

CFD simulation and measurement of the thermal behavior inside a room of the institutional library: a comparative study

Simulação CFD e medição do comportamento térmico no interior de uma sala da biblioteca institucional: um estudo comparativo

Efrén Vázquez Silva
Franco David Cajas Muñoz
Marcelo Xavier Asitimbay Deleg
Paúl Bolívar Torres Jara
Gabriela Abad Farfán

Abstract

This article presents the results of the comparison between the CFD simulation and temperature measurements, both in the time domain, at a certain point of interest within a specific closed space (cubicle) of the institutional library of the Salesian Polytechnic University (UPS), at its headquarters in the city of Cuenca, Republic of Ecuador. In this specific case, solar radiation is considered as the main heat transfer mechanism, which is why it was considered in the applied simulation method. An acceptable relative error was obtained between the simulated and measured temperature values. During the summer period, the thermal conditions inside the cubicle are not suitable for the comfort of the users. The study developed can constitute a basic tool for possible future research related to the implementation of climate conditioning for the cubicle, the library in general and any other site with similar constructive and operational characteristics.

¹Efrén Vázquez Silva
¹Universidade Politécnica Salesiana
Cuenca - Ecuador

²Franco David Cajas Muñoz
²Universidade Politécnica Salesiana
Cuenca - Ecuador

³Marcelo Xavier Asitimbay
Deleg
³Universidade Politécnica Salesiana
Cuenca - Ecuador

⁴Paúl Bolívar Torres Jara
⁴Universidade Politécnica Salesiana
Cuenca - Ecuador

⁵Gabriela Abad Farfán
⁵Universidade Politécnica Salesiana
Cuenca - Ecuador

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Resumo

Esse artigo apresenta os resultados da comparação entre a simulação CFD e as medições de temperatura, ambas no domínio do tempo, em um determinado ponto de interesse dentro de um espaço fechado específico (cubículo) da biblioteca institucional da Universidade Politécnica Salesiana (UPS), na sua sede na cidade de Cuenca, República do Equador. Neste caso, a radiação solar é considerada como o principal mecanismo de transferência de calor, razão pela qual este mecanismo é considerado no método de simulação aplicado. Um erro relativo aceitável foi obtido entre os valores de temperatura simulados e medidos. Durante o período de verão, as condições térmicas dentro do cubículo não são adequadas para o conforto dos usuários. O estudo desenvolvido pode constituir uma ferramenta básica para possíveis pesquisas futuras relacionadas à implementação do condicionamento climático para o cubículo, a biblioteca em geral e qualquer outro local com semelhantes características construtivas e operacionais.

Palavras-chave: Radiação solar. Transferência de calor. CFD.

Introduction

Heat gains or losses in closed spaces are through opaque and semi-transparent materials: roofs, walls, skylights and windows. Semi-transparent materials are responsible for a larger amount of unwanted heat gains and losses, representing a high risk of thermal discomfort Gijón-Rivera *et al.*, (2013). The improvement of living and working conditions of human beings has been a constant concern of researchers throughout the history of society. In recent stages we can see this problem reflected in works such as, for example, that of González-Cruz and González-García (2013), where passive cooling systems of the roofs of certain enclosures are studied, through the application of roof-pond metallic typology. Ordóñez and Pérez (2015) make a comparison related to energy savings, between green and white roofs in a construction with a joint presented system with concrete and vault. Also, in Muñoz *et al.* (2015), the authors foresee the optimal use of natural ventilation according to the location and orientation of a building.

Another line of work in this regard has been the development of research in which numerical techniques are applied. In this case we can point out the works of Esteban *et al.* (2015, 2016). In Esteban *et al.* (2015) the transient phenomenon of natural convection is numerically analyzed in a trapezoidal enclosure. The authors characterize the aspect ratios: quotient between height and length of the enclosure and the angle of inclination of the walls of this space, which depends on the so-called aspect ratio. Whereas in Esteban *et al.* (2016) the same authors address this problem, for the same type of enclosure; however, in this case the active walls (lower and upper) are symmetrically inclined.

Within the same line of research other studies were conducted, for example, Gowreesunker and Tassou (2013), Barbason and Reiter (2014) and Gijón-Rivera *et al.* (2013). In Gowreesunker and Tassou (2013) a validation study of Computational Fluid Dynamics (CFD) models used to predict the effect of phase change material-clay boards on the control of indoor environments, in ventilated and non-ventilated situations is reported. On the other hand, in Barbason and Reiter, (2014) the authors report the coupling of a building energy simulation (BES) made with the commercial software package developed at the University of Wisconsin (TRNSYS) with a CFD simulation made with ANSYS FLUENT, and its application to a typical Belgian two-storey house. Whereas in Gijón-Rivera

et al. (2013) the advantages of using a BES-CFD instead individual solutions are shown; and the results are applied to a room on top of a building with three different glazed configurations in Mexico City.

