Building Simulation 2003
Eighth International IBPSA Conference
Eindhoven, Netherlands
August 11-14, 2003

NUMERICAL SIMULATION OF BUILDINGS THERMAL BEHAVIOUR AND HUMAN THERMAL COMFORT MULTI-NODE MODELS

Eusébio Z. E. Conceição
FCMA – University of Algarve
8000 Faro - Portugal

ABSTRACT

In this work two numerical models are presented. The first one simulates the buildings thermal response and evaluates the internal air quality, while the second one simulates the human and clothing thermal systems and calculates the thermal comfort level in non-uniform environments. The results obtained by the first model are used as input data in the second one.

These programs will be used in the simulation of the thermal behaviour of a building, in project phase, located in the South of Portugal in a Winter day with clean sky, and in the evaluation of the thermal comfort level that an occupant is subjected, in a compartment located in the second floor with a window turned towards West.

INTRODUCTION

The topic of numerical simulation of building thermal behaviour and human thermal response has been studied by several authors. The first topic was analysed, for example, by Ozeki *et al.* (1992), Cammarata *et al.* (1994) and Mendes and Santos (2001), while the second one has been studied, for example, by Fiala *et al.* (1999), Huizenga *et al.* (1999) and Farrington *et al.* (2001). In the philosophy used in the present work, the building thermal behaviour model is used, in the first phase, to calculate not only the temperatures evolution in compartments and building bodies, but also the contaminants mass evolution in the compartments. In a second phase, these informations are used by other model, that simulates the human and clothing thermal behaviour simultaneously for a group of persons, to evaluate the thermal comfort level that an occupant is subjected inside the several compartments and in different locations of interest.

The first numerical model, that simulates the building thermal response and evaluates the internal air quality, considers all spaces and all building bodies. This model calculates not only the temperature of the air inside the different compartments, the several windows glasses, the different interior bodies (furniture, curtains, climatization systems,...) located inside spaces and the several slices of the building main bodies (doors, walls, ground, roofs, ceilings,...), but also the water vapour mass inside spaces and in the interior surfaces and the mass of contaminants (CO_2, O_2,...) inside spaces. It also calculates (1) the real distribution of incident solar radiation in the internal and external surfaces, (2) the view factors between different interior surfaces in each space, (3) the radiative heat exchange between internal surfaces, using the radiosity method, (4) the radiative heat exchange between building external surfaces and the surrounding bodies, (5) the heat and mass transfer coefficients by convection, between the surfaces and the air, (6) the glasses radiative coefficients, (7) the relative humidity inside different compartments and (8) the mass transfer between different spaces and between several spaces and the external environment.

The second numerical model, that simulates the human body and clothing thermal responses and analyses simultaneously several persons inside a space, considers each human body divided in 35 cylindrical and spherical elements. This model calculates not only the temperature of the human body tissue slices, arterial and venous blood, and clothing slices, but also the mass of blood and transpired water in the skin surface and clothing slices, in each element. It also calculates the (1) human posture, (2) view factors between the human body elements and the surrounding surfaces, (3) heat exchange between the body and surrounding surfaces, using the radiant temperature, (4) solar radiation that each element is subjected inside the compartment, (5) the heat and mass transfer coefficients by convection and (6) the thermal comfort level in non-uniform environments, using the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indexes (see ISO 7730 (1994)).

INPUT DATA

The input data used by the buildings thermal behaviour model are the tridimensional geometry, the materials thermal proprieties and other conditions. Firstly, all spaces are identified. The compartments geometry is defined through the introduction of involving bodies: building main bodies and windows glasses bodies. These bodies, with complex geometry, that are associated to the boundary of two compartments (or of a compartment and the external environment), are flat. As the main bodies are divided in several slices, in order to simulate the thermal stratification verified in these bodies, it is also necessary to identify the slices thickness. In the compartments geometry is important to introduce the more relevant interior bodies in the simulation. In the second part, are introduced the main bodies, windows glasses and interior bodies thermal proprieties. Finally, it is also necessary to introduce the external environmental and geographical conditions, the initial conditions of the simulation, the heat load released by the human bodies, heating and air-conditioning systems (and other internal sources), air recirculation, air exchanges between compartments, air exchange between each compartment and the external environment and to identify the internal mass generation and its intensity.

