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Application of the mean radiant temperature method in the evaluation of radiative heat exchanges between a fire front and a group of firemen

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Abstract
In this work will be studied the application of the Mean Radiant Temperature method in the evaluation of radiative heat exchanges between a fire front and a group of firemen. The development and the application of the Mean Radiant Temperature method will be presented in this work.
The obtained results are used to analyse the protection made by firemen bodies in the others firemen in front a fire front. The obtained protection can be used in order to reduce the fire front radiative flux value that the firemen are subjected.
In this study will be used a numerical model, that evaluates the human and clothing thermal response, in steady-state and transient conditions. The software calculates not only the temperature field in the human body tissue, arterial and venous blood and clothing, but also the blood and tissue mass field in the human body and the water mass field in body skin surface and clothing.
This model considers the human body divided in 25 cylindrical and spherical elements, being each one sub-divided in 12 layers, which could be protected from the external environment through some clothing layers. The computational model of the human body and clothing thermal system is based on the energy balance integral equations for the human body tissue, blood and clothing as well as mass balance integral equations for the blood and transpired water in the skin surface and in the clothing. A thermoregulatory system model was adapted to control the human body tissue temperature.
The radiative heat exchange numerical model between a fire front and the firemen is based in the Mean Radiant Temperature method. This numerical model considers the view factors determination between the firemen bodies and the surrounding surfaces (fire front and environment) and between the occupants' section. In this calculus the grid generation around the firemen and in the fire front is used to evaluate the view factors.
In the numerical simulation, presented in this study, is considered a fire front, the floor, the environment and a group of firemen. The numerical model calculates the Mean Radiant Temperature, that a group of 9 firemen are subjected.

***Keywords**: Fire Behaviour and Modelling, Human and Clothing Thermal Response, Mean Radiant Temperature Method, Numerical Simulation.*

1. Introduction

This study is a continuation of Conceição (2002), Conceição *et al*. (2006B) and Conceição and Viegas (2010). In the previous work the view factors between a firemen and the fire front was made, while in this work the numerical model considers the view factors determination between the firemen bodies and the surrounding surfaces (fire front, floor and environment) and between the occupants' section.
In Conceição (2002) the numerical model was used to study the fireman thermal sensation nearby a fire front. In the three analyzed situations, the radiant temperature, body skin and clothing temperatures and transpired sweat rate field were calculated. The more uncomfortable situation was verified when the fireman is localized in front to the fire central area and distanced 5 m from the flames, being the allowable exposure time, for a non-acclimatized subject with the warning criteria, of around 4.5 hours. During the fire extinction was suggested that the distance between the fireman and the fire front should be the highest possible. It was also suggested that the fireman should avoid being located in front to the flames central area.

In Conceição *et al*. (2006B) the numerical model, that simulates the human and clothing thermal responses, in steady-state and transient conditions, were used to study the fireman thermal sensation nearby a fire front. This numerical model was used to evaluate the thermal sensation that a fireman, equipped with special protective clothing, is subjected nearby vertical flames, with a height of 2 m and a length of 10 m. In this theoretical study the fireman was placed 5 m distanced from the flames and localized in front to the flames central area. The body and clothing temperatures, the radiant temperature, the heat and mass fluxes field and the comfort levels were calculated. The influence of the clothing thickness and the special protective clothing emissivity coefficient reduces, in the fireman thermal comfort sensation were analyzed. The theory used to evaluate the fireman thermal comfort was based in the extension of the PMV model. This extension, used in warm environments, combines the "static" PMV model and the adaptive model. The idea was to use the traditional PMV model, that considers the human body thermal balance, and the expectations verified in the adaptive model. It was verified that the Predicted Percentage of Dissatisfied people increases lightly when the clothing thickness increases and decreases when the special protective clothing emissivity coefficient reduces.
In Conceição and Viegas (2010) the radiative heat exchanges between the fire front and two firemen was evaluated. In the radiative heat exchanges the Mean Radiant Temperature method, with correction, was applied. The Mean Radiant Temperature, the skin and clothing temperature and the Predicted Percentage of Dissatisfied people were evaluated. The fireman located behind was protected to the fire front by the fireman located in front. In accordance with the obtained results the radiant protection, promoted by the fireman located in from, with a Predicted Percentage of Dissatisfied people of 25.0 %, reduced the Predicted Percentage of Dissatisfied people, that the fireman located behind is subjected, for 18.1 %.