The study of the thermal behavior of habitable space of buildings of different types also developed. In the case of the use of adobe as a construction material, Cárdenas (2015) can be mentioned. Another way to evaluate this thermal behavior is the simultaneous collection, indoors and outdoors, of temperature and relative humidity data, in order to propose bioclimatic design strategies (see Rodríguez and Peñaranda (2015)). In Muñoz *et al.* (2014) the authors proceeded in a similar way, as they analyzed continuous and systematic measurements of temperature and humidity at specific points in the interior of a building, and external meteorological variables. This information was correlated to an analytical model that explained the contributions of conductivity, radiation and convection due to the wind in the consideration of the thermal properties of the building. In Varini (2015), Varini studied a constructive model of family housing and simulated its behavior in terms of ventilation flows, temperature and relative humidity inside, under various conditions, all focused on issuing conclusions on the thermal comfort of the tenants.

Finally, we refer to Felices and collaborators, who in Felices *et al.* (2017) reflected the study of the thermal performance of a solar space adhered to a bioclimatic building. In this case, the effect of direct solar radiation and the absorption of opaque building systems and the thermal properties of the air enclosed in the solar space was analyzed through the comparison of experimental and numerical data to predict thermal performance.

In the present work, only the variation of the temperature in a certain enclosure within the university library was simulated, and the comparison with measurements experimentally taken in the same space was made. The library of the Salesian Polytechnic University, in Cuenca, within its facilities has 8 cubicles designated to work in groups (see Figure 1), so that the study conditions of other users are not affected. Another aspect that impacts the activity of students in this space is thermal comfort. In this sense, there was a need to evaluate the thermal behavior inside the cubicle.

Figure 1 - UPS library building



Figure 2 - Position of the cubicle inside the structure

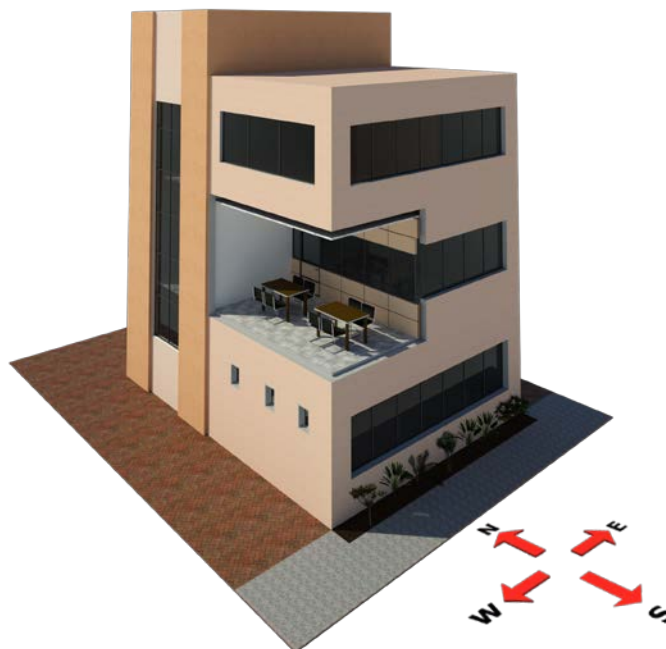


Figure 2 shows the modeling of the building in which the library is located, where it is possible to view the location of the reference cubicle.

One of the factors that affects such behavior, and that manifests with greater force in the considered space, is the heating caused by solar radiation and natural convection. Thus, we proposed in this study to simulate the thermal behavior in a certain area of interest in the enclosure, in which its occupants perceive the greatest influence of heat, considering only the action of the solar rays during a critical interval of the day, in the absence of people. Simulation that, enriched with other parameters (that is, for example, factors related to human comfort and others, reported, for example, in

Instituto Ecuatoriano de Normalización (2019), Çengel and Ghajar (2011), Çengel and Boles (2003), Decrofet (2019) and Fernández (1994)), could be used as an additional criterion for the design of an appropriate climate conditioning system for enclosures with similar conditions to those considered.

The work is organized as followed: The applied methodology is exposed in the next section. Afterwards, following sections address the physical situation and the analysis of results obtained with a CFD simulation. The conclusions about the developed study, and recommendations for possible future investigations are offered at the end of the study.

Methodology

The temperature in the center of the cubicle was measured during a certain time interval, with an electronic sensor, which together with a microprocessor and software, allowed to store and interpret the obtained data. Then, these results were compared with the temperature variation curve obtained with the help of the simulation developed in the FLUENT module of the ANSYS software (software used because UPS acquired its license). Temperature data were also collected on the surfaces that delimit the enclosure, to determine the boundary conditions (input data for the software) that would later be used in the simulation. This methodology is described through its different phases:

Data collection

Initially the dimensions of the cubicle were measured and the recognition of the type of constituent materials of the elements or structures that delimit the enclosure was made (Table 2) (AMERICAN..., 2013). Then, during several days, temperature measurements were taken inside the space and throughout the day. This allowed to establish the time interval during which the temperature inside reached maximum values (15:00 to 17:00 hours). For this reason, both the simulation and the temperature measurements were performed synchronously, with an increase in time of 240s and setting as initial time at 15:00 hours. The

temperature values were acquired through a LM35 sensor, which is part of an ARDUINO-MATLAB interface, located at the point of interest. This way, it was possible to obtain a database with temperature values for each instant of time at one second intervals.

