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Evaluation of thermal comfort conditions in a classroom equipped with radiant cooling systems and subjected to uniform convective environment

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ABSTRACT

The aim of this work is to evaluate numerically the human thermal response that 24 students and 1 teacher feel in a classroom equipped with radiant cooling systems and subjected to uniform convective environments, in lightly warm conditions. The evolution of thermal comfort conditions, using the PMV index, is made by the multi-nodal human thermal comfort model.

In this numerical model, that works in transient or steady-state conditions and simulates simultaneously a group of persons, the three-dimensional body is divided in 24 cylindrical and 1 spherical elements. Each element is divided in four parts (core, muscle, fat and skin), sub-divided in several layers, and protected by several clothing layers. This numerical model is divided in six parts: human body thermal system, clothing thermal system, integral equations resolution system, thermoregulatory system, heat exchange between the body and the environment and thermal comfort evaluation.

Seven different radiant systems are combined to three convective environments. In the radiant systems (1) no radiant system without warmed curtain, (2) no radiant system with warmed curtain, (3) radiant floors cooling system with warmed curtain, (4) radiant panels cooling system with warmed curtain, (5) radiant ceiling cooling system with warmed curtain, (6) radiant floor and panels cooling system with warmed curtain and (7) radiant ceiling and panels cooling system with warmed curtain are analysed, while in the convective environments (1) without air velocity field and with uniform air velocity field of (2) 0.2 m/s and (3) 0.6 m/s are also analysed. The internal air temperature and internal surfaces temperature are 28 °C, the radiant cooling surfaces temperature are 19 °C and the warmed internal curtains surfaces temperatures, subjected to direct solar radiation, are 40 °C.

The numerical model calculates the Mean Radiant Temperature field, the human bodies' temperatures field and the thermal comfort level, for the 25 occupants, for the 21 analysed situations.

Without uniform air velocity field, when only one individual radiant cooling system is used, the Predicted Percentage of Dissatisfied people is lowest when the radiant floor cooling system is applied and is highest when the radiant panel cooling system is applied. When are combined the radiant ceiling or the floor cooling systems with the radiant panel cooling system the Predicted Percentage of Dissatisfied people decreases.

When the uniform air velocity increases the thermal comfort level, that the occupants are subjected, increases. When the radiant floor cooling system or the combination of radiant floor and panel cooling systems without uniform air velocity field is applied,

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the Category C is verified for some occupants. However, with a convective uniform air velocity field of 0.2 m/s the Category B is verified and with a convective uniform air velocity field of 0.6 m/s the Category A is verify for some occupants. In the last situation the Category C is verified, in general, for all occupants.

1. Introduction

In the Algarve region (South of Portugal), with a Mediterranean climate, during Summer conditions, the air temperature values present high levels and the solar radiation values also present high levels. Nevertheless, in this season the students are in holidays. In Spring and Autumn, in general, the air temperature values present relatively high levels and the solar radiation values also present relatively high levels. These internal conditions, with lightly warm conditions, do not promote acceptable comfort conditions for the students. Thus, in these internal conditions, are important to introduce thermal systems to contribute to increase the thermal comfort level that students and teacher are subjected.

The main ventilation system in the school buildings classrooms in the Algarve Region is made by natural means. In general, the ventilation is guaranteed by small windows placed above the main door and main windows level, using a crossed ventilation philosophy. In lightly warm conditions, when the air temperature increases, due to the inlet solar radiation, the fabrics curtains can be closed. Nevertheless, in these conditions, usually, the main windows and door should be open, to guarantee acceptable conditions (also see [1]).

A greater number of radiant cooling systems and combination of radiant cooling with convective systems were analysed in the last years using numerical or experimental means. Some examples of this kind of studies can be found, as example, in [2–8]. In these kinds of studies, in general, the radiant surface temperature and the environment variables are measured. This information, with a comfort model, is used to evaluate the thermal comfort level and the local thermal discomfort level that occupants are subjected.

In the present paper, continuing of the previous works, the multi-nodal human thermal comfort model is used in the evaluation of thermal comfort level that 24 students and 1 teacher feel in a real classroom equipped with seven different radiant cooling radiant systems and subjected to three different uniform convective environments, in lightly warm conditions. The heat exchange betweens the occupants and the surrounding environments, as well as the surfaces and the human thermal comfort sensation are analysed in detail.

To evaluate the thermal comfort conditions in this study the PMV, Predicted Mean Vote, and PPD, Predicted Percentage of Dissatisfied people indexes, presented in [9,10], are used. These indexes are influenced by the values of four environmental variables such as air temperature, velocity and relative humidity, around the different body sections, and Mean Radiant Temperature, that each body section is subjected, and two personal parameters such as clothing and activity levels. In order to select a priori the thermal environment in classes, ISO 7730 [10] classifies the thermal environments according to three categories of quality: Category A, B and C.

A person can be subjected to comfort conditions and feel local thermal discomfort conditions. Local thermal discomfort sensations in localized regions of the body may occur, as example, by draught risks, radiant asymmetries, difference of vertical air temperature or floor temperatures [10]. In accord to [11] the local thermal discomfort, due to the draught risks, depends on the local air temperature, velocity and turbulence intensity.

2. Numerical model

This numerical model is divided in six parts: human body thermal system, clothing thermal system, integral equations resolution system, thermoregulatory system, heat exchange between the body and the environment and thermal comfort evaluation.

In the numerical model developed in this work the human body thermal system is based on energy balance integral equations for the human body tissue layers and arterial and venous blood, as well as mass balance integral equations for the blood and transpired water in the skin surface for each element, while the clothing thermal system is based on energy balance integral equations for the clothing layers, as well as mass balance integral equations for the clothing layers in each element. The energy (or mass) balance integral equations are written with the sensible heat (or mass) storing term in the left member and the heat flux (or mass flow rate) terms in the right one.

