Modelling of Coupled Heat Transfer and Mass Transfer In Unconditioned Buildings : Application to the Winter Thermal Comfort.

L. Gharbi[1], N.Ghrab-Morcos[1] and J. J. Roux[2]

[1] Ecole Nationale d'Ingénieurs de Tunis, U.R Energétique des Bâtiments et Systèmes Solaires,
BP 37, 1002 Tunis Belvédère, Tunisie
[2] Centre de Thermique de Lyon, INSA de Lyon, 20 Av. Albert Einstein, Villeurbanne, France
CNRS-UMR 5008 – UCBL – INSA de LYON

ABSTRACT

Modelling thermal and aerial behaviour of unconditioned buildings requires an accurate knowledge of the air temperature and velocities fields inside the considered spaces. Furthermore, in our Mediterranean context, thermal and aerial aspects must be considered coupled together, because of their very strong interdependence. We have then developed a three-dimensional dynamic modular model of coupled heat transfer and airflow calculation. Its coupling with a thermal comfort model permits to evaluate the thermal quality of buildings by the prediction of a comfort vote.

This paper presents an application of our coupled simulation tool dealing with the influence of a passive solar component, upon the winter thermal comfort of an unconditioned Tunisian building. The results obtained have shown that the zonal modelling approach transcends the limitations of isotherm models to describe realistically the thermal comfort within a building.

KEYWORDS

Zonal model, Heat transfer, Temperature field, Thermal comfort, Sun patch, ZAER.

NOMENCLATURE

C_d	discharge coefficient [-]
$[F]$	view factors matrix (NftxNft)
$[I]$	Identity matrix (NftxNft)
M	molar mass of air [kg/mole]
$\dot{m}_{s,i}$	mass flow rate of supplied air [kg/s]
Nft	facets number
P	air pressure [Pa]
R	gas constant [kg.m^2/mole.s^2.K]
S	facet surface [m^2]
T	zone air temperature [°C]
$T_{s,i}$	supplied air temperature [°C]

Greek symbols

α	absorption coefficient for radiation [-]
ε	emissivity [-]
$[\varepsilon_{LW}]$	diagonal emissivities matrix (NftxNft)
φ	heat flux density [W/m^2]
ρ	air density [kg/m^3]
$[\rho_{SW}]$	diagonal reflectivities matrix (NftxNft)
σ	Stefan–Boltzmann constant

Subscripts

b	relative to beam solar radiation
i	relative to the zone or the surface i
v	relative to the glazing

INTRODUCTION

The assessment of the thermal and the aerial behaviour of buildings in the Mediterranean context necessitates an accurate knowledge of the air velocities and the air temperature within the considered space. Indeed, most of the Tunisian dwellings are not air-conditioned and their thermal performances are generally based on the thermal comfort quality they procure for their occupants. An accurate evaluation of the thermal comfort requires detailed information about temperature field and airflow pattern. Furthermore, in our particular context where active solutions of air-conditioning should be avoided, thermal and aerial aspects must be considered coupled together, because of their very strong interdependence.

Several computer models for calculating heat transfer and air flow in buildings have been developed since some years as TRNSYS (1994), Esp-r (1996)…. However, if most of them calculate accurately the heat transfer, they evaluate the air flow with a simplified way by assuming that the considered room is a single zone with homogeneous air temperature and pressure. The majority of these software do not allow to describe the indoor air stratification nor the air velocity distribution inside the building.

These reasons lead us to develop a three-dimensional modular simulation tool of coupled heat transfer and airflow, ZAER (Gharbi and al 2004), that permits to study the thermal and aerial behaviour of our buildings in transient conditions and to evaluate the thermal sensation of their occupants by its coupling with a Comfort model (Ghrab 1991).

This paper presents an application of the model ZAER dealing with the influence of a passive solar component, on the winter thermal comfort of a free running temperature Tunisian building. We have particularly take interest to the thermal sensation of a building's occupant according to his location regarding to the sun patch.