Simulation

As input conditions for the software, some thermal properties (emissivity, thermal conductivity, specific heat and absorptivity), the density and the filtering capacity of the solar rays of the different materials described in the previous phase, were considered. In addition, the coefficient of heat transfer (or thermal transmittance) for each type of material was calculated. Also, data of the average temperature on each boundary surface of the cubicle were collected with the help of thermography camera brand TESTO, model 875, with manual entry of the value of the emissivity coefficient of each type of material. All this information constituted the input data (see Tables 1, 2 and 3) (AMERICAN..., 2013). That is, the set of boundary conditions for the mathematical model of the simulation was conformed for each type of constituent material of the limiting surfaces of the cubicle, by the thermal properties of each material; the temperature of each surface at the initial instant, taken with the camera TESTO; and the ambient temperature inside the enclosure at the initial instant.

Table 1 - Thermal properties of materials

Material	Density (kg/m ³)	Specific Heat (J/KG k)	Thermal Conductivity (w /m k)
Glass	2470	750	1.0
Wood	750	2390	0.176
Concrete (Floor)	2300	653	0.93
Concrete (Walls)	1970	800	0.7
Gypsum	1200	1080	0.43
Air	1.196	1007	0.0252

Table 2 -Thermal conditions

Zone	Thermal conditions	Material name	Heat transfer coefficient (w/m ² -k)	Free stream temperature (°C)	Internal emissivity	Wall thickness (m)
Roof	convection	Gypsum panel	2.33	23.7	0,90	0,1
Floor	convection	Concrete	1.64	23.7	0,85	0,25
Walls	convection	Hollow block	2.63	23.7	0,85	0,15
Door	convection	Wood panel	1.39	23.7	0,90	0,08
Glass	convection	Glass	5.56	23.7	0,94	0,01

Table 3 -Radiation conditions

Zone	Boundary condition type	Participates in solar ray tracing	Absorptivity direct visible	Absorptivity direct infrared rays	Transmissivity direct visible	Transmissivity direct infrared rays
Roof	opaque	no	-	-	-	-
Floor	opaque	yes	0,65	0,65	-	-
Walls	opaque	yes	0,65	0,65	-	-
Door	opaque	yes	0,59	0,59	-	-
Glass	semi-transparent	yes	0,15	0,15	0,88	0,88

The heat transfer coefficient (Table 2) (AMERICAN..., 2013) is a property of the materials that depends on the wall thickness and the thermal conductivity, the values presented were calculated by the authors. The ambient temperature inside the cubicle is the arithmetic mean of the different temperatures at which the cubicle air was at 15:00 hours (start of the analysis) during 10 days in which the measurements were made. Finally, the internal emissivity values were taken from ASHRAE (AMERICAN..., 2013).

The false ceiling does not participate in solar radiation because there is another level above the enclosure and the solar rays have no incidence on the ceiling; it only participates in convection. In addition, the respective values were taken from ASHRAE (AMERICAN..., 2013).

Subsequently, the three-dimensional model of the enclosure under study was obtained and its orientation towards the sun was taken into account (Figure 3). For the runs of the simulation, the software calculated the relative initial position of the sun with respect to the cubicle and its trajectory from that moment; and for this it was necessary to enter, also as input data, the date, the time of day, the time zone and the geographic coordinates of the building. Because of these software facilities, it was possible to perform the synchronous analysis, that is, the times of increase and duration of the measurements and of the simulation were equal.

Finally, the simulation of the combined action of the different thermal transfer mechanisms from the limiting surfaces towards the interior of the room was carried out. The mathematical model on which the FLUENT module was supported can be consulted, for example, in Gowreesunker and Tassou (2013):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = S_M \quad \text{Eq. 1}$$

$$\frac{\partial}{\partial t} (\rho H) = - \frac{\partial}{\partial x_j} (\rho u_j C_p T) + \frac{\partial}{\partial x_j} \left(\lambda \frac{\partial T}{\partial x_j} \right) + S_E \quad \text{Eq. 2}$$

$$\frac{\partial}{\partial t} (\rho u_j) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = - \frac{\partial}{\partial x_j} (P) + \frac{\partial}{\partial x_j} (\bar{\tau}) + \rho g_j + F_j \quad \text{Eq. 3}$$

Equations 1, 2 and 3 are continuity equation, energy equation and momentum equation respectively; in which: ρ : density; x_j : direction vector; u_j, u_i : velocity vectors; S_M : mass source term; H : enthalpy; C_p : specific heat capacity; T : temperature; λ : thermal conductivity; S_E : energy source term; P : static pressure; $\bar{\tau}$: stress tensor; g_j : gravitational force vector; F_j : body force vector.

The FLUENT module of the ANSYS implemented second-order explicit methods for the discretization of the transient terms of the equations of momentum and energy; as well as for the advective and diffusive terms.