The simplifications hypothesis considered in the development model are the:

– human anatomy and clothing geometry is approximated by cylindrical and spherical elements;
– each layer consisting of an uniform porous material;
– each layer the properties are uniform and the temperature is constant;

Nomenclature

Complete symbol

H	vapourisation or condensation latent heat (J kg^{-1})
t	time (s)
δ	take the value 1 when the element contain the lungs and 0 in the others
ε	surface emissivity
φ_c	take the value 1 for the clothed and 0 in the unclothed elements
φ_e	take the value 1 for the tissue external layer and 0 in the other tissue layers
φ_i	take the value 1 for the tissue layer located in the core of each element and 0 in the other tissue layers
σ	Stefan–Boltzmann constant (W m^{-2} °C^{-4})

Main symbol

$\dot{Q}$	heat flux (W)
A	surface area (m^2)
Cp	specific heat to the constant pressure (J °C^{-1} kg^{-1})
h	mean convective heat transfer coefficient (W m^{-2} °C^{-1})
m	mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
P	vapour partial pressure (N m^{-2})
R	thermal resistance (°C W^{-1})
T	temperature (°C)

Sub-indexes

(i,j)	element located in the (i,j) position (see Fig. 1)
a	arterial blood
b	blood
$body$	human body
c	clothing
$Cond$	conduction with contact surfaces
$Conv$	heat or mass convection
E	heat evaporation
g	total metabolism heat generated
M	massic value
p	pulmonary respiration
R	heat radiate
Sun	direct solar radiation
T	thermal value
t	tissue of the human body
$Transf$	blood transferred due to the thermoregulatory system
v	venous blood
w	water vapour

Super-indexes

(k)	human tissue or clothing layers
(n_t)	number of tissue layers of an element

- radiant heat exchanges between external surfaces of the body elements are neglected;
- transpired water in the skin surface is uniformly distributed in each element;
- heat flux in the clothing layers is considered unidirectional;
- blood flow rate, that depends on the activity level, is not distributed uniformly in the human body;
- arteries and veins are located in the central layer of an element;
- sweat transpired in the skin surface is evaporated to environment through convective (without clothing) and diffusive (with clothing) phenomena.

2.1. Energy balance integral equations

The energy balance integral equation for the human body tissue, in a layer, is done by:

$$m_{t_{(i,j)}}^{(k)} Cp_t \frac{dT_{t_{(i,j)}}^{(k)}}{dt} = \underbrace{\sum_{q=1}^{2-4}\left(\frac{T_{t_q} - T_{t_{(i,j)}}^{(k)}}{R_{T_q}}\right)}_{(1t)} + \underbrace{\dot{Q}_{g_{(i,j)}}^{(k)}}_{(2t)} + \underbrace{Cp_b(\dot{m}_{at_{(i,j)}}^{(k)} T_{a_{(i,j-1)}} - \dot{m}_{tv_{(i,j)}}^{(k)} T_{t_{(i,j)}}^{(k)})}_{(3t)} + \underbrace{Q_{Transf}}_{(4t)} + \underbrace{\varphi_i h_{at} A_{at}(T_{a_{(i,j)}} - T_{t_{(i,j)}}^{(1)})}_{(5t)}$$
$$+ \underbrace{\varphi_i h_{vt} A_{vt}(T_{v_{(i,j)}} - T_{t_{(i,j)}}^{(1)})}_{(6t)} + \underbrace{\delta \dot{m}_p Cp_b(T_{v_{(i,j)}} - T_{t_{(i,j)}}^{(1)})}_{(7t)} + \underbrace{(1-\varphi_c)\varphi_e \dot{Q}_{Conv_{(i,j)}}^{(n_t)}}_{(8t)} + \underbrace{(1-\varphi_c)\varphi_e \dot{Q}_{R_{(i,j)}}^{(n_t)}}_{(9t)}$$
$$+ \underbrace{(1-\varphi_c)\varphi_e \dot{Q}_{Sun_{(i,j)}}^{(n_t)}}_{(10t)} + \underbrace{(1-\varphi_c)\varphi_e \dot{Q}_{Cond_{(i,j)}}^{(n_t)}}_{(11t)} + \underbrace{\varphi_e \varphi_c \varepsilon \sigma A_{t_{(i,j)}}^{(n_t)}\left[(T_{c_{(i,j)}}^{(1)} + 273)^4 - (T_{t_{(i,j)}}^{(n_t)} + 273)^4\right]}_{(12t)}$$
$$+ \underbrace{\varphi_e \dot{m}_{w,t_{(i,j)}}^{(n_t)} H}_{(13t)} + \underbrace{(1-\varphi_c)\varphi_e \dot{Q}_{E,Conv_{(i,j)}}^{(n_t)}}_{(14t)} + \underbrace{\varphi_e \varphi_c H \frac{P_{c_{(i,j)}}^{(1)} - P_{t_{(i,j)}}^{(n_t)}}{R_{M_{(i,j)}}^{(1,n_t)}}}_{(15t)} + \underbrace{\varphi_e \varphi_c \frac{T_{c_{(i,j)}}^{(1)} - T_{t_{(i,j)}}^{(n_t)}}{R_{T_{(i,j)}}^{(1,n_t)}}}_{(16t)}. \quad (1)$$

In the energy balance integral equation for the human body tissue, the left member is associated to the accumulated sensible heat in the human body tissue layer, while in the right member the terms represents, respectively, the heat flux due to the:

- conduction through the human body tissue (1t);
- generation by metabolic reactions in the human body tissue (2t);
- blood circulation in the capillary system (3t);
- thermoregulation from the internal to external human body tissue (4t);
- convection between the human body tissue and the arterial blood (5t);
- convection between the human body tissue and the venous blood (6t);
- pulmonary respiratory system (7t);
- convection between the skin surface and the environment (8t);
- radiant heat exchange between the skin surface and the surrounding surfaces (9t);
- skin surface incident direct solar radiation (10t);
- conduction between the skin surface and the surrounding surfaces (11);
- radiant heat exchanges between the skin surface and the clothing (12t);
- evaporation of sweat secreted in the skin surface due to the thermoregulatory system (13t);
- evaporation of the water vapour by convection between the skin surface and the environment (14t),
- diffusion between the skin surface and the clothing (15t);
- conduction between the skin surface and the clothing (16t).

In the energy balance integral equation for the arterial and venous blood the left member is associated to the accumulated sensible heat in the blood, while in the right member the terms represents, respectively, the heat flux due to the:

- blood circulation;
- convection between the blood (arterial and venous) and the human body tissue;
- convection between the arteries and veins;
- arterial blood coming from the pulmonary respiratory system;
- venous blood from the capillaries;
- pulmonary respiratory system.

