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Evaluation of the Thermodynamic Performance of the Traditional Passive Systems

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Abstract: The energy consumption of buildings in urban areas is one of the greatest source of energy wasting and, consequently, ofincreasing of CO_2 emission. Research is currently focused on the reduction of this consumption through the use of passive air-conditioning systems, that can be integrated with conventional systems and give rise to the so-called hybrid systems. Historically, these passive systems were developed in the Mediterranean and Middle East area. The research approach on this topic involves the application of design strategies and the development of computational tools and control systems. The development of the hybrid systems is the result of the synergy between current scientific knowledge, advanced manufacturing and information technology. In this study, a modular housing system has been investigated under different conditions. Simulations have been repeated, in order to identify the configuration that provides the highest indoor comfort. The analysis of the different conditions has been carried out using a CFD (computational fluid dynamic) software. The paper shows the results developed by the Dipartimento di Architettura of the Università di Palermo in the analysis of the natural ventilation effect on the indoor comfort.

Key words: Building, CFD simulation, passive systems, energy saving.

1. Introduction

The indoor comfort mainly depends on climatic conditions and, particularly, on climatic conditions of urban areas, where almost the 50% of the world population lives.

Temperature, humidity and wind circulation patterns are affected by the presence of an urban area. For a medium-sized city, the temperature difference between centre and rural areas ranges from 0.5 °C to 3 °C with significant variations in microclimate [1].

These variations can be determined by the following factors:

(1) In urban areas building materials have different thermal properties (capacity and thermal conductivity) and radiative properties (albedo and emissivity) if compared with building materials used in rural areas;

(2) The lack of natural evaporative surface and vegetation;

(3) In urban areas, the exposed surface is greater if compared to a flat surface, because of the presence of buildings;

(4) The heat produced by human activities and energy consumption;

(5) The air pollution, that can affect the radiative properties of the atmosphere, reducing the incoming solar radiation and the outgoing infrared radiation.

Natural ventilation can be an effective strategy to be adopted in regions with warm climate, improving the internal conditions of comfort, especially during the summer and the afternoon when the heat is stronger.

This research starts from the need to improve the conditions of indoor comfort in buildings using instruments that exploit the natural climatic conditions.

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2. Natural Ventilation in the Traditional Urban Construction

Since about one third of world population lives in hot-dry or warm-moist climatic conditions, passive systems started to be developed. And also most of the internal continental areas show, during summer, temperatures exceed the level of comfort.

Formerly, many cities of the east were originally built with empirically developed passive systems of cooling.

These systems make use of natural ventilation, evaporative cooling, control of solar radiation, thermal mass of the building and heat exchange with the ground [2]. At the moment, passive systems are becoming the key element of sustainable design in all weather conditions.

In the traditional building construction, ventilation was induced by natural forces able to generate dynamic (wind) and thermal (temperature difference) airflows.

The wind effect produces a positive pressure on the side of the building affected by the current and a negative one on the opposite side.

These pressure differences generate an air flow going from one side to another through the openings.

This phenomenon can be added to the convective air flow due to the difference in temperature and, consequently, in air density: the less dense warm air moves upward carrying cooler air from below.

Most of the traditional passive systems, including wind towers and rooms with different temperatures (Fig. 1), using these physical principles. The wind towers, used for the collection and capture of the air, are composed of architectural elements configured as vertical chimney, higher than the roofs; their openings are properly oriented, designed to capture the flow of wind, convey it inside the building and facilitate the air movement, in order to cool off the living spaces.

Thecentral spacehigher is a natural ventilation system, probably of Turkish origin, composed by different parts (Iwan-Durqa'a- Iwan).

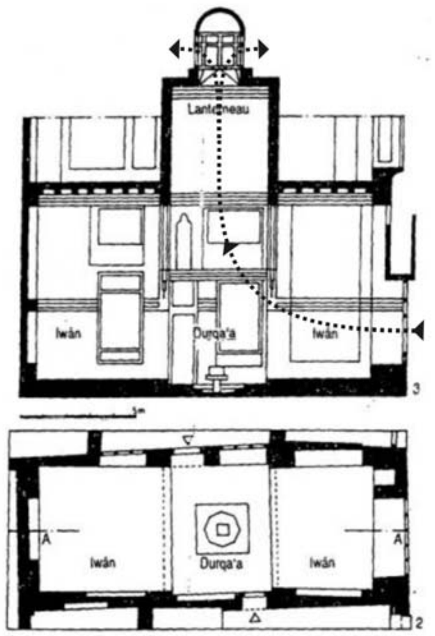


Fig. 1 The scheme shows, in a typical oriental house, the natural ventilation activate by the difference of temperature.