Reading of the analytical outputs, and graphic

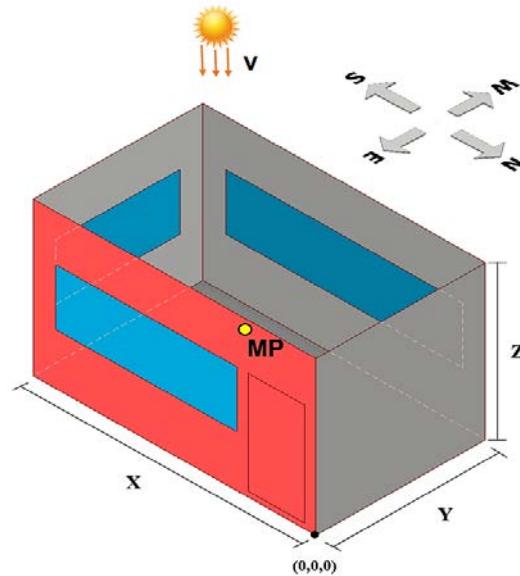
The used software allowed to obtaining the curves of temperature versus time in any surface or point of the cubicle, and images of the temperature distribution on walls and on any fictitious planes inside the enclosure.

Physical situation

For the computational simulation, only the cubicle was modeled, however, indirectly, the possible incidence of the neighboring rooms on the corresponding limiting surfaces of the place of interest was taken into account in the input data. The study area was characterized by the absence of air flows, because it generally remained closed. It had only the access door (possible way of air intake, however, this was not considered because when the room was being used, the door was kept closed due to institutional regulations) and did not have no any kind ventilation.

Simulation test runs were carried out assuming the mathematical model with and without turbulence, and the differences in the results were negligible. However, the turbulence model considerably increases the computation times. So, for this and the previous reason, for the simulation, a model of turbulence was not used.

Figure 3 - Three-dimensional model of the cubicle



Nor was the incidence of relative humidity considered for the simulation because in the region of the country where the building was located, the average annual relative humidity remained within the human comfort zone (62%) (PESÁNTES, 2012).

The coordinates of the measurement point in the cubicle, called MP, were (2.65 m, 1.45 m, 1.50 m); considered from the origin (0, 0, 0) as shown in Figure 1. In addition, the cubicle had the following dimensions:

$$X = 5.3 \text{ m}$$

$$Y = 2.9 \text{ m}$$

$$Z = 3.2 \text{ m}$$

In the same figure 1 the colors identify:

Blue = Glass;

Gray = Concrete walls; and

Red = Wooden wall and door.

Also, the location of the Sun is specified as follows:

\vec{v} : direction vector of the Sun

$$\vec{v} = (-0.502, 0.305, 0.808)$$

The cubicle was located in a corner of a two-story building, on the first floor; in such a way that two of its walls were in direct contact with the exterior, oriented towards the west and the south (see Figure 2).

Results and discution

The information collected in phase 1, of the ambient temperature of the enclosure at the measurement

point MP, was compared with the results of the computational simulation, obtained with three mesh resolutions: fine, medium and coarse. The data were obtained within the same time range (15:00 to 17:00 hours) and with the same time-step (240s), obtaining the following graph of temperature variation (see Figure 3).

Next, in Figure 4, it is possible to observe details of the different types of grids used for the simulation runs, and this offers a visual idea about the relationship between the size of the differential element and the dimensions of the cubicle (information provided by the software itself). Table 4 shows a summary of the characteristics of the grids (the values of skewness and orthogonal quality are averaged).

It can be seen, according to the distribution of points in the plane shown in Figure 5, that there was no considerable deviation between the two results; the stabilization time was approximately the same and also the maximum temperature was reached for the same value of t in both cases.

Similarly, it can be seen that once the maximum temperature was reached, it was maintained until approximately 16:20 hours due to the thermal inertia in the room, and from that moment it began to decay due to the Earth's rotation effect.

To corroborate the results of the previous graph, below is a summary table (Table 5) that shows the relative errors between each temperature value measured over the time interval of interest and the corresponding simulated value, for each mesh resolution and also the total average error between simulated and measured results.

Figure 4 - Details of the different types of meshing; hexahedral elements.

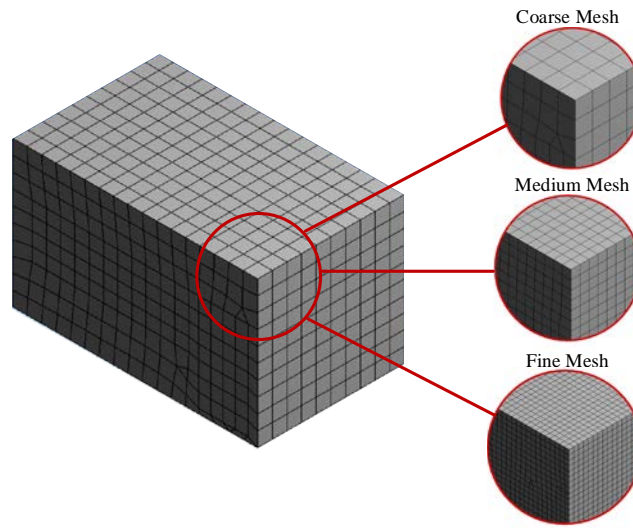


Table 4 - Summary of meshing characteristics

Grid	Number of elements	Number of nodes	Skewness	Orthogonal Quality
Coarse	2089	2260	0,204	0,880
Medium	14706	16172	0,068	0,971
Fine	116177	116055	0,101	0,942

