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Influence of the radiative heat exchanges between the fire front and vehicle passengers in a road

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Abstract

The influence of the radiative heat exchanges between the fire front and vehicle passengers' in a road is made in this study. Numerical software, that simulates the vehicle thermal behaviour with complex topology and the human thermal response, in transient conditions, is developed and used.

The numerical model that simulates the vehicle thermal behaviour and the passenger thermal response is based in energy and mass balance integral equations and works in transient conditions. These equations, solved by the Runge-Kutta-Felberg method with error control, are based in conduction, convection and radiation phenomena. All coefficients used in these equations are evaluated by a sub-model that calculates the internal and external view factors, radiative heat exchanges, glass radiative properties, occupation cycle, ventilation strategy, human thermo-physiology and heat and mass transfer coefficients by convection using empirical expressions.

In the numerical simulation a bus, that runs in a road nearby a fire front, occupied with 52 passengers is used. The radiative heat exchanges numerical model between the fire front and the vehicle and between the vehicle and the passengers, based in Mean Radiant Temperature method, is used.

The work is divided in three parts: the bus geometry, the passenger geometry and the fire front geometry (1), the view factor inside the and outside the bus passenger compartment (2) and the Mean Radiant Temperature that each bus bodies and human body section are subject (3).

***Keywords**: Vehicle Thermal Behaviour, Human and Clothing Thermal Response, Mean Radiant Temperature, Numerical Simulation, view factors.*

1. Introduction

The vehicles and the passengers placed near a fire front are subjected to high radiative heat exchange. The passenger is subjected to thermal discomfort and the vehicles are, inclusively, subjected to ignition phenomena. Thus, it is an important and interesting topic to be analysed in detail.

In this preliminary study a numerical simulation of a bus, that runs in a road nearby a fire front, occupied with 52 passengers is used. The radiative heat exchanges numerical model between the fire front and the vehicle and between the vehicle and the passengers, based in Mean Radiant Temperature method, is developed and applied.

This study is a continuation of Conceição *et al*. (1997), Conceição *et al*. (1997), Conceição *et al*. (1997), Conceição *et al*. (2000), Conceição *et al*. (2000) and Conceição (2001). In the previous work only vehicle thermal behaviour and the internal airflow are analysed, while in this and in the following works the vehicle, the passengers and the fire front are considered.

In the vehicle thermal behaviour numerical models, analysed by several authors, have been given special attention to the passenger compartment, namely, the vehicle body (main and interior bodies and windows) and thermal phenomena (radiation, convection, human generation, glass radiative properties, air renovation and others).

The numerical model that simulates the vehicles thermal behaviour, presented in this work, considers all spaces and all vehicle bodies spatially defined. It calculates not only the solar radiation incident in the internal and external surfaces, but also the radiative heat exchange between internal, in each space, and external surfaces, between vehicle and surrounding bodies. In the radiative calculus are considered, in the internal and external calculus, the shading effect.

Finally, to evaluate the passengers thermal comfort level is used a human multi-node comfort model (see, as example, Conceição, 2000, Conceição *et al*., 2006 and Conceição and Lúcio, 2010). More details of the multi-node comfort model, based in Stolwijk (1970), can be see Conceição *et al*. (2014).

2. Physical Model

In the physical model, the numerical program defines the vehicle, passengers and fire front geometry. The vehicle, in general, is divides in several compartments (passengers, luggage and motor), main bodies (panels, doors, ceiling and floor), interior bodies (benches and motors) and glasses.
The passengers are divided in 25 cylindrical or spherical elements and each element is sub-divided in 12 cylindrical or spherical layers and could be still protected of the external environment through several clothing slices.
The fire front is identifying using one, or more, geometric surfaces.
Using the geometry inputs the programs built the energy and mass balance equations system.

3. Vehicle Mathematical Model

The vehicles thermal behaviour model is based not only in energy balance integral equations for the air inside each spaces, different slices of vehicle main bodies, several windows glasses and interiors bodies, but also in mass balance integral equations for the several air contaminants inside the spaces. It considers the convective (natural, forced and mixed), conductive (in the main bodies divided in several slices), radiative (shortwave and long wave radiation outside and inside the vehicle) and mass transfer (inside the compartments) phenomena.

In the radiative calculus each surface is sub-divided in several small areas. In the vehicle external surfaces are considered:

- the absorbed solar radiation by the main bodies and windows glasses surfaces;
- the long wave radiative heat exchange between the vehicle external surfaces and the nocturnal sky, during the night, and the surrounding surfaces, during the day.