This kind of system is common in densely urbanized cities, characterized by a slower outward movement of air, that makes impossible the ventilation through windows.

The ventilation process is activated by the pressure difference between different areas and between indoor and outdoor.

The air, getting inside from the lower levels, is first channeled into the Iwan and, once it arrives in in central and higher space, tends to go up.

This effect is due to the temperature difference in the highest part of the central room corresponding to the lantern, that is open during the summer.

This temperature difference is able to generate the air flow even in absence of wind [3].

3. Application to a Case Study—The Choice of a Module

The case study analyzed refers to a modular housing system applicable to different situations (Fig. 2).

The examined module is a 5 × 15 m rectangle, 5 m high aligned north/south lengthwise. The south-side of the module has a large revolving opening with a front arcade, 5 m wide. On the northward part of the roof,

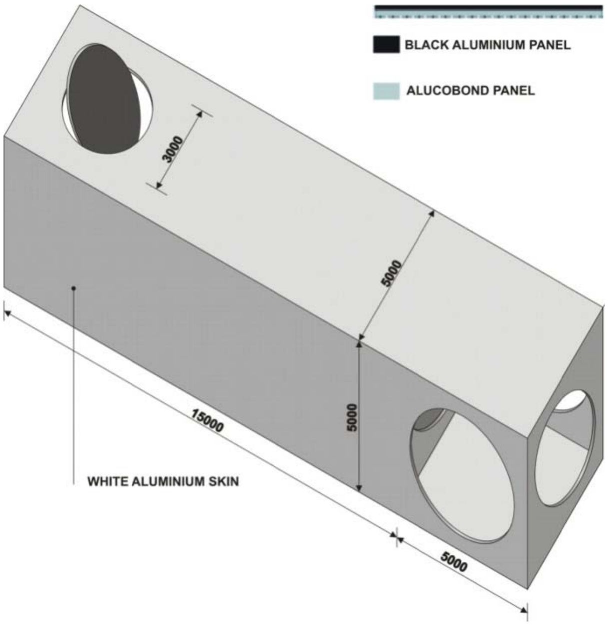


Fig. 2 Simplification model forCFD simulation.

there is an adjustable opening. The envelope is made of sandwich panels with an outer layer of aluminum. The circular panel on the roof is designed with a double skin: a black aluminum absorbent side and a glossy white aluminum side characterized by a high value of albedo [4]. Inside the module, the cooling is obtained exploiting the natural ventilation due to the draft effect [5]. The panel on the roof turns outward the black side, that is characterized by a high value of absorbance, specifically equal to 0.96; therefore, it significantly gets warm and creates a negative pressure, drawing fresh air from the opening at the bottom of the south side. The panel on the roof can take an angle of inclination, referred to a horizontal plane, monthly and daily variable in order to better capture the rays of sun.

In the summer, during the afternoon, the panel is open and its black side is outward (Fig. 3).

During the morning, the panel is closed and its reflective side is outward in order to prevent overheating. The circular openings, if supported by a building management system, should adapt the passive system to the variations of internal and external factors.

The windows can be moved manually or through electromechanical systems. For the indoor comfort, an automatic control system is cheaper. The automated handling of the windows, for the buildings cooling systems in summer or for the air recirculation in winter, requires the installation of an intelligent control system consisting of sensors and actuators, that will close or open the window depending on the internal and external environmental conditions [6].

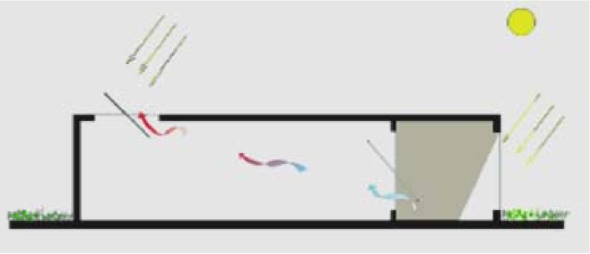


Fig. 3 Natural ventilation scheme during the summer time.