In the energy balance integral equation for the clothing, the left member is associated to the accumulated sensible heat in the clothing layer (constituted by clothing fibbers and water vapour), while in the right member the terms represents, respectively, the heat flux due to the:

- conduction through the clothing and immobilized air between a layer and the previous;
- conduction through the clothing and immobilized air between a layer and the posterior;
- radiant heat exchange between a layer and the previous;
- radiant heat exchange between a layer and the posterior;
- evaporation of the water vapour by diffusion between a layer and the previous;
- evaporation of the water vapour by diffusion between a layer and the posterior;
- conduction between the clothing internal layer and human body skin;
- evaporation of the water vapour by diffusion between the clothing internal layer and the human body skin;
- radiant heat exchanges between the clothing internal layer and human body skin.

2.2. Mass balance integral equations

The mass balance integral equation for the arterial blood, in elements located among others, is determined by:

$$\frac{dm_{a_{(i,j)}}}{dt} = \underbrace{\dot{m}_{a_{(i,j-1)}}}_{(1b)} - \underbrace{\dot{m}_{a_{(i,j+1)}}}_{(2b)} - \underbrace{\sum_{k=1}^{n_t} \dot{m}_{at_{(i,j)}}^{(k)}}_{(3b)} \tag{2}$$

The same kind of equations for the venous blood is determined by:

$$\frac{dm_{v_{(i,j)}}}{dt} = \underbrace{\dot{m}_{v_{(i,j+1)}}}_{(1b)} - \underbrace{\dot{m}_{v_{(i,j-1)}}}_{(2b)} + \underbrace{\sum_{k=1}^{n_t} \dot{m}_{tv_{(i,j)}}^{(k)}}_{(3b)} \tag{3}$$

In the mass balance integral equation for the blood (arterial and venous) the left member is associated to the accumulated blood in the central layer element, while in the right member the terms represent, respectively, the mass flux due to the:

- inlet blood (1*b*),
- outlet blood (2*b*),
- blood circulation in the capillaries system in an element (3*b*).

The mass balance integral equations for the arterial and venous blood in the hands, thoracic and abdominal zone also have in account the blood flow rate proceeding from several elements.

In the mass balance integral equation for the skin water vapour the left member is associated to the accumulated water in the skin layer element, while in the right member the terms represent, respectively, the mass flux due to the:

- sweat transpired in the human body skin;
- water vapour evaporated by convection between the human body skin and the environment;
- water vapour evaporated by diffusion between the human body skin and the internal clothing layer.

The water vapour amount in the clothing is the sum of the water in the air inside the clothing and the water vapour adsorbed in the clothing textile fibbers. In the mass balance integral equation for the clothing water vapour, the left member is associated to the accumulated water in the clothing layer element, while in the right member the terms represent, respectively, the mass flux due to the:

- water vapour diffusion between a layer and the previous;
- water vapour diffusion between a layer and the posterior;
- water vapour diffusion between the interior layer and the human body skin surface;
- water vapour adsorption from the air inside the clothing to the clothing fibbers;
- water vapour desorbed from the clothing fibbers to the air inside the clothing;
- water vapour convection between the clothing external layer and the external environment.

In the mass balance integral equation for the clothing adsorbed water vapour, the left member is associated to the accumulated water in the clothing layer element, while in the right member the terms represent, respectively, the mass flux due to the:

- water vapour adsorption from the air inside the clothing to the clothing fibbers;
- water vapour desorbed from the clothing fibbers to the air inside the clothing.

2.3. Thermal exchanges with the environment

The heat generated inside the human body, by metabolic reactions, is transported by conduction, through the tissue, and by blood convection to the skin. The heat exchanged between the body and the environment (or clothing) is done by conduction, convection, evaporation, respiration and radiation (long and short wave).

2.3.1. Conduction

The conduction, that depends on the temperature value of the skin (or clothing surface) and the external bodies surfaces, is verify between the skin (or clothing) and the contact external bodies surfaces.

2.3.2. Convection

The convection, that depends on the temperature value of the skin (or clothing surface) and the surrounding external air velocity and temperature, is verified between the skin (or clothing) and the surrounding external air environment. The heat transfer coefficient by natural, mixed or forced convection is calculated through empirical expressions presented in the specialized bibliography.

2.3.3. Evaporation

The evaporation (or condensation), that depends on the vapour pressure value of the skin (or clothing surface) and the surrounding external air vapour pressure, temperature and velocity, is verified by diffusion or convection between the skin (or clothing surface) and the surrounding air environment. The water vapour diffusion is verified between two clothing layers or between a skin and internal clothing layers, while the water vapour convection is verified between the external clothing layers (or skin surface) and the external air environment. The mass transfer coefficients by natural, forced or mixed convection are calculated through empirical expressions presented in the specialized bibliography.

2.3.4. Respiration

The respiration, that depends on the internal temperature value and the external temperature and water vapour partial pressure values, is verified in the expiration and inspiration. The respiration airflow rate is function to the activity level.

2.3.5. Radiation

The radiation, that depends on the temperature value of the skin (or clothing surface) and the surrounding external surfaces temperatures, is verified between the skin (or clothing surface) and the surrounding external surfaces. The skin (or clothing surface) is subjected to radiant heat exchanges between the body and the involving surfaces (longwave radiation) and solar radiation (shortwave radiation). The first one is calculated using the Mean Radiant Temperature value in each body element (see [9]), based in the view factors and in the surrounding surfaces temperatures, while the second one is determined using the incident solar radiation in each element. In these calculus are considered the shading effect that the body elements and the interior body surfaces cause in each element.

In the view factors determination the human body elements and the surrounding surfaces are divided in several infinitesimal elements. In the analytical determination of the view factors (see [12]) the central area of each infinitesimal element is considered.

