Review of the existing state of the art regarding the use of CFD and human thermophysiological models for the vehicular comfort assessment

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Abstract. The aim of this article is to present a comprehensive review of the state of the art regarding the use of the human thermophysiological model into computational fluid dynamics and the coupling of these two techniques. This article will focus on the modelling of the car cabin thermal environment, the integration of virtual thermal manikins and the thermal comfort assessment. Though the complexity of the car cabin geometry, the inhomogeneous air temperature/velocity fields, and transient conditions a CFD-simulation is a very powerful tool providing detailed results for a given sufficient computing power. Understanding the human body's thermal aspects and quantifying cabin's parameters are essential for a reliable computation. Virtual thermal manikins have become an important asset in numerical simulation, providing accurate predictions of human thermal sensation. For vehicular thermal comfort assessment, this article reviews the relevant thermal comfort indices. From 70’s, several human thermophysiological models have been developed based on the human energy balance equation to achieve realistic human thermal responses. This article introduces the most common human thermophysiological models classifies them into one-node, two-node, multi-node and multi-element thermal models. Today, in automotive R&D, the coupling technique is became a powerful tool for optimizing and evaluating the passenger’s thermal comfort.

1. Introduction

Vehicular Thermal Comfort (VTC) has become in recent decades a very important factor for automotive industries since a comfortable thermal environment can influence directly driver’s stress or fatigue, driver’s and passengers’ health, and indirectly energy consumption and emissions [1]. The control of the in-cabin air temperature and relative humidity contributes clearing either avoiding the windshield’s fogging, ensuring clear visibility, and safer driving [2]. On the other hand, Computational Fluid Dynamics (CFD) is a powerful tool which was boosted in the last decades by the tremendous hardware development and software improvements. The automotive industry relies on the CFD techniques and models for different advanced parametric studies improving the design [3]. When applying modelling methods for VTC assessment, several aspects are involved such as the inside geometry of the cabin along with the involved thermal loads which might be: the occupants...
themselves, the various Heating, Ventilation, and Air Conditioning (HVAC) systems and complex non-uniform cabin conditions. In recent years, there is an ongoing interest for the human thermophysiological model as an effective tool for predicting the human response to the thermal environments assessing VTC. Moreover, the coupling between the previously mentioned CFD approaches and the human thermophysiological model represents a powerful tool for optimizing and evaluating VTC in the past decade.

2. **CFD and thermal comfort assessment**

CFD has become very popular for the VTC assessment due to its capabilities to deliver a high amount of information within a relatively reduced time and with relatively low costs. For cabin modelling, CFD models are more performant than zonal models: i) for zonal models, airflow exchange between adjacent zones need to be characterized by experiments or simulations resulting into a high level of uncertainty in the outcome [4]; ii) in CFD, air exchange between neighbouring elements composing the computational domain is calculated by solving physical flow equations. There are a lot of examples in the recent literature of studies using CFD to analyse the cabin air flow (including the use of HVAC equipment and the presence of the individuals) starting from small family cars [5-9, 22] and finishing with military applications [10,11]. In this type of numerical approach, the major role is played by the passengers. This way the human body is represented by what is called a Virtual Thermal Manikin (VTM). VTMs might be simple – representing for instance just a heat source, or very sophisticated – from the detailed zoning of the human body such as a measuring real thermal manikin and up to the representation also of the breathing flows. In this way not only the thermal plumes of the human body might be represented but also some comfort indexes might be extracted (such as equivalent temperature (Teq)) and moreover an investigation regarding the air quality might be performed [12,13]. The human microenvironment is highly influenced by the convective and radiant heat transfer between the body surface and its surroundings. Therefore, it is important to identify best CFD practices for implementation of realistic VTMs.