4. CFD Evaluation

The effectiveness of the passive system has been assessed through CFD (computational fluid dynamics), which is a valuable aid in the design of these systems, since it allows one to appraise and to compare the real effectiveness of different design solutions in terms of environmental comfort.

The ability to assess the effects of air flows, according to the geometric and spatial configurations, positioning in the soil, latitude, prevailing climatic conditions etc., has now become a tool for the designing of low-power energy [7].

In particular, it allowed:

- to evaluate indoor flows (temperature, pressure and speed parameters);
- to change the size and shape of the openings according to the comfort conditions.

The CFD methodology used is based on heat transfer and on the energy equation in the following form:

$$\frac{\partial y}{\partial t}(\rho E) + \nabla\left(\vec{v}\,(\rho E + p)\right) = \nabla\left(k_{eff}\,\nabla T - \sum_j h_j \vec{J_j} + \left(\overline{\overline{\tau_{eff}}}\,\vec{v}\right)\right) + S_h \tag{1}$$

where k_{eff} is the effective conductivity ($k + k_t$), where k_t is the turbulent thermal conductivity, (defined according to the turbulence model being used), and J_j is the diffusion flux of species j.

The first three terms on the right side of equation represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively.

It includes the heat of chemical reaction, and any other volumetric heat defined sources.

The used models are the RSM (reynolds stress model) and radiation model.

Reynolds stress model RSM is the most elaborate type of turbulence model. The RSM closes the Reynolds-averaged Navier-Stokes equations by solving transport equations for the Reynolds stresses, together with an equation for the dissipation rate.

4.1 Reynolds Stress Transport Equations

The exact transport equations for the transport of the Reynolds stresses, $\overline{\rho u_i' u_j'}$, may be written as follows:

$$\underbrace{\frac{\partial}{\partial t}\left(\rho\overline{u_i' u_j'}\right)} + \underbrace{\frac{\partial}{\partial x_k}\left(\rho u_k \overline{u_i' u_j'}\right)}$$

$$= \underbrace{-\frac{\partial}{\partial x_k}\left[\rho\overline{u_i' u_j' u_k'} + \overline{p\left(\delta_{kj} u_i' + \delta_{ik} u_j'\right)}\right]}$$

Local Time Derivative $C_{ij} \equiv$ Convection $DT_{,ij} \equiv$ Turbulent Diffusion

$$+\underbrace{\frac{\partial}{\partial x_k}\left[\mu\frac{\partial}{\partial x_k}\left(\overline{u_i' u_j'}\right)\right]} - \underbrace{\rho\left(\overline{u_i' u_j'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial x_k}\right)}$$

$$-\rho\beta\left(g_i\overline{u_j'\theta} + g_j\overline{u_i'\theta}\right)$$

$DL_{,ij} \equiv$ Molecular Diffusion $P_{ij} \equiv$ Stress Production $G_{ij} \equiv$ BuoyancyProduction

$$+\underbrace{\overline{p\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)}} - \underbrace{\overline{2\mu\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}}}$$

$\Phi_{ij} \equiv$ Pressure Strain $\epsilon_{ij} \equiv$ Dissipation

$$\underbrace{-2\rho\Omega_K\left(\overline{u_j' u_m'}\epsilon_{ikm} + \overline{u_i' u_m'}\epsilon_{jkm}\right)} + S_{user} \quad (2)$$

$F_{ij} \equiv$ Production by System Rotation User-Defined Source Term

Between the various terms in these exact equations, C_{ij}, $DL_{,ij}$, P_{ij}, and F_{ij} do not require any modeling. However, $DT_{,ij}$, G_{ij}, Φ_{ij} and ϵ_{ij} need to be modeled in order to close the equations. The following sections describe the modeling assumptions required to close the equation set.

4.2 The DO Model Equations

The DO (discrete ordinates) model considers the RTE (radiative transfer equation) in the direction as a field equation. Thus equation is written as:

$$\nabla\left(I(\vec{r},\vec{s})\vec{s}\right) + \left(a + \sigma_s\right)I(\vec{r},\vec{s}) = an^2\frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{s}')\Phi\left(\vec{s},\vec{s}'\right)d\Omega' \quad (3)$$

CFD software also allows the modeling of non-gray radiation using a gray-band model.

