Thermal model of an unconditioned, heated and ventilated seat to predict human thermo-physiological response and local thermal sensation.

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ABSTRACT

Local conditioning technologies such as seat heating and ventilation have been shown to improve thermal sensation and comfort, with reduced energy demands compared to conventional methods of heating and cooling. Investigation of the conditioning effectivity is demanding in terms of time and resources, as it is mainly based on human subject or thermal manikin testing. One promising method of rapidly investigating a wide range of environmental conditions is thermo-physiological and thermal sensation modelling. Until now, however, one of the most important properties of the seat, its thermal diffusivity, has been neglected in such simulations. We therefore developed a methodology that involves one-dimensional, thermal model of the seat coupled with a multi-node thermo-physiological model and thermal sensation models. The seat thermal model showed realistic predictions of heat flux in the seat contact interface for control (no conditioning), heated, and ventilated seats. The modelling results were validated against our original experimental data and data from the literature for unconditioned. The root mean square deviation (RMSD) and bias of the local skin temperatures were within the standard deviation of the measurement, typically within 1°C. In the case of the predicted local thermal sensations, we found the RMSD and bias to be below two standard deviations of the human votes in two out of three of the thermal sensation models examined. Less accurate predictions were found for the seat contact, where further model refinement is needed.

KEYWORDS:

Heating; Ventilation; Seat; Human; Thermo-physiology; Fiala model; Thermal sensation

1 Introduction

Ensuring thermal comfort for occupants of indoor environments using heating ventilation and air-conditioning (HVAC) systems is typically related to substantial energy consumption and the production of environmental pollutants [1]. This topic is particularly critical in the development of electric mobility, where energy used for microclimate management is supplied at the expense of the vehicle's driving range. Here, the thermal management of a passenger compartment is challenging for the following reasons:

- The transient and asymmetric thermal environment;
- The broad range of radiant, air, and contact temperatures (between approximately -20° and 60°C);
- Substantial solar gains through windows and the greenhouse effect;
- Low thermal insulation of the cabin and the consequent high impact of ambient conditions on the cabin microclimate;
- High ventilation rates and local air velocities of up to 2 m/s [2];
- Contact with surrounding surfaces such as seats (18% of total body area [3]), and the application of local conditioning technologies such as heated and ventilated seats.

The conditions described above may cause thermal discomfort and negatively influence the cognitive abilities of a driver [4], [5]. According to Alahmer et al. [6], the most critical period of exposure is a transient and non-uniform phase with rapid cooling of a *hot-soaked cabin*. Furthermore, approximately 85% of car trips made within Europe are shorter than 18 km and no longer than 30 minutes [7], and highly transient situations involving intensive cooling or heating are most likely to occur. New solutions with localised delivery of heat or cold are therefore being investigated in order to address these situations. Research done on heated and ventilated (cooled) seats indicates their potential in rapidly enhancing thermal comfort while requiring low energy consumption [8]–[14]. The lower energy demands are possible through targeted delivery of the heating or cooling power exactly where needed, rather than treating the entire air volume around the occupant. This broadens the boundaries of comfortable ambient temperatures and may bring energy savings of up to 40% on the conventional HVAC systems [12], [13]. Such studies are normally carried out with human participants or thermal manikins, making investigation of the effectivity of these local conditioning solutions time- and resource-consuming. Thus, tools for rapid design and optimisation of personalised thermal comfort systems are needed.

A promising solution to this demand is the modelling of the thermo-physiological response and local human thermal sensation in a dynamically changing thermal environment. The review paper by Katic et al. [15] lists and discusses differences among the contemporary thermo-physiological models in detail. For instance, the most frequently cited models are the 65MN model by

Tanabe et al. [16], the Berkeley model [17], [18], and several Fiala-based models – ThermoSEM by Kingma [19], FPCm by ErgonSim [20], [21], Fiala-FE by Theseus FE [22], FMTK by Pokorný et al. [23], and the Human Thermal Module in TAItherm by Thermoanalytics Inc. [24]. These models are all segmented into at least ten body parts, in order to cover the main body segmentation of the upper and lower limbs, torso and head, thus allowing the investigation of local thermal responses and the consequent modelling of local thermal sensation. However, for reliable applications of the models, their validation is crucial. By far the most extensively and successfully validated model worldwide with over 100 published validation cases is the FPCm5.3 (Fiala Physiological and Comfort model – FPCm5.3, ErgonSim, Germany [20], [21]).

Although numerous thermal sensation models are available [29], the number of well-documented and validated local thermal sensation models is limited [30]. One of the models developed specifically for automotive applications is the MTV model by Nilsson [31], [32], which later became part of the ISO 14505 standard [33]. This model correlates the mean thermal vote with an equivalent temperature (t_{eq}), defined as the temperature of a uniform enclosure in which a person would lose heat at the same rate as in the actual environment [34]. The advantage of this method in practical applications is that the calculation of t_{eq} can be based on heat flux data from a human body, a thermal manikin, or an equivalent temperature sensor [35]. Another automotive-oriented approach is the thermal sensation and comfort (TSZ) model proposed by Zhang et al. [36], [37]. The major focus of the development of this model was the local heterogeneous cooling conditions, with rather high gradients typical of car cabins. Here, the thermal sensation is predicted on the basis of multiple regressions of skin and core temperatures with human thermal sensation votes. Finally, the TSV model proposed by Jin et al. [38] represents an approach predicting local and global thermal sensation on the basis of skin temperatures only. The model was developed based on a pool of Chinese subjects by applying local ventilation to various body parts, thus creating asymmetric thermal conditions.

Transparently validated and well-documented methodology to model the effects of conditioned seats on human thermo-physiology is scarcely available in the literature. An example of a one-dimensional dynamic thermal model to predict skin temperatures, heat fluxes, and thermal sensation in the seat-occupant interface with heating and ventilation was proposed by Karimi et al. [39], [40]. While the paper described a broad physical background of the heat and mass transfer, the particular material properties and validation data to achieve presented results were absent. The model validation for winter and summer driving conditions showed the estimated average error below 21% in skin temperatures. The study, however, demonstrated advantages of one-dimensional modeling (1D) such as a low number of input parameters, low computational power demands, and potentially realistic outputs in a defined range of conditions. In this respect, the 1D approach can be a valuable tool to run parametric studies where numerous inputs can be changed to screen for potential technical solutions.

A more advanced approach based on three-dimensional (3D) transient numerical model can be used for detailed inspection of a specific design. Shin et al. [41] proposed a 3D model to resolve the seat-occupant contact of a ventilated seat. However, the model validation with human data revealed large discrepancies of up to 12°C for skin and seat surface temperatures, which significantly limits the model for thermal sensation modelling applications. The reason for this was that the 3D model required precise boundary conditions addressing conduction, convection, evaporation, and radiation in three-dimensional space, which are far more difficult to obtain as well as lead to higher uncertainty and computing demands and times.

