ANALYSIS AND OPTIMIZATION OF THE THERMAL COMFORT OF A NON AIR-CONDITIONED 16 000 M2 TENT, WITH TRANSIENT AND CFD SIMULATIONS

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ABSTRACT

The Haima is a non air-conditioned 16,000 m^2 tent designed to house fifteen exhibitions about conditions for peace, viewed as solutions to economic, cultural and environmental conflict, during the Barcelona Forum 2004. The Haima is composed of several tents connected to each other's and to the exterior environment through large openings. The whole structure is placed on the middle of a large square, next to the Mediterranean Sea.

The aim of the study is to analyze and optimize the thermal comfort of the Haima taking into account the specific external conditions (weather data), the internal conditions (occupancy, gains, etc.), the materials and all the parameters that affect this singular construction. The main objective was to avoid any HVAC equipment and to assure that the visitants would be comfortable. To do so, some transient simulations have been carried out using TRNSYS software (SEL, 2003) to obtain the internal temperatures and thermal comfort indexes. These temperatures were further exported as boundary conditions to a CFD code to carry out natural and forced convection airflow simulations inside the tents to improve the reliability of the thermal analysis. The CFD code is a finite element code developed at the Polytechnic University of Catalonia. Any details on the formulation can be found in the internal monographs (Codina 1993) and (Houzeaux and Codina 2002).

This paper explains the methodology used in the project, analyze the proposals made to improve the thermal comfort of the Haima by the authors to the design team and present the results.

INTRODUCTION

The Barcelona Forum 2004 was an unclassifiable event where 30 hectares were filled with ideas, distributed throughout parks, streets, auditoriums. The Haima was conceived as one of the main spaces occupying the central square of the area. This huge surface provides opportunities to watch and listen, create, experiment, taste, discover and get excited. The opening season of the Forum was from beginning of May to the end of September 2004, thus covering the hottest period in summer. One of the main concerns of the persons in charge of the design was to guarantee the thermal comfort of the visitants during summer and at the same time to avoid the air-conditioning of the space. One of the key topics in the Forum was the promotion of a new energy model based on improved use and research on renewable energy sources, as well as more efficient consumption, especially in urban environments. Figures 1 and 2 show different pictures of the Haima during the celebration of the Forum.

Figure 1 View of the Haima from inside

Figure 2 View of the Haima from outside

Starting from a basic proposal of the architects and engineers in charge of the project and the building process, a handful of proposals were analyzed together with the architecture and engineering team. The aim of the proposals was to assure pleasing thermal comfort conditions during the majority of the hours of the opening period. PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) (ISO, 1994) were used as the thermal comfort indexes to compare the kindness of the proposals.

The influence of the sea breeze in the local climate in the area (500 m far from the sea) was detailed studied and considered. A detailed analysis of the climatic data was developed, as it was essential for the realization of the study. Three periods of time with real data were used to complete the comfort analysis, named the design period, the extreme period and the opening periods.

To do so, some transient simulations have been carried out using TRNSYS software to obtain the internal temperatures and the comfort indexes. These temperatures were further exported as boundary conditions to a CFD software to carry out natural and forced convection airflow simulations inside the tents to improve the reliability of the thermal analysis and refine the assumptions of the dynamic simulation.

ANALYSIS OF LOCAL CLIMATE

When ventilation plays a significant role in the conception and behavior of a building, studies and measurements at microclimatic scale are important and essential for a good prediction of the energetic performance of the building (Santamouris et al., 1998). During the years 2001, 2002 and 2003, a meteorological station was placed in the Barcelona Forum 2004 area to register temperature, relative humidity as well as wind velocity and direction every 30 minutes. Solar radiation was also measured. The data measurements took time from August 2001 to September 2003.