2. Physical Model

In the numerical program the human body is divided in 25 cylindrical or spherical elements: the head, the neck, the trunk divided in three, the arms divided in four, the hands, the legs divided in four and the feet. Each element is sub-divided in 12 cylindrical or spherical layers (1 in the core, 2 in the muscle, 2 in the fat and 7 in the skin) and could be still protected of the external environment through several clothing slices. The main arteries and veins and the capillary blood system is also considered in this work.
In the methodologies used in view factors determination each human body element or surrounding surfaces, with inclinations, dimensions and temperatures equal to the respective body or surrounding section, 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.

3. Mathematical Model

The human body thermal system is based on the energy and mass balance integral equations:

- The energy balance integral equations are developed for each tissue slice and for the arterial and venous blood, of each human body element;
- The mass balance integral equations are developed, in each element, for the blood and for the transpired water in the skin surface.

To simulate the clothing thermal system are also developed energy and mass balance integral equations:

- The energy balance integral equations are developed for each clothing layers, in each element;

- The mass balance integral equations are developed for the clothing layers and for the adsorbed/desorbed water vapour in the clothing fibber layers.

The thermoregulatory system, used in the control of the human body temperature, is constituted by (see Stolwijk, 1970):

- heat transport from internal to external tissue;
- heat loss by evaporation;
- additional heat through shivering.

More details about the numerical model are presented in Conceição (2002), Conceição *et al*. (2006A), Conceição *et al*. (2006B), Conceição and Lúcio (2010) and Conceição *et al*. (2010).

4. Mean Radiant Temperature

The radiant heat exchanges by long wave phenomena are calculated, in this work, using the Mean Radiant Temperature method (Fanger, 1970), with correction (see Conceição and Lúcio (2010). The Mean Radiant Temperature model, presented in Fanger (1970), considers, only, the heat exchanges by radiation between the human bodies sections and the surrounding surfaces. The Mean Radiant Temperature used the view factors calculated between the human body sections and the surrounding surfaces and the surrounding surfaces temperature.
The Mean Radiant Temperature method, developed in this work, considers:

- the heat exchanges between the human body sections and the surrounding surfaces, namely the fire front, the floor and the environment;
- heat exchanges between the human bodies sections of each occupant;
- heat exchanges between the human bodies sections of different occupants.

The Mean Radiant Temperature method, that also considers the view factors correction, calculates, step by step, the Mean Radiant Temperature, using the human body and surrounding surfaces temperatures, calculated in each iteration, and the pre-calculated view factors.

5. Results and Discussion

In this work the radiant heat exchanges that 9 firemen are subjected nearby vertical flames, with a height of 4 m and a length of 10 m, is evaluate. In this theoretical study the firemen, placed in front to the fire front, are distanced 4, 5 and 6 m front to the flames central area. In this study the Mean Radiant Temperature, the body and clothing temperature field, that 9 protected fireman are subjected, are evaluated.
The obtained results are used to analyse the protection made by firemen bodies in the others firemen in front a fire front. The obtained protection can be used in order to reduce the fire front radiative value that the firemen are subjected.
In figure 1 the grid generation in the 9 firemen, in the ground, in the environment and in the fire front is presented, while the figure 2 the detailed grid generation in the 9 firemen is presented. The location of the fireman and the flame is also presented in the same figure.
In the grid generation is considered that the surroundings surfaces are divides in 100 elementary surfaces and that each human body sections surface is divided in 68 elementary surfaces. The increase of the elementary surfaces number the computational time increase substantially, while the reduction of the elementary surfaces number the approximation of the view factors is bad.
In the view factors determination, used to evaluate the Mean Radiant Temperature, are considered 9 occupants divided in 25 cylindrical or spherical human bodies sections, namely the head, the neck, the trunk divided in three, the arms divided in four, the hands, the legs divided in four and the feet.

In each human body section are calculated:

- 6 view factor for each surrounding surface (1350 view factor);
- 25 view factors between each human bodies sections of each occupant (5625 view factor);
- 25 view factors between each human bodies sections of different occupant (50625 view factor);

Thus, in general, the total view factors calculated is 57600. However, in each view factors determined between one human body and one plan 6800 calculations is made, while in each view factors determined between two elements 4624 calculations is made.
The Mean Radiant Temperature is presented in figures 3. In the Mean Radiant Temperature evaluation is used the surface temperature field and the view factor between the human body sections and the surrounding surfaces.
The surrounding and firemen temperature is evaluated:

- In the surrounding temperature field the fire front, floor and environment temperature are introduced in the numerical model;
- In the firemen temperature field the human body sections temperature is calculated in the numerical model.