The human subject studies on thermo-physiological responses to seats with conditioning technologies seldom report the full set of information that could be used for validation of modelling [8], [12], [42]–[45]. This information includes the time-dependent skin and seat surface temperatures, detailed information about clothing, local thermal sensation, and heat exchange at the contact with body parts. The last parameter is the most critical, and is usually unknown or is presented as the heating power delivered to the seat rather than the heat exchanged with a human body [8], [42]. Since the seat has a substantial heat capacity and a heterogeneous structure, an unknown proportion of the delivered heat dissipates into the seat. Additionally, in the first moments of contact with the seat, the temperature gradient between the seat surface and skin can be high, and may be accompanied by rapid cooling or heating of the skin and intense discomfort. This important heat exchange during the first contact is dependent on the thermal diffusivity of the seat, which is calculated from the thermal conductivity, the density, and the heat capacity of the seat. However, the seat boundary condition is usually addressed in the form of thermal and evaporative resistances [33], [34], [46], [47], which are dependent only on the thermal conductivity of the seat, and are therefore clearly insufficient.

The aim of this study is to present a complex methodology for reliable and efficient simulations of the effects of unconditioned, heated, and ventilated seats on human thermo-physiology and thermal sensation in steady-state and transient conditions. The desired applicability of this approach should cover typical indoor environment cabins of any kind (vehicles, machinery, trains, airplanes etc.) and buildings. To do so, we proposed and transparently validated a physical one-dimensional model of transient local heat transfer between a seat and its occupant. Most importantly, a complete information package was presented, which enables instant model implementation. Secondly, to demonstrate the model's applicability in real-life situations, the coupling methodology of the physical model and the model of human thermoregulation FPCm5.3 was devised to provide the local boundary conditions at the regions of the body that are affected by the seat. The thermo-physiological model outputs were supplied to three local thermal sensation models (MTV, TSZ, and TSV) to predict local thermal sensation. Finally, we presented original experiments with human participants to validate the developed simulation approach using comparison of heat fluxes,

local skin and seat temperatures, and local thermal sensation votes in detail. The validation was carried out under both cool and hot environmental conditions, including conditioning technologies such as seat heating to a constant temperature, constant heat flux and seat ventilation.

2 Methods

2.1 Development of the seat heat transfer model

The heat transfer between a human body and a seat can be described by fundamental heat transfer principles in three-dimensional space. A thermal system consisting of a human body, clothing, seat and the ambient environment can be solved using energy conservation in control volumes for each node described by Equation (1):

$$Q_{stor,m} = Q_{gen,m} + Q_{cond,m} + Q_{conv,m} + Q_{evap,m} + Q_{rad,m} \quad (1)$$

where m denotes an arbitrary node, $Q_{stor,m}$ (W) is the stored heat within the volume, $Q_{gen,m}$ (W) the generated heat within the volume, $Q_{cond,i}$ (W) the heat transfer by conduction, $Q_{conv,i}$ (W) the heat transfer by convection, $Q_{evap,i}$ (W) the heat transfer by evaporation, and $Q_{rad,i}$ (W) the heat transfer by radiation.

Equation (1) can be simplified to a one-dimensional problem if we assume that the dominant heat flux is in a direction perpendicular to the plane of the seat. Compared to three-dimensional models, the simplifications are expected to be counterbalanced by substantially lower number of input parameters and lower computing power demands. Another simplification, in our model, was related to the evaporation, which was replaced by a heat sink or a prescribed temperature profile at the seat surface. While the main cause of cooling in the ventilated seat is sweat evaporation, in practical applications, it is not feasible to determine the parameters necessary for psychrometric calculations precisely. This is especially related to the measurement of the airflow, air humidity, and air temperature in the contact, which are burden with a substantial uncertainty. The proposed approach is expected to yield an equivalent heat flux density, as if the evaporation was assumed.

With respect to the previous assumptions, for any internal node m between two solid materials A and B , $Q_{conv,m}$, $Q_{evap,m}$, and $Q_{rad,m}$ from Equation (1) can be neglected due to the high evaporative resistance of the seat and the negligible convection and radiation in the highly compressed layers of clothing and seat. The solution to Equation (1) under these conditions can be obtained using the finite-difference method; this yields an explicit finite-difference equation that considers half of the thickness of materials A and B for a node (2):

$$k_A \frac{T_{m-1}^p - T_m^p}{\Delta x_A} + k_B \frac{T_{m+1}^p - T_m^p}{\Delta x_B} + \dot{q}_{gen,A} \frac{\Delta x_A}{2} + \dot{q}_{gen,B} \frac{\Delta x_B}{2} = \left(\rho_A c_A \frac{\Delta x_A}{2} + \rho_B c_B \frac{\Delta x_B}{2} \right) \frac{T_m^{p+1} - T_m^p}{\Delta t} \quad (2)$$

where the subscripts A, B denote the materials; the superscript p is used to denote the time dependence of the temperature T , and the new time derivative is associated with $p+1$; k (W/mK) is the heat conductivity; Δx is the discretised thickness of the control volume; q_{gen} (W/m³) is the heat generation per unit volume; ρ (kg/m³) is the material density; and c (W/mK) is the specific heat of the material.

For nodes that lie at the border with the ambient air, such as at the back of the seat, we neglected evaporation due to the high evaporative resistance of the seat. The problematic of solar irradiation goes into great level of details. The seat in the cabin is partially shaded from the sun, presumably meaning that the temperature difference between the seat and the adjacent surfaces in the cabin is low. This will obviously depend on many factors (e.g. geography, time of the year and day). For the purpose of validation presented in this study, the focus was on well-controlled setup and practical aspect of measurement equipment. Therefore, we neglected the contribution of the radiative heat exchange with the cockpit on the thermal balance of the seat. Thus, the explicit solution for heat exchange is described by Equation (3):

$$h(T_{\infty}^p - T_m^p) + k \frac{T_{m-1}^p - T_m^p}{\Delta x} + \dot{q}_{gen} \frac{\Delta x}{2} = \rho \frac{\Delta x}{2} c \frac{T_m^{p+1} - T_m^p}{\Delta t} \quad (3)$$

where h is a convective heat transfer coefficient (m²K/W) and T_{∞}^p is the ambient air temperature.

Equations (2) and (3) were applied to solve for the heat transfer at the seat cushion and backrest, respectively, using a discretised time step of 0.05 sec. As a representative human body part in the contact with backrest, posterior thorax and abdomen were selected. Similarly, posterior thighs and pelvis were chosen to represent body parts in the contact with seat cushion. An overview of the nodes and constants used in this study is presented in Table 1. The amount of nodes can be changed with respect to desired application and differences in the seat construction. The properties of human tissues were adopted from Fiala et al. [48] and the properties of the seat from Kolich et al. [49]. The initial temperatures of the human tissues were taken from the Fiala Physiological and Comfort model (FPCm5.3, Ergonsim, Germany) [20], [21] at the moment of just before sitting down on the seat. The initial temperature distribution of the seat was assumed to be homogeneous and equal to the pre-conditioning air temperature in the chamber.