Figure 5 - Experimental and simulated results

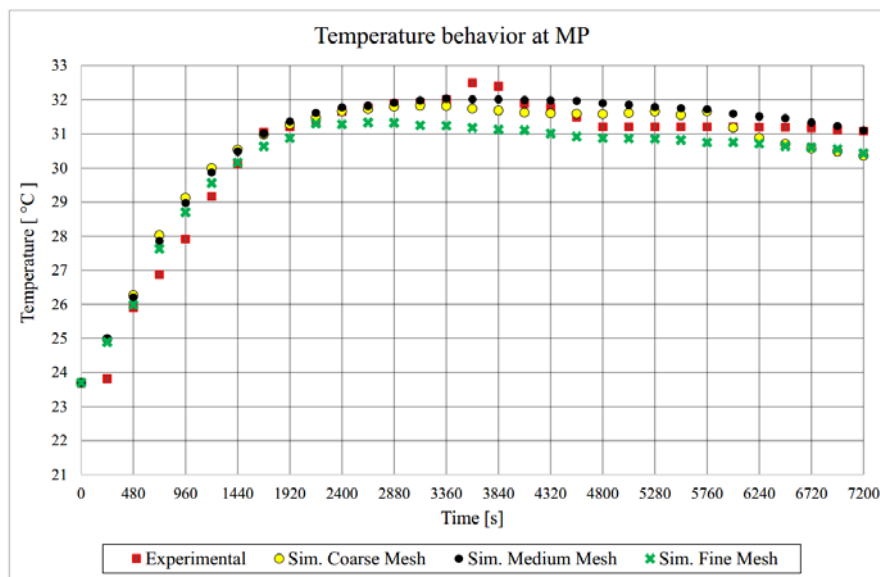


Table 5 - Summary of relative errors

Time (s)	Measured temperature (°C)	Simulated temperature (fine mesh, °C)	Error (%)	Simulated temperature (medium mesh, °C)	Error (%)	Simulated temperature (coarse mesh, °C)	Error (%)
1	23,691	23,700	0,038	23,700	0,038	23,700	0,038
240	23,812	24,895	4,548	24,990	4,947	24,983	4,917
480	25,900	25,981	0,313	26,200	1,158	26,261	1,394
720	26,870	27,628	2,822	27,850	3,647	28,024	4,294
960	27,910	28,697	2,820	28,970	3,798	29,124	4,351
1200	29,170	29,558	1,329	29,870	2,400	29,995	2,829
1440	30,120	30,157	0,123	30,480	1,195	30,537	1,384
1680	31,050	30,629	1,355	31,000	0,161	30,980	0,226
1920	31,200	30,872	1,051	31,360	0,513	31,277	0,248
2160	31,400	31,305	0,302	31,620	0,701	31,473	0,233
2400	31,660	31,284	1,189	31,780	0,379	31,664	0,013
2640	31,770	31,332	1,378	31,820	0,157	31,727	0,135
2880	31,890	31,323	1,778	31,910	0,063	31,798	0,288
3120	31,920	31,248	2,106	31,980	0,188	31,827	0,293
3360	32,000	31,237	2,385	32,030	0,094	31,818	0,568
3600	32,500	31,180	4,062	32,010	1,508	31,736	2,351
3840	32,400	31,124	3,939	32,010	1,204	31,682	2,216
4080	31,890	31,107	2,456	31,990	0,314	31,627	0,823
4320	31,780	31,010	2,422	31,980	0,629	31,601	0,565
4560	31,500	30,920	1,842	31,970	1,492	31,592	0,292
4800	31,200	30,872	1,051	31,890	2,212	31,576	1,207
5040	31,200	30,864	1,078	31,850	2,083	31,611	1,317
5280	31,200	30,852	1,114	31,790	1,891	31,661	1,478
5520	31,200	30,822	1,213	31,750	1,763	31,552	1,127
5760	31,200	30,748	1,449	31,720	1,667	31,663	1,484
6000	31,200	30,754	1,428	31,590	1,250	31,177	0,074
6240	31,190	30,710	1,539	31,510	1,026	30,877	1,004
6480	31,185	30,634	1,768	31,457	0,872	30,708	1,529
6720	31,172	30,596	1,849	31,338	0,533	30,570	1,931
6960	31,114	30,555	1,798	31,229	0,370	30,479	2,040
7200	31,085	30,425	2,122	31,103	0,058	30,353	2,355
Total average error			1,763		1,236		1,387

The total average error between both systems is equal to 1.763%; 1.236 % and 1.387 % approximately, considering the three mesh resolutions. These results validate the simulation of the phenomenon, since the simulated thermal behavior was similar to the temperature values taken in the enclosure. It is also seen in Table 5 that the relative average error for the fine grid was greater than the corresponding error for the medium one, and this is in correspondence with the skewness and orthogonal quality properties, which had worse behavior for the fine grid. Likewise, the Grid Convergence Index (GCI), which provides a consistent way to study the refinement phenomenon of the mesh Roache *et al.* (1986) and Roache (1998), was calculated. In this case $GCI = 0,67$ was obtained. This value is adequate and corresponds to the decrease in grid quality, in terms of skewness

and orthogonality, for the fine grid (the assumed time-step guarantees stability of the solution). This suggests an additional future analysis regarding the initial side length of the cubic element, assumed for the coarse grid, which was 30 cm.