This huge amount of data was treated to extract the essential information for the design of the Haima. The first and most important point to make clear is the evolution and direction of the wind in the area of study. In the figures that follow below, details of the results of the analysis for the summer months could be appreciated. In figure 3 we can clearly detect two predominant directions of the wind: between S and SSW during the day (i.e., coming from the sea) and between N and NNE at night, being the mean velocity in the south direction greater than the velocity from the north. In days with no calm, wind velocity usually reaches about 4-5 m/s. In summer, as can be appreciated in the figure, the period of the day when sea breeze is blowing goes from mid morning to late evening. At night, the wind is blowing mainly from the north, the countryside. This behavior could be clearly appreciated in Figure 4. Figure 5 shows the location of the Haima with respect to the north and in relation with the prevailing wind directions.

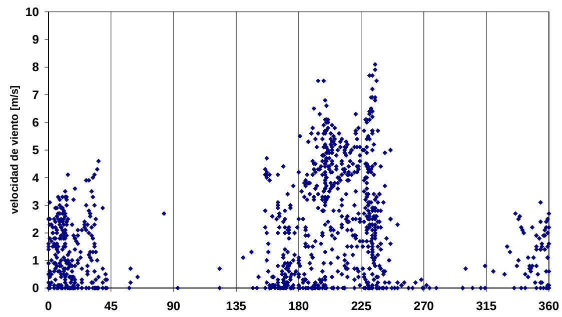

Figure 3 Wind direction (º) and velocity (m/s). Dispersion graph for different hours in a summer month

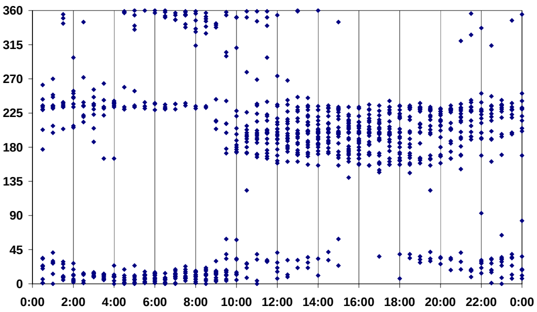

Figure 14 Hours of the day and wind direction (º). Dispersion graph for different hours in a summer month

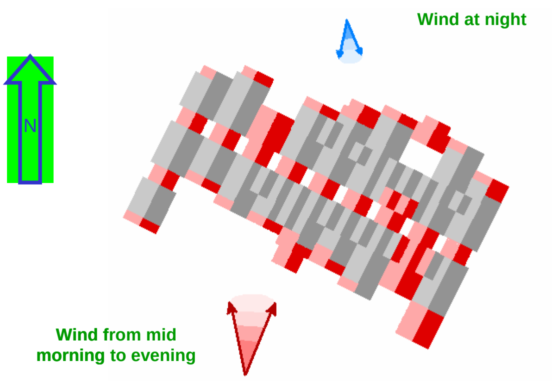

Figure 5 Localization of the Haima. Prevailing wind directions by day and night.

In order to test the design of the Haima in several situations, three periods of time were considered. The first one is the named **design period**. It is a real four days period in summer with high solar radiation and high temperatures, extracted from the available measured data. The highest temperature in the period is 29.1 ºC. As it was depicted in figures 7, the period is characterized by a typical profile of wind blowing with a maximum air velocity of 6 m/s.