The RTE (3) for the spectral intensity can be written as:

$$\nabla\left(I_\lambda(\vec{r},\vec{s})\vec{s}\right) + \left(a_y + \sigma_s\right)I_\lambda(\vec{r},\vec{s}) = a_y n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda(\vec{r},\vec{s}')\Phi\left(\vec{s},\vec{s}'\right)d\Omega' \quad (4)$$

Here λ is the wavelength, a_y is the spectral absorption coefficient, and I_{by} is the black body intensity given by the Planck function. The scattering coefficient, the scattering phase function, and there fractive index n are assumed independent of wavelength. The non-gray DO implementation divides the radiation spectrum into N wavelength bands, which need not be contiguous or equal in extent. The wavelength intervals are supplied by the user, and correspond to values in vacuum ($n = 1$).

The RTE (3) is integrated over each wavelength interval, resulting in transport equations for the quantity $I\lambda\Delta\lambda$, the radiant energy contained in the wavelength band $\Delta\lambda$. The behavior in each band is assumed gray. The black body emission in the wavelength band per unit solid angle is written as:

$$\left[F(0 \to n\lambda_2 T) - F(0 \to n\lambda_1 T)\right]n^2\frac{\sigma T^4}{\pi} \quad (5)$$

where $F(0 \to n\lambda T)$ is the fraction of radiant energy emitted by a black body in the wavelength interval from 0 to λ at temperature T in a medium of refractive index n. λ_2 and λ_1 are the wavelength boundaries of the band. The total intensity $I(\vec{r},\vec{s})$ in each direction $\vec{s}$ at position $\vec{r}$ is computed using:

$$I(\vec{r},\vec{s}) = \sum_k I_{\lambda_k}(\vec{r},\vec{s})\,\Delta\lambda_k \quad (6)$$

where the summation is over the wavelength bands.

Boundary conditions for the non-gray DO model are applied on a band basis. The treatment within a band is the same as that for the gray DO model.

To carry out the CFD (computational fluid dynamic) simulations boundary conditions have been set according to a dynamic thermal simulation [8].

In order to check the efficiency of the system, the effects generated on the same model with the same outside conditions, but with different configurations, were examined. These configurations are:

- Closed module (Fig. 4);
- Module with a revolving panel (black aluminum skin) opened on the roof and the window opened in front (Fig. 5);
- Module with a revolving panel (white aluminum skin) opened on the roof and the window opened in front (Fig. 6).

The study was essentially developed through three phases:

- First phase: defining the boundary conditions (material, temperature, wind speed, etc.), the flow model, the solar parameters, etc.;
- Second phase: it is the calculation step, in which the time steps, the number of iterations, etc., have been defined and the simulations have been started up;
- Third phase: plans and views have been set and the characteristics of the airflow (temperature, velocity, pressure, etc.) have been displayed.

4.3 Boundary Conditions

In order to obtain the boundary conditions, simulations were conducted with a thermodynamic software. The study was carried out referring to the hottest summer day in Rome (August 7) at 1:00 p.m. (34 °C) (Fig. 7). In particular, the temperature inside the module, at different times of day and the exposure to solar absorption values for each wall bounding the building, has been calculated. In the computational

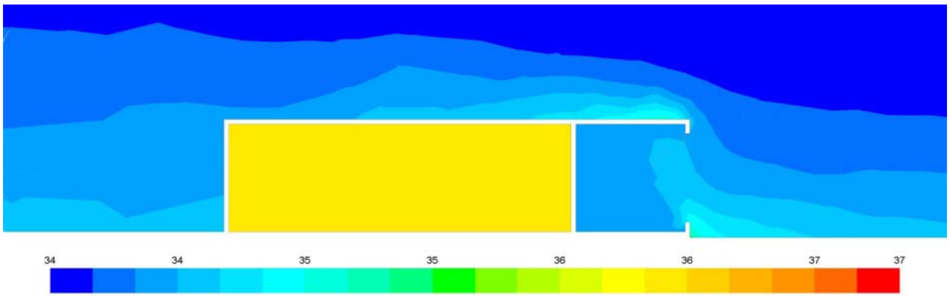


Fig. 4 Air temperatures distribution (°C): closed module.