Next, in Figures 6 and 7, it is possible to see the polynomial settings for the experimental and simulated data, respectively.

The equations of the temperature-time curves, for experimental and simulated data respectively, are given as example by the following equations:

$$T = -10t^3 - 6t^2 + 0.0075t + 22.97 \quad \text{Eq. 4} \\ (R^2 = 0.9816)$$

$$T = -10t^3 - 6t^2 + 0.008t + 22.081 \quad \text{Eq. 5} \\ (R^2 = 0.9924)$$

Figure 6 - Polynomial fit to experimental data

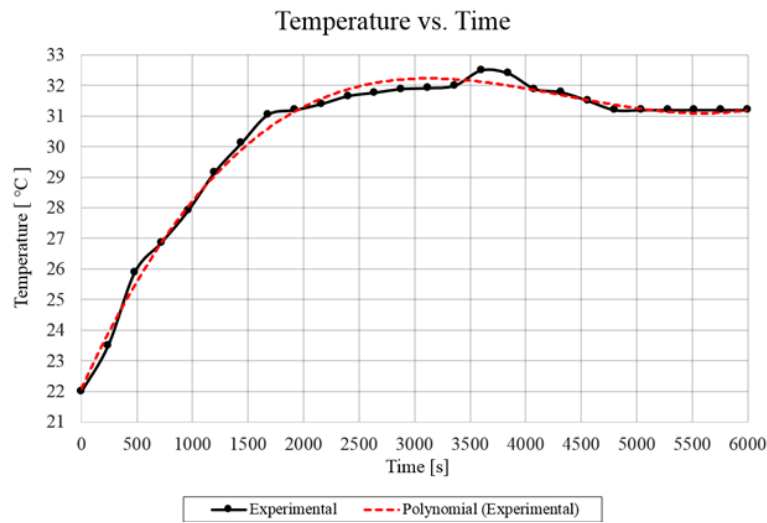
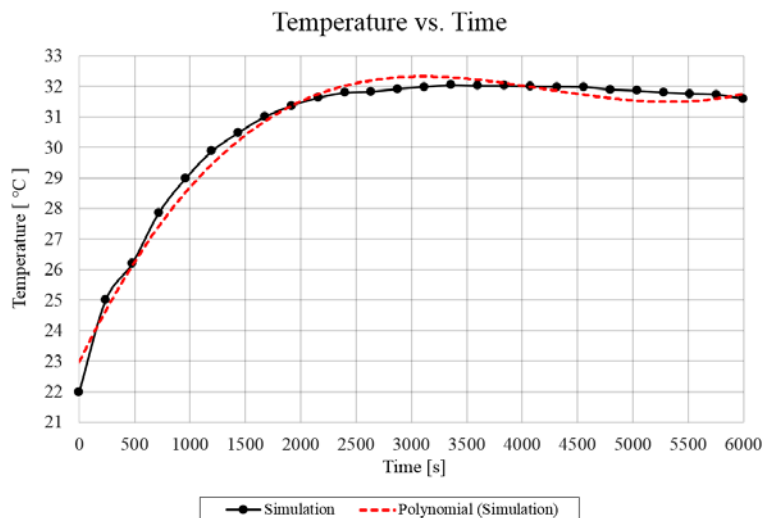


Figure 7 - Polynomial fit to simulated data



A fictitious plane was considered at a height 1.5 m above the ground (approximate height at which sated occupants of the cubicle would perceive temperature variations) (see Figure 8).

In Figure 8 it can be noticed that the temperature was higher in the north and east walls of the enclosure, and this is the result of the incidence of solar rays that managed to cross the glasses located in the south and west walls.

In the following sequence of images, the distribution of the temperature on the fictitious plane is observed at 15-minute time intervals (see Table 6).

In addition, equations 4 and 5 show that the time temperature setting, for experimental and simulated results, is good considering that the value of the

coefficient of determination is 98.16% and 99.24% respectively.

As seen in the previous table, the greatest heat transfer on the reference plane occurred by convection from the areas of incidence of the solar rays on the north and east walls of the cubicle. During the first 60 minutes an increase of 7 degrees centigrade approximately in relation to the initial temperature was noted. From this moment the temperature tended to stabilize inside the enclosure. The reason for such behavior is the change in the position of the sun over time and this affects the north and south walls of the cubicle, decreasing the effect by convection inside the space considered.