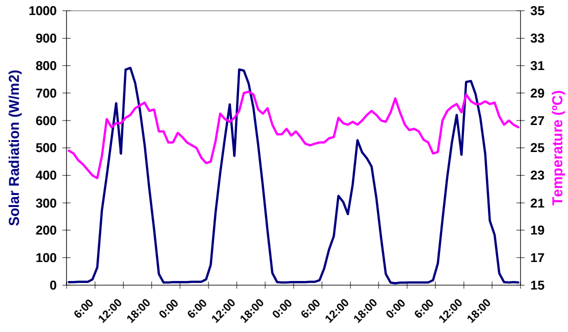

Figure 6 Temperature (ºC) and Solar Radiation (W/m^2) in the design period

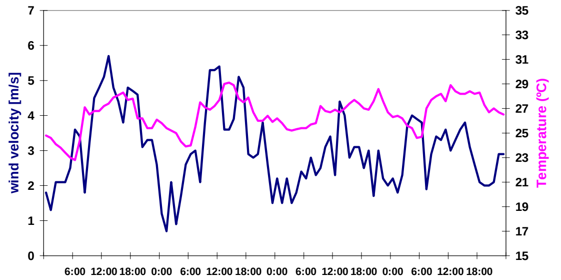

Figure 7 Temperature (ºC) and Wind Velocity (m/s) in the design period

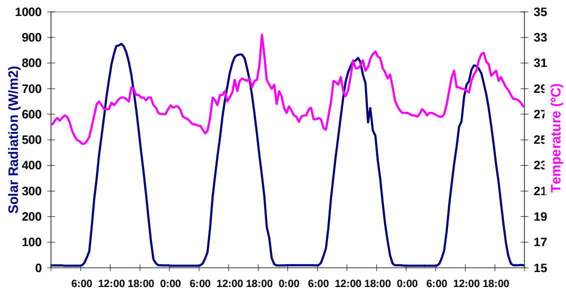

Figure 8 Temperature (ºC) and Solar Radiation (W/m^2) in the extreme period

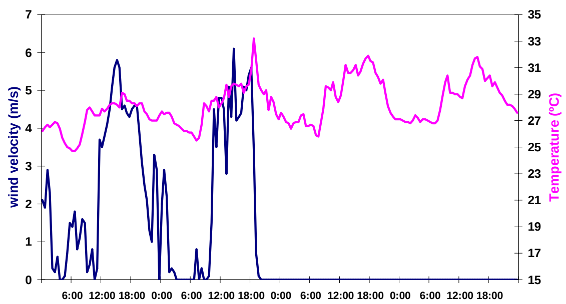

Figure 9 Temperature (ºC) and Wind Velocity (m/s) in the extreme period

The so-called **extreme period** was also defined, corresponding to one of the extreme periods of year 2002. It is also a four-day period with extremely high radiation; the maximum temperatures in three of the four days are higher than 32 ºC. Figure 8 and 9 shows temperature, solar radiation and wind velocity in that period. One of the main differences between design period and chosen extreme period is that for this last one two or the four days are calmed, i.e. in the absence of wind. Finally, another period was defined covering the whole opening season of the event, from beginning of May to the end of September. The period is named **opening period**. Data used are from a TMY created with CLIMED (Aguiar, 2002).

DESIGN PROPOSALS

Description of the Haima basic design

Several like row modules of 20 m wide and different lengths compose the Haima. This design imitates the tents used by the Tuaregs in the Sahara desert. The interior space of the tents was conceived as an open space for hosting exhibitions, fairs and temporary events to be visited by people while they are rambling. Only the essential internal divisions were planned. The center of the Haima is 7.8 meters tall and the height of the sidelongs is about 1.5 meters. A sketch of the section of the Haima can be appreciated in Figure 10.

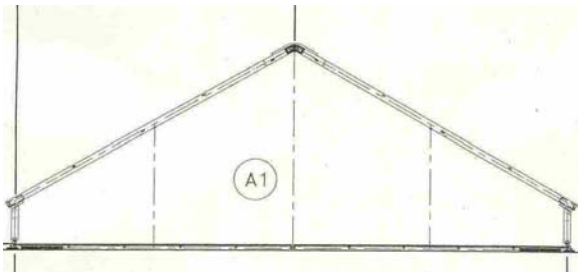

Figure 10 Section of the Haima. Sketch

The cover of the tent was formed by a double envelope of canvas. The inner cover was canvas made of cotton. The color is clear and it was assumed that the layer is 5% transparent to solar radiation. The outer cover of was made of CANATEX® 18, with a porosity of 18%. The color was in the base clear but this outer cover was serigraphed with colored pictures. An air space of 20 cm separates the two layers of the envelope along its whole length. At the low and the top of the chamber, the air chamber is open so air could freely enter and exit through the chamber by its outermost sides and also by the outer and porous cover. A special finishing was placed at the building top, made up of metallic veneer, as a small dome. The top was initially designed to allow exhaust air to exit from the Haima and with the same shape along every row.