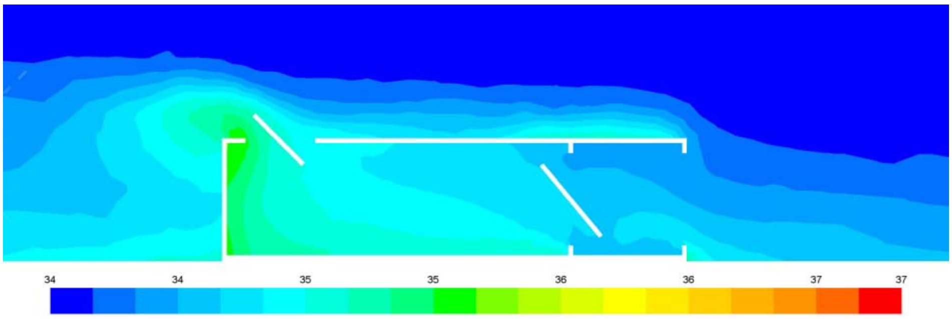


Fig. 5 Air temperatures distribution (°C): open panel on the roof (white aluminum side).

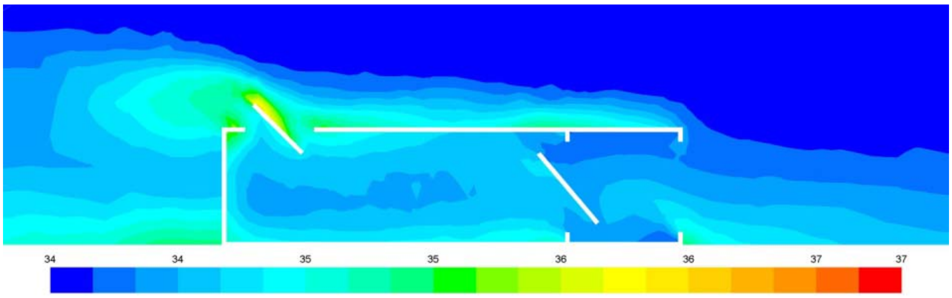


Fig. 6 Air temperatures distribution (°C): open panel on the roof (black aluminum side).

model the panel has been considered inclined of 45°. The temperature increase of outside surfaces, due to the proportion of absorbed solar radiation, has been calculated using the following equation [9]:

$$T_S = T_0 + G \times \alpha \times R_{SO} \qquad (7)$$

where T_s (K) is the surface temperature, T_0 (K) is the outside temperature, G (W/m^2) is the global irradiance, α is the absorption coefficient which mainly depends on material and surface color, R_{SO} (m^{2}K/W) is the threshold level of surface thermal resistance.

The $G \times \alpha$ has been calculated by a thermodynamic software. From the above formula, the temperature values in Tables 1 and 2 were obtained.

4.4 Calculation Phase

The model analyzed by CFD was created defining the surfaces that enclose the domain of fluid to be examined. For the flow analysis, a model consisting of two volumes of air, one inside and one outside the module, has been imported. The model is divided in elements of a triangular or tetrahedral mesh (Fig. 8).

The dimensions of the mesh are:

- Min size : 5.7103 e-002 m;
- Max face size: 5.71030 m;
- Max tet size: 11.4210 m;
- Smoothing: medium;
- Transition: slow;
- Span angle center: fine;
- Curvature normal angle: 0.314160 rad;
- Growth rate: 1, 2;
- Min edge length: 1.0097 e-002 m.

The used software separates the model into faces. Therefore, a certain number of cells and nodes is defined.

The characteristics of materials and their temperatures, derived from thermal simulation, have been attributed to the outside boundary of the model. For the volume of outside air, the temperature was set equal to 34 °C and the air speed equal to 1 m/s (maximum value for the indoor comfort).

4.5 Flow Analysis

In the third phase of the study, the distributions of temperature and air velocity were shown.

In the closed module, the inner temperatures are considerably higher. The model with open panels develops a process of natural ventilation, due to air circulation, with a consequent decrease in temperature of about 1.3 ° C (from 36.5 °C to 35.2 °C).

A black panel placed on the roof, and tilted open, will act as a sensor that decreases the density of air when it gets warm, drawing fresh air from the inside and allowing a greater cooling of the building. In this case, it is possible to observe a decreasing of the inside temperature of 1.2° C (35.2° C to 34° C).