MODELING METHODS

Our methodology consisted of developing a zonal model in temperature and pressure to evaluate the air temperature distribution and the airflow pattern within a room, and a thermal model based upon the coupling of heat transfer conduction reduced-order state models to calculate the surface temperatures of the considered room. Our simulation code ZAER is based upon the coupling of these two models by an iterative strategy of connection. Different simulation results have shown that ZAER can predict satisfactorily air temperature field and air flow within a room (Gharbi 2005).

Description of the Aerial Model

Zonal models are based on an approach that is intermediate between CFD models like Fluent (1996) that give detailed information about air temperature and velocities but are computationally intensive, and multizone models with single-node air temperature and pressure like COMIS (Feustel 1999) which can not give informations about the airflow pattern and the air temperature distribution within a room.

The zonal method is based on the spatial division of the air volume into a finite number of parallelepiped control volumes (zones) in which air temperature and air density are supposed to be constant, while pressure varies hydrostatically. These zones are connected between them by interfaces through which circulate airflow and heat flux.

Our model is based on solving the indoor pressure field to predict the air mass flow rates and the air temperatures within a given building, assuming that the air velocities through the interfaces are only generated by the pressure difference on both sides (Bouia 1993). This formulation of zonal models is founded on the uniformity and the low amplitude of the air velocities of the current zones. High velocity zones must be modelled with specific laws to describe realistically the air flow.

The mass flow rate $\dot{m}_{ij}$ through the interface of two adjacent current zones i and j is assumed to be monodirectionnel and governed by a power-law equation (Eqn. 1):

$$\dot{m}_{ij} = \sqrt{2\rho}\varepsilon_{ij}C_d S_{ij}\left|\Delta P\right|^{\frac{1}{2}} \tag{1}$$

with: $\left|\varepsilon_{ij}\right| = 1$, $\mathrm{sign}\left(\varepsilon_{ij}\right) = \mathrm{sign}\left(\Delta P_{ij}\right)$, $\rho = \rho_j$ if $\varepsilon_{ij} = 1$ and $\rho = \rho_i$ if $\varepsilon_{ij} = -1$

For an horizontal border, the pressure drop $\Delta P_{ij} = P_j - P_i - \frac{1}{2}\left(\rho_i g h_i + \rho_j g h_j\right)$

We neglect heat conduction in the air and we assume that there is no internal heat source in the air supposed to be incompressible. Under these assumptions, mass and thermal balance equations are applied to each cell of the computational domain, with air considered as an ideal gas. Solving these equations enables us to determine air temperature and density in each zone, and unknown airflows between their interfaces.

Description of the Thermal Model

The envelope model has to be adapted for the coupling with the aerial zonal model, it has also to calculate accurately the internal distribution of long-wave and short-wave radiation, in order to simulate realistically the thermal behaviour of buildings in transient conditions. Our thermal model is based on the energy balance equation applied to all the interior and exterior envelope facets. We present briefly the modeling methods used to evaluate the conductive heat transfer and the interior radiative transfer within a room; more details can be founded in Gharbi and al (2005).

Modeling conductive heat transfer

The particularity of our envelope model is that the conductive heat transfer is based upon the coupling of reduced-order state models (Roux 1993). The reduction technique used is the linear aggregation method. This modelling approach allows the accurate characterisation of the dynamic behaviour of the building using reduced dimension systems. It permits an accurate calculation of conductive heat transfer through geometrically complex walls. The building materials of the walls are not considered as homogeneous layers, as is the case for most thermal software, but are described accurately.

Modeling interior distribution of short-wave and long-wave radiation

Each wall of the building envelope is discretized into several surfaces called facets. Every interior facet of the envelope model is connected with one air temperature node of the zonal aerial model.

The radiosities method is used to compute the net LW radiation fluxes absorbed by the interior facets of the building envelope. An accurate evaluation of the internal distribution of the LW radiation necessitates an exact knowledge of the view factors between the different facets. Thus the modelling approach was developed to calculate them precisely.