The side covers of the tent were designed to allow air circulates as much as possible between the different rows and between the tent and the outside. Then, no internal division existed between rows. The side covers were made of CANATEX® 27, having a porosity of 27%, allowing daylighting to the interior. The usual floor in non-permanent exhibitions was planned by the Haimas, with the only feature that the whole structure was 15 cm over the square where it was placed.

Proposals of improving thermal comfort

The main purpose of the study was to demonstrate that the design of the Haima combined with the effect of the sea breeze is enough to assure a minimum number of hours of thermal discomfort in the hot summer period.

A first analysis shows that the situation in the months of July and August was critical and could be out of the range of acceptability. So, in parallel some proposals have been made to the architects. Not all the proposals were deeply studied, because some were rejected at the very begin of the process, for economical or other type reasons. One type of proposals intended to reduce the solar radiation entering the space; a second type of proposals intends to increase the convective exchange with the outside; others are trying to reduce the radiant temperature inside and other ones try to increase the relative velocity of the air inside the Haima helping to have better thermal comfort. Here you have a summary of those proposals:

- Reflective surface between the two canvas layers.
- Automatic and periodic cleaning system of the cover, in order not to allow the increase of the absorptivity by dirt.
- Using green plants in the laterals, with the objective to reduce direct solar gains.
- Increase ventilation and velocity of the air inside the Haima by mechanical devices.
- Increase natural ventilation inside the Haima with a new design of the dome.
- Localized cooling system in areas with the highest internal gains planned (some exhibition areas), through a floor cooling system.

Finally, the proposals accepted were to assure natural ventilation with an improved design of the Haima's top and to force ventilation when it was needed by mechanical devices.

DYNAMIC SIMULATIONS

Hypothesis

Transient simulation computation using TRNSYS has been held in order to evaluate approximately the energetic behavior of the Haima. Selected modules of the Haima were selected depending of the level of planned internal gains (internal gains are dominated by the occupancy and the effect of the different exhibitions) and the relative position in the Haima.

Cover was treated as a thermal zone limited by the two canvas layers and with a level of infiltrations directly related with the wind velocity. The following table shows the solar heat gain coefficient (g-value) and the visible transmission (t-vis) of the transparent materials. Canvas layers were treated at the simulation level as windows.

Table 1
Features of the canvas covers: material, g-value and visible transmission

COVER	MATERIAL	G-VALUE	T-VIS
Outer top	CANATEX 18	0.25	0.18
Inner top	COTTON	0.15	0.05
Sidelong	CANATEX 27	0.33	0.27

Measured values in a prototype installed in October 2003 allow comparing how the movement of the air is in the air chamber and inside the space, depending of the wind velocity outside the tent. The correlation extracted from this measured values was adopted for estimating the ventilation inside the air chamber and the tent as a first approach.

Limitation of dynamic simulation with TRNSYS and using its Type56 multi-zone building model is that is not appropriate to simulate energetic behavior in cases where thermal stratification plays a significant role. Model used by TRNSYS assume that the air in a zone is well mixed. More detailed simulation as CFD simulations were necessary to complete the study by this reason

Thermal comfort

Thermal comfort calculation is based on EN ISO 7730. The normative, based on the theory of Fanger, determines two indexes, the named PMV (Predicted Mean Vote) and the PPD Predicted Percentage of Dissatisfied), which are dependent of the thermal conditions (air temperature, radiant temperature and relative humidity) and of other factors as:

- the clothes dressed by occupants
- the metabolic rate which represents a heat production depending on the activity level
- the external work and
- the air velocity relative to the occupants

Table 2 shows the values considered to compute PMV and PPD in the project.

Table 2
Default values for the PMV and PPD calculus

VARIABLE	VALUE
Clothing factor	0.5 clo

Metabolic rate	1.6 met
External work	0.0 met
Relative air velocity	Variable, depending of wind outside

CFD SIMULATIONS

Introduction

CFD simulations were carried to analyze the airflow in the following situations, as sketched in figure 11:

- Series 1. Airflow in the square around the Haima.
- Series 2. Forced convection airflow inside a single module of Haima.
- Series 3. Natural convection airflow inside a single module of Haima.