Correctly modelling turbulence is one of the keys to obtain correct, repeatable and reliable results. The direct solving of the Navier Stokes equations in applied fluid mechanics will remain not possible for large scale, complex flows in a foreseeable future. So CFD studies primarily Reynolds-averaged Navier–Stokes (RANS) equations methods based on supplementary equations for the Reynolds stress called turbulence models. For cabin modelling, k-ε and Low-Re realizable k-ε, turbulence models are well adapted. An example is provided in Bosbach et al. [14] where Particle Image Velocimetry (PIV) measurements validation was performed for an aircraft cabin. Large Eddy Simulation (LES) compared to RANS models offer the possibility to characterize the dynamic details of the flows and heat and mass transfer [2] but this type of modelling is still not adapted to the large scales since it consumes high resources. When the RANS model is not sufficiently accurate and LES is too expensive, Detached Eddy Simulation (DES) method is used in recent studies. A comparative study between DES, LES and RANS shows that DES could be promising to be an accurate turbulence model [15]. However, this method needs to be further studied before it can be widely used for simulations of the indoor car environment. It is necessary to investigate the use of more advanced models, to improve the balance between outcome accuracy and required computational effort. When introducing VTMs in CFD, it is important to consider VTM’s geometry and the best fitted boundary conditions for the considered problem. The use of VTM's depends mainly on the research purposes and there are no relevant standards for the size, shape and position of VTMs. Computational requirements are mainly determined by the geometric complexity of the human body. VTM’s size is closest to an adult body, with a height between (1.65-1.90 m) and an area (1.6-1.8 m²). Different studies simulate a body seated by a cube [16], a standing person with an oval-section cylinder [17] and also with parallelepipeds of the same height to visualize the flow field [18] and determine thermal comfort [19]. The meshing difficulty to generate complex geometry requires unstructured cells and a relatively large cell number for VTM [20,21,28]. Due to the complex human body geometry and interaction, hybrid grids, including tetrahedral, hexahedral, and prismatic grids, were commonly adopted in the simulation domain. The prismatic grids were used for boundary layers in the
proximity of surfaces boundary layers. Tetrahedral and prismatic grids were mainly used to study complex VTM shapes and car cabin models [4,22]. Grid independence of the solution analysis must be sufficiently considered, instead of simply comparing absolute or relative errors for limited variables in an ambient environment or on the body surface. Usually, authors try to investigate the influence of one physical parameter (be it air velocity, solar radiation either relative humidity) into the in-cabin conditions, in a quest of knowledge regarding the phenomena around the interactions between the human body and its environment. Sorensen for instance [23] calculated the view-factors for radiation heat fluxes between a human body and surrounding surfaces. Other research [20,21] focused on velocity field, radiative and convective heat flux released by the body. Currle [24] used CFD to simulate temperature and air-flow field in car cabins and discussed VTC by considering passenger’s thermal model, natural convection, convective and radiative heat transfer. Zhang et al. [25] used CFD to obtain temperature distributions and velocity fields in a car compartment with and without passengers. Murakami et al. [26] used a VTM with a curved shape to investigate dynamic airflow effects around the human body and to predict thermal comfort. The cornerstone was the convective heat transfer analysis between the airflow and the human body, which is difficult to analyse in human skin experiments. The thermal boundary conditions for VTMs representing the heat source can be modelled by constant surface temperature, constant surface sensible heat flux and total sensible heat power output through the volume (ANSYS Fluent) [27]. Sevilgen et al. [28] used different boundary conditions types on the human body surfaces to determine the suitable boundary condition for VTC. Any CFD study needs attention to modelling performance focused on computational grids, convergence criteria, and validation. Through calibration and validation, the aspects of grid convergence, turbulence models, and radiation model were identified and qualified, accounting for errors associated with both the computational model and experiment.

Thermal comfort indices (as Predicted Mean Vote (PMV), Draught Rate (DR)) have their disadvantages and have been controversial in many studies [29,30]. Han et al. [31] combined, CFD, refrigeration cycle analysis, solar load and VTM with PMV analysis but it was not regarded as the main criterion for thermal comfort. Reda et al [32] used CFD for airflow study and VTC by obtaining local PMV/ Predicted Percentage of Dissatisfied (PPD) distributions with solar load model with two configurations (rectangular and circle shape) for air terminals HVAC system and with four passengers. When representing the human body as a model, the main challenge is the thermal control mechanism which is very complex and difficult to model. The most relevant thermal comfort models and indexes used to assess local comfort in the field of HVAC are presented with advantages and disadvantages in Table 1. Global Thermal Comfort Index (GTCI) defined by Neacsu [33] is a new method to link the available thermal comfort models, which helps to predict how close we are to target conditions for VTC. Kantoon et al. [34] used three thermal comfort indexes PMV/PPD, modified PMV (mPMV)), Teq, were linked using GTCI to evaluate VTC influenced by solar radiation. Thermal comfort indices were determine with a VTM in the sitting posture and wearing cotton shirts with half sleeves. Simulations showed inhomogeneous airflow distribution but then steady-state velocity and temperature distribution were observed afterward. Results of conventional ventilation schemes have shown that the airflow generated by the central and side air ventilation vents is strongly deflected near the driver’s body, resulting in complex movements and high airflow mixing. The Teq surpassed the other models (homogenous assumption limit). mPMV was 12% more sensitive when evaluated using GTCI. Yang et al [35] developed a coupling between a VTM controlled by a multi-node model and CFD to simulate heat transfer and physiological responses of the unclothed human body in hot environments. This coupling system provides an effective tool to predict thermal comfort, heat stress, and skin burn. Coupling CFD - human thermophysiological model has attractive interest because VTMs do not have thermoregulation functions that can respond to the microenvironment as human body [35].