The results obtained by the first model, which are associated to the air mean temperature and relative humidity in the compartment, the surrounding surfaces temperatures, solar radiation and compartment geometry, are used as input data to the second model. It is also needed to introduce the occupant's location and to define their postures. The air velocity around the occupants is also possible to introduce.

Using these input data the programs built one energy and mass balance integral equations system for the building and a second one for the occupants. In the resolution of these systems is used the Runge-Kutta-Fehlberg method with error control (see Burden and Faires (1985)). The software can also visualise the building and occupant geometry or export a file to be seen in a compatible code.

BUILDING THERMAL BEHAVIOR

The buildings thermal behaviour multi-node model, that works in transient conditions, is based in energy and mass balance integral equations. The energy balance integral equation are developed for the air inside compartments, the windows glasses, the interior bodies located inside spaces and the different building main bodies, while the mass balance integral equations are developed for the water vapour inside spaces and in the interior surfaces (main bodies, windows glasses and interior bodies) and air contaminants (CO_2, O_2, ...) inside spaces. This kind of equations, applied in buildings, had been used by several authors, for example, by Cammarata *et al.* (1994), Strand *et al.* (2001) and Mendes and Santos (2001).

The model considers the conductive phenomena between different slices of the main bodies. In the ground is imposed a fixed temperature at a predefined dept.

There are considered natural, forced and mixed convection phenomena between the internal and external buildings surfaces and the adjacent fluid. In the determination of the heat transfer coefficient by convection are used empirical expressions published in specialised bibliography (see, for example, Guyer and Brownell (1999)).

The mass transport phenomena (water vapour and other gases) are divided in four parts: mass exchange between different compartments (1), mass exchange between each space and the external environment (2) and mass generation inside spaces (human respiration and transpiration) (3) (see Berne (1994)). In the water vapour transport are also considered the mass exchange between the internal surfaces and the air inside spaces (4). Using the water vapour mass values and the air temperature values the model calculates the air relative humidity (see ASHRAE Handbook (2001)).

Finally, the radiative phenomena (verified inside and outside the building), in the present model, are divided in short-wave and long-wave radiation.

In short-wave radiation, associated to the solar radiation, it is calculated the real distribution of the solar radiation not only in external surfaces (main bodies and windows glasses), but also in the internal surfaces (main and interior bodies). In the external surfaces (see figure 1a) are calculated the absorbed and reflected radiation in the main bodies and the absorbed, reflected and transmitted radiation in the windows glasses, while in the interior surfaces (see figure 1b), using the transmitted solar radiation through the glasses, are calculated the absorbed and reflected radiation in the main and interior bodies surfaces (see Ozeki *et al.* (1992)).

In the long-wave radiation, the model considers not only the heat exchange between the building external surfaces and the nocturnal sky and the surrounding surfaces (other buildings, vegetation,...), during the day, but also heat exchange between the internal surfaces (main bodies, windows glasses and interior bodies) of each space (see figure 2). The diffuse radiation between grey surfaces, in each enclosure, is calculated through the radiosity method, through the view factors and the surfaces temperature (see Ozeki *et al.* (1992)).