2.4. Predicted Mean Vote index

To evaluate the thermal comfort level, in steady-state conditions, the PMV and PPD indexes [9] are used. In this calculus, based in the heat fluxes exchanged between the human body and the environment of all human body elements, a modified Fanger model (see [13]) is used. The PMV index is evaluated by:

$$
\begin{aligned}
\mathrm{PMV} = {} & (0.303e^{-0.036\dot{Q}_g+0.028})\Bigg\{\dot{Q}_g - \frac{1}{A_{body}}\sum_{i=1}^{5}\sum_{j=1}^{5}\Bigg[\underbrace{(1-\varphi_c)\varphi_e\dot{Q}^{(n_t)}_{Conv_{(i,j)}}}_{\text{1PMV}} + \underbrace{(1-\varphi_c)\varphi_e\dot{Q}^{(n_t)}_{R_{(i,j)}}}_{\text{2PMV}} + \underbrace{(1-\varphi_c)\varphi_e\dot{Q}^{(n_t)}_{Sun_{(i,j)}}}_{\text{3PMV}} \\
& + \underbrace{(1-\varphi_c)\varphi_e\dot{Q}^{(n_t)}_{Cond_{(i,j)}}}_{\text{4PMV}} + \underbrace{\varphi_c\varphi_e\varepsilon\sigma A^{(n_t)}_{t_{(i,j)}}((T^{(n_t)}_{t_{(i,j)}}+273)^4-(T^{(1)}_{c_{(i,j)}}+273)^4)}_{\text{5PMV}} + \underbrace{\varphi_e\dot{m}^{(n_t)}_{w,t_{(i,j)}}H}_{\text{6PMV}} + \underbrace{\varphi_e(1-\varphi_c)\dot{Q}^{(n_t)}_{E,Conv_{(i,j)}}}_{\text{7PMV}} \\
& + \underbrace{\varphi_e\varphi_c H\frac{P^{(1)}_{c_{(i,j)}}-P^{(n_t)}_{t_{(i,j)}}}{R^{(1,n_t)}_{M_{(i,j)}}}}_{\text{8PMV}} + \underbrace{\varphi_e\varphi_c\frac{T^{(1)}_{c_{(i,j)}}-T^{(n_t)}_{t_{(i,j)}}}{R^{(1,n_t)}_{T_{(i,j)}}}}_{\text{9PMV}}\Bigg] - \frac{\dot{Q}_p}{A_{body}}\Bigg\}
\end{aligned}
\quad (4)
$$

While the terms are associated with the:

- convection between the body skin external surface and the environment (1PMV);
- radiant heat exchanges between the body skin external surface and the surrounding surfaces (2PMV);
- incident direct solar radiation (3PMV);
- conduction between the body skin and the contact surrounding surfaces (4PMV);
- radiant heat exchanges between the body skin external surface and the clothing surfaces (5PMV);
- evaporation of sweat secreted in the skin surface due to thermoregulatory system (6PMV);
- evaporation of the water vapour by convection between the skin surface and the environment (7PMV);
- diffusion between the skin surface and the clothing (8PMV);
- conduction between the skin surface and the clothing (9PMV).

2.5. Human body thermoregulatory and integral equation systems

In order to control the human body tissue temperature a thermoregulatory system model was adapted. More details can be seen, for example, in [14].

In the energy and mass integral equations system resolution, the Runge–Kutta–Fehlberg method with error control is used. In these calculations, for each occupant, 300 energy balance integral equations for the human body tissue, 25 energy balance integral equations for the arterial blood, 20 energy balance integral equations for the venous blood, 9 energy balance integral equations for the clothing, 25 water vapour mass balance integral equations for the skin surface, 9 water vapour mass balance integral equations for the clothing and 9 adsorbed water vapour mass balance integral equations for the clothing, were used. Thus, for each occupant 397 integral equations and for 25 occupants 9925 integral equations were used.

3. Numerical methodology

In this work the thermal comfort level that 24 students and 1 teacher feel, in a typical classroom, is evaluated in lightly warm conditions, equipped with a combination of seven different radiant cooling systems and three uniform convective environments.

3.1. Numerical tests

In the radiant cooling systems, the following systems are analysed:

– radiant floor cooling system (F),
– radiant panels cooling system (P),
– radiant ceiling cooling system (C),
– radiant floor (F) and panels (P) cooling system,
– radiant ceiling (C) and panels (P) cooling system.

The study also includes two more radiant situations, used as reference:

– uniformed environment (surrounding internal surfaces temperatures equal to the internal air temperature) with windows (W) not subjected to solar radiation (internal curtain temperature equal to the internal air temperature);
– uniformed environment (surrounding internal surfaces temperatures equal to the internal air temperature with windows (W) subjected to solar radiation (internal curtain temperature different to the internal air temperature).

In the convective uniform environments are analysed the following situations:

– without air velocity field;
– with an uniform air velocity field of 0.2 m/s;
– with an uniform air velocity field of 0.6 m/s.

When an uniform air velocity field of 0.2 m/s is used the Category A of local thermal discomfort is considered (see [10]), while when an uniform air velocity field of 0.6 m/s is used the Category C of local thermal discomfort is considered (see [10]). In these calculi a turbulence intensity value around 20%, obtained experimentally in [1], is considered.

The environmental inputs of the model are the air temperature, air relative humidity, air velocity and Mean Radiant Temperature, that each human body element is subjected. The air temperature and the relative humidity are 28 °C and 50%, respectively. In the air velocity are used the value of 0, 0.2 and 0.6 m/s. In the evaluation of the Mean Radiant Temperature the compartment internal surfaces temperatures of 28 °C, the radiant cooling surfaces temperatures of 19 °C and the internal curtains surfaces (C), when subjected to direct solar radiation, of 40 °C, are considered. The used radiant cooling surfaces temperature is obtained in [10] in order to guarantee acceptable local thermal discomfort levels.

Each of the 25 occupants have 1.70 m of height, 70 kg of weight, 1.2 Met. of activity and 0.5 Clo. of clothing.

3.2. Human body geometry

In the numerical model the three-dimentional body is divided in 24 cylindrical and 1 spherical elements. Each element is divided in 4 parts (core, muscle, fat and skin), sub-divided in several layers, and could be still protected from the external environment through some clothing layers. The core is divided in 1 layer, the muscle is divided in 2 layers, the fat is divided in 2 layers and the skin is divided in 7 layers. This is, the human body is divided in 420 nodes. The skin, in accord with [15], have a depth of 5.4 mm.

In these calculations the human body is divided in 25 elements (see Fig. 1), namely the head, neck, chest, upper abdomen, lower abdomen, right upper shoulder, right lower shoulder, right upper arm, right lower arm, right hand, left upper shoulder, left lower shoulder, left upper arm, left lower arm, left hand, right upper thigh, right lower thigh, right upper leg, right lower leg, right foot, left upper thigh, left lower thigh, left upper leg, left lower leg and left foot. Each element or surrounding surfaces, with inclinations, dimensions and temperatures equal to the respective body section or surrounding surfaces, will be divided in infinitesimal areas.