Table 1. Overview of the calculation nodes and their properties

BACKREST / SEAT CUSHION	NODES OF HUMAN BODY [48]					NODES OF ADJACENT LAYERS			
	LUNGS	BONE	MUSCLE	FAT	SKIN	CLOTHING [50] (cotton)	SEAT COVER [50] (leather/polyester)	HEAT SOURCE/SINK	PU CUSH- ION
Δx (m)	0.077 / -	0.012 / 0.022	0.034 / 0.026	0.003 / 0.005	0.002	< 0.001*	0.002‡	0.001	0.050‡
k (W/mK)	0.280	0.750	0.420	0.160	0.470	0.040	0.140 / 0.050	-	0.048

c_p (J/kgK)	3718	1700	3768	2300	3680	976	1500 / 976	-	1331
ρ (kg/m ³)	550	1357	1085	850	1085	365	365 / 365	-	62
q_{gen} (W/ m ³)	600	-	684	58	368	-	-	†	-

*assuming uniform clothing coverage; † value depending on the heating/cooling strategy, positive heat flux for heating;‡may vary for specific seats.

2.2 Validation strategy and integration of the seat heat transfer model into FPCm5.3

The aim of the validation is to show a generic tool for simulation of the effects of seats with and without conditioning for any desired purpose in buildings or passenger transportation cabins. To understand the effects of the seat, we designed an experiment where one parameter was changed at a time – the seat conditioning strategy (Table 2, Case 18°C). Next, an additional parameter was changed – the ambient environment (Table 2, Case 41°C). The complete workflow of the validation strategy is depicted in Figure 1, and consists of three steps. The experimental data extracted from human trials was necessary to demonstrate accuracy of the approach in each of the three steps and to demonstrate its superiority to methods applied until now.

In the first step, the heat flux density at the seat-human interface, calculated by the heat transfer model, was validated against our own measurements for cases at 18°C and 41°C, as other datasets were not available. Secondly, the time-dependent heat flux calculated by the seat heat transfer model was supplied to the FPCm5.3 to predict the human thermal responses in the contact areas. Here, validation was focused on the predicted local skin temperatures, with and without the seat contact. Thirdly, the FPCm5.3 was coupled with three local thermal sensation models to predict the thermal sensation at nine body sites. The pool of examined cases was extended by data from literature to demonstrate the effects of unconditioned (control) seats, two modes of seat heating, and ventilated seats under a range of environmental conditions from 5°C to 41°C (details in Table 2).

Table 2. Complete overview of the cases used for validation of the methodology

	Case	Preconditioning of subjects 60 minutes t_{amb} (°C)/ t_{rad} (°C)/ Rh (%)/ w_{air} (m/s)	Chamber exp. t_{amb} (°C)/ Rh (%)/ w_{air} (m/s)	Seat conditioning	Males Un- cond./ Cond.	Females Un- cond./ Cond.	BMI M/ F (kg.m ⁻²)	Available data for validation
This study	18 °C	22.5 / 21 / 40 / 0.05	18 / 40 / 0.15	Uncond./ Heated const. temp.	8 / 14	2 / 6	25 / 23	8 skin temp**; backrest & seat cushion surf. temp and heat flux; TS votes
	41 °C	25 / 21 / 30 / 0.05	41-25* / 30 / 0.15	Uncond. / Ventilated	7 / 7	2 / 2	26 / 28	8 skin temp; backrest & seat surf. temp and heat flux; TS votes
Oi et. al [8]	5 °C	22 / 22 / 50 / 0.05	5 / 50 / 0.15	Uncond./ Heated const. HF	8 / 8	-	18.6 / -	Skin temp at backrest & seat cush- ion
	10 °C	22 / 22 / 50 / 0.05	10 / 50 / 0.15	Uncond./ Heated const. HF	8 / 8	-	18.6 / -	Skin temp at backrest & seat cush- ion
	15 °C	22 / 22 / 50 / 0.05	15 / 50 / 0.15	Uncond./ Heated const. HF	8 / 8	-	18.6 / -	Skin temp at backrest & seat cush- ion
	20 °C	22 / 22 / 50 / 0.05	20 / 50 / 0.15	Uncond./ Heated const. HF	8 / 8	-	18.6 / -	Skin temp at backrest & seat cush- ion

t_{amb} – ambient air temperature; t_{rad} – mean radiant temperature; Rh – relative air humidity; w_{air} – mean air speed; BMI – body mass index;

*25°C reached after 20 min of exposure; **skin temperatures unavailable for unconditioned case

Figure 1. Overview of the methodology comprising the seat heat transfer model, FPCm model, and three thermal sensation models (references: MTV [31], TSZ [36], [37], and TSV [38]). The highlighted parts were developed in this study.

2.2.1 Human subjects and clothing

The first dataset was acquired at the Brno University of Technology (BUT) based on our own measurements in a climatic chamber (Figure 2). All participants were informed about the experiment and gave written consent for their voluntary participation in the study. The research was approved by the Ethical Committee at the Department of Biomedical Engineering, BUT. To ensure similar initial conditions, the participants were instructed not to eat, smoke, or exercise for at least two hours before the experiment as well as to wear their own indoor clothing for the relevant season (summer or winter). In the case of the cool condition, this was typically a cotton T-shirt or a short-sleeved shirt, light pullover, trousers, underwear, socks, and a pair of shoes (thermal insulation of 1.1 clo). In the hot condition, the clothing consisted of a T-shirt or a short-sleeved shirt, light trousers, underwear, socks, and a pair of light shoes (thermal insulation of 0.6 clo).

Figure 2 Experimental setup in the climatic chamber at BUT. Left – preconditioning of participants.. Right – experimental assembly inside a climatic chamber (left seat – control/heated seat with textile upholstery; right seat – ventilated seat with leather upholstery). The seats were placed in the geometrical centre of the chamber.

The second set of experimental data was collected from study by Oi et al. [8], who examined a pool of subjects consisting of eight male university students wearing an undershirt, long-sleeved shirt, jacket, underpants, trousers, socks and shoes, with an overall thermal insulation of 0.9 clo. The following mean characteristics were presented, with standard deviation indicated in brackets: age 22.5 years (1.1 years); height 175.0 cm (1.3 cm); weight 57.2 kg (3.2 kg).

2.2.2 Seat instrumentation and skin temperature measurements

In our experiments, serial-production front seats from a middle-range passenger car were used with following construction layers: a polyester cover, resistance heating wire, polyurethane foam cushioning, and metal inner chassis (Figure2, for more details on seat see [3] and chamber [51]). Exposures with the ventilated seat were equipped with a similar seat having perforated leather upholstery. In order to ensure identical initial conditions before the human exposures, the seats were conditioned in the climatic chamber for at least two hours. The seats were instrumented with two heat flux blankets (Mahöle Messtechnik, Germany), one of which was placed at the backrest and one at the seat cushion. The blanket had a resolution of 16×16 points distributed in a square grid of 48×48 cm. Each point measured heat flux indirectly using two thermistors (relative accuracy $< 0.3^\circ\text{C}$; response time < 1.5 s) separated by a solid with a known thermal resistance. This allowed us to determine both the heat fluxes and seat temperatures simultaneously. Additionally, from the practical point of view, it is of major interest to place temperature probes within the seat rather onto participants' skin.