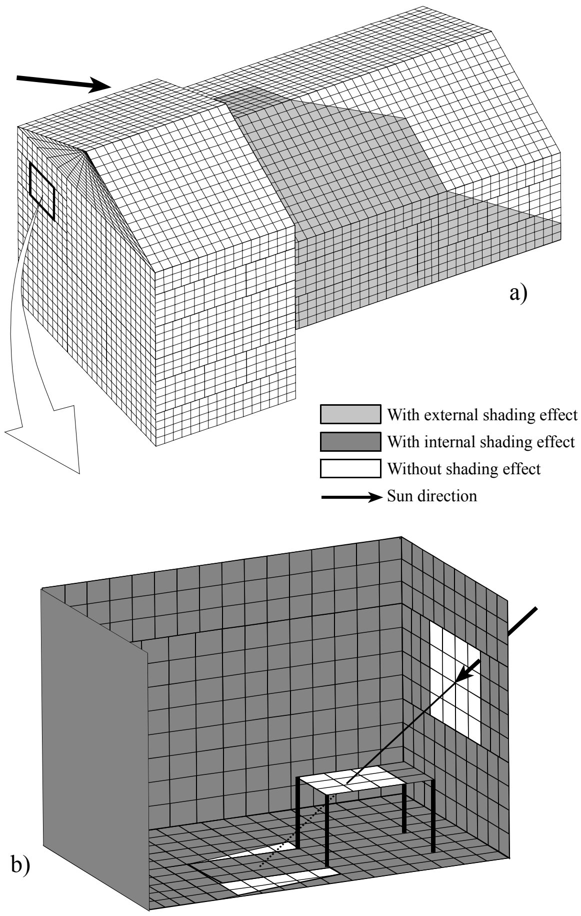


Figure 1 – Scheme of the real distribution of solar radiation in external (a) and internal (b) surfaces with and without shading effect.

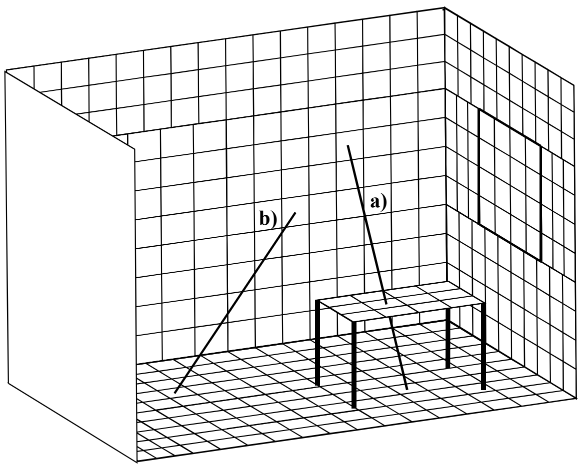


Figure 2 – Scheme used in the internal long-wave radiation with (a) and without (b) shading effect.

In the radiative calculus, of long-wave and short-wave radiations, are considered the shading effect caused by the surrounding surfaces (buildings or other obstacles) and by internal surfaces (main and interior bodies in each compartment) (see Corrado *et al.* (1995)). In these calculus all building surfaces (main bodies, windows glasses and interior bodies) are sub-divided in several small areas (see figures 1 and 2).

HUMAN THERMAL COMFORT

In the human thermal comfort multi-node model, that works in transient conditions and simultaneously simulates a group of persons, the tridimentional body is divided in 34 cylindrical and 1 spherical elements. Each element is sub-divided in 12 cylindrical (or spherical) slices and could be still protected from the external environment through some clothing slices. More details about this simplified human body can be analysed, for example, in Conceição (2000), Conceição and Lúcio (2001) or in Conceição and Lúcio (2002).

The human thermal response is based on energy balance integral equations for the human body tissue slices 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. The clothing thermal response is based on energy balance integral equations for the clothing slices, as well as mass balance integral equations for the clothing slices in each element. These integral equations are based in the following phenomena (see Conceição (2000)): internal metabolism, heat conduction through the tissue, blood circulatory convection, heat loss by respiration to the environment, heat exchange between the body and the environment (or clothing) by radiation, convection, conduction and evaporation. To control the human body temperature is implemented a model, based in Stolwijk (1970), that simulates the thermo-regulatory system.

The human body, inside an internal space, is subjected to short-wave to long-wave radiations. In this calculus the 35 human body elements and the surrounding external surfaces are divided in small areas. More details about the grid generation around the human body and in the surrounding surfaces, in complex topology, can be analysed in Conceição (2003). The philosophy used in the short-wave radiation calculus, with the parallel ray method (see, for example, Ozeki *et al.* (1998)), can be seen in figure 3 (a1, b1 and c1). To calculate the heat exchange by radiation between the human body external surface and the surrounding surfaces are used the mean radiant temperature (see Fanger (1970)). These calculus are based in the view factors and in the surrounding surface temperatures (see figure 3 (a2, b2 and c2)). In the radiative calculus, long-wave and short-wave radiations, were considered the shading effect of the human body elements (see figure 3b) and the surrounding surfaces (see figure 3c) (see Corrado *et al.* (1995)).