The view factor between the human body sections and the surrounding surfaces is evaluated:

- the view factor between the human body sections and the surrounding surfaces, namely the fire front, the floor and the environment;
- the view factor between the human bodies sections of each occupant;
- the view factor between the human bodies sections of different occupants.

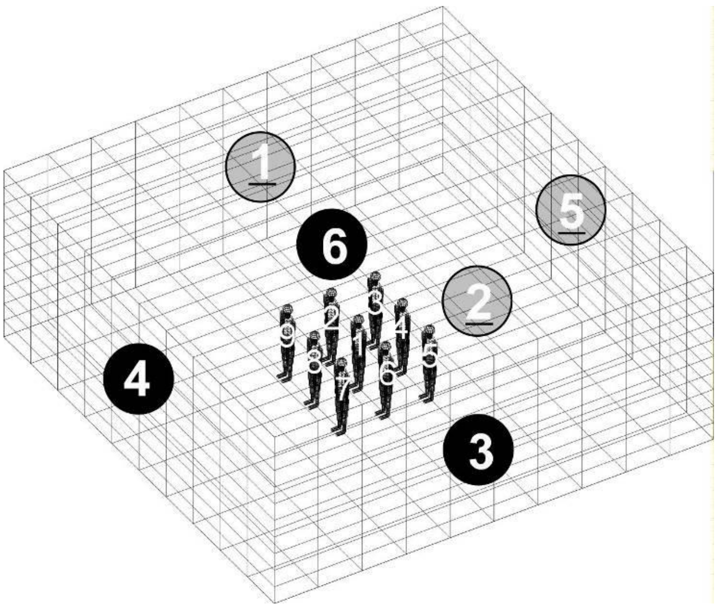

Figure 1. Grid generation in the 9 firemen, in the ground, in the environment in the fire front. Surface 4 are associated with the fire front, surface 2 are associated with the floor and the others surfaces are associated with the environment.

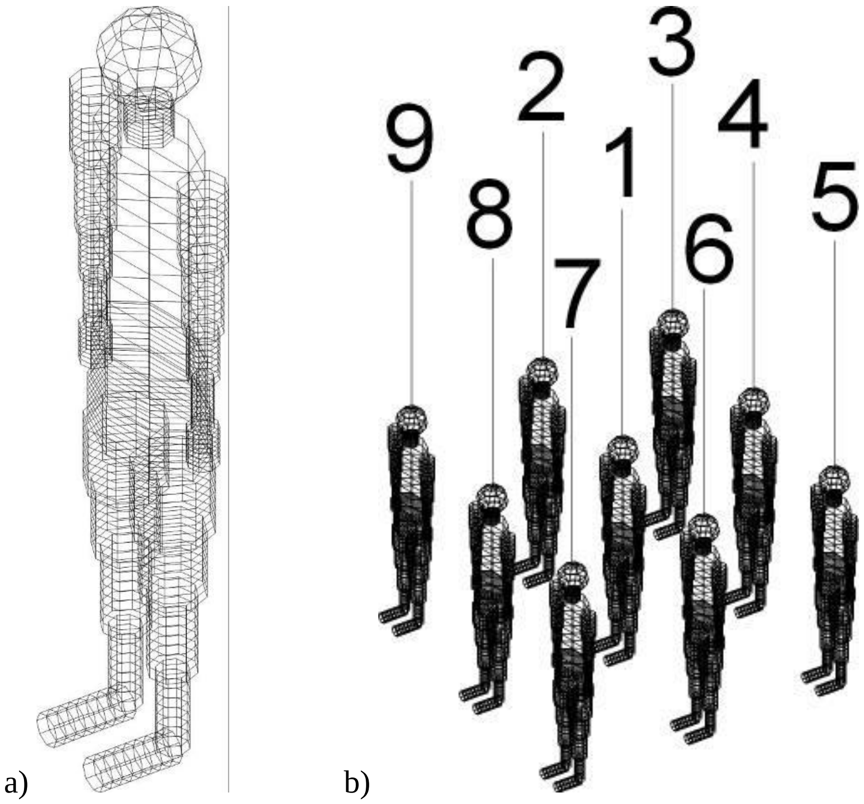

Figure 2. Grid generation around a fireman a) and around a group of firemen b).