Table 1. Thermal comfort models in THESEUS-FE [47].

| PMV-index | DTS-index | Teq (En ISO 14505-2) | Zhang’s Local comfort index |
|-----------|-----------|----------------------|-----------------------------|
| Fanger (1970) | Fiala (1998) | mPMV, PPD, mPMV, Teq | (2003) |
### Parameters

- **Parameter**
  - Activity level
  - Global boundary conditions: Air-wall temperature, air-velocity, humidity, clothing
  - Mean skin temperature
  - Core temperature
  - Local heat loss values
  - Core temperature
  - Mean skin temperature
  - Locale skin temperature

### Validity

- **Type**
  - Stationary, Global
  - Dynamic, Global
  - Stationary, Local + Global
  - Dynamic, Local + Global
  - 6 assessment regions
  - 13 body parts

### Remarks

- **DTS similar to PMV**
- **Model also provides max thermal comfort value**
- **Applicable for optimization**
- **Not coupled with thermal manikin response**
- **Differing assessment for summer and winter clothing**
- **Model also provides max thermal comfort value**

### Disadvantage

- **Not applicable for contact boundary conditions**
- **Model requires global cloth. definition (clo-value)**
- **Less validated for dynamic load cases**
- **Compared with Zhang: locale comfort predictions are quite undifferentiated**
- **Very complex model**
- **Results sometime not transparent (\textit{\textquotedbl}black box\textit{\textquotedbl})**

### Indices

- **Global therm. sensation on a 7-step-scale**
  - -3: cold
  - -2: cool
  - -1: slightly cool
  - 0: neutral
  - +1: slightly warm
  - +2: warm
  - +3: hot

- **Local therm. sensation and comfort on a 5-step-scale**
  - 1: too cold (uncomfort.)
  - 2: cold (but comfort.)
  - 3: neutral (comfortable)
  - 4: warm (but comfort.)
  - 5: too warm (uncomfort.)

- **Global and local therm. sensation on a 9-step-scale**
  - From -4 (very cold) to +4 (very hot)

### 3. Human thermophysiological models

Human thermophysiological models [36] are a mathematical representation of the human body consisting of: i) the passive system simulates physical body and dynamic heat transfer (by heat balance equation [37] or bioheat equation [38]) inside the human body and its surroundings, ii) the active system simulates the human body regulatory response of vasoconstriction, vasodilation, shivering, and sweating to control the thermal exchange and to keep the deep tissue temperature around 37°C. Only, the mathematical models following Hardy’s classification [39] are considered. There are two main types of partitioning for the human body: i) body segments as a set of interconnected components; ii) thermal nodes or multiple concentric layers for each segment with physical properties. There are 24 different models without variants [37]. Specified models will be discussed on the base of one-, two-, multi-node and multi-element models.

![Figure 1](image)

**Figure 1.** The main concept of the passive system and the active system of the human thermophysiological model [49].

#### 3.1. One-node or empirical models

These models treat the human body as a unit and describe it using a single thermal equilibrium equation without thermoregulatory systems. Fanger’s model [2,37] is capable to predict the overall thermal sensation. The model includes predictions of the mean thermal sensation vote (Predicted Mean Vote-
PMV) and the results are expressed on the 7-point ASHRAE thermal sensation scale that is widely accepted and used.

3.2. Two-node models
Gagge’s model is capable to predict thermal sensation under transient environmental conditions [40]. The passive system is composed of two concentric cylinders (core, skin) with a clothing layer. Heat transfer takes place: i) core to skin by conduction, and convection. There are also metabolic energy and muscle work; ii) skin to environment by evaporation, convection, radiation. The active system is based on three reference temperatures (core, skin and average) compared with the setpoint values to produce the error signal (cold, hot) activating appropriate commands for sweating, vasodilatation, vasoconstriction and shivering.

3.3. Multi-node models
Stolwijk’s model [36] should be considered as a milestone. This 25-node model was developed for NASA to create a mathematical model of human thermoregulation. The passive system consists of six segments and each segment is divided into four layers: the core, fat, muscles and skin. Also, the model includes a central blood compartment that is thermally connected to all the other nodes. The effects of counter-current heat exchange (CCX) in the blood flow and the blood flow characteristics in local tissue are not included in the Stolwijk model. The reevaluation suggests that the Stolwijk model accurately predicts both the absolute and the tendency in transient mean skin temperature of an “average” person under low activity conditions.