To evaluate the thermal comfort level, in steady state conditions, are used the PMV and PPD indexes, presented by Fanger (1970). These indexes are based in the heat flux exchanged between the body and the environment (see also Miyanaga and Nakamo (1998)).

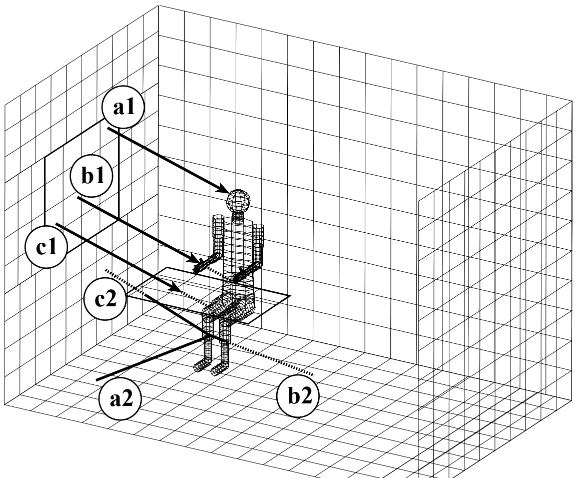


Figure 3 – Scheme of short-wave (number 1) and long-wave (number 2) radiations, without (a) and with shading effect caused by the human body elements (b) and the surrounding surfaces (c).

NUMERICAL SIMULATION

In this work these models are used to simulate the thermal behaviour of a building, with complex geometry, and to evaluate the global thermal comfort level, in a non-uniform environment. The idea is to use the results obtained in the first model (related with the surrounding surfaces temperature field, the air temperature and relative humidity, and the solar radiation in the occupied space and the compartment geometry), in the second model to evaluate the human thermal comfort level in a specified situation.

Building Thermal behaviour

This numerical model, that also was used and validated in multi-nodal vehicles (see Conceição (2001)), after being validated with some preliminary experimental tests in buildings, was used to evaluate the thermal response of a building, in project phase, located in the South of Portugal during a Winter day with clean sky. In this building (see figure 4), divided in 11 compartments, were considered 118 main bodies, 8 window glasses and 4 interior bodies (stairs located in the first floor and a desk located in the second floor).

In the main bodies, windows glasses and interior bodies was used a composition similar to real buildings in this country.

In the beginning of the simulation were calculated, inside the 11 spaces, 3890 view factors. In this calculus each surface was divided in areas not higher than 0.25×0.25 m^2. In figure 5 is presented the grid generation used in the short-wave and long-wave radiative calculus in the building. In the building thermal simulation of air recirculation and renovation, the heat and mass sources in spaces, the heating systems and the human heat load were not considered. The doors and windows were closed and the windows shading devices had not been considered in this calculus.

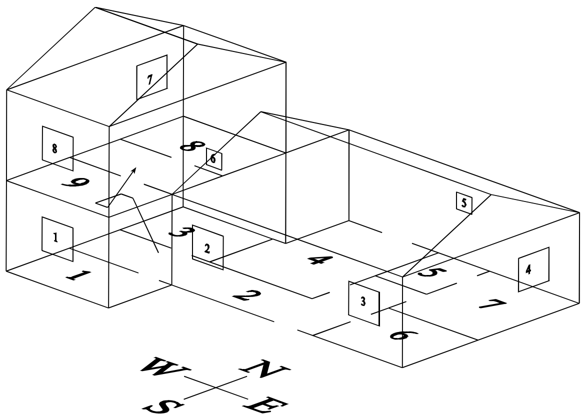


Figure 4 - Scheme of the analysed building. The horizontal and vertical numbers are associated, respectively, to compartments and windows locations.