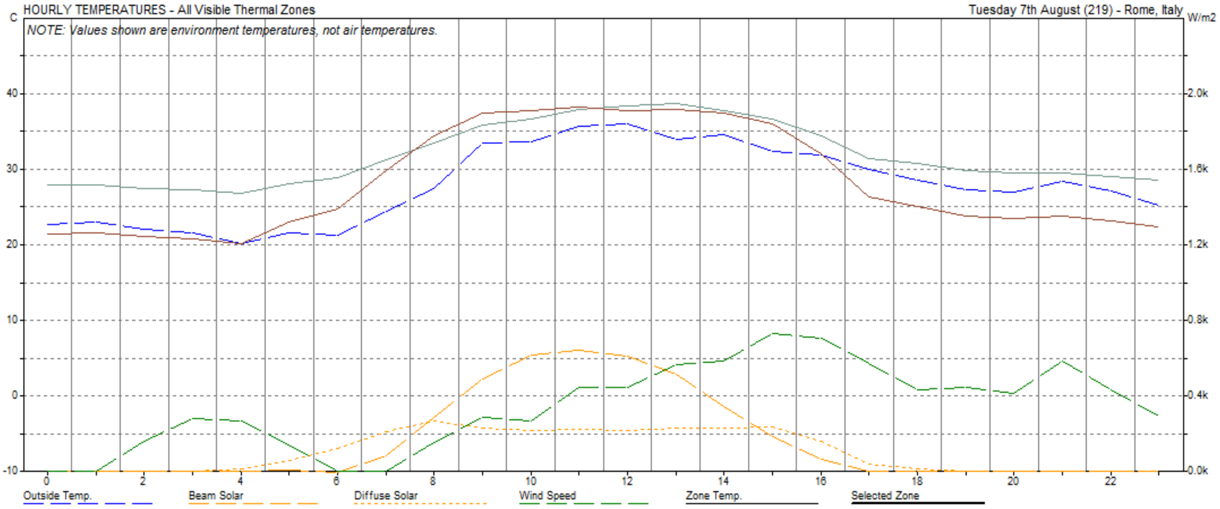


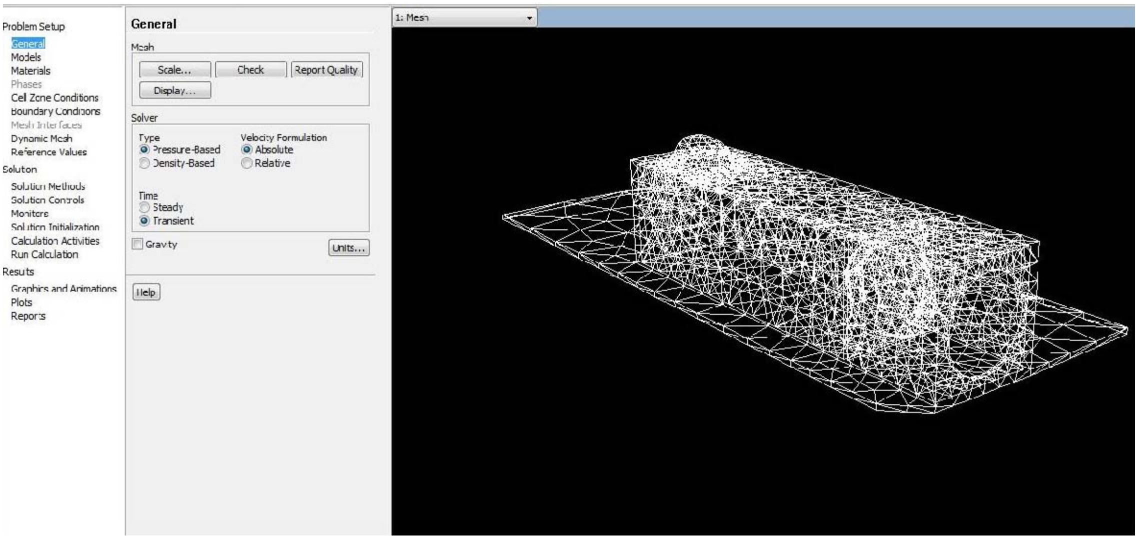
Fig. 7 Climate data (August 7, Rome, Italy).

Table 1 Threshold level of surface thermal resistance.

	External horizontal surfaces (very exposed)	Roof (normal exposure)	Inclined panel (very exposed)	Vertical walls (normal exposure)
R_{SO} (m^2K/W)	0.02	0.04	0.02	0.06

Table 2 Surface temperatures.

	Roof	Closed aluminum panel	Open black panel	Open white panel	East wall	North wall	West wall	South wall
T_s (°C)	46.30	46.30	71.62	43.48	36.04	36.04	37.6	40.00



Solver

Type
● Pressure-Based
○ Density-Based

Velocity Formulation
● Absolute
○ Relative

Time
○ Steady
● Transient

☐ Gravity

Fig. 8 Mesh visualization.