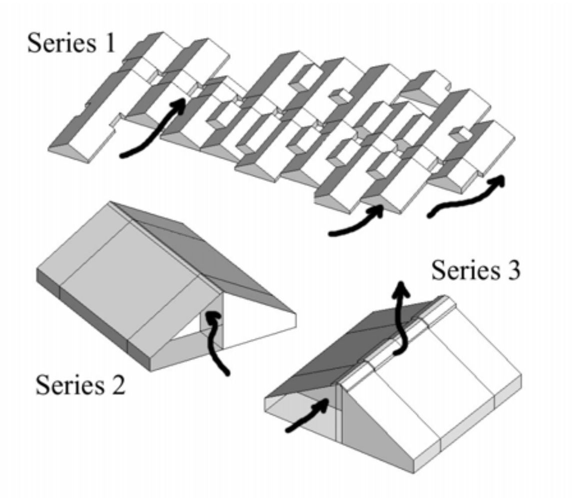

Figure11. Three cases studied through CFD

The first series of simulations consisted in simulating the airflow blowing through the square, inside and around the Haima. The objective was to obtain the mean wind velocities at each tent to forecast their natural ventilation possibilities. The second series consisted in solving the forced convection flow due to wind across a tent, including the effects of the curtains used to protect the occupants from possible high velocity wind. Finally, the last series consisted in simulating the stack effect occurring in rough summer conditions in a tent, in the absence of wind.

Governing equations

At the physical level, the three flows under consideration have some similitudes and differences. They all involve turbulent flows. Flows 1 and 2 are considered iso-thermal as they are governed by forced convection phenomena. Flow 3 involves natural convection and is therefore thermally coupled. Despite these singular characteristics, they are all modeled with the same system of governing equations, and turbulence is treated with a single one turbulence model, namely Spalart-Allmaras (SA) model (Spalart and Allmaras, 1992). While the two-equation k-ε turbulence model is extensively used in the simulation of ventilation problems (Chen, 1995), SA model was preferred for several reasons: it involves only one additional differential equation; it is computationally robust; in many situations (forced convection) it gives similar results to two-equation turbulence models. The use of this model in the case of non-isothermal flows has not been well explored. However, we do not pretend to capture here precise wall behavior, heat transfer, etc.

Let ν be the kinematic viscosity of air; κ its thermal diffusivity; $\mathbf{u}$ its velocity; p its kinematic pressure; T its temperature. The governing equations are the following:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} - 2\nabla\cdot\left[(\nu+\nu_t)\,\varepsilon(\mathbf{u})\right] + \nabla p + s\mathbf{u} = \mathbf{f}$$

$$\nabla\cdot\mathbf{u} = 0\,.$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T - \nabla\cdot\left[(\kappa+\kappa_t)\nabla T\right] = 0$$

The quantity $\varepsilon(\mathbf{u})$ is the velocity symmetrical gradient tensor such that

$$\varepsilon(\mathbf{u}) = \frac{1}{2}\left(\nabla\mathbf{u} + \nabla\mathbf{u}^T\right).$$

$\mathbf{f}$ is the vector of body forces per unit of mass. It includes the gravity acceleration $\mathbf{g}$ and the buoyancy term coming from the Boussinesq assumption, which is:

$$\mathbf{f} = \mathbf{g} - \mathbf{g}\beta(T - T_0)\,,$$

Variable s is porosity like term added to model the curtains of the Haima. T_0 is the reference temperature. The variables ν_t and κ_t are the eddy viscosity and diffusivity respectively, the latter one being given as a function of ν_t

$$\kappa_t = \frac{\nu_t}{\mathrm{Pr}_t}\,,$$

where Pr_t is a dimensionless parameter called the turbulent Prandtl number (which varies between 0.9 and 1.0 for air). The turbulent viscosity is computed using SA turbulence model, which consists of a single partial differential equation that solves directly for the eddy viscosity