The participant's local skin temperature was measured at eight body sites according to the ISO 9886:2004 standard [52]: forehead, right scapula, left upper chest, right upper arm, left forearm, left hand, right anterior thigh, and left calf. The eight skin temperatures were averaged using the weighting coefficients from the standard [52] to calculate the mean skin temperature. The 8-point was adopted to verify the overall prediction capabilities of the models besides the contact parts – however,

this was not a main focus of the study. The local skin temperatures were measured with oscillator-based digital thermometers (iButton, Maxim Integrated, USA, accuracy ± 0.5 °C). The sensors were attached to the participants' skin using medical tape (Hypafix 16002, BSN Medical GmbH, Germany) made from nonwoven polyester with acrylic adhesive, cut to 35 mm $\times$ 50 mm patches [53].

Oi et al. [8] used automotive front seats for the experimental exposures with unconditioned (control) and heated seats. The seat construction comprised a leather upper cover, silicone rubber heating pads, polyurethane foam cushioning, and metal inner chassis. The heating was provided for both the seat cushion and the backrest with an equal heating power density of 268 W/m² [8]. The skin temperature was measured at 16 body sides using epoxy-coated thermistor probes (Nikkiso-Therm, Musashino, Japan) attached to the skin surface by surgical tape.

2.2.3 Human exposures with unconditioned (control) seat

The cool exposure at 18°C was carried out at BUT. The participants were pre-conditioned in thermo-neutral conditions for one hour while sitting. The chamber session was designed as a benchmark case for steady indoor environments with ambient temperature below thermo-neutrality and duration of 30 minutes. This measurement provided crucial data on heat flux density in the seat contact, development of local skin temperatures as well as subjective local thermal sensation votes.

The hot exposure at 41°C was also carried out at BUT. This case was design to mimic hot summer conditions, and the rapid cooling of an overheated cabin by a conventional air-conditioning system. Here, the chamber exposure consisted of 10 minutes of walking at a pace of 4 km/h to initiate sweating, after which the participants were seated on an seat for 30 minutes. At this point, chamber cooling was initiated (at a cooling rate of -0.8 °C/min) for the first 20 minutes of the exposure to reach the pre-conditioning conditions ($t_{\text{air}} = 25^\circ\text{C}$, Rh 30%, $w = 0.15$ m.s⁻¹). A detailed summary of the exposures is presented in Table 2.

The last dataset for unconditioned seats was adopted from Oi et al. [8] (Table 2), including data about global thermal sensation and comfort in a climatic chamber at constant environmental conditions at 5°C, 10°C, 15°C and 20°C. Local skin temperature, for buttocks and back, were obtained based on a personal communication with the main author of 24th October 2017. The experimental procedure started with one hour of subject's preconditioning under thermo-neutral conditions (Table 2). After this period, the participants were exposed to the automotive seat in the climate chamber for 20 minutes.

2.2.4 Human exposures with seat heated to constant heat flux and constant temperature

For the case at 18°C, the experimental procedure started in the same way as for the unconditioned seat, followed by 30 min of chamber exposure with heated seats to constant temperature of 38°C. The seat heating was initiated immediately after the participants took their seats in the climate chamber. To maintain the seat surface temperature, a feedback sensor (DS18S20,

Dallas Semiconductor, USA, accuracy $\pm 0.5^{\circ}\text{C}$) was sewn onto the seat cushion in the contact area of the buttocks and was used. The standard deviations of the seat surface temperatures at the seat cushion and the backrest were 0.8°C and 1.8°C , respectively. The participants could turn off the heating at any time; however, none of them used this option. The data from the constant heat flux heating mode were adopted from Oi et al. [8]. The experimental protocol and the equipment were identical to the unconditioned seat cases at 5°C , 10°C , 15°C and 20°C (Section 2.2.3).

2.2.5 Human exposures with ventilated seat

The experimental protocol for the exposure using the ventilated seat is identical as the procedure from the unconditioned seat at 41°C (Section 2.2.3). The seat was set to its maximal ventilation rate, extracting approximately $18\text{ m}^3/\text{h}$ of air from the seat and back cushion when occupied. However, this value depends on the proportions of the occupant's body and one has to be cautious in its interpretation. The resulting airflow through the seat ventilation system also contains a part of the air that passes through the unoccupied parts of the seat. Therefore, it should not be used as a boundary condition for the ventilated seat modelling.

2.2.6 Thermo-physiological modelling

We used the Fiala-based thermo-physiological model (FPCm5.3, Ergosim, Germany) [21] to reproduce the human trials listed in Table 2 and described in Sections 2.2.3–2.2.5. The model was selected based on its extensive validation and documentation in the range from 5 to 50°C and exercise levels from 0.8 met to 10 met and most importantly, the validation covered also near-to-comfort conditions [25]–[28], where it *is without peer*. The model yields predicted thermal responses for an average person (height 1.69 m , weight 71.4 kg and skin surface 1.83 m^2) for 13 individual body parts, which are further divided into spatial sectors.

The presented thermo-physiological modelling approach takes into consideration major factors influencing thermal sensation and heat exchange: environmental factors, clothing, and metabolic heat production. These parameters were also controlled in our original study. The local clothing thermal properties were adopted from our previous research [54], in which we examined comparable garments to the ones in this study using state-of-the-art methods. The local clothing area factor f_{cl} was obtained from four repetitions of three-dimensional body scanning. The local intrinsic clothing insulation and evaporative resistance were determined by a Newton type thermal manikin (Thermetrics, Seattle, USA) based on three repetitions. The exact values were adopted from Figures 2 and 3 – Case 1 in Fojtlin et al. [54]. To achieve the most realistic results, measurements were carried out in the sitting position, since body posture has a strong influence on all three local thermal clothing properties [54]. The metabolic production of 1.3 met was selected from a database presented by Ainsworth et al. [55] as an average from reading, typing, and driving.

The missing link in the modelling, the parametric physical model of the seat (Section 2.1), was used to calculate time-dependent heat exchange between the seat and the occupant. The material properties were changed according to the seat construction used (Table 1). The heat flux density boundary condition at the seat interface was used at the posterior thighs, posterior hip, posterior abdomen and posterior thorax. These parts realistically represent the human contact surface area with a seat in FPCm5.3 [3].

Additionally, to illustrate the difference between our new approach to seat simulation and previous methods, such as treating the seat as an additional resistance, we carried out two simulations based on the 5°C case and reported the temperatures at the seat contact, with and without use of the seat heat transfer model. To achieve this, the unconditioned seat in the 5°C case was approximated as additional thermal and evaporative resistances of $0.7 \text{ m}^2\text{K}\cdot\text{W}^{-1}$ and $120 \text{ m}^2\text{Pa}\cdot\text{W}^{-1}$, respectively [46]. The clothing area factor f_{cl} of the seat, defined as the ratio of the seat surface area to the body surface area, was estimated as 2.0 units. In the same case with heating, a heat flux density of 268 W/m^2 was applied directly to the skin in the FPCm5.3. This simulation was carried out to demonstrate the differences between the complex approach represented by the seat heat transfer model with heat generation and the assumption of adiabatic behaviour of the seat cushioning. In this way, a constant heat flux is transferred to the human body, disregarding the thermal effects of the seat.

2.3 Coupling with the thermal sensation models

The outputs from the seat heat transfer model and FPCm5.3 indicate the thermal state of a human body. Despite the complex mechanisms responsible for human thermal perception, this information can be translated into an average predicted thermal sensation vote using a thermal sensation model [56]. Such an approach is applicable to a given set of conditions defined by metabolic activity, clothing and a range of environmental conditions. In asymmetric thermal environments such as cabins, it is meaningful to use local thermal sensation predictions rather than global ones, due to the difficulties in identifying the prevailing thermal sensation when contradictory sensations are perceived [57].