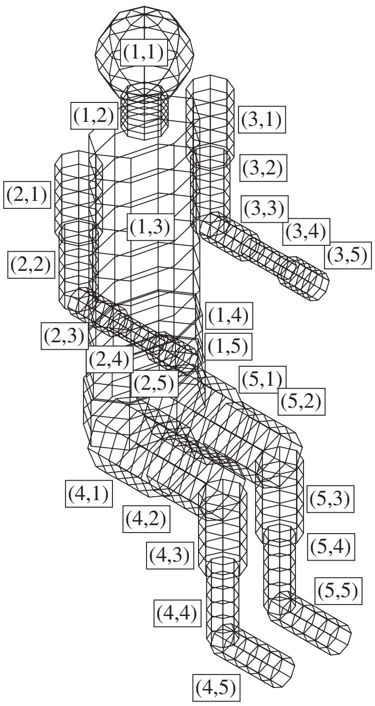

Fig. 1. Human body scheme, divided in 25 elements, human body grid generation and human body section numeration.

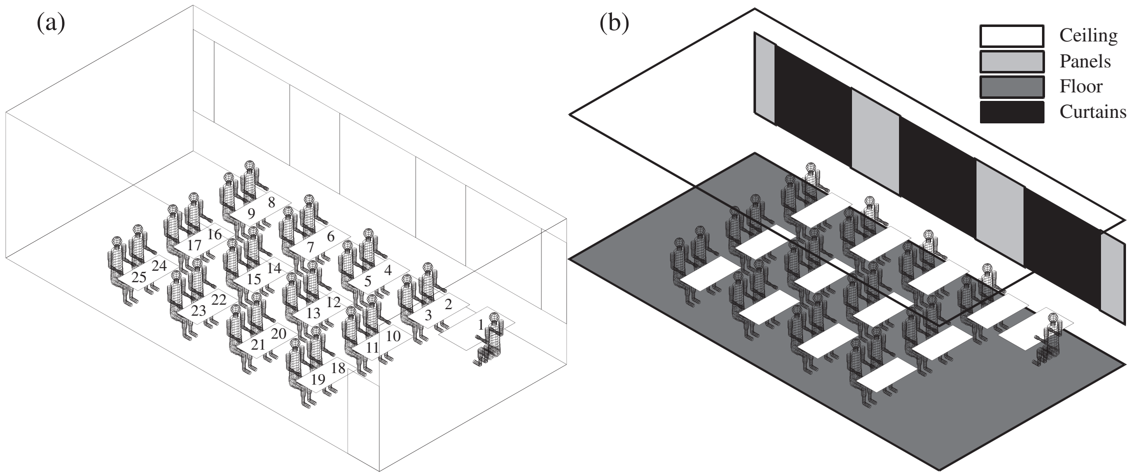

Fig. 2. Scheme of the identification of the occupants (a) and the individual radiant systems (b).

In this work the main arteries and veins as well as the capillary system of the circulatory system are considered. In the blood circulatory system of the human body main parts, namely in the head, neck, trunk, arms, hands, fingers, legs, feet, heart, lungs, kidney, liver, stomach, intestine and dull, are also considered.

3.3. Classroom geometry

The analysed classroom, equipped with 13 desks, is formed by 17 surfaces: 1 floor, 4 lateral panels, 1 ceiling, 1 door, 3 windows with internal curtains and other walls (see Fig. 2).

In [16], in a study of radiant heat exchanges between the body and the environment, where the view factors technique is implemented and applied, was verified that the decrease of the infinitesimal areas improve the view factors determination, however the calculation time increases substantially. It was also verified that in small surfaces is important to define a minimum values of small areas, in order to guarantee a representative value of infinitesimal areas. In this work a compromise

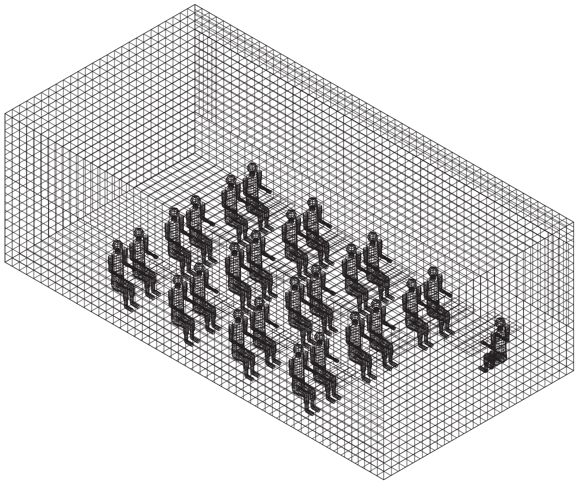

Fig. 3. Scheme of the grid generation around the occupants and surrounding surfaces.

value, between the view factors determination and the calculus time run, were obtained with a spaced of a maximum value in the grid generation of 0.3 m and a minimum value of infinitesimal areas for small surfaces of 25 unities.

In Fig. 3, the grid generation around the occupants and surrounding surfaces is presented.

4. Validation tests

In the validation tests results obtained in previous works and obtained in this work, with similar thermal conditions analysed in this study are presented.

The multi-nodal human thermal comfort model was subjected to different validation tests. In these tests the numerical values, obtained by the present numerical model, were compared with experimental data obtained in laboratorial controlled conditions or presented in the specialized bibliography.