In the internal surfaces are considered:

- the solar radiation transmitted through the glasses and received by the main and interior bodies surfaces;
- the long wave radiative heat exchange between the internal surfaces (glasses and main and interior bodies), of each space. The diffuse radiations between grey surfaces, in each enclosure, are determined by radiosity equations system and view factors.

It is considered the shading effect caused by the surrounding surfaces (buildings or other vehicles), when the car is parked, and the internal surfaces (main and interior bodies in each compartment).
In the mass transfer inside each space are considered the human respiration and transpiration, outdoor infiltration and mass exchange between different compartments. Using the water vapour concentration and the air temperature value the model calculates the air relative humidity.

4. Heat exchanges by radiation

The radiant heat exchanges by long wave phenomena are calculated, in this work, using the Mean Radiant Temperature method (Fanger, 1970). The Mean Radiant Temperature, used to evaluate the heat exchanges that each human body section is subjected, considers the view factors calculated between the human body sections and the surrounding surfaces and the surrounding surfaces temperature. In the methodologies used in view factors determination each human body element, vehicle surfaces and external surfaces, with inclinations and dimensions equal to the respective body, are divided in infinitesimal areas. In the radiation by long wave phenomena calculus are also considered the shading effects that the body elements surfaces promote in each element.

The Mean Radiant Temperature method, with correction, is divided in two parts:
- Heat exchange in the human body;
- Heat exchange in the vehicle.

The human body consider:
- heat exchanges between the human body sections and the surrounding surfaces (main and interiors bodies and glass);
- heat exchanges between the human bodies sections of each passenger and between the human bodies sections of different passengers;

The vehicle body consider:
- heat exchanges between the vehicle surfaces (main and interiors bodies and glass) itself;
- heat exchanges between the vehicle surfaces (main and interiors bodies and glass) and the passengers;
- heat exchanges between the vehicle surfaces (main and interiors bodies and glass) and the external surfaces (floor, environment and fire front).

The Mean Radiant Temperature method, with correction, calculates, step by step, the Mean Radiant Temperature, using the human body and vehicles bodies, calculated in each iteration, and the pre-calculated view factors.

5. Results and Discussion

This preliminary work is divided in three parts:
- the bus geometry, the passenger geometry and the fire front geometry;
- the view factor inside the and outside the bus passenger compartment;
- the Mean Radiant Temperature that each bus bodies and human body section are subject.

In the bus studied, divided in 6 compartments (frontal ventilation ducts, luggage, motor, passengers and two ventilation ducts over the seats), are considered 99 main bodies, 18 window glasses and 105 interior bodies (see figure 1). The same figure, as example, show also a small fire front, placed in the vehicle left side.
Each of these surfaces, in order to evaluate the view factors, is divided in several infinitesimal areas. In general, in accordance with previously numerical simulation obtained in the view factors determination, all surfaces are subdivided in both directions in a grid spaced in a maximum of 0.2 m and divided in a minimum of 100 elementary areas.
Figure 2 show the grid generation in the vehicle passenger's compartment surfaces and the 52 passengers used in the view factor determination. The passengers considered has 1.7 m of height, 70 kg of weight and 1 met of activity and 0.8 Clo of clothing level.
In figure 2 the vehicles surfaces are subdivided in elementary surfaces, defined previously, while in the passengers the spherical head is divided in 64 elementary areas (a grid in the azimuthal angle direction of 8 divisions and a grid in the polar angle direction of 8 divisions), while the others passenger bodies cylindrical elements are also divided in 64 elements (a grid in the longitudinal direction of 8 divisions and a grid in the radial direction of 8 divisions).
In the geometry definition all vehicles surfaces (main bodies and transparent bodies) are in contact. However, in the interior bodies only the seats, defined by a vertical and an inclined surface, are defined. In the passengers all elements are disposed in similar way to the human body posture. The neck, the arms divided in four and the legs divided in four are connected to the trunk with dimensions and angles

similar to the human body sections. The head is connected to the neck, the hands are connected to the arms and the feet are connected to the legs. In the neck, shoulders, elbows, hips, knees and ankles are placed rotation elements. The dimensions and inclination of each element are obtained using a numerical model based in the human body weight and height.
All passengers are not in contact between them and all passengers are not in contact with the seat and with all vehicle surfaces.