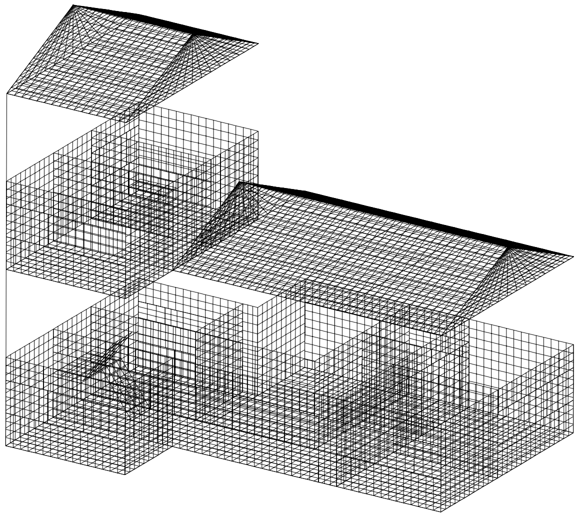


Figure 5 – Scheme of grid generation used in the radiative calculus in the building.

The air temperature (see figure 6) and relative humidity (see figure 7), in the external environment, was obtained experimentally in a Winter typical day. During the experimental test the sky remained clean and there was no wind.

In figure 8 are presented the evolutions of air mean temperatures inside the compartments 1 (in the first floor, with a window turned towards South), 3 (in the first floor, with a window turned towards North), 7 (in the first floor, with a window turned towards East), 8 (in the second floor, with a window turned towards West) and 9 (in the second floor, with a window turned towards South). In this simulation, done in 5th February, it was also considered the five previous days, to evaluate the heat stored in building materials. The evolution of the glasses temperature in the windows 1, 2, 4, 6 and 7 is presented in figure 9.

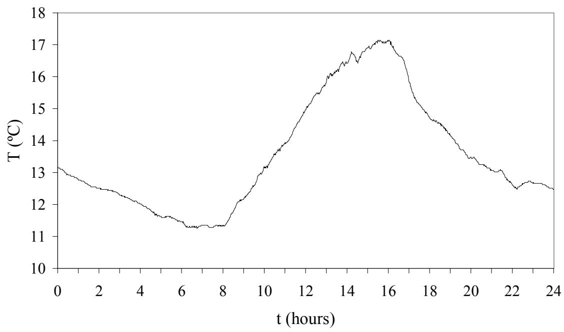


Figure 6 – Air temperature in the external environment obtained experimentally in a winter typical day with clean sky.

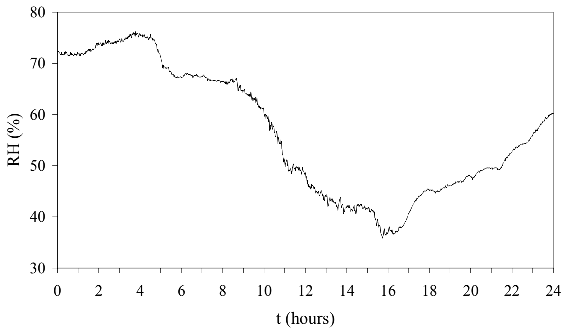


Figure 7 – Air relative humidity in the external environment obtained experimentally in a winter typical day with clean sky.

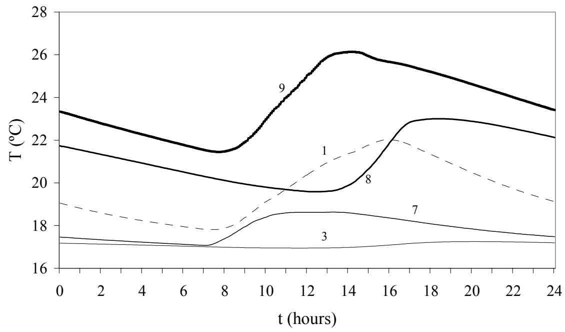


Figure 8 - Evolution of the air mean temperature inside the compartments 1, 3, 7, 8 and 9.

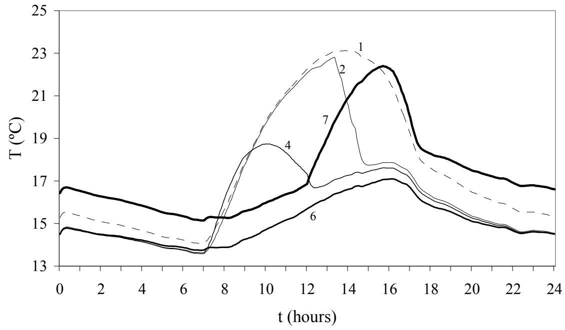


Figure 9 - Evolution of the glasses temperature in the windows 1, 2, 4, 6 and 7.