3.4. Multi-element models
Wissler’s model [36,41] found out all the physical and physiological factors that a model has to consider: i) local differences of temperature; ii) convective heat transfers due to differences of temperature; iii) convective heat transfers by blood flow; iv) body layout; v) thermal conductivity of fat and epidermal layer; vi) CCX between arterial and veins; vii) evaporative flow due to breath and on the skin; viii) heat storage into the body; ix) environmental parameters. The model has been developed continuously over the past 50 years [43] aiming to study new classes of physiological. The evolution of the human body partitioning was: i) 6- (1961); ii) 15- (250 nodes, 1964); iii) 21- (3780 nodes, 2009); iv) 25-element man’s models (6400 nodes, 2013). The bioheat equation was solving by using finite difference technique. There are no explicitly active system for regulating local metabolic heat production, sweating rate, or blood flow rate. These parameters must be specified in the appropriate input file allowing transient simulation settings. The existing Fortran code was translated in C. A graphical interface has been developed to specify input and output variables and format data representations. New physiological elements have been added to represent the hands and feet, including a unique vascular structure suitable for heat transfer associated with glabrous skin.

Fiala’s Model [36] was developed to predict the human thermal responses in cold, cool, neutral, warm and hot environments (in- and outdoor). The passive system idealized the whole body as 15 cylindrical or spherical elements consisting of seven different tissue layers to enable simulation of spatial asymmetric. Skin is modelled as: i) inner skin (blood perfused region) with some metabolic heat; ii) outer skin (superficial layer) for modelling skin evaporation. The heat transfer mechanisms within the body was modelled by the bioheat equation with a finite-difference (Crank Nicholson) scheme. The environmental heat exchange was modelled including local heat losses from the body by mix (free and forced) convection, solar irradiation, long-wave radiation, evaporation of moisture from the skin and insulation effect of the clothing. The active system through four regulatory responses controls the heat transfer within the passive system. Governing factors of the thermoregulatory system are the hypothalamus temperature ($T_{hy}$), the mean skin temperature ($T_{sk,m}$) and the rate of change of skin temperature ($dT_{sk,m}/dt$). The active system is expressed as a state function.

$$F = F(T_{hy}, T_{sk,m} \frac{dT_{sk,m}}{dt})$$ (1)
This non-linear state function was developed based on simulation and statistical regression analysis of adequate experiments with specific control coefficients for individual thermoregulatory responses. The model was adapted into a new UTCI-Fiala model for UTCI index [36] with an adaptive clothing model. Fiala model and the most evolved version called Fiala human Physiology and thermal comfort (FPC) model is worldwide accepted as reference tool due to a validation in a wide range of experimental conditions (5-50°C, 0.8-10 m/s) and its excellent performances.

Tanabe’s model is based on Stolwijk’s model and refined as JOS-2 model to account for convective heat transfer between veins and arteries [36]. There are four main differences with the first model: i) human body partition; ii) additional clothing layer; iii) integration with CFD; iv) active system. The whole body divided into 16 segments has four tissue layers each one. All body parts in JOS-2 model have artery and vein blood pools included superficial veins and arteriovenous anastomosis in the vascular system of the extremities. The four essential thermoregulatory are also included in the model. Since body’s thermal characteristics depend on height, weight, gender, age, body fat percentage, basal metabolic rate, and heat index, these physical parameters can be changed.

Berkeley model (hybrid Stolwijk/Tanabe) [3,36] includes several significant improvements in comparison with Stolwijk’s model: i) unlimited number of body segments; ii) improved blood flow model, including CCX in the extremities; iii) improved convection and radiation heat transfer coefficients; iv) clothing model with heat and moisture transfers; v) heat loss by conduction to surfaces in contact with the body are considered; vi) incorporation of a short- and long-wave radiation heat flux model. The human body was initially divided into 16 segments with four tissue layers and a clothing layer. The blood compartments are represented with a separate series of nodes. Physiological mechanisms like vasoconstriction, vasodilatation, sweating and metabolic heat production are explicitly considered. The model incorporates a set of physiological parameters that may be used to predict variations in thermal response between individuals. The model has incorporated the bodybuilder function with relationships between the model inputs and the predicted physiological data.