The net long-wave radiative flux density vector, exchanged between all the interior facets of the envelope is expressed as:

$$\overrightarrow{\varphi_{riLW}} = \left[RILW\right]\overrightarrow{T_{si}^4} \tag{2}$$

$\left[RILW\right]=\sigma\left[\left[I\right]-\left[F\right]\right]\left[\left[I\right]-\left[\left[I\right]-\left[\varepsilon_{LW}\right]\right]\left[F\right]\right]^{-1}\left[\varepsilon_{LW}\right]$ is the matrix of the LW radiative interior exchanges. It depends only on the building geometry and on the facets emissivities. It is then calculated at the beginning of the simulation, for the considered building.

To compute the internal distribution of SW radiation we have used a method similar to that of the radiosities, which enabled the accurate evaluation of the multiple reflections between the facets. It introduces a total exchange factor $\hat{F}_{ij}$ which is defined as the fraction of diffuse radiation leaving the facet i and striking the facet j after multiple reflections (Ghrab 1991). The total exchange factor matrix $\left[\hat{F}\right]=\left[\left[I\right]-\left[F\right]\left[\rho_{SW}\right]\right]^{-1}\left[F\right]$ depends only upon the building geometry and the facets reflectivities for the SW radiation.

The net radiative SW flux density of an interior envelope facet i has the following expression:

$$\varphi_{riSW}=-\alpha_{iSW}\left(B_i+\frac{\sum_{k=1}^{Nft}\rho_{kSW}\hat{F}_{ki}S_kB_k+\sum_{v=1}^{Nv}\hat{F}_{vi}\tau_{bv}S_vE_{bv}}{S_i}\right) \tag{3}$$

Where B_i represents the beam solar radiation that strikes the facet i from the direct solar radiation passing through the Nv building glazings.

DESCRIPTION OF THE SIMULATED CASE

The simulated building is a parallelepiped room which has a floor area of 24 m², and a height of 3 m. It has a glazed surface of 3 m² located on its south wall.

Simulations were performed for a winter day which corresponds to the 21 December. Our thermal model does not include a sun patch model; we have calculate its location for the considered day at noon(Figure 1), regarding to the solar altitude h, the latitude of Tunis (36.8°) and the declination wich is equal to -23.45°.
We assume that the room is occupied by a person having a light activity (1.5 met), the thermal resistance of his clothes is 1 clo, which corresponds to winter clothes.

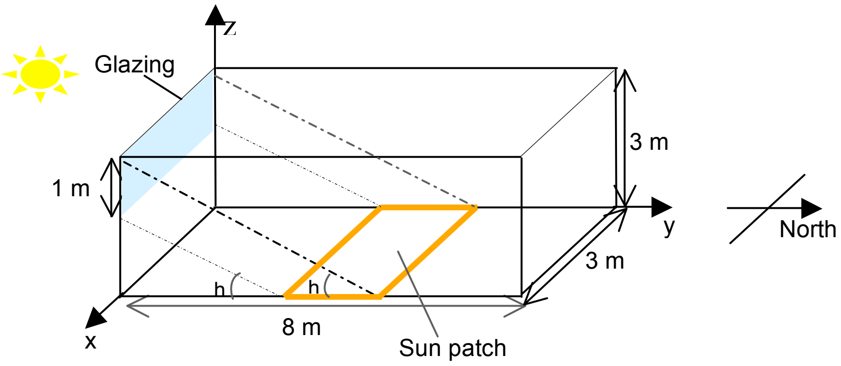

Figure 1: Location of the sun patch

RESULTS AND DISCUSSION

Figure 2 presents the isotherms in the y-z middle plane of the room, at 1:00 pm. To evaluate accurately the thermal comfort inside the room, we have plotted the isovalues of the comfort votes (Figure 3) and the corresponding PMV (Figure 4).