The presence of the black panel, in the described conditions, causes an increase of the speed and a decrease of the pressure, triggering a greater air draft and drawing fresh air in rooms, but with air speed always lower than 1 m/s.

5. Conclusions—Result Evaluation and Future Development

Simulation results showed, in adverse weather conditions, in time and in the hottest day of the year, a decrease in temperature. It is possible to observe a decrease of the inner temperature of 2.5° C (from 36.5° C to 34° C); the temperature, under conditions of closed model (Fig. 6), is equal to 36.5 °C and, under conditions of open model with black panel on the roof, and tilted open, and the frame open in front, is equal to 34.0 °C (Fig. 8).

Inside the model, it is also possible to observe an increase of the air flow speed of about 0.2 m/s. Under the conditions of black panel (Fig. 9) the inner speed ranges from 0.22 m/s to 0.45 m/s, while, under the conditions of open model with aluminum panel (Fig. 10) the inner speed ranges from 0.00 m/s to 0.22 m/s. The presence of the black panel, (Fig. 9) in the described conditions, causes an increase of the speed, a decrease of the pressure, triggering a greater air draft and drawing fresh air in rooms, but with air speed always lower than 1 m/s.

These conditions allow, under normal conditions of use, to increase the thermal differential and the relative pressure, increasing thereby the flow rate of the natural flow of air and generating a greater thermal comfort inside the model.

This substantial decrease in temperature can contribute to energy savings by integrating a series of conventional air conditioning system with the adopted passive system.

The CFD is a valuable aid in the design since it allows one:

- according to the geometric and spatial configurations,

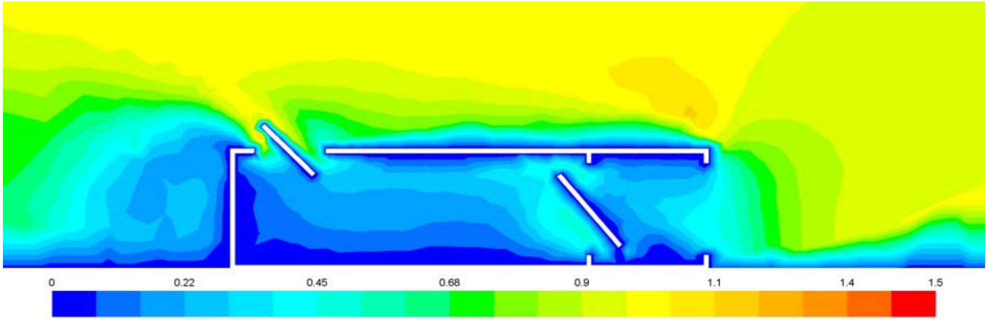


Fig. 9 Air speeds distribution (m/s): open panel on the roof (black aluminum side).

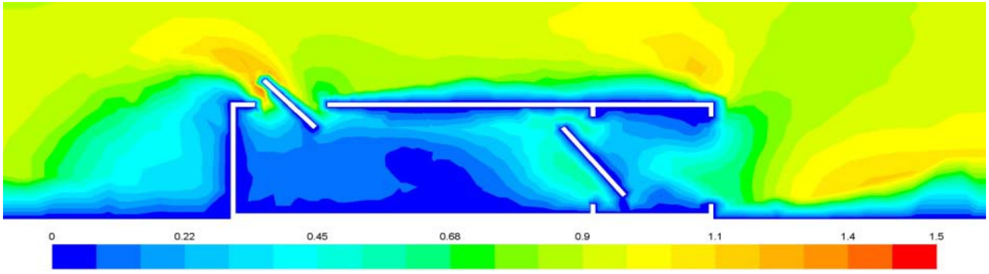


Fig. 10 Air speeds distribution (m/s): open panel on the roof (white aluminum side).

positioning in the soil, latitude and prevailing climatic conditions;

- to evaluate indoor flows (temperature, pressure and speed parameters);
- to change the size and shape of the openings according to the comfort conditions;
- to carefully design plant engineering and technological elements;
- to change buildings size and shape in relation to the indoor comfort.

A future development of this work could include an application to a residential area, in which smaller cells could be considered as a habitation module, that can be assembled side by side or overlapped.

In this case, the two openings can be suitably controlled through thin slits slats.

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