-uniform conditions will be limited to temperature (air, operative and radiant temperature) and air velocity (including turbulence-intesity). The remaining parameters, like relative humidity and illumination, will be kept constant during the measurement session. In this way it is possible to exclude possible side effects of the other parameters. In the design of the cases (full scale experiments) it is important to enable variant studies in terms of numerical simulations.

For the conditions a distinction has been made between the summer and winter situation. In general these can be translated to cooling and heating cases. Furthermore, in case of cooling two ventilation principles will be investigated: mixing and displacement ventilation.

Heating

In case of heating two different realistic cases are defined:

1. Low Temperature Heating (e.g. floor heating) in combination with a natural ventilation system.
2. Low Temperature Heating in combination with mixing ventilation and a large glass pane which provides cold downdraught.

Cooling

For cooling three cases are defined:

3. High temperature cooling in terms of increased air velocity and turbulence-intensity through mixing ventilation.
4. High temperature cooling in terms of increased air velocity and turbulence-intensity through displacement ventilation.
5. High temperature cooling through (a) radiant panel(s) in combination with displacement/ mixing ventilation.

For the indoor air temperature during the cooling season two situations can be distinguished: a typical summer situation and a worst case scenario, the outdoor air temperature in these situations is respectively 25ºC and 32ºC [ISSO 33, 1996; KNMI, 2008].

Case description

In the design of the cases, the conditions will be defined which need to occur near the subject. After completion of the climate chamber the requirements will be defined which need to be fulfilled by the HVAC system. With respect to the standards, the borders for thermal comfort are limited to a PPD of 10%. To study the effects of different situations and outside the comfort zone these limits will be extended to ± 25%. In the design of the cases several assumptions have been made:

Activity level: 1.2 met (70 W/m^2); represents light office work

Clothing level: 0.7 clo for the cooling cases; represents typical summer clothing (RGD, 1999) and 1.0 clo for the heating cases: represents a typical business suite (ISO 7730, 2005).

Relative humidity: 40%

Illuminance: 500 lux

Control situation
To be able to distinguish between effects of time and experimental conditions, a control situation will be included. During this control situation the conditions are adopted to a thermal sensation, according to PMV, equal to neutral (PMV=0). Furthermore, this is a uniform and steady-state situation. Given the assumptions the following conditions are required:

For comparison of heating cases:
Air/ mean radiant temperature: 22.0°C
Mean air velocity: 0.1m/s
Turbulence intensity: <40%

For comparison of cooling cases:
Air/ mean radiant temperature: 24.5°C
Mean air velocity: 0.2m/s
Turbulence intensity: <40%

CONCLUDING REMARKS

Following the above, the objective of the future work is to develop a method to assess thermal comfort (global and local) under transient and non-uniform conditions. And, most important, emphasis is on a more individual assessment since the characteristics (e.g. gender, age, body composition etc.) of people deviate from the more general assumptions that form the basis for PMV and hence influence the thermal comfort perception. Regression based models, as for example the PMV/ PPD model, are not capable to account for these effects. Conversely, physiological based models, like ThermoSEM, are suitable to cope for individual characteristics. However, the question remains how to couple physiological responses to a thermal comfort assessment on a more physiological basis (i.e. less empirical derived regression formulas), in comparison to current existing models (e.g. the DTS model of Fiala (2003), Zhang (2010a,b,c)), and that accounts for both radiant and convective effects. To answer this question five test cases have been defined to validate the methodology.

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