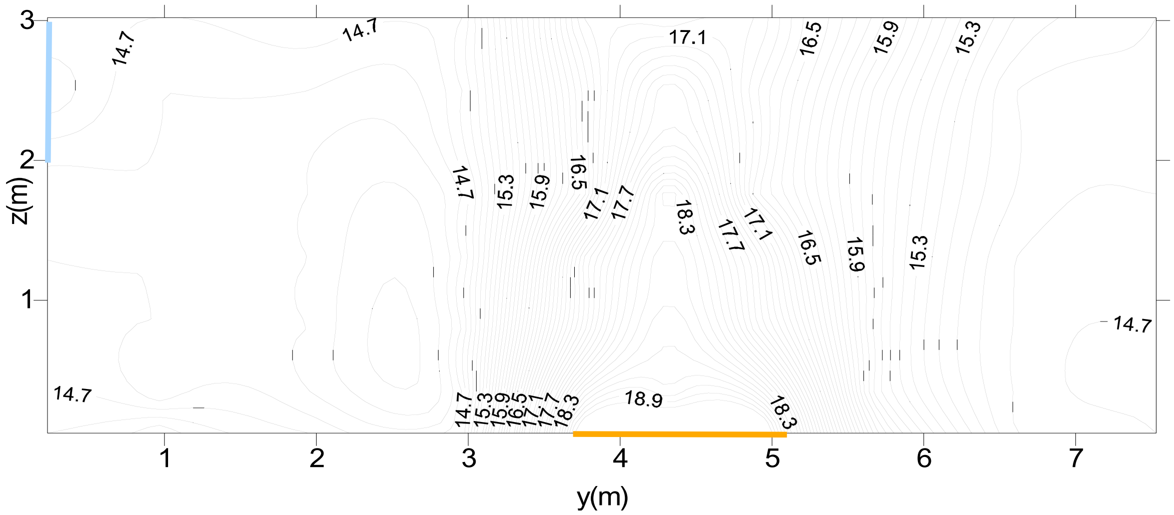

Figure 2: Isotherms in the y-z middle plane at 1:00 pm.

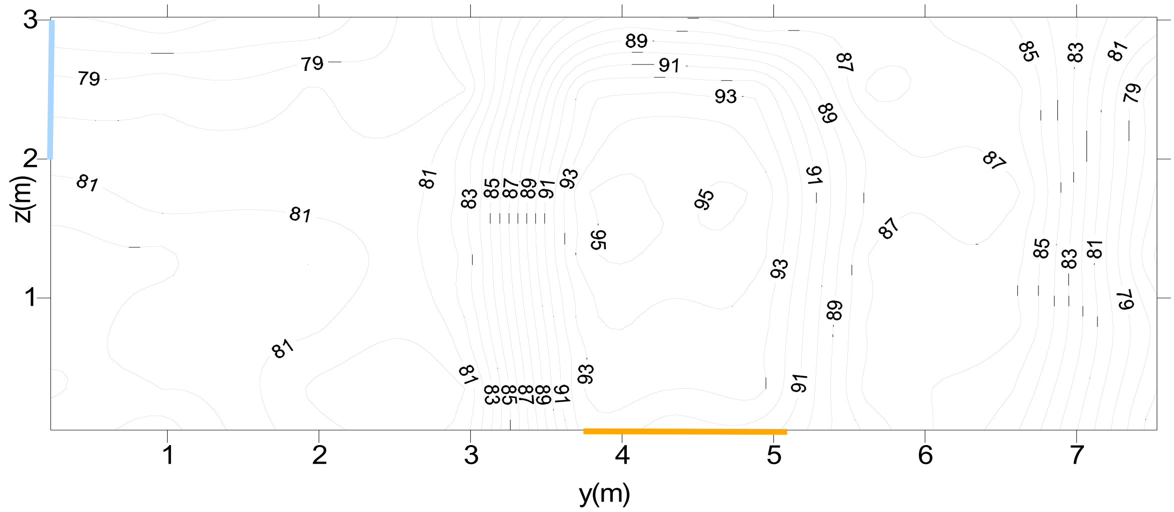

Figure 3: Iso-comfort votes in the y-z middle plane at 1:00 pm.