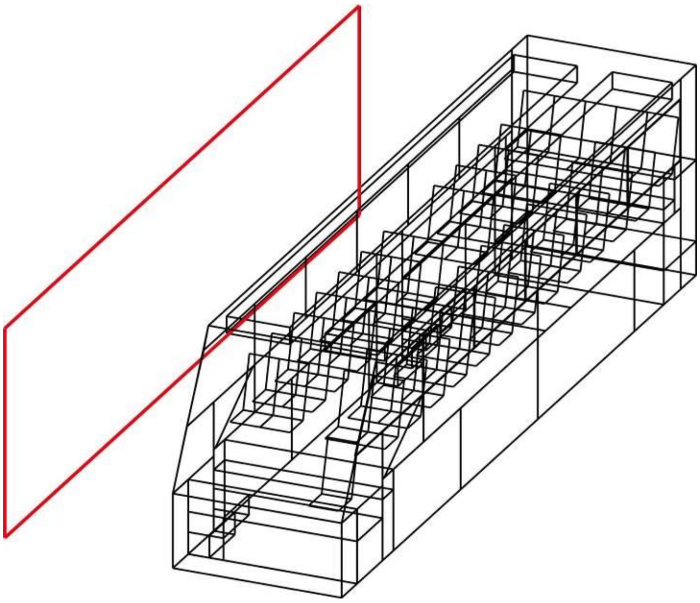

Figure 1. Scheme of a bus with 6 spaces, 99 main bodies, 105 interior bodies, 18 windows and 1 fire front.

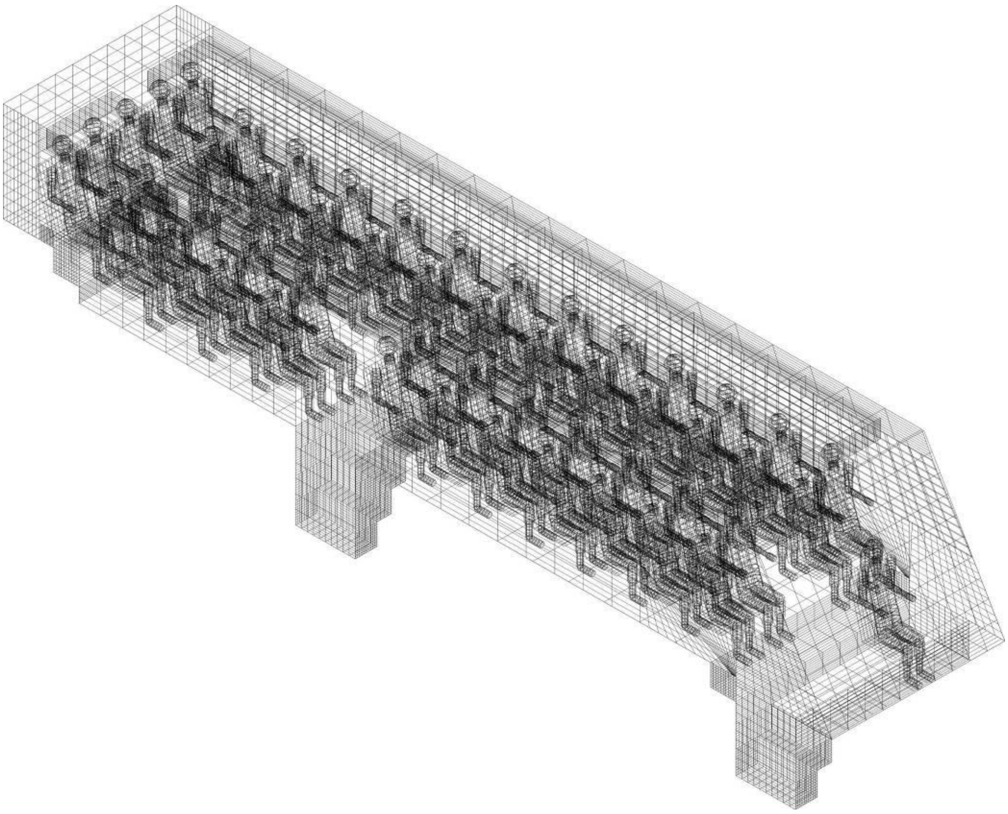

Figure 2. Grid generation in the vehicle passenger's compartment surfaces and in the 52 passengers used in the view factor determination.

In figure 3, as example, the Mean Radiant Temperature that each human body sections are subjected is presented. In these calculus the air temperature and relative humidity, evaluated in the external environment are, respectively, 18 ºC and 50 %, while the external floor is 18 ºC.