The human body numerical model validation is divided in three parts, namely:

- *Heat and mass coefficients and fluxes.* The numerical and experimental values for the heat transfer coefficients by convection, the view factors and the heat and mass fluxes are compared. In the heat transfer coefficients by forced convection (see [17]) the numerical values, for seated people, are compared with empirical results presented in [9,18]. In the radiant exchanges between one typical person (standing and seated in the centre of a compartment with complex topology) and the surrounding 17 surfaces, numerical view factors are calculated and compared with empirical results presented in [9] (see [16]). In order to validate the numerical convection, radiation and respiration heat fluxes and transpiration mass fluxes values, the numerical and empirical results (see [9]) are compared [17]. It is possible to verify a good performance of this model in the determination of the above mentioned values.
- *Body temperatures*. The numerical and experimental human body temperatures without and with clothing are compared. In the first part the human body temperatures without clothing presented in the specialized bibliography are used, while in the second one these values are experimentally determined in the laboratory in controlled conditions. In the last situation the measured values through an infrared thermo tracer system for different air temperatures and clothing levels (see [19]) and the skin surface temperature, for five persons, dressing with similar clothing level, is measured in the head, abdomen, shoulder, arm, thigh and leg (see [17]). It is verified, in general, a good agreement between the numerical and the experimental values.
- *Human comfort index*. The numerical and experimental human comfort indexes are also compared. In order to validate the thermal comfort level, using the PMV and PPD indexes developed by Fanger [9], the numerical values and the experimental results are compared for uniform (using results presented in the specialized bibliography, see [17,19]) and non-uniform environments (using results obtained in subjective testes in the laboratory conditions, see [20]). The model forecast, associated to the global thermal comfort in non-uniform and uniform environment, is in accord to the subjective and empirical responses.

In this work the air temperature is 28 °C, the air relative humidity is 50%, the air velocity changes between 0 m/s and 0.6 m/s, while the Mean Radiant Temperature, that the human body sections are subjected, in accord to the following results, change in general between the 19 °C and the 37 °C. The considered occupants had 1.70 m of height, 70 kg of weight, 1.2 Met. of activity and 0.5 Clo. of clothing level.

In Fig. 4 the PMV index, in function to the Mean Radiant Temperature and the air velocity, calculated by the numerical model and by the Fanger model (see [9]), for uniform environment, is presented.

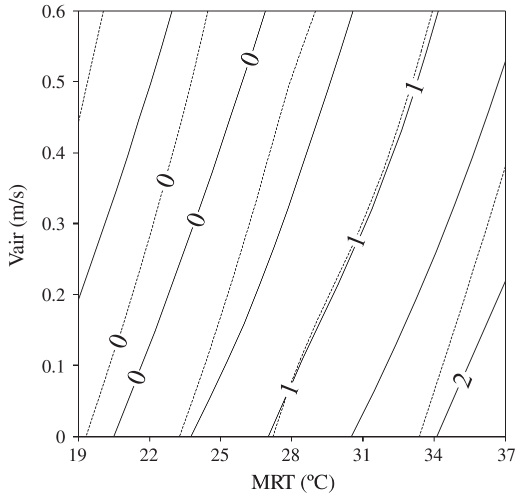

Fig. 4. Comparison between the Fanger (continuous line) and the numerical model (interrupted line) results obtained in uniform environments.

The difference between the results obtained by the Fanger model and the numerical model is highest when the air velocity is highest and the Mean Radiant Temperature is lowest and when the air velocity is lowest and the Mean Radiant Temperature is highest. In accordance with the obtained values the best correlation, between the two results, are obtained for the PMV index around the value 1. However, in the PMV index between 0 and 1.5 this difference, between the two results, is lower than 0.3.

5. Results and discussion

In this work the thermal comfort level that 24 students and 1 teacher are subjected in a classroom, in a lightly warm environment, equipped with radiant cooling non-uniform systems and subjected to convective uniform environments is evaluated.

The Mean Radiant Temperature, that each body section of the 25 occupants are subjected, calculated by the numerical model, for the individual three radiant cooling systems are presented from Figs. 5–7. In the first one the radiant floor cooling system, in the second one the radiant panels cooling system, while in the third one the radiant ceiling cooling system, are considered.

In accord to the obtained results, in general, is possible to conclude that, individually, the radiant floor cooling system presents the lowest Mean Radiant Temperature values, while the radiant panel cooling system presents the highest Mean Radiant Temperature values in the human body sections.

The radiant panel cooling system presents the highest radiant temperature asymmetries, mainly in the human body upper members of the occupants located near the warm curtain surface.

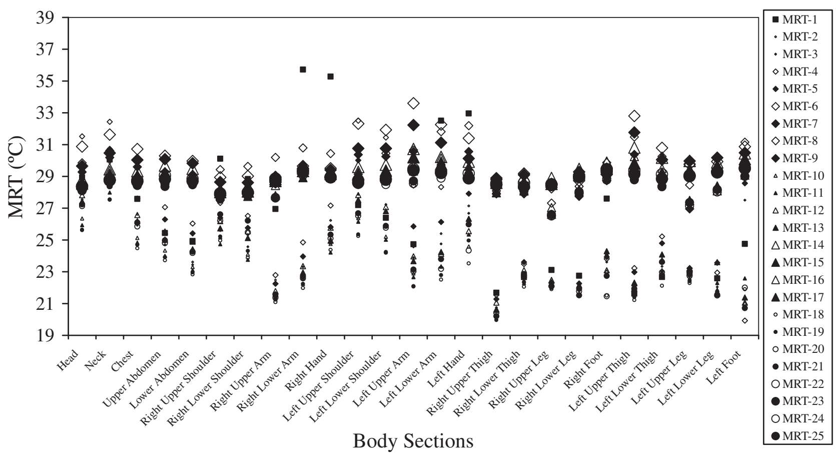

Fig. 5. Mean Radiant Temperature for each human body section of the 25 occupants, with radiant floor cooling system.

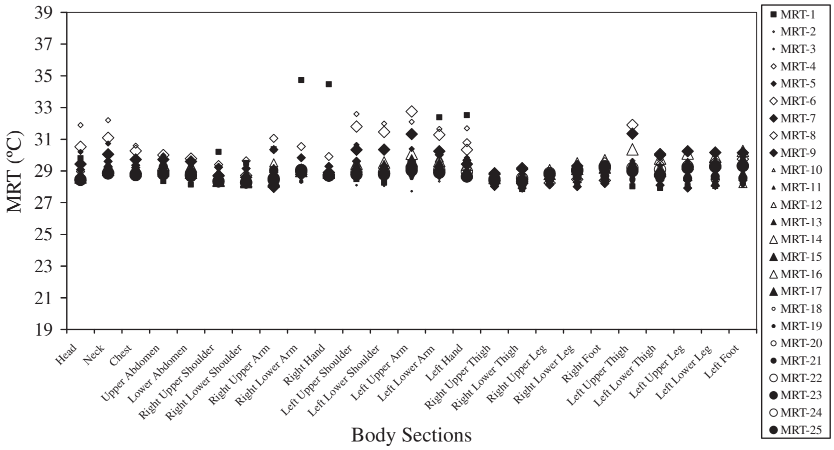

Fig. 6. Mean Radiant Temperature for each human body section of the 25 occupants, with radiant panels cooling system.