$$\frac{\partial \nu_t}{\partial t} + \mathbf{u}\cdot\nabla\nu_t + c_{w1} f_w \frac{\nu_t^2}{d^2} - \frac{1}{\sigma}\nabla\cdot\left[(\nu+\nu_t)\nabla\nu_t\right] = \frac{c_{b2}}{\sigma}(\nabla\nu_t)^2 + c_{b1} S \nu_t\,,$$

where c_{w1}, σ, c_{b1} and c_{b2} are constants of the model, S is the module of the vorticity, d is the distance to the wall and f_w is a function of the vorticity, the distance to the wall, and the eddy viscosity itself. The version displayed here is to be used for high-Reynolds number flows. A low-Reynolds number version, which includes additional terms, is also available. It is not shown here for the sake of clarity.

Boundary conditions

The boundary conditions used here are the following:

- On walls: law of the wall for **u,** T and ν_t.
- At inflow:
  - Series 1 and 2: **u** and ν_t.
  - Series 3: Zero traction, T and ν_t.
- At outflow:
  - Zero traction, zero heat flux and zero eddy-viscosity flux.

Series 3 was treated differently from series 1 and 2 for the following reason. In natural convection, the airflow is driven by temperature gradients. We have thus in principle no a-priori information on the velocity (equivalently the flow rate) to impose, and where to impose it. To be able to simulate such flows, the computational domain was extended far away from the Haima, where we have imposed a zero traction boundary condition (equivalently zero pressure). Then, the temperature and eddy viscosity were imposed only on those parts of the boundary which are inflows, that is wherever $\mathbf{u} \cdot \mathbf{n} < 0$, **n** being the exterior normal to the boundary.

Numerical model

The set of partial differential equations is solved using the finite element method. We will not give any detail concerning the precise numerical model used in this work but only mention the most important points. The time integration uses either the backward Euler or the Crank-Nicholson schemes. Both are unconditionally stable. The former is of first order while the latter is of second order.

Once the variational problems have been established, the next step is to undertake the finite element approximations to them. It is also necessary to use a stabilization method capable of dealing with all the instabilities that the standard Galerkin method presents. For the particular case of the Navier-Stokes equations it includes the pressure instability (equal order interpolation is used) and the instability arising in convection-dominated situations. The stabilization technique used here is the Algebraic Subgrid Scale model (ASGS) of (Codina, 2001) and originally proposed in (Hugues, 1995).

Coupling Dynamic simulation and CFD

Coupling dynamic simulation and CFD programs is an attractive idea explored recently with the aim of improving building design (Zhai et al, 2002). The exchange of information between TRNSYS and CFD is made in two-step and only for selected time steps. In the dynamic simulation using TRNSYS the infiltration inside the Haima is imposed as boundary condition of the problem, while the objective is to estimate the thermal comfort inside. In cases, where there is some wind blowing, the problem is not so dependant of the temperature gradients. So based in experimental measures in the prototypes and in the CFD-based series 1 simulation, it could be possible to estimate the wind velocity in each region of the Haima. Using the velocity and the volume of each space in the Haima, it could be possible to compute the air changes per hour (ACH) and give them as boundary condition for the dynamic simulation.

In cases when airflow is driven by temperature gradients, as occurs in the absence of wind or sea breeze, having realistic values of air changes by hour inside the Haima was more difficult. CFD computation (series 3) was ideated to estimate the mass flow entering and out of the Haima for computing the air changes by hour. However, as the problem is temperature dependent and airflow and energetic behavior are coupled, dynamic simulations were used to estimate surface temperature of the inner cover. Once the value of the temperature is known, it is used as boundary condition for the CFD computation. The process is repeated iteratively three times.

DISCUSSION AND RESULT ANALYSIS

Series 1 of simulations with CFD consisted in simulating the airflow blowing through the square, inside and around the Haima. Each module of the Haima was numbered as it is depicted in figure 12. Tent's modules numbered from c21 to c28 are in windward position and the rest are at the leeward side. Module of the wind velocities at each tent entrance was obtained with a far away wind velocity of 1.5 m/s, with and without entrance curtains (made of CANATEX® 27), figures 13 and 14, respectively, where only selected modules are shown. In both cases, it was detected that natural ventilation is hard to be achieved in the modules placed at the leeward side. In case with absence of curtains, velocity of the air in leeward modules ranges from 0.3 to 0.7 m/s. In consequence, it was decided to modify the design of the entrance curtains of the Haima's modules, allowing to partially open them. This solution improved the natural ventilation in Haima's modules located at the leeward side.