The amount of well-documented and validated thermal sensation models is low and thus, more models were selected that seemed to be most suitable for this application with regards to body resolution and sufficient equation documentation. As shown in the diagram in Figure 1, the outputs from the thermo-physiological modelling were processed using three local thermal sensation models for a seated position, to investigate their performance. Firstly, the model by Nilsson [31] was used; this is based on heat transfer (MTV) as part of the ISO 14505 [33], and was implemented due to its standardisation and practical applicability. The model uses a seven-point Bedford scale that combines thermal sensation votes with thermal comfort (much too cold, too cold, cold but comfortable, neutral, hot but comfortable, too hot, much too hot). The model is applicable over a

range of ambient temperatures from 19°C to 29°C. Next, we applied the model by Zhang (TSZ) [36], [37] dedicated to vehicular cabins, which predicts local thermal sensation using an extended nine-point ISO scale with two additional extreme thermal sensation votes (very cold, very hot). The model was developed for a range of air temperatures between 20°C and 33°C. Finally, we implemented the model by Jin et al. (TSV) [38], which uses local skin temperatures as inputs and yields a local thermal sensation on the seven-point ISO scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot) [58]. Since the division of a human body into segments is not identical in each model, in some cases two body parts (e.g. upper and lower arms) were merged into a single segment and the area-weighted average was used to obtain the resulting thermal sensation.

2.3.1 Verification of skin temperatures and thermal sensation predictions

Before using the outputs from the FPCm5.3 to model thermal sensation, the predicted local skin temperatures were verified against human data for the 18°C and 41°C cases, since the local skin temperatures for other cases, as reported by Oi et al., were not available. Similarly, in order to verify the predicted local thermal sensation votes, local human thermal sensation votes were collected from the participants for the 18°C and 41°C cases at major body sites (back/backrest, buttocks/ seat cushion, face, chest, arms, hands, anterior thighs, lower legs, and feet). The votes were recorded at the end of the pre-conditioning phase and every three minutes during the actual chamber exposure, using the seven-point ISO scale [58] (*-3 Cold, -2 Cool, -1 Slightly cool, 0 Neutral, 1 Slightly warm, 2 Warm, 3 Hot*).

2.3.2 Statistical analysis of thermo-physiological and thermal sensation responses

One-minute averages and their standard deviation were calculated for each parameter measured. The accuracy of all parameters predicted by the seat heat transfer model, FPCm5.3, and the thermal sensation models (heat flux, seat temperatures, skin temperatures, and thermal sensation votes) was assessed by means of root mean square deviation (RMSD), which measures the average difference between the measured and predicted values. The second descriptor examined here, bias, is expected to be close to zero for unbiased simulations, and a negative value indicates an over-prediction of the examined value. Predictions were assumed to have high precision if the RMSD and bias were within the standard deviation of the measurement.

3 Results

3.1 Validation of the seat heat transfer model and its integration into FPCm5.3

The validation of the seat heat transfer model was carried out on the basis of heat fluxes measured separately at the surface of the backrest (corresponding body parts: posterior thorax and abdomen) and seat cushion (corresponding body parts: posterior thighs and pelvis). These measurements were available only for cases at 18°C and 41°C. In the next step, the predicted heat fluxes from the seat heat transfer model were used as a seat boundary condition in FPCm5.3. Here, cases from literature at 5°C, 10°C, 15°C, and 20°C were available as well as our own measurement at 18°C and 41°C.

Exposure to the unconditioned seat and a summary of the RMSD and bias of the simulations with the FPCm5.3 model for all control seat cases is depicted in Figure 3, where the development of the contact skin temperatures at 5°C, seat surface temperatures at 18°C and 41°C, and heat fluxes at 5°C, 18°C and 41°C over 20 minutes are shown. A positive heat flux represents heat loss from the skin. To quantify the error induced by addressing the seat by thermal and evaporative resistances, neglecting the seat thermal mass, we carried out such case at 5°C (Figure 3, dotted line) and compared it to the proposed methodology (Figure 3, dashed line). The mean of experimental data was depicted as circles and the error bars represent standard deviation.

Figure 3 Unconditioned (control) seats: skin (5°C case) and seat surface temperatures (18°C and 41°C cases), and heat fluxes (5°C, 18°C and 41°C cases) at the seat-body contact area as well as RMSD, bias, and standard deviation (SD, also shown as error bars in the graphs) of the data. Seating began at time 0 min. Case 5°C * depicts results of simulations where the seat was represented by thermal and evaporative insulation.

Figure 4 depicts the development of the contact skin temperatures (5°C case) and seat surface temperatures (18°C case), and heat fluxes (18°C and 41°C cases) for 20 minutes of exposure to the heated seat, together with a summary of the RMSD and bias of the simulations from the thermo-physiological model from all heated seat cases. In addition to the measured data (circles), the FPCm5.3 simulation results (continuous line), corresponding calculations using the seat heat transfer model

(dashed lines), and dotted lines illustrate the development of skin temperature when the heat flux density of 268 W/m² (reported by Oi et al. [9]) is prescribed in the FPCm5.3 simulations directly at the skin, neglecting the presence of the seat.

Figure 4 Heated seats: skin temperatures (5°C case), seat surface temperatures (18°C case), and heat fluxes (5°C and 18°C cases) at the seat-body contact area and the RMSD, bias and standard deviation (SD, also shown as error bars in the graphs) of the data. Seating started at time 0 min. The 5°C * case depicts results of simulations where the heated seat was represented by a constant heat flux applied to the skin.

Figure 5 shows the seat surface temperatures and heat fluxes for 20 minutes of exposure to the ventilated seat (41°C case) together with an overview of the RMSD and bias of the FPCm5.3 simulations. The measured data are depicted via circles, FPCm5.3 simulation results via continuous lines, and calculations using the seat heat transfer model by dashed lines.

Figure 5 Ventilated seats: seat surface temperatures and heat fluxes in contact with the ventilated seat and the RMSD and bias for temperatures and heat fluxes from the FPCm simulations. The error bars depict standard deviation. Seating began at time 0 min.

Table 3 presents the RMSD, bias and mean standard deviation of the predicted data in comparison with the experimental data for skin temperatures in regions without seat-body contact, which were available only for the 18°C and 41°C cases. The RMSD and bias were calculated throughout the whole duration of exposure in the climate chamber and compared to the average SD of the measurements.

Table 3 RMSD and bias of eight local skin temperatures at regions without seat-body contact and mean skin temperatures in the 18°C and 41°C cases. The bold values indicate a low accuracy of prediction (greater than two standard deviations of the corresponding value).