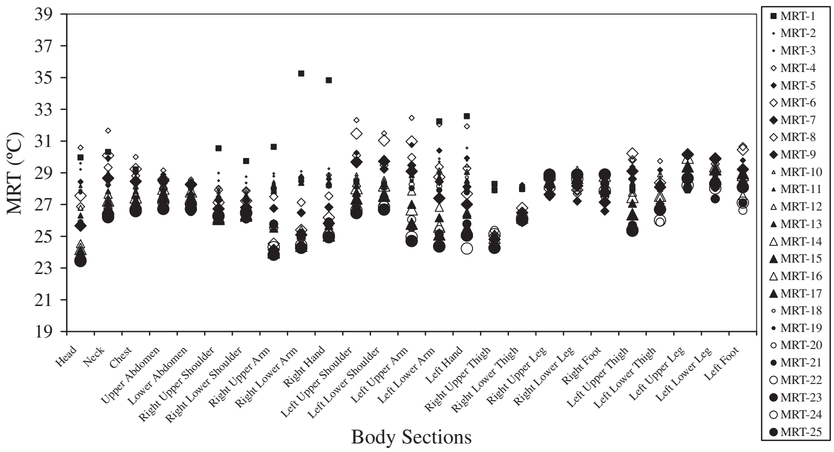

Fig. 7. Mean Radiant Temperature for each human body section of the 25 occupants, with radiant ceiling cooling system.

The radiant floor cooling system presents the lowest Mean Radiant Temperature values, in general, in the human body lower members, being the body upper members protected by the desk. The radiant ceiling cooling system presents, in general, opposite results.

The radiant ceiling cooling system presents lower Mean Radiant Temperature values in the human body section of the occupants located far from the teacher than the occupants located near the teacher, while the radiant floor cooling system presents opposite results.

The combination of radiant panel cooling systems with the radiant floor cooling systems or the radiant ceiling cooling systems, in general, decrease the Mean Radiant Temperature values in the human body sections, mainly in occupants located near the windows.

The Predicted Percentage of Dissatisfied people, for each occupant, without airflow field and with uniform airflow field of 0.2 and 0.6 m/s, are presented, respectively, in Figs. 8–10. In these figures the black symbols (⧫ and •) are associated to combined radiant cooling systems, the white symbols (◇, □ and ○) are associated to individual radiant cooling systems and the others symbols (× and ∗) are associated to referential situations. The W, Air, F, P and C presented in the legend of the figures are associated, respectively, to the Window protected to internal curtains, internal Air, radiant Floor cooling system, radiant Panel cooling system and radiant Ceiling cooling system.

In the first analysed situation in this work, without air velocity field and with uniform radiant environment (without radiant cooling system and with internal curtains temperature equal to the internal air temperature), the PMV index calculated for all occupants by the numerical model is 1.14 (PPD = 32.55%), while the PMV index calculated by Fanger model (see [9]) is 1.15 (PPD = 33.29%). These values show a difference, between the PMV index calculated through the numerical model and the empirical model presented in [9], of 0.01 (difference of the PPD index of 0.74%). Thus, in accordance with these results, a good agreement between the numerical and the empirical values for uniform environments is verified.

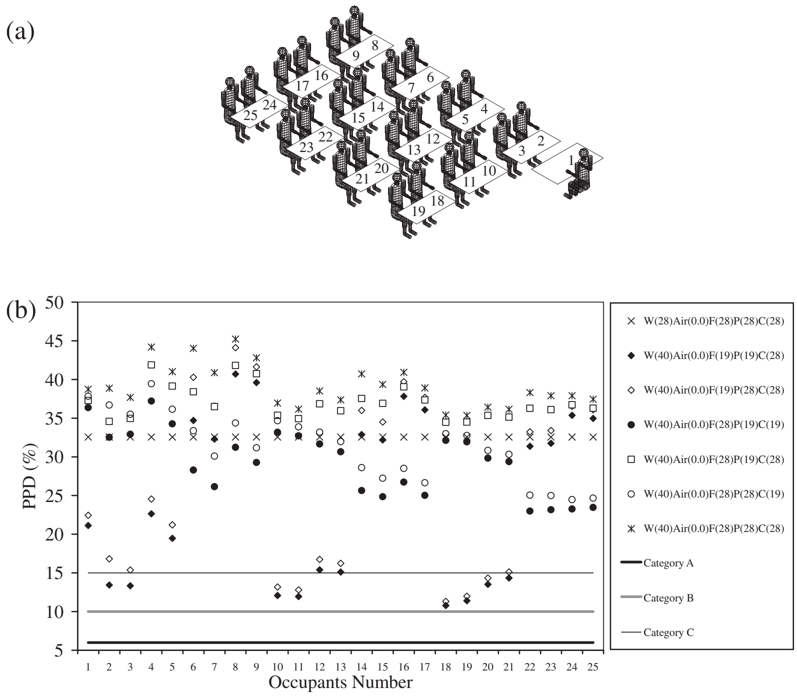

Fig. 8. PPD index for 25 occupants, for each analysed situation, without airflow field. Figure (a) shows the occupation locations and figure (b) the obtained results.

