Impact of different radiation types on thermal comfort modelling

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ABSTRACT

Different radiation types are present in everyday environments, and have a major impact on human thermal perception and ultimately on comfort. In a study with participants, we found that humans perceive long-wave radiation (e.g. a warm wall) differently from short-wave radiation (e.g. sunlight). Straightforward comfort models do not directly account for this difference. In more complex thermal simulations, it is possible to consider such different radiation types. To evaluate this modelling approach, the experimental conditions are recreated and assessed in simulations. In analogy to the study with participants, in the simulation a human manikin with a comfort model predicts human thermal perception. Then, participants' responses are contrasted to the comfort model predictions. Comparison of simulated and participant-reported results allow identification of deviations between the model and the actual perception, and thereby suggestions for further enhancements of simulations are derived.

KEYWORDS

Human Comfort Model, Radiation, Simulation, Thermal Comfort, Thermal Management

Introduction

In environments as vehicles or buildings, the human thermal perception is a key aspect of overall comfort. Thermal perception is correlated to air temperature, air movement and other factors [Gen19]. Here, a major aspect of thermal perception is the radiative heat exchange between a human body and its environment. Typically, different kinds of radiation – for example sunlight, radiative heaters and enclosing surfaces (walls) – can be of significance.

Conventional comfort models, for instance the *Predicted Mean Vote* (PMV) model developed by Fanger [Fan72], allow for a straightforward assessment of thermal environments. To account for radiation, such conventional models summarize different kinds of radiation to a single *mean radiant temperature*. However, this conventional approach drastically simplifies the radiation's characteristics [Hir21].

In recent decades, the understanding of human thermal perception advanced significantly. Several investigations focused on the *transient* thermal evaluation in *non-uniform environments* [Che12]. In contrast to straightforward, conventional comfort models, advanced comfort simulations typically include three components [Gua03]:

- Firstly, a physical model simulates the heat transfer (e.g. convection, radiation) between the human body and its environment. By modelling heat transfer in an exact way, such an approach might better account for the actual radiative heat exchange than the *mean radiant temperature*-approach of conventional models.

- Secondly, a physiological model represents the active and passive thermal behavior of the human body. For instance, the model by Fiala et. al. simulates the physiological behavior of a human body, considering the passive thermal system (e.g. temperatures at various body parts and layers) as well as active thermoregulation (e.g. shivering) [Fia99, Fia01].
- Thirdly, the psychological perception of thermal sensation and thermal comfort is predicted. [Gua03]. Such an assessment of human thermal sensation and thermal comfort at various body segments (e.g. thermal sensation at hands, face, etc.) might be carried out with the *Berkeley Comfort Model* by Zhang et. al. [Zha10a, Zha10b, Zha10c].

Considerations on modelling radiation's effect on thermal perception require a basic understanding of radiation. Different kinds of radiation are distinguished by their respective wavelength λ [Iso07]. There is typically an exchange of long-wave infrared radiation (IR-C with $\lambda \geq 3$ µm) between a human body and the enclosing surfaces. Furthermore, sunlight or certain heaters provide additional short-wave irradiation (IR-A radiation with λ 0.78 µm to 1.4 µm, as well as visible light). [Hir21]

The radiation properties of human skin are highly depending on the radiation wavelength. In several measurements, it was confirmed that human skin absorbs more than 90 % of incident long-wave radiation [Pia10, Ter86, San09]. In contrast, 30 to 70 % of incident short-wave radiation are reflected and not absorbed by human skin [Pia10, Jaq55, Ter86]. Concerning clothing, a very similar trend was observed for a cotton fabric specimen [Car97]. Notably, only absorbed shares of incident radiation contribute to the human heat balance, and conclusively to the thermal perception.

Radiation of different wavelength differs also by its penetration depth into human skin. Long-wave radiation penetrates only the outermost skin layer, while short-waves' penetration depth partially exceeds skin depth [Pia10, Ter86, Hir21]. As human thermal sensation is based on thermoreceptors in the upper skin region [Str11], the penetration depth of radiation supposedly has an effect on the thermoreceptors' response and ultimately on human thermal perception [Hir21].

The authors previously investigated the effects of different radiation types on human thermal perception [Hir21] on the basis of a study with participants [Gen19]. To integrate observations of this study into comfort modelling, it is intended to recreate and investigate the experimental conditions in thermal simulations.

Materials and Methods

In the first part of this section, the experimental setup is briefly recapitulated. For a detailed description, the reader is referred to the original publications [Gen19, Hir21] on the experiment. The second part comprehensively outlines the simulation approach.