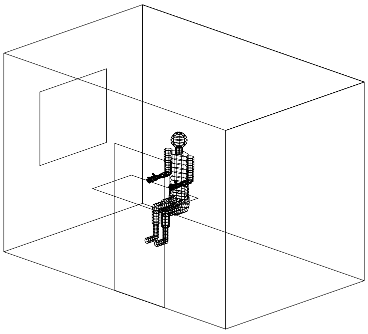
The results obtained in the first part of this study, related to the building thermal behaviour, show that:

- in general, the air temperature values are the lowest in compartments with windows turned towards North and the highest in compartments with windows turned towards South;
- the air temperature values in compartments located in the second floor, in general, are higher than in compartments located in the first floor;
- the glasses temperature, in general, are the highest for windows turned towards South. Nevertheless, when they are shaded by building bodies this is not verified (see the glass temperature evolution for the window 2 after 13.30 p.m.).

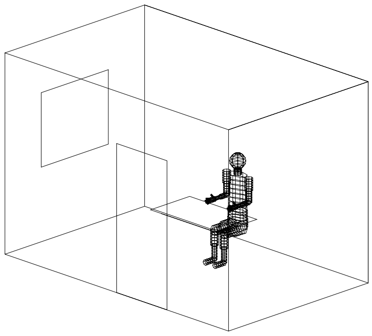
Human Thermal Comfort

After being validated, with experimental data obtained in laboratory and presented in specialised bibliography (see, for example, Conceição and Lúcio (2001)), the model is used to evaluate the thermal comfort level that an occupant is subjected in the compartment 8, when is seated in the desk near (see figure 10a) and far from (see figure 10b) the window. After being verified that the solar radiation field that an occupant is subjected (when is seated in the desk near the window) is highest around 16 p.m., was decided to analyse the human thermal comfort at this hour.

Figure 11 shows the grid generation in the external surface of the seated occupant.



a)



b)

Figure 10 – Scheme of the location of the occupant in the compartment 8, when he is seated near (a) and far from (b) the window.

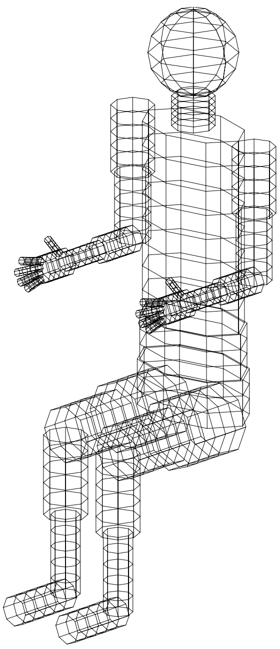


Figure 11 – Grid generation in the seated occupant's body external surface.

The occupant considered was 1.7 m of height, 70 Kg of weight, 1.2 met of activity and 1.1 Clo of clothing level (light underwear, shirt with long sleeves, pullover, long trousers, light socks and shoes). The air temperature and relative humidity, calculated by the buildings thermal behaviour multi-node model, were 21.9 ºC and 42.2 %, respectively. The radiant mean temperature and the solar radiation flux, calculated by the human comfort multi-node model, are presented in the figures 12 and 13, respectively. Finally, the PMV and the PPD indexes, that the occupant is subjected at 16 p.m., when is seated near and far from the window, are presented in table 1.

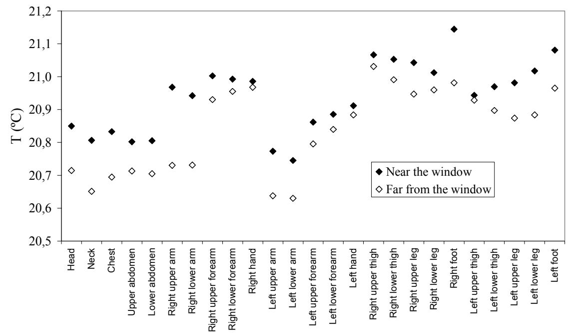


Figure 12 – Radiant mean temperature in the human body elements, when the occupant is seated near and far from the window.