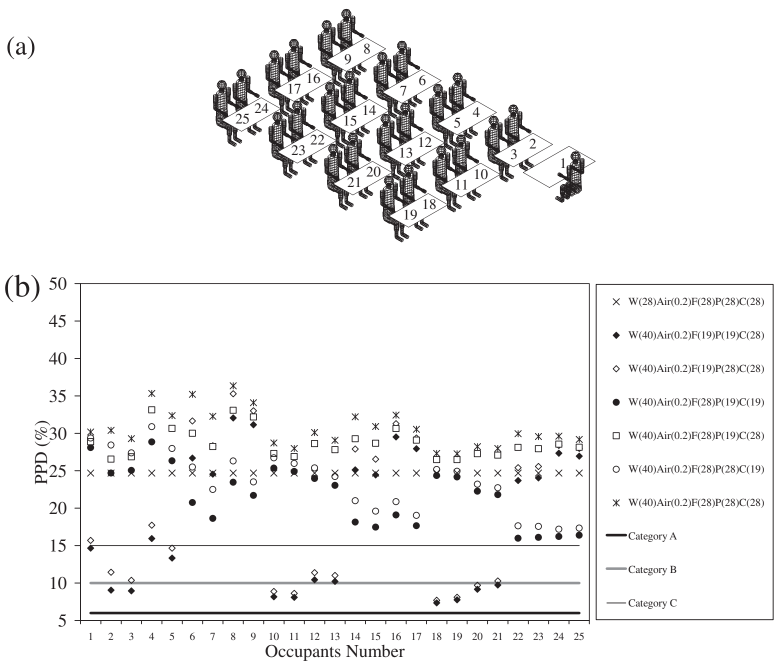

Fig. 9. PPD index for 25 occupants, for each analysed situation, with an uniform airflow field of 0.2. Figure (a) shows the occupation locations and figure (b) the obtained results.

In the second analysed situation, without air velocity field and with non-uniform radiant environment (without radiant cooling system and with internal curtains temperature different to the internal air temperature), the Predicted Percentage of Dissatisfied value for the occupants located near the windows is highest and the Predicted Percentage of Dissatisfied value

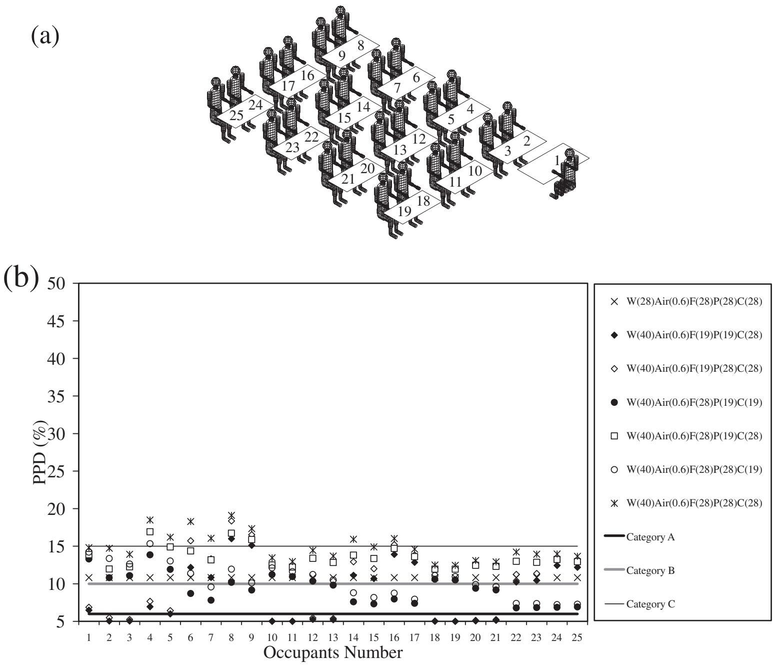

Fig. 10. PPD index for 25 occupants, for each analysed situation, with an uniform airflow field of 0.6 m/s. Figure (a) shows the occupation locations and figure (b) the obtained results.

for the occupants located far from the window is lowest. It is also verified that the Predicted Percentage of Dissatisfied value for the occupants located near the teacher is lowest and the Predicted Percentage of Dissatisfied value for the occupants located far from the teacher is highest.

In the third analysed situation, without air velocity field and with non-uniform radiant environment (with radiant cooling systems and with internal curtains temperature different to the internal air temperature), the Predicted Percentage of Dissatisfied value is lower for the radiant floor cooling system than the radiant ceiling cooling system and is lower for the radiant ceiling cooling system than the radiant panel cooling system. In general, in the radiant floor cooling system, the Predicted Percentage of Dissatisfied people is lowest near the teacher and highest far from the teacher, nevertheless in the radiant ceiling cooling system the opposite conclusions is verified. When the radiant ceiling or floor cooling systems with the radiant panel cooling system are combined the Predicted Percentage of Dissatisfied people decreases.

Finally, in the fourth analysed situation, with air velocity field and with non-uniform radiant environment (with radiant cooling systems and with internal curtains temperature different to the internal air temperature), the increases of the uniform air velocity increases the thermal comfort level, that the occupants are subjected. When the radiant floor cooling system or the combination of radiant floor and panel cooling systems without uniform air velocity field are applied the Category C is verified for some occupants. When a convective uniform air velocity field of 0.2 m/s is applied the Category B is verified for some occupants. Finally, when a convective uniform air velocity field of 0.6 m/s is applied the Category A is verified for some occupants. In the last situation the Category C is verified, in general, for all occupants.

6. Conclusions

In this work the thermal comfort level that 24 students and 1 teacher feel in a classroom, in a lightly warm environment, equipped with radiant cooling systems and subjected to convective uniform environments was evaluated. The combination of seven radiant cooling systems and three convective uniform environments were analysed.

The horizontal asymmetry in the human body sections is highest in the lateral radiant panel cooling system, mainly near the windows surfaces, nevertheless the vertical asymmetry in the human body is highest in the radiant floor or ceiling cooling systems. The combination of radiant panel cooling systems with the radiant floor cooling systems or the combination of the radiant panel cooling systems with the radiant ceiling cooling systems, in general, decrease the Mean Radiant Temperature values in the human body sections, mainly in occupants located near the windows.

The comfort conditions are higher in radiant floor cooling system than in radiant ceiling cooling system. Nevertheless, when the radiant ceiling cooling system or the radiant floor cooling system are combined with the radiant panel cooling system the thermal comfort conditions increase.

For the radiant floor cooling system the PPD value is lowest near the teacher and highest far from the teacher, nevertheless for the radiant ceiling cooling system the opposite conclusions are verified.

When the uniform air velocity increase the thermal comfort level, that the occupants are subjected, increases. When the radiant floor cooling system or the combination of radiant floor and panel cooling systems without uniform air velocity field are applied the Category C is verified for some occupants. However, with a convective uniform air velocity field of 0.2 m/s the Category B is verified and with a convective uniform air velocity field of 0.6 m/s the Category A is verified for some occupants. In the last situation the Category C is verified, in general, for all occupants.

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