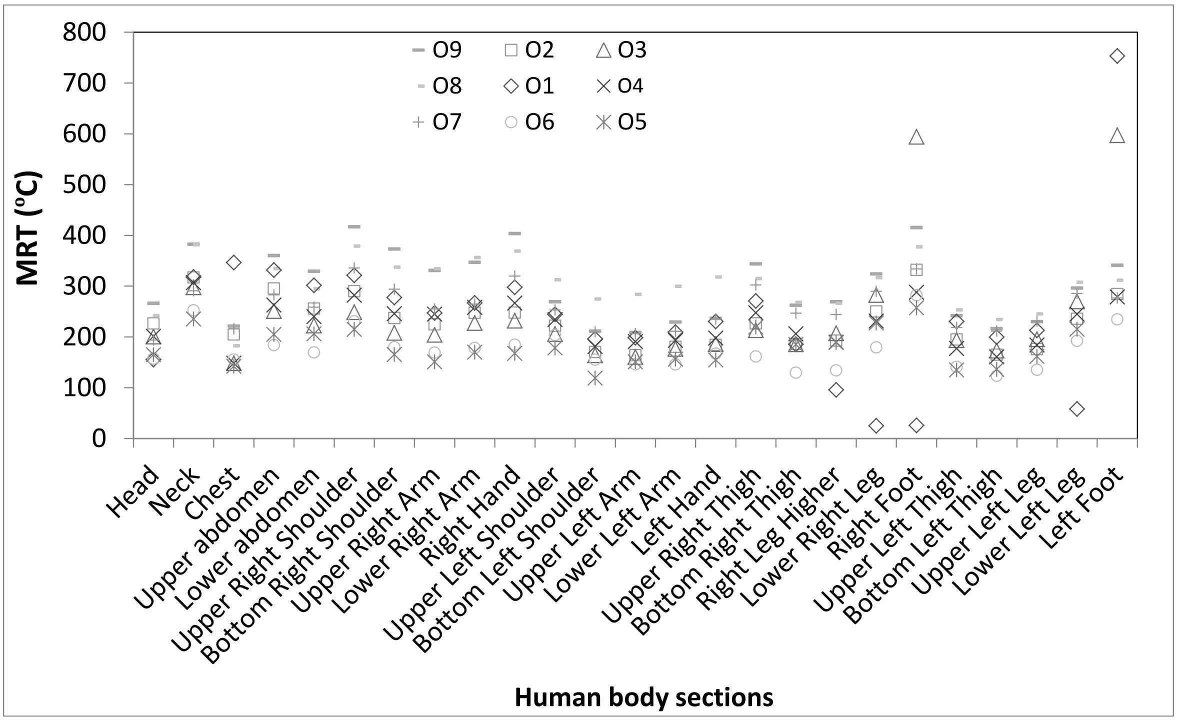

Figure 3. Mean Radiant Temperature.

In accord to the obtained results, is verifying that:

- In general, the highest Mean Radiant Temperature is verified in firemen located in the front of the group and the lowest Mean Radiant Temperature is verified in firemen located in the behind of the group. This fact is associated with the protection that the fireman located in front promote in the fireman located behind and due the distance between the fire front and the fireman is highest for the fireman located behind;

- However, in some firemen sections, as example in the foot, the previous conclusions are not verified;
- In general, the protection made by the firemen posture, located in front, is higher than 150 ºC (Mean Radiant temperature).

6. Conclusions

In this work is studied the application of the Mean Radiant Temperature method in the evaluation of radiative heat exchanges between a fire front and a group of 9 firemen placed in front of the fire front. The obtained results are used to analyse the protection made by firemen bodies in the others firemen in front a fire front. The obtained protection can be used in order to reduce the fire front radiative value that the firemen are subjected.

The Mean Radiant Temperature evaluation, used to evaluate radiative heat exchange between the firemen and the surrounding surfaces, is evaluated fiction to the view factors between the firemen body section and the surrounding surfaces and the surrounding surfaces temperature. In accordance with the obtained results, in the view factor determination, the increase of the elementary surfaces number the computational time increase substantially, while the reduction of the elementary surfaces number the approximation of the view factors is bad.

In general, the highest Mean Radiant Temperature is verified in firemen located in the front group and the lowest Mean Radiant Temperature is verified in firemen located in the behind group. In general, the protection made by the firemen posture, located in front of the fire front, is higher than 150 ºC (Mean Radiant Temperature)

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