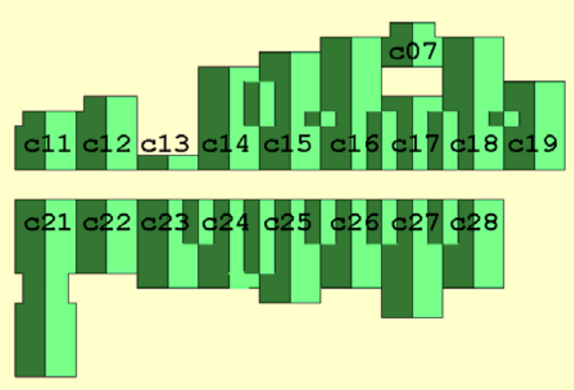

Figure12. Nomenclature of the Haima's modules for CFD simulations, series 1

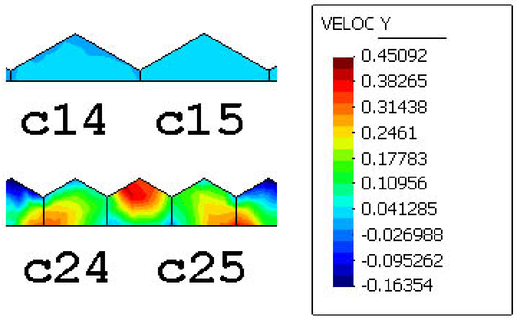

Figure13. Wind velocity module (m/s) in Haima's section with curtains at the entrance.

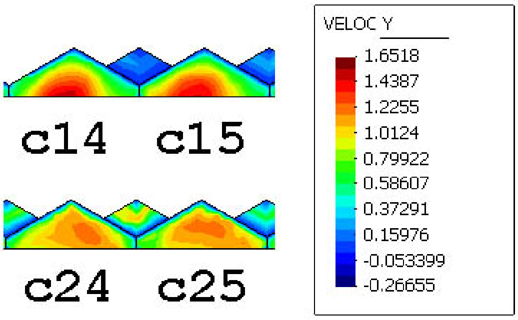

Figure14. Wind velocity module (m/s) in Haima's section with absence of curtains at the entrance.

The initial design of the Haima-top was changed, with the objective to improve natural ventilation. In figure 2, the final design could be distinguished. Each 5 meters, the dome was elevated 30 cm. This solution increases the difference of pressures in case that the sea breeze is blowing from the prevailing wind directions. The circulation of air through the Haima increases comparing with the situation than the dome was uniform. The design of the rooftop helps in case of airflow movement is driven by temperature gradients in situations of calm. CFD simulation were performed to assure that in calm situations, the temperature difference of temperatures in hot days allow circulation of air. Figure 15 shows the result of one of the CFD simulations of series 3, with no wind outside. Sections depicted in the figure shows how certain stratification of the air occurs. That helps to assure a more comfortable thermal ambient at the level occupied by persons occupying the space. This level of detail cannot be computed by the building model used in TRNSYS. Renovation of the air and air movement are also assured in hot summer conditions with relative air velocity at the entrance of the Haima of about 0.3 m/s.

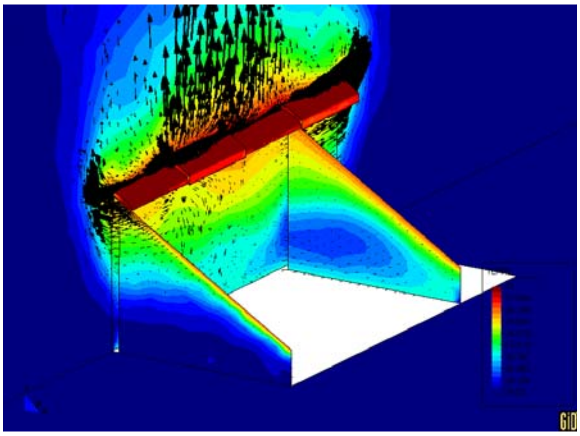

Figure15. CFD simulations, series 3. Temperature contours and velocity vectors in absence of wind.