As Gentner et. al [Gen19] describe, participants in a study were exposed to short-wave infrared A radiation and to long-wave infrared C radiation and rated their thermal sensation and their thermal comfort. On this behalf, the thermo-acoustic chamber at the Institute for Automotive Engineering (RWTH Aachen University) was equipped with a setup of radiant heaters. Short-wave radiation lamps (peak wavelength 1.2 µm) as well as long-wave radiative heaters (peak wavelength ~ 8 µm) were installed at different locations. The chamber provided defined thermal conditions, and the study was carried out at approximate air temperatures of 16°C and 22°C. Participants were positioned on a movable automotive seat. Two irradiance levels (100 W/m² and 200 W/m²), each at two air temperatures (16°C and 22°C), were investigated and compared to baselines (no additional irradiance). Participants were exposed to every condition for about 10 minutes, while they repeatedly reported their thermal sensation and their thermal comfort. Thermal sensation was rated on a scale from cold (-3) over cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2) to hot (+3). Thermal comfort was assessed on a scale from very uncomfortable (1) to very comfortable (10). [Gen19] For demonstrative purposes, the result section presents arithmetic means of the participant-

reported thermal sensation. More details, including statistical parameters and boxplots, are provided in the publication on the experiment [Hir21].

In addition to the participant study, extensive measurements were conducted in the thermo-acoustic chamber to fully capture the thermal environment within every experimental condition. Local irradiance was measured at a reference plane, located at the participant positions. Furthermore, the air temperature, air velocity, air humidity, and globe temperature within every experimental condition was measured. These measurements provide sufficient input to Fanger's PMV model. Thereby it is possible to predict thermal sensation within every experimental condition in a very straightforward way. [Hir21]

For the purpose of the present investigation, the experimental conditions at an air temperature of 16°C are addressed. The analysis will thereby focus on five conditions, which are presented in Table 1.

Table 1: Experimental conditions (adapted from [Hir21])

Spectrum	**Short-wave (IR-A)**		**Long-wave (IR-C)**		**-**
Irradiance	**200 W/m²**	**100 W/m²**	**200 W/m²**	**100 W/m²**	**0 W/m²**
Reference Number	C3	C4	C5	C6	C7 (Baseline)

Based on the study with participants, the experimental conditions were recreated and assessed in simulations. Firstly, a three-dimensional geometric model of the thermo-acoustic chamber was set up. Geometric models of the radiation sources and of the participant seat were added to the chamber model. Derived from anthropometric data, the geometry of a sitting woman (50 % percentile, female European) was defined. All geometry was imported into the thermal simulation software *TAItherm* (Version 2021.1.1).

To allow for an accurate simulation of the radiative heat transfer, a detailed model of the radiation sources is eminent. In the experiment, long-wave radiation sources (modified Digel CL-900 heaters) consisted of large heated surfaces. The temperature distribution on these surfaces is known from thermographic measurements. This temperature distribution was accordingly implemented into the simulation model. On the other hand, the employed short-wave radiators (Optron IRE 380L) behave similar to certain incandescent lamps. Data on the intensity distribution of these radiation lamps was provided by the manufacturer. This distribution data was implemented into the *TAItherm* simulation model. In analogy to the experiments, where irradiance was measured at reference planes, comparable simulations were carried out. The irradiance on the simulated reference plane was contrasted to irradiance measurements in the actual experimental setup. This step ensured that the simulation model correctly predicted the rather complex radiative heat transfer situation.

Within the simulation software, the model was further prepared for simulations. Thermal properties (e.g. material characteristics) as well as boundary conditions (air velocity, air temperature) obtained from measurements were implemented into the simulation model. The manikin geometry was placed on the participant seat, and clothing was added in alignment with the actual participant's clothing. With this configuration, the software is able to compute the heat transfer (radiation, convection and conduction) between the manikin and the thermal environment including radiation sources. The wavelength-depended properties of human skin and clothing were implemented into the simulation model by separately accounting for short- and long-wave radiation. For long-wave radiation, an absorptivity of 0.98 (skin) and 0.95 (clothing) was specified. In contrast, the short-wave absorptivity of skin was adjusted to 0.65, and of clothing to 0.60. These values are also default values in the used software [Tai21].

Beside heat exchange with the environment, also thermal properties within the human body were of interest. The *Human Modeling Extension* allows to simulate the physiological behaviour of a human body within TAItherm. The model considers 19 body segments (e.g. head, hands, …) and their typical layered structure (bones, muscles, tissue). The blood flow, as well as active and passive thermoregulation is considered as well. Thereby, metrics as skin and core temperatures, and various heat rates can be predicted. [Tai21] We assigned the manikin geometry to the Human Modelling Extension, and thereby obtained a complete model of the thermal properties within the manikin.

On the basis of physiological metrics of the manikin, also human thermal sensation can be predicted. A model developed at UC Berkeley correlates skin temperatures and other physiological data to predict thermal sensation and comfort [Zha10a, Zha10b, Zha10c]. This *Berkeley Comfort Model* is used for the simulations, to predict thermal sensation within the experimental conditions.