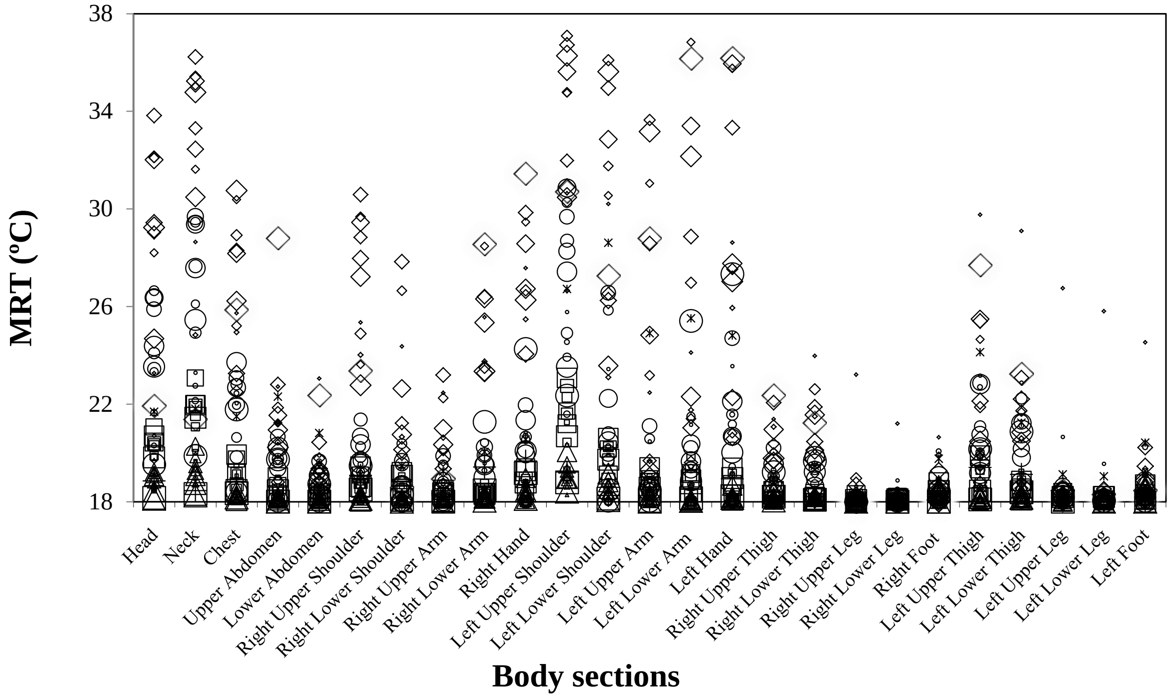

Figure 3. Distribution of the Mean Radiant Temperature that each human body section of the 52 passengers are subjected.

In accordance with the obtained results, in this preliminary study, is possible to verify that:

- The Mean Radiant Temperature is highest for passenger located near the left side vehicle;
- The Mean Radiant Temperature is higher for the left side passenger sections than right side passenger sections;
- The Mean Radiant Temperature is higher in upper passenger sections than in lower passenger sections.

6. Conclusions

In this work the influence of the radiative heat exchanges between the fire front and vehicle passengers' in a road is made. In the study a numerical software that integrate the vehicle thermal behavior with complex topology and the human thermal response, in transient conditions, is developed and used.
In this preliminary study, divided in three parts, are defined the bus geometry, the passenger geometry and the fire front geometry (1), are calculated the view factor inside the and outside the bus passenger compartment (2) and are evaluated the Mean Radiant Temperature that each bus bodies and human body section are subject (3).
In accordance the obtained preliminary results the grid generation in the vehicle geometry, in the passenger geometry and in the fire front geometry, in general, promote a good compromise between the view factors obtained and the computational time used. The increase of the grid generation increase substantially the computational time used, while the reduction cannot obtained good view factors values.
The preliminary obtained values show a slight asymmetry in the Mean Radiant Temperature values. The Mean Radiant Temperature is highest for passenger located near the left side vehicle, the Mean Radiant Temperature is higher for the left side passenger sections than right side passenger sections

and the Mean Radiant Temperature is higher in upper passenger sections than in lower passenger sections.
In the future the obtained information will be used in the evaluation of the vehicle temperature distribution and the human body temperature distribution. The vehicle temperature distribution will be used to evaluate the ignition risk that a vehicle is subjected near a fire front, while the human body temperature distribution will be used to evaluate the human thermal comfort and local discomfort levels.

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