MORPHEUS’s Model (hybrid Fiala/Tanabe) [42] allows a real-time estimation of individual-specific thermoregulatory responses and thermal comfort under transient and inhomogeneous environmental conditions. The model allows to include individual specific properties (height, gender and age). MORPHEUS is implemented in the acausal modelling language Modelica with a component-based implementation approach. Dymola software exports the model as functional mock-up unit (FMU) for co-simulation. The model requires knowledge about several boundary conditions such as global and body-part-specific air temperatures, relative humidity, local air velocity and radiant temperature. The passive system describes the human anatomy via 19 segments divided in seven virtual tissue materials. The heat exchange between the body parts is implemented via a central blood flow model. All geometrical model parameters can be scaled, which enables their adaptation towards body composition parameters of individuals. The active system considers the thermoregulatory functions of the central nervous system, which are triggered via variations of the body core and skin temperature. Here, the model considers the four thermoregulatory responses. The latter two alter the blood perfusion of the skin thus affecting the energy transfer between the human body and the environment. The ambient model contains heat transfer models for convection, radiation and evaporation. A clothing model is also considered. Table 2 specifies basic characteristics of all human thermophysiological models considered.

| Model   | Year | Class | Applicability conditions | PS    | AS    |
|---------|------|-------|--------------------------|-------|-------|
| Fanger  | 1970 | 1-N   | Steady-state and transient, non-uniform | HBE   | No    |
4. Coupling CFD and human thermophysiological models

The deepen knowledge of human thermal response to non-uniform and transient environments as in a car cabin is important to provide thermal boundary condition to CFD solver using thermoregulatory models. The coupled process includes the data exchange to body segment heat fluxes and temperatures, and detailed local micro environment parameters [4, 42]. The quality of coupling is highly dependent upon VTM geometry, heat transfer around VTMs, clothing, and computational resources. Thus, the primary task for the application of coupled CFD with thermoregulation models is still to ensure the accuracy and efficiency of VTM simulations. This type of coupling has been extensively employed in car cabin environments [4, 43-45]. Car cabin temperature and airflow field distribution has been studied using a coupling THESEUS-FE/Fluent for three different fan controller positions with two sub-cases (face or face + legs). PMV/PPD, Dynamic Thermal Sensation (DTS), and Thermal Sensation (TS) were used to evaluate VTC [43]. With a coupling THESEUS/OpenFoam [44], the thermal sensation was studied on Fiala model with Zhang Local Comfort index (ZLC) and Zhang Local Sensation (ZLS) index taking into account the effect of a four air vents configuration. Fanger and Berkeley model comparison [45] was made by coupled RadTerm/Fluent. Lorentz [4] developed a coupled method (Fluent/MatLab) including cabin airflow CFD model, a heat transfer model of the solid cabin parts, FPC model and a new model for window fogging prediction. The film condensation model satisfactorily reproduces the heat and mass transfer.

5. Conclusion

For cabin modelling, CFD models are more performant than zonal models [4]. CFD/VTM coupling shown some limitations because VTMs do not have thermoregulation functions as human bodies [35]. Due to the lack of spatial discretization, one- and two-models are limited to a uniform environment. Multi-node models take into account the anatomy and thermophysiological characteristics of the human body to simulate heat transfer inside and at its surface. In terms of predicting thermal comfort, the main advantage of these complex models is that they can be applied to complex environmental situations that are difficult or impossible to solve with simple equations. Car cabins are confined spaces, in which convection, radiation or conduction heat transfer mechanisms causes thermal
asymmetry in the human body, which affects the overall thermal sensation and comfort. Compared with Gagge’s model, multi-node models takes into account the inhomogeneous temperature distribution and thermoregulatory response of all parts of the human body. Multi element models with advanced vasomotion model can predict local skin temperature in various parts of the human body. It has also been observed that human-to-human physiological differences are not considered in some models. Human thermal response to the environment is greatly affected by physiological changes between individuals. Wissler 3D Model close to Fiala model and another variant are among the most sophisticated models currently available. NASA has improved its 41 Node Man model based on Fiala model with implemented code in MatLab for space flight applications [46]. From our point of view, FPC, Berkeley and MORPHEUS models offer one of the best compromises between sophistication and digital robustness. FPC model is one of the models commonly used in automotive, aerospace, medical, military, textile industry and biometeorology research. For the coupling, there are two main options at the moment which give very good results in thermal comfort assessment: i) CFD with THESEUS-FE, RadTherm [43-45]; ii) Fluent with MatLab [4]. In March 2020, FIALA-FE 2 FEM model [47] was updated with new modular Manikin Handling based on Typical Male Subject (TMS), Typical Female Subject (TFS) and Asian male from the MORPHEUS model [42].

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