CFD computations allow to improve the correlations used in dynamic simulations regarding the air changes by hour due to infiltration, both in cases where wind is present or not. Figure 16 shows that for one of the more critical modules in the Haima, the percentage of hours (taking as a base the occupied hours; from 11:00 to 01:00) distributed depending of the PMV index. It was established that a value of PMV = 1.5, corresponding to a 50.90 % of dissatisfied persons (PPD) was not acceptable. Following the figure, this percentage is about 20% in the months of July and August.

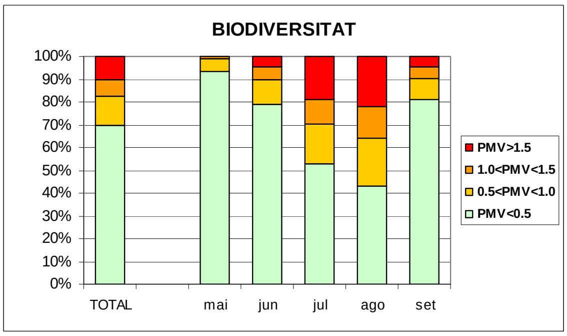

Figure16. Percentage of occupied hours distributed by PMV (Predicted Mean Vote) index

The other aspect is that this high value of PMV is produced from noon to the evening, as it is depicted in figure 17. Results of PPD index for the design period are shown, indicating at what hours the PPD is higher than 50% (PMV=1.5) and between 26% and 50%.

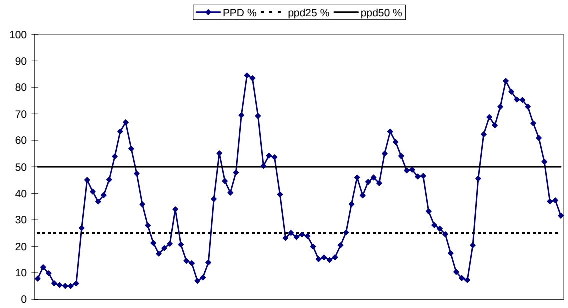

Figure 17. PPD index for the design period

CONCLUSION

After being analyzing the results for the complete opening period and for the design and extreme period, the following conclusions could be made:

- Due to the sea breeze and the design of the Haima, the air temperatures and the thermal comfort remains acceptable inside. At months of July and August a percentage of hours over the 20% are identified as critical ones.
- Due to the absence of any cooling system, air temperature in the critical hours in summer will be 1 or 3 ºC over the ambient temperature. 32 ºC could be achieved for the extreme temperature in the design period (29ºC).
- New design of the rooftop improves the infiltration of air, both cases when wind is blowing and in hours dominated by stack effect.
- Certain stratification is produced; so thermal comfort indexes in occupied zones are better than the mean.
- However, it was expected that thermal indexes are high (PPD>26%) or extremely high (PPD>50%) in the following situations:
  - Absence of sea breeze
  - Extreme temperatures outside (> 29 ºC)
  - In Haima's modules located at the leeward side when sea breeze blows.

In order to overcome the critical situations described at the last point, mechanical fans were installed inside the Haima, to improve the thermal comfort increasing the relative air velocity and providing extra air change with outside.

This study is an example as transient zone methods could be used in parallel with CFD simulations and coupled in order to improve boundary conditions of each method and design by providing complementary information of the Haima's performance. Transient simulations have been carried out using TRNSYS software to obtain the internal temperatures and thermal comfort indexes and CFD computations have carried out to improve the reliability of the thermal analysis. Several design solutions were proposed and simulated achieving that for the whole opening season of the event (from May to September 2004) discomfort conditions were produced only at the 10% of the opening hours. Real experience when the event was hold, confirms that the solutions adopted have worked as expected and people has remained comfortable at the Haima.

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