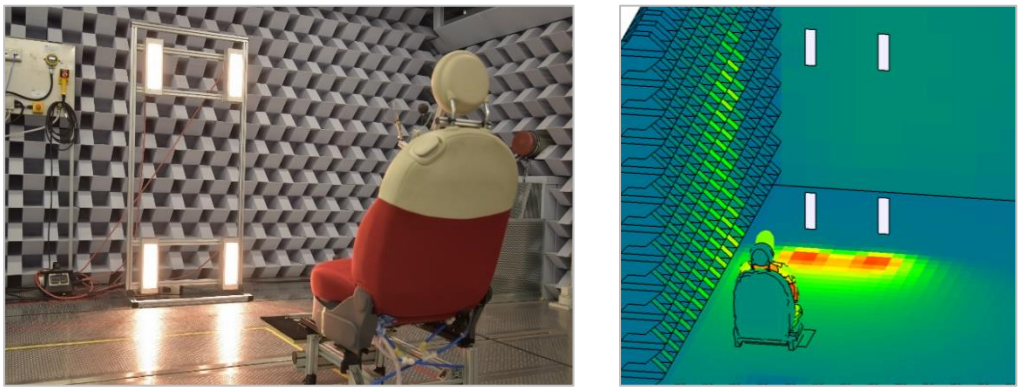

Figure 1: Experimental setup of condition C4 with short-wave heaters and the participant seat. On the left, a photo depicts the actual setup [Gen19]. On the right, the respective simulation is presented.

Summarizing, the heat exchange between manikin and environment is simulated in a first step. A software extension allows to simultaneously simulate the physiological behaviour of the manikin itself. On that basis, a further model predicts human thermal sensation. With these three components, the aforementioned typical composition of advanced comfort simulations is complete. Figure 1 illustrates this complete simulation setup for one experimental condition. All simulations are transient, and the simulated timing matches the actual durations of the experiment.

To compare experimental results to model predictions, overall thermal sensations are contrasted for the five experimental conditions. Participant-reported sensations are thereby compared to simulation output. All comparisons are carried out for the thermal sensation at five minutes of exposure to the specific experimental condition. Two different predicted thermal sensations are evaluated: Firstly, we considered PMV predictions obtained with the straightforward Fanger model. Secondly, rather complex predictions were derived from 3D-simulations and on the basis of the Berkeley comfort model. Regarding thermal sensation, two different scales are commonly used and are depicted in Figure 2. Participants reported their thermal sensation on a scale that is identical to the PMV model scale (Figure 2, a). On the other hand, the Berkeley comfort model uses a similar scale, but with extensions for very extreme conditions (Figure 2, b). It should be noted, that a direct comparison of values at different scales might be misleading. The interpretation of thermal sensation scales is a current focus of research (for instance [Schw17]). For a first interpretation however, the deviation between the two scales is neglected in our analysis.

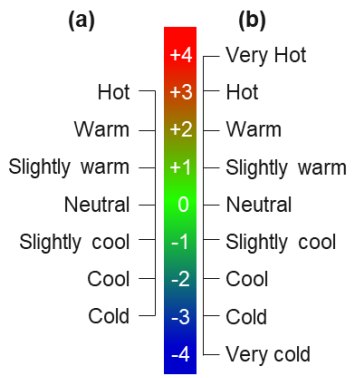

Figure 2: Thermal sensation scales. Participants reported their perception on scale (a), which is also used by the PMV model. The Berkeley comfort model uses a slightly different scale (b).

Results and Analysis

When comparing irradiation at the reference planes, the simulated irradiation distribution closely matched the measurement results. Exemplarily, results from measurement and simulation of condition C4 (short-wave radiation at 100 W/m²) are depicted in Figure 3. A similar accordance between simulation and measurement was observed in the other conditions as well.

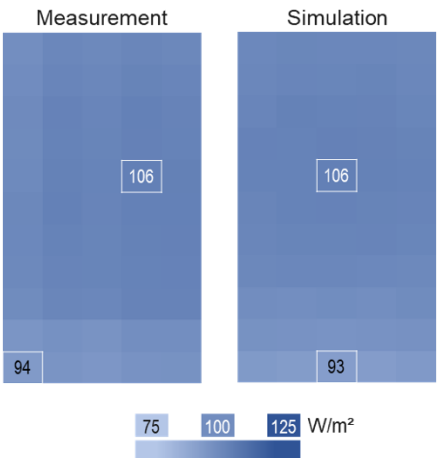

Figure 3: Irradiance distribution for experimental condition C4, from measurement [Hir21] and from simulation. Minimum and maximum values are indicated.