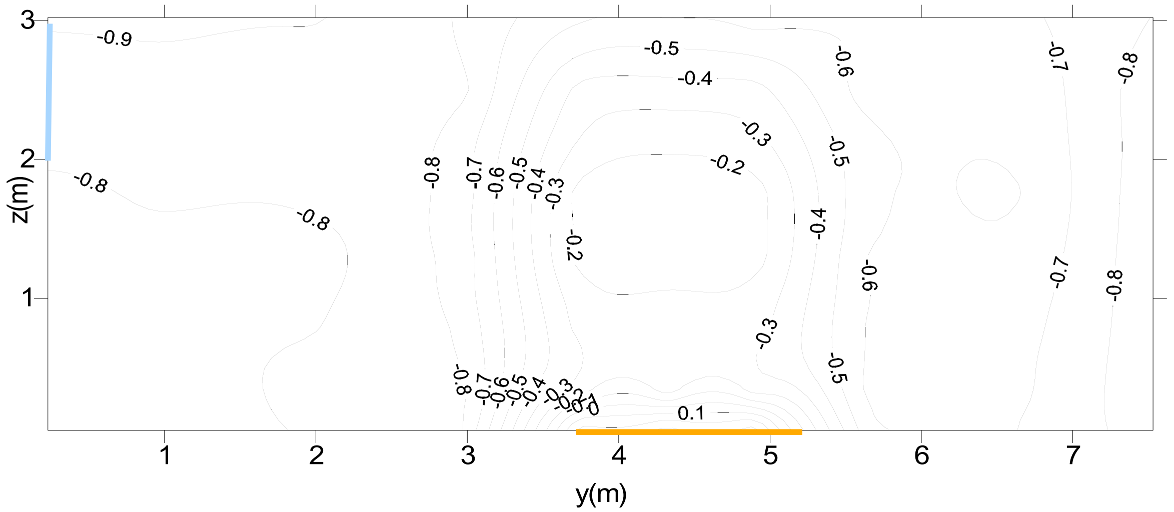

Figure 4: Iso-PMV in the y-z middle plane at 1:00 pm.

Figure 2 shows a non-homogeneous temperature distribution in the region of the room where the sun patch is located. The air temperature near the floor is close to 19°C, it decreases progressively according to the room height until it reaches 17°C near the roof. We also observ an horizontale stratification in the Oy direction, the temperature difference between the sun patch region and the zones near the south and north walls is about 3.5°C. Except this central region of the room, the temperature field is quite homogeneous and close to 14.7°C.
According to Figure 3, we notice that the thermal sensation of an occupant varies depending on his position within the room. In fact, a person located in the sun patch region will be in a situation of thermal well being, with a comfort vote varying between 89% and 95% and a PMV varying between -0.4 and 0.1 (see Figure 4). An identical person, located in the same plane, but near the walls, will not be very satisfied by the thermal quality of the room, the comfort vote varying between 79% and 81% with a corresponding PMV equal to -0.8, which corresponds to a cool sensation.

These results show that the global evaluation of the thermal comfort of a building, based upon mean values of air temperatures and comfort votes, is inadequate for predicting realistically the thermal sensation of its occupants. By considering mean values, we obtained a comfort vote of 89% inside the room at 1:00 pm. However, at the same time, a person located in certain zones of this room will feel a thermal discomfort.

CONCLUSION

We have developed a 3D modular code of coupled heat transfer and airflow, ZAER, which allows the prediction of the air temperature field and the airflow pattern within a room, in transient conditions. We have studied the influence of a glazing upon the air temperature distribution and the thermal comfort quality in an unconditioned room, using our coupled model. The obtained results have shown that a passive solar component can be an efficient heating measure to improve thermal winter comfort in our Mediterranean context. We have also demonstrated, through this example, that our coupled model transcends the limitations of isotherm models to describe realistically the thermal comfort within a building. The work in progress is the insertion of a sun patch model to improve the prediction of the thermal and aerial behaviour of large highly glazed buildings.

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