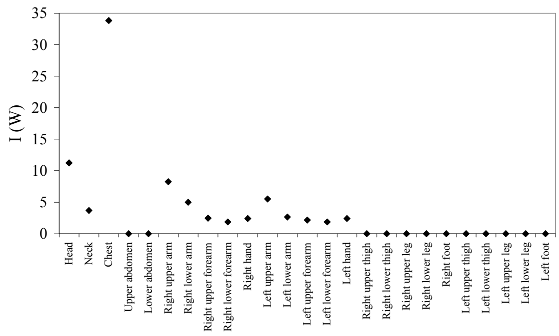


Figure 13 – Solar radiation flux in the human body elements, when he is seated near the window.

Table 1 – PMV and PPD indexes that an occupant is subjected near and far from the window.

Location	PMV	PPD (%)
Near the window	1.2	35.2
Far from the window	-0.3	7.2

The analysis of the results shows that:

- the radiant mean temperature field that an occupant is subjected is lightly higher near the window than far from the window. This value is lightly higher in the body right side than in the left side. Nevertheless, this asymmetry is not very significant;

- the occupant seated in the desk near the window is subjected to direct solar radiation in the head, neck, chest and upper members. In the abdomen and inferior members the solar radiation is shading by the desk;
- in accord to ISO 7730 (1994), the occupant seated near the window is thermally uncomfortable. Nevertheless, when he is far from the window, not subjected to solar radiation, he is in thermal comfort conditions.

CONCLUSIONS

In this work two numerical models, that evaluate respectively the buildings thermal behaviour and the human thermal comfort, were presented. The first one was used in the thermal study of a building, with two floors, located in the South of Portugal in a Winter day with clean sky. The second one was used in the evaluation of thermal comfort level that an occupant is subjected, when he is seated in a compartment with a window turned towards West.

It was verified that at 16 p.m., when the occupant is seated near the window, uncomfortable conditions were obtained. Nevertheless, if the occupant is not subjected to direct solar radiation, the comfort thermal conditions are obtained.

These models, in collaboration, can be used to develop buildings thermally efficient with optimised thermal comfort levels. They are a very important tool to be used not only in the study of special compartments, like offices, classrooms and atria, for example, where is important to create good comfort conditions for seated occupants, but also in the project of localised heating, ventilation, air conditioning and radiant panel systems, in non-uniform environments.

In this work was not analysed the local discomfort level. This topic will be done in future studies. The building thermal behaviour model, in the near future research, will be subjected to more experimental tests in buildings with complex topology.

ACKNOWLEDGEMENT

The author acknowledges the support by INOVALGARVE program, CCR-Alg and DREALG, sponsored by the European comunitary fund FEDER.

Part of this research activity is also being developed inside a project approved and financed by the FCT and POCTI, sponsored by the European comunitary fund FEDER.

REFERENCES

ASHRAE Handbook, “Fundamentals”, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, USA, 2001.

Berne, Ph., “Prediction of the Concentration Decay in a Ventilated Enclosure by the Multi-zone Model”, RoomVent 1994 - 4th Int. Conference on Air Distribution in Rooms, Kraków, Poland, 1994.

Burden, R. L. and Faires, J. D., “Numerical Analysis”, Prindle, Weber & Schmidt, Boston, USA, 1985.

Cammarata, G.; Fichera, A.; Forgia. F.; Marletta, L. and Muscato, G., “Thermal Load Buildings General Models and Reduce Models”, Healthy Buildings 1994, Proc. of the 3rd Int. Conference, Budapest, Hungary, 1994.

Conceição, E. Z. E. and Lúcio, Mª M. J. R., “Influence of Non-Uniform Airflow from Different Directions in the Thermal Comfort Level in Seated Persons”, RoomVent 2002 - 8th Int Conference on Air Distribution in Rooms, Copenhagen, Denmark, 2002

Conceição, E. Z. E. and Lúcio, Mª M. J. R., “Numerical and Subjective Responses of Human Thermal Sensation”, BioEng 2001, 6th Portuguese Conference on Biomedical Engeering, University of Algarve, Faro, Portugal, 2001.