In the following figure (see Figure 9) it is possible to view the results of the simulation of the temperature distribution on the limiting surfaces of the enclosure (isometric view) at 15:15 hours.

Figure 8 - Temperature distribution on a XY plane at height Z = 1,5 m

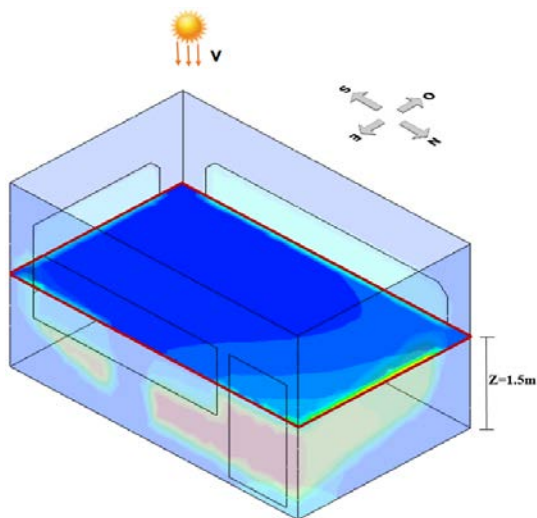


Table 6 -Distribution of the temperature on the fictitious plane, every 15 min

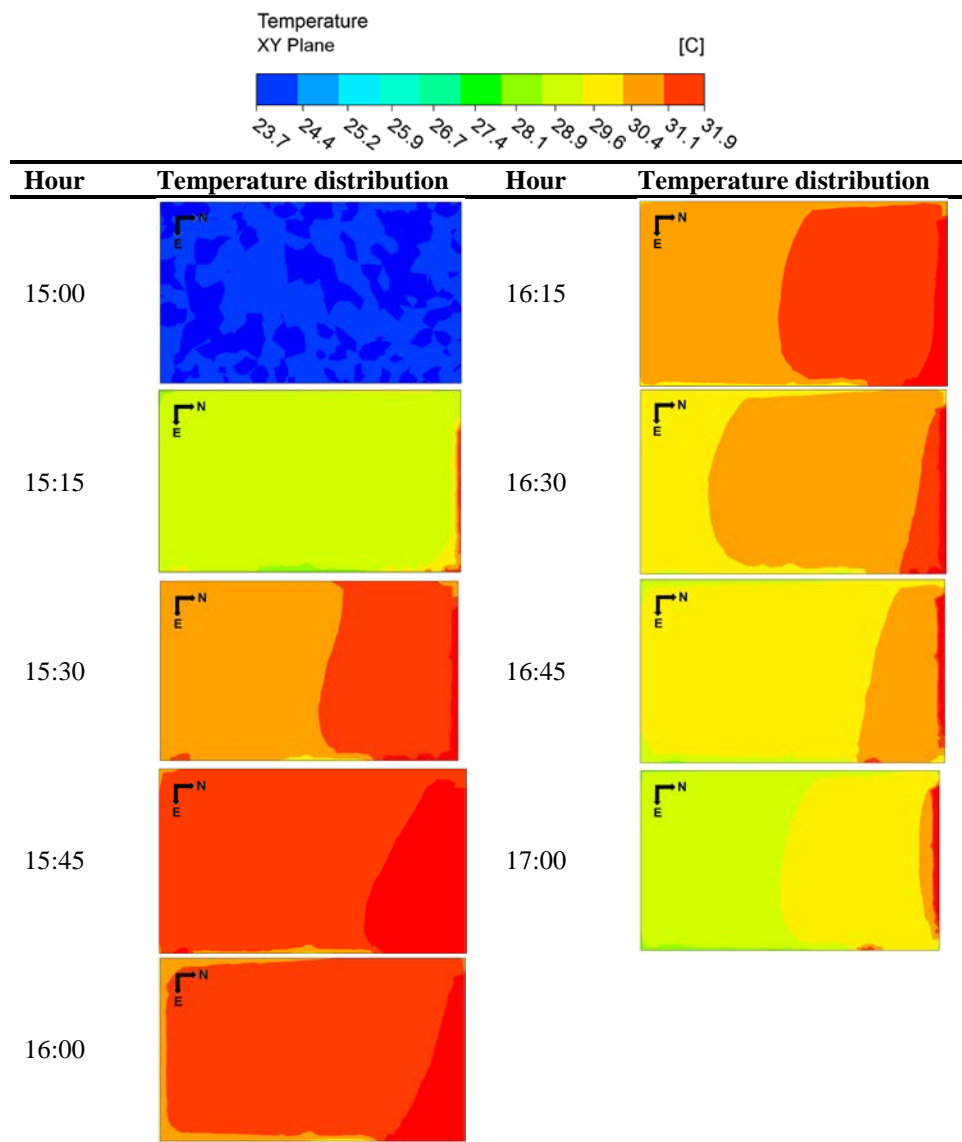
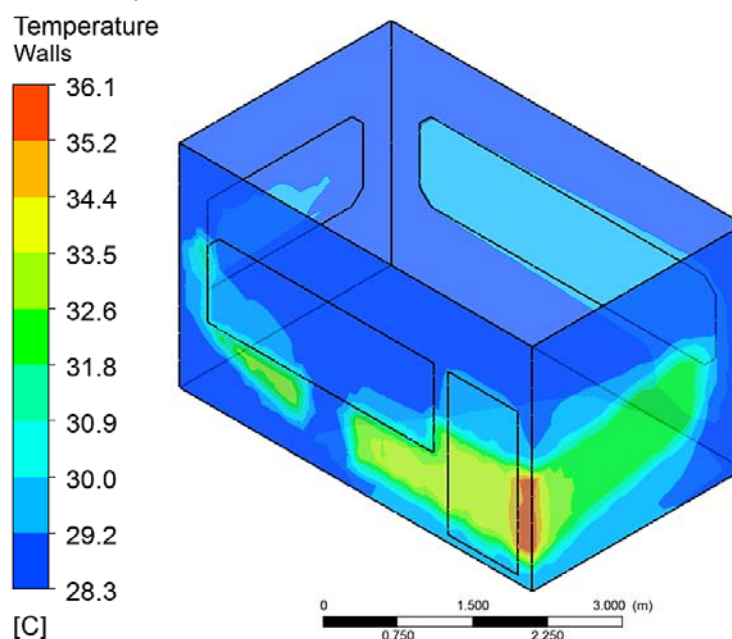