Case	Skin temperatures (°C)	UNCONDITIONED EXPOSURE			EXPOSURE WITH COND.		
		RMSD	Bias	AVG SD	RMSD	Bias	AVG SD
18°C	Forehead	1.9	-1.9	1.5	-	-	-
	Chest	0.1	-0.1	1.6	-	-	-
	Upper arm	0.4	0.4	1.2	-	-	-
	Lower arm	0.6	0.5	1.4	-	-	-
	Hand	0.7	-0.7	1.8	-	-	-
	Anterior thigh	0.2	-0.2	0.9	-	-	-
	Calf	2.4	-2.4	0.4	-	-	-
	Mean skin temp. (mTsk)	0.5	-0.4	0.4	-	-	-
41°C	Forehead	0.4	0	0.6	0.5	-0.2	0.7
	Chest	0.8	-0.8	1.3	0.7	-0.7	1.3
	Upper arm	0.7	0.6	0.5	0.5	0.4	0.6

Lower arm	0.9	0.8	0.6	1.3	1.2	0.8
Hand	0.5	-0.3	0.5	0.5	0.0	0.5
Anterior thigh	0.3	0.1	0.8	0.4	0.2	0.8
Calf	1.4	-1.4	0.7	0.9	-0.9	1
Mean skin temp. (mTsk)	0.5	-0.4	0.4	0.4	-0.3	0.5

3.2 Coupling with the thermal sensation models

Figure 6 depicts local thermal sensations at four body sites: two body parts in contact with the seat (backrest and seat cushion), one uncovered body part (hand) and one body part covered with clothing (chest), as predicted by the three thermal sensation models (details in Section 2.2.5) for both the 18°C and 41°C cases. In the case of heating at constant heat flux, the local thermal sensation votes were not available. The RMSD, bias, and mean standard deviation for all body parts are presented in Table 4. It should be noted that each of the thermal sensation models uses a distinct scale. However, comparison of thermal sensation scales is a problematic that was broadly discussed by Koelblen et al. [56] and Schweiker et al. [59]. Since there is no conclusion, this question requires further investigation and we left the scales in their original form as they were developed.

Figure 6 Thermal sensation votes at the seat cushion (posterior thighs and pelvis), backrest (posterior thorax and abdomen), hand and chest, as predicted by three thermal sensation models for unconditioned (at 18°C and 41°C), ventilated (at 41°C) and heated seats at a constant temperature (obtained for the 18°C case). The error bars indicate the standard deviation. Please note that MTV uses a seven-point Bedford scale, TSZ uses a nine-point ISO 10551 scale, and TSV uses a seven-point ISO 10551 scale.

Table 4 RMSD, bias and mean standard deviation of the experimental data for local thermal sensation at 18°C and 41°C. The values in brackets indicate the RMSD and bias within the first six minutes of exposure. The bold values indicate low accuracy of the predictions, greater than two standard deviations of the corresponding value.

	Thermal sens. (-)	MTV RMSD	MTV BIAS	TSZ RMSD	TSZ BIAS	TSV RMSD	TSV BIAS	AVG SD
Unconditioned 18°C	Backrest	0.8 (1.0)	-0.2 (0.8)	1.2 (0.2)	-0.9 (-0.2)	1.0 (0.6)	-0.9 (-0.6)	0.5
	Seat cushion	1.2 (2.2)	0.4 (2.2)	1.3 (0.6)	-1.1 (-0.6)	-	-	0.5
	Face	0.5	-0.5	0.7	0.7	0.2	0.1	0.5
	Chest	0.5	-0.4	0.3	0.1	0.4	0.3	0.4
	Arms average	0.1	0.0	1.0	1.0	1.7	1.7	0.5
	Hands	0.7	0.7	1.1	1.1	1.5	1.4	0.4
	Anterior thighs	0.7	-0.6	0.5	-0.4	-	-	0.5
	Lower legs	0.3	-0.3	0.1	0.1	1.3	1.3	0.5
	Feet	0.3	0.3	0.5	0.5	0.7	0.7	0.9
Unconditioned 41°C	Backrest	0.4 (0.5)	0.1 (0.0)	1.0 (1.1)	-0.2 (0.9)	0.7 (1.3)	0.0 (1.3)	0.6
	Seat cushion	0.8 (0.3)	-0.5 (-0.2)	0.7 (0.2)	-0.4 (0.2)	-	-	0.7
	Face	0.7	-0.7	0.4	0.3	1.2	1.1	0.7
	Chest	0.2	-0.2	1.2	1.1	1.4	1.4	0.6
	Arms average	0.4	-0.2	0.7	-0.7	1.6	1.5	0.6
	Hands	0.3	0.3	1.0	-0.9	1.2	1.2	0.6
	Anterior thighs	0.4	0.0	0.4	0.3	-	-	0.6
	Lower legs	0.5	-0.4	0.9	0.8	1.3	1.2	0.7
	Feet	0.3	-0.1	0.3	0.3	1.8	1.7	0.6
Heated 18°C	Backrest	1.7 (2.3)	-0.6 (1.1)	2.0 (0.9)	-1.4 (0.5)	1.1 (1.0)	-0.5 (0.4)	0.5
	Seat cushion	1.5 (1.9)	-0.4 (1.0)	2.0 (1.3)	-1.5 (-0.5)	-	-	0.5
	Face	0.3	-0.2	0.9	0.8	0.3	0.3	0.5
	Chest	0.3	0.3	0.8	0.7	0.9	0.9	0.4
	Arms average	0.1	0.0	0.9	0.9	1.7	1.7	0.5
	Hands	1.0	1.0	1.3	1.3	1.7	1.7	0.4
	Anterior thighs	0.5	0.4	0.5	0.4	-	-	0.5
	Lower legs	0.2	-0.1	0.2	0.2	1.5	1.5	0.5
	Feet	0.4	0.4	0.6	0.5	0.9	0.9	0.9
Ventilated 41°C	Backrest	1.4 (1.5)	-1.0 (-0.9)	2.0 (1.3)	-1.5 (-0.1)	1.6 (1.3)	-1.2 (0.1)	0.9
	Seat cushion	0.9 (0.8)	-0.7 (-0.7)	1.3 (0.3)	-1.1 (-0.2)	-	-	0.7
	Face	0.9	-0.8	0.4	0.2	1.8	-1.8	0.6
	Chest	0.5	-0.4	0.9	0.9	1.2	1.2	0.6
	Arms average	0.5	-0.4	0.6	-0.5	1.5	1.4	0.7
	Hands	0.4	0.4	1.0	-0.8	1.3	1.3	0.7
	Anterior thighs	0.5	-0.3	0.2	0.0	-	-	0.5
	Lower legs	0.8	-0.7	0.8	0.5	0.9	0.9	0.6
	Feet	0.4	-0.4	0.2	0.0	1.5	1.4	0.6

4 Discussion

4.1 The seat heat transfer model and its integration into FPCm5.3

4.1.1 Validation of the seat heat transfer model

The seat heat transfer model was developed to calculate the time-dependent thermal interaction between the seat and its occupant. The human tissue layers represented an average unisex human, based on the FPCm5.3 [21], and the seat was composed of individual clothing and seat construction layers (Table 1). In total, four validation cases were available, including unconditioned, heated, and ventilated seats. In all cases, the predicted heat fluxes exhibited a good fit to the experimental data, and the RMSD and the bias were generally within two standard deviations of the measurement (Figures 3-5). The only exception was found in the case of the unconditioned seat at 18°C, where the RMSD was 9.2 W/m² (SD 2.9 W/m²) at the backrest and 8.1 W/m² (SD 1.6 W/m²) at the seat cushion. This discrepancy was still less than 10% of the peak heat flux density after sitting, and we considered that the heat flux predictions were sufficiently accurate to be coupled with the FPCm5.3 to obtain the local thermo-physiological responses for the whole body.