Conceição, E. Z. E., “Evaluation of Thermal Comfort and Local Discomfort Conditions Using the Numerical Modelling of the Human and Clothing Thermal System”, RoomVent 2000 - 7th Int. Conference on Air Distribution in Rooms, University of Reading, United Kingdom, 2000.

Conceição, E. Z. E., “Geração de Malha em Torno de Ocupantes em Compartimentos com Topologia Complexa”, VII Congresso de Mecânia Aplicada e Computacional, University of Évora, Évora, Portugal, 2003.

Conceição, E. Z. E., “Multi-nodal Models of Vehicles Thermal Behaviour and Passenger Thermal Response”, Florence ATA 2001 - 7th Int. Conference, Florence, Italy, 2001.

Corrado, C.; Pretti, M. and Sacchi, A. “Routine for Calculation of Angle Factors Between Human Body and Car Driver’s Cabin”, Proc. ATA Congress, Bologne, Italy, 1995.

Fanger, P. O., “Thermal Comfort: Analysis and Applications in Environmental Engineering”, McGraw-Hill Book Company, USA, 1970.

Farrington, R; Barber, G.; Hendrichs, T.; Marion, W.; Markel, T.; McGuffin, R. and Rugh, J., “Integred Modeling to Predict Occupant Thermal Comfort”, Florence ATA 2001 - 7th Int. Conference, Florence, Italy, 2001.

Fiala, D.; Lomas, K. J. and Stohrer, M., “A Computer Model of Human Thermoregulation for a Wide Range of Environmental Conditions: the Passive System”, Journal of Applied Physiology, Vol. 87, Issue 5, November, pp.1957-1972, 1999.

Guyer, E. C. and Brownell, D. L., “Handbook of Applied Thermal Design”, Taylor & Francis, Philadelphia, USA, 1999.

Huizenga, C.; Hui, Z. ; Duan, T. and Arens, E., “An Improved Multinode of Human Physiology and Thermal Comfort”, in Proc. of 6th Int. IBPSA Conference Building Simulation 1999, Vol. 1, pp. 353-359, 1999.

ISO 7730, “Moderate Thermal Environments - Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort”, International Organisation for Normalisation, Switzerland, 1994.

Mendes, N. and Santos, G. H., “Dynamic Analysis of building Hygrothermal Behavior”, in Proc. of 7th Int. IBPSA Conference Building Simulation 2001, Vol. 1, pp. 117-123, 2001.

Miyanaga, T. and Nakamo, Y., “Analysis of Thermal Sensation in a Radiant Cooled Room by Modified PMV”, RoomVent 1998 - 6th Int. Conference on Air Distribution in Rooms, KTH, Stockholm, Sweden, 1998.

Ozeki, Y.; Konishi, M.; Narita. C. and Tanabe, S., “Effective Radiation Area of Human Body Calculated by a Numerical Simulation”, RoomVent 1998 - 6th Int. Conference on Air Distribution in Rooms, Stockholm, Sweden, 1998.

Ozeki, Y.; Yamamoto, M.; Saito, T.; Ohgaki, S. and Sonda, Y., “Simulation on Temperature and Flow Field in the Atrium (Part1. Computation of Solar Radiation, Radiative Heat Transfer, Air Flow, and Temperature”, RoomVent 1992 – 3rd Int. Conference on Air Distribution in Rooms, Aalborg, Denmark, 1992.

Stolwijk, J. A. J. “Mathematical Model of Thermoregulation”, in Hardy, J. D., Gagge, A. P. and Stolwijk, J. A. J. “Physiological and Behaviour Thermoregulation”, Thomas, Springfield, pp. 703-721, 1970.

Strand, R. K.; Pedersen, C. O. and Crawley, D. B., “Modularization and Simulation Techniques for Heat Balance Based Energy and Loads Calculation Programs: the Experience of the ASHRAE Loads Toolkit and Energyplus”, in Proc. of 7th Int. IBPSA Conference Building Simulation 2001, Vol. 1, pp. 43-50, 2001.