Figure 9 - Distribution of the temperature on the walls of the enclosure (t = 15:15 hours).



Final considerations

The curves (temperature vs. time) shown in Figure 5, refer to the measurement point (PM), and considering the location of this point inside the cubicle, it is clear that the highest incidence on the phenomenon studied was caused by the effect of radiation. Thus, the tolerance of the thermography camera TESTO, used to obtain temperature values on the limiting surfaces of the enclosure (part of the boundary conditions) had an action on the final results, which could be considered negligible. In addition, to measure the temperature in PM, a LM35 sensor was used that had an error tolerance of up to $\pm \frac{3}{4}$ °C. Thus, independently of the deviations of the temperature curve that resulted from the recorded measurements, with respect to the computational ones; the biggest relative error between two measurement points was 4.947%.

The validation of the study performed in FLUENT was based on the dynamic evolution of temperature at a specific point and on a certain fictitious plane in the test-cell, compared to the corresponding experimental data. In this sense, one of the ways of continuity of the present investigation is related to experimentation in order to avoid the reduction of mesh quality (skewness and orthogonality) when it is passed to the mesh with the smallest step. Regardless of this, the sequence of images in Table 6 describes, with acceptable precision, the thermal processes that take place on the fictitious plane, at a significant height in terms of the effect on thermal comfort of people who are using that space, during the critical time interval.

It was perceived that the curves of variation of the temperature with respect to the time, if the same interval of the day is observed (15:00 - 17:00 hours), had a similar behavior to those shown in other investigations, where other factors and combinations of factors were studied Gowreesunker and Tassou (2013), Barbason and Reiter (2014) and Gijón-Rivera *et al.* (2013). In addition, the Equations 4 and 5 that can describe such behaviors explain the phenomenon in high percentages (98.16% and 99.24% for experimental and simulated data respectively). All this guarantees the possibility of applying the developed simulation as a support tool when describing the process of temperature variation in any type of enclosure. This method could be applied as a complement to more complete analysis to determine the air conditioning needs, modifying and adjusting the values that make up the set of input conditions for the software.

To continue this line of research and to improve the obtained results, it would be advisable to use a better measurement instrumentation, with, also, the consideration of possible thermal loads constant in time, inside the cubicle.

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Efrén Vázquez Silva

Faculdade de Engenharia Mecânica | Universidade Politécnica Salesiana | Calle Vieja, 12-30 e Elia Liut, El Vecino | Cuenca - Ecuador | CP 010105 | Tel.: +(593) 7286-2213 | E-mail: evazquez@ups.edu.ec

Franco David Cajas Muñoz

Faculdade de Engenharia Mecânica | Universidade Politécnica Salesiana | E-mail: fcajas@est.ups.edu.ec

Marcelo Xavier Asitimbay Deleg

Faculdade de Engenharia Mecânica | Universidade Politécnica Salesiana | E-mail: masitimbayd@est.ups.edu.ec

Paúl Bolívar Torres Jara

Faculdade de Engenharia Mecânica | Universidade Politécnica Salesiana | E-mail: ptorresj@ups.edu.ec

Gabriela Abad Farfán

Faculdade de Engenharia Mecânica | Universidade Politécnica Salesiana | E-mail: gabadf@ups.edu.ec

Revista Ambiente Construído

Associação Nacional de Tecnologia do Ambiente Construído

Av. Osvaldo Aranha, 99 - 3º andar, Centro

Porto Alegre - RS - Brasil

CEP 90035-190

Telefone: +55 (51) 3308-4084

Fax: +55 (51) 3308-4054

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E-mail: ambienteconstruido@ufrgs.br



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