In comparison to the study by Shin et al. [41], we achieved realistic heat flux predictions (Figure 5) in the complex heat and mass transfer situation in the ventilated seat despite using a one-dimensional model. Thus, from the point of heat transfer, it seems to be possible to use the proposed simplifications to obtain realistic results while avoiding the elaborative determination of the parameters necessary for the calculation of the evaporative cooling. Our solution predicted a heat flux equivalent to the measurement using only the input parameter of the seat surface temperature. Finally, in our model, seat cooling can be represented using a heat sink if the cooling power is known.

4.1.2 Exposures with unconditioned seat

The predicted skin and seat surface temperatures from the FPCm5.3 simulations coupled with the seat heat transfer model were in good agreement with measurements (Figure 3). The RMSD and bias of the predicted seat contact temperatures were mostly lower than 1°C, and at the same time were lower than the standard deviation of the measurement. The only outlier was found in the 18°C case, where the RMSD and bias of the seat cushion temperature reached 1.5°C and 1.3°C, respectively. Here, the predictions were inaccurate only between the first and fourth minutes (Figure 3), and the rest of the exposure simulation agreed with the experiment. The SD was also typically higher in the first six minutes after sitting down than during the rest of the exposure, and mostly overlapped with the predictions. The reason for the inaccuracy is a highly transient period, where also the calculated heat flux had an error of between 3% and 10% (Figure 3). In comparison to a similar study using one-dimensional model by Karimi et al. [40], we achieved consistent results throughout the temperature range from 5°C to 41°C.

The simulation carried out using the thermal and evaporative insulation as a seat boundary condition did not capture the substantial drop of 3°C in the contact skin temperature (Figure 3 – FPCm simul. insulation) as opposed to the seat heat transfer model approach coupled with FPCm5.3 (Figure 3 – FPCm simul. HT model). This confirms our hypothesis that neglecting the thermal diffusivity and the low initial seat temperature of 5°C leads to a critical error. Furthermore, the actual skin temperature recovery to the initial state took more than 20 minutes. According to Koelblen et al. [60] and Veselá et al. [61], a skin temperature deviation of 1°C can be related to a considerable change in local thermal sensation from approximately 0.5 to 1.5 units, depending on the thermal sensation model and its scale, meaning that the neglected temperature drop would naturally lead to a faulty thermal sensation prediction. This shows the importance of addressing the thermal mass of contact surfaces in thermo-physiological modelling, especially when examining environments that are exposed to conditions far from thermo-neutrality, such as vehicular cabins and a range of occupational settings.

4.1.3 Exposures with seat heating to constant heat flux or constant temperature

In the 18°C case, where the seat is heated to a constant temperature, very good agreement was found between the measured and simulated contact temperatures, as indicated by the RMSD and bias being below the experimental standard deviation (Figure 4). In the 5°C, 10°C, 15°C and 20°C cases with constant heat flux control, the predicted contact temperatures were on average up to 2.3°C higher than the experimental values in the coldest case. The simulations, however, agreed with the measurements until approximately the fifth minute of the exposure, and were over-predicted towards the end of the exposure, when the heating started to have a major impact on the development of temperature (Figure 4). We can also observe a decreasing trend in the RMSD and bias with an increase in the temperature of the exposure (see the table in Figure 4). Since the seat heat transfer model neglects the lateral heat losses from the seat, which may be influential especially at lower temperatures, this is a likely reason for the discrepancy. Secondly, the seat heat transfer model is based on constant thermal properties of human tissues, whereas the FPCm5.3 contains an active thermoregulation system that influences the thermal properties of tissue depending on the thermal state of the body. A combination of both of these factors might explain the higher predicted skin temperature that is apparent in Figure 4 at 5°C.

In Figure 4 (FPCm simul. const. heat flux) it is demonstrated that the error of assuming an adiabatic boundary condition at the seat cushioning, thus setting the seat heating power purely to the skin of the seat's occupant. This approach causes not only an unacceptable overestimation of the contact skin temperature by more than 8°C, but also an immediate steep increase in the skin temperature, rather than its initial cooling by the thermal diffusivity of the cold seat. Under the same conditions, the FPCm5.3 coupled with the seat heat transfer model provides results that are four times more accurate in terms of RMSD and bias (Figure 4, FPCm simul. HT model). Our approach showed a leap in improving the quality of predictions compared to added

thermal insulation and delivered realistic outputs also in the cases taken from the literature, where very little qualitative information about the experiment was available, such as a basic description of the seat, clothing, and the environment [8].

4.1.4 Exposures with ventilated seat

In the 41°C case, we obtained accurate predictions for the seat surface temperatures where the RMSD and bias were within the standard deviation of the measurement (Figure 5). In the study by Shin et al. [41], where three-dimensional model of ventilated seat was used, the good agreement in the seat and skin temperatures were found only within the first two minutes of exposure, followed by an error of up to 12°C in the fifth minute. We achieved consistent results despite simplifying the heat and mass transfer to the resulting heat flux density between the seat and the occupant. The 41°C case also confirms the applicability of this approach at high ambient temperatures.

4.1.5 Predicted skin temperatures at the body sites without seat contact

The skin temperatures for eight main body parts without seat contact were predicted very accurately in both cases, i.e. at 18°C and 41°C. The RMSD and bias of the FPCm5.3 simulations were mostly below the standard deviation of the measurements, with an average of 0.9°C (Table 3). To put this into the context of the previous FPCm5.3 validation studies, such as the study by Martínez et al. [27], an average RMSD of 1.3°C for local skin temperatures was determined based on 43 distinct human exposures. The study reported an increased RMSD at the forehead of 1.6°C, which is in line with our findings (RMSD 1.9, bias -1.9°C, SD 1.5). This discrepancy can be explained by the variations in the hair coverage of the forehead and the evaporative cooling capacity of sweat [62]. At the calves, the simulation results exhibited constant over-predictions of 2.4°C and 1.8°C for the cases of 18°C and 41°C, respectively (Table 3). This contradicts the findings of a prior validation study [62], where good prediction power was found at the calves. An explanation can be found in a possible discrepancy in the local clothing input. The participants were instructed to wear their own clothing, consisting of typical garments for the appropriate season, and we did not control for the fit of the clothing. The fit defines the size of the air gaps between the skin and clothing, and consequently influences the resulting thermal and evaporative insulation of the clothing [63]. Finally, the predicted mean skin temperature was satisfactory in both cases, with an RMSD and bias close to the experimental SD of 0.5°C (Table 3).

4.2 Coupling with the thermal sensation models

Overall, the most realistic performance under all conditions examined here was found in MTV and TSZ, where in the vast majority of cases, the RMSD and bias were within two standard deviations of the human votes (with an average of 1.1 thermal sensation units, Table 4). The two standard deviations of the thermal sensation votes were selected to cover 95% of their dispersion due to the relatively low number of participants (details of this are given in Table 2). High accuracy of the thermal sensation predictions was also found for body parts with less precisely predicted skin temperatures, namely the lower legs and

forehead. The only outliers were the hands, which were under-predicted by approximately 1.3 units in the case of 18°C. This phenomenon was apparent in all three models, and can be attributed to the higher local activity of the hands (filling out questionnaires and usage of smart devices) and the subconscious resting of the hands on the warmer thighs.