For the five investigated conditions, the respective thermal sensations are comprehensively illustrated in Figure 4. The dots (●) represent mean values of the participant's perception after five minutes of exposure to a condition. From the participants' responses, it was confirmed that any irradiation induced a warmer thermal sensation [Hir21]. A further outcome of the original study is linked to the radiation wavelength. The perception of condition C4 and C6 was almost identical, while condition C3 and C5 were perceived differently. Notably, this difference is statistical significant [Hir21], so in this rather moderate condition, the both radiation types are perceived differently. As potential cause for this observation, the wavelength-dependent skin reflectance and skin penetration were discussed [Hir21].

As can be seen from Figure 4, predictions on the basis of Fanger's PMV model (▲) are in some cases very close to the actual perceptions. Especially for the baseline C7, where the radiation sources were deactivated, the model predictions are rather accurate. While additional irradiation leads to higher PMV values, this straightforward model underestimated the effect magnitude. When pairwisely comparing situations distinguished only by the radiation type (e.g. C4 – C6), the PMV values are

very close to each other. Apparently, the PMV model does not directly account for the diverging human perception of short-wave and long-wave radiation [Hir21]. In principle, it would be feasible to integrate such effects into the calculation method of the mean radiant temperature.

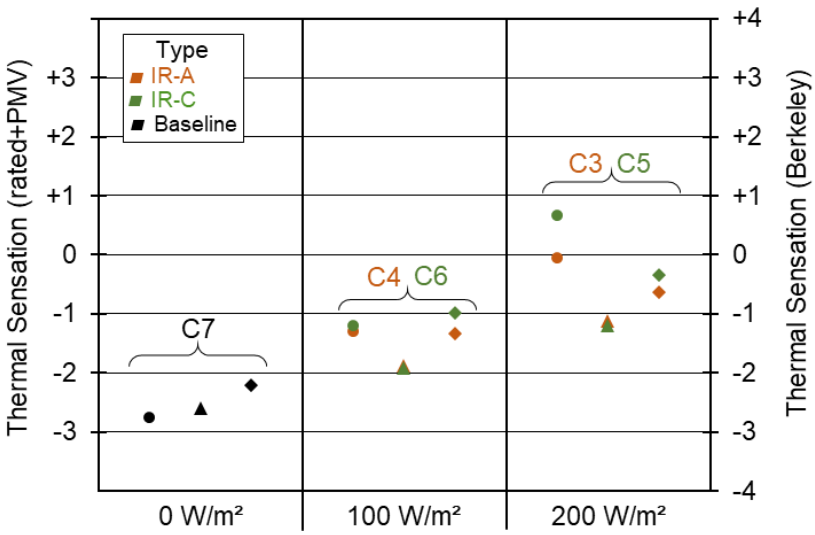

Figure 4: Thermal sensation within the five experimental conditions. Participant-reported mean thermal sensations are plotted as dots ●, predictions from Fanger's PMV model as triangles ▲, and predictions from a simulation with the Berkeley Comfort Model as diamonds ◆.
Participant responses and PMV values from [Hir21].

Figure 4 furthermore presents predictions based on elaborate 3D-simulations and the Berkeley Comfort Model (plotted as diamonds ◆). The predicted thermal sensation of the baseline situation C7 is near the actual perception. With increased irradiation, the Berkeley model predicts a warmer thermal sensation. However, apparently for the conditions with an irradiation of 200 W/m² (C3, C5), the magnitude of the simulated increase appears to be smaller than the actual effect.

Furthermore, the two different kinds of radiation show a different effect in the Berkeley comfort simulations. In analogy to the actual responses, long-wave radiation (conditions C5, C6) effected a warmer thermal sensation than the respective short-wave counterpart (conditions C3, C4). Thereby the 3D simulations appropriately considered the diverging human perception of different kinds of radiation.

The general agreement between actual and simulated thermal sensation might require further fine-tuning. Firstly, transient effects might play a role. The exposure time of five minutes might not be sufficient for obtaining a steady-state response. While transient simulations (Berkeley model) show that a nearly constant level of thermal sensation is reached after 3 to 5 minutes, the actual perception of the participants might not have settled at a constant level after 5 minutes. Furthermore, as mentioned in Figure 2, the different scaling might lead to a misconception when directly comparing simulated and actual thermal sensation. Some deviation might also result from an approximate model of convective heat transfer (based on [Fia99]), which was implemented in the simulations.

Concluding, the experimental situations with two kinds of radiation sources were accurately recreated in 3D simulations. The actual human perception, as well as elaborate simulations with the Berkeley comfort model, did confirm that short-wave and long-wave radiation diverge in their effect on human thermal sensation. The simulated prediction of thermal sensation might be further improved by considering also transient effects on thermal sensation, by enhanced modelling of convective heat transfer, and by taking different scales of thermal sensation into account.

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