Despite the realistic predictions of the skin temperatures at the seat contact, the predicted thermal sensation was clearly less accurate than for body parts without seat contact (Table 4). To differentiate between the entire duration of the seat exposure and the first six minutes after taking the seat, when rapid changes of thermal sensation took place, the RMSD and bias were calculated separately for these periods (Table 4). In both the cool conditions (18°C) and the hot conditions (41°C), TSZ performed well in the first six minutes, with an RMSD and bias within two standard deviations. However, after this period, TSZ tended to drift towards higher thermal sensation votes and exceeded the limit of two standard deviations. The MTV model, on the other hand, over-estimated the effects of the cold seat by between 0.8 to 2.3 units in the first six minutes of the cool exposure, mainly because the initial cooling was as high as 150 W/m². The rest of the cool exposure typically mirrored the trends of the experimental data. Under hot conditions, predictions by MTV were the most accurate of the three models, and good accuracy was achieved, with an RMSD and bias of approximately one standard deviation (Table 4 and Figure 6).

In the case of the TSV model, the RMSD and bias exceeded two standard deviations in more than half of the body parts examined. More importantly, TSV did not respond either to the temperature step change or to the cooling ramp (Figure 6). Secondly, the segmentation of the model allows us to examine only one contact part, namely the backrest. These findings mean that TSV is less suitable for applications in vehicular cabins than the two other examined models. One of the major parameters influencing the results of the TSV model is the neutral skin temperature that is used to measure the deviation from the thermo-neutral state for a given body part. The TSV model was developed based on data from 40 Chinese participants, as opposed to the central European population investigated in this study. Using the baseline thermo-neutral skin temperature directly from FPCm5.3, which was on average 1.1°C higher, did not provide any major improvements to the predicted thermal sensation. Koelblen et al. showed that this model did not perform better for the Asian population than for the other two thermal sensation models developed based on white or mixed populations.

One possible reason for the low precision of all models in the seat contact may stem from the broader range of skin temperatures in the contact compared to the non-contact ones (Figure 3). Thus, at the seat contact, the thermal sensation models were at or beyond their limit of applicability. Another explanation for this lower accuracy has been proposed by Oi et al. [8], who concluded that there was a need for higher skin temperatures at the seat contact at lower ambient temperatures to achieve optimal thermal sensation in the contact parts. Similar conclusions were also presented by Zhang et al. [10] for heated and

cooled seats in a range of temperatures of between 15°C and 45°C. However, this relativity is not captured in any of the examined models, and further work is needed on the extension of the current thermal sensation models.

4.3 Practical implications

As opposed to the detailed three-dimensional computing methods, the main advantages using the proposed models can be summarized in the following points:

- Easily accessible input parameters and boundary conditions;
- Low computing power demands;
- Quick results with an acceptable error margin (typically < SD of local skin temperature) within conditions defined in this study;
- Simple implementation.

The proposed methodology was validated in a range of conditions between 5°C and 41°C. This range is not only typical in automotive applications, but also in occupational environments with higher heat strain due to a technological process installed. Therefore, a broad community of environmental engineers can benefit from our findings. Next, thanks to the rapid calculation times, it is possible to run parametric studies and studies focused on optimisation of the environmental parameters with respect to energy savings. These are the priorities in diminishing the carbon foot print and in the development of electric vehicles. Finally, the methodology has a great potential to significantly reduce needs for human studies and prototyping, and thus accelerate product development.

4.4 Limitations

The aim of the proposed model is to approximate the heat transfer between a solid with considerable thermal mass (seat) and an adjacent body part, rather than to act as a substitute for complex thermo-physiological models such as the FPCm5.3. For this reason several simplifications had to be assumed. On the site of the human, the model calculates the heat transfer for individual body parts and does not assume any connection with the rest of the human body by blood circulation. Next, the tissue thermal properties were constant, which is not the case in reality if a thermoregulatory action (such as vasomotor response, sweating, and shivering) occurs. Therefore, the seat heat transfer model may be prone to error under conditions where the human core temperature is changing substantially and thermoregulatory actions are present. On the site of the seat, the simplifications were mainly related to the assumption of one-dimensional heat flux. This might be influential under cold conditions with heating, where we found an increasing trend in the skin temperature error with decreasing ambient temperature (overestimation of 2.3°C found at 5°C of ambient temperature). In case of the seat ventilation, the sweat evaporation was

substituted by a heat sink or a temperature profile prescribed at the seat. This approach was shown to yield an equivalent heat flux, which can be used as a heat flux boundary condition in thermo-physiological modelling. It has to be noted that this boundary condition type restricts evaluation of the sweating and moisture propagation. Although contemporary thermal sensation models do not account for moisture, skin wettedness is one of the parameters influencing human comfort. For this reason, future advancements should also comprise humidity at the skin.

5 Conclusions

For the first time, this study has demonstrated a thorough methodology for simulating the human thermal response and thermal sensation in contact with heated and ventilated seats. This was done under a broad variety of environmental conditions ranging from 5°C to 41°C, including transient and thermally asymmetric exposures with and without local seat conditioning technologies. The seat heat transfer model was found to be a key component in calculating realistic boundary conditions for body contact with a seat, for the accurate prediction of thermo-physiological responses and thermal sensation. The typical error in the calculated heat flux between the seat and the occupant was less than two standard deviations of the measurement. Consequently, the error in the predicted seat contact temperatures using the FPCm5.3 was typically lower than 1°C, or within the standard deviation of the measurement in the majority of cases. Furthermore, the benefits of the model were underlined by comparing it with the conventional way of treating the seat as a thermal and evaporative resistance and, in the heated case, as a constant heat flux applied directly to the skin. These conventional approaches lead to an unrealistic development of the skin temperatures and errors four times higher than those obtained using the seat heat transfer model.

The high precision of the FPCm5.3 model in predicting skin temperatures at eight main body parts without seat contact was also confirmed, with an RMSD and bias typically within the SD of the measurement and below 1°C. This verification was necessary to provide reliable inputs to the thermal sensation models. Overall, the best performing models were MTV and TSZ, while TSV performed the worst. The predictions were the least accurate in the seat contact area, especially under cool conditions at 18°C. Here, all models typically exceeded two standard deviations of the human votes. Within the six-minute highly transient period after taking the seat, the best performing model was TSZ. After this phase, MTV provided robust and acceptably accurate results that realistically mirrored the human thermal sensation votes. A further extension of the current models is therefore needed to improve their performance under conditions with local conditioning.

Since the proposed methodology is valid in conditions between 5°C and 41°C, we can assume that the set of models can be used in a broad variety of environments, such as passenger transportation and occupational environments with higher heat

strain. The approach presented here can be of great merit within rapidly developing industries such as electric vehicle engineering. The virtual optimisation of the seat conditioning strategies reduces the need for human studies and prototyping, and may allow for energy savings and potentially increase the driving range.

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