View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by idUS. Depósito de Investigación Universidad de Sevilla

LC 2015
Le Corbusier, 50 years later
International Congress
Valencia 18th - 20th November 2015
UNIVERSITAT POLITÈCNICA DE VALÈNCIA

DOI: http://dx.doi.org/10.4995/LC2015.2015.899

The mur neutralisant as an active thermal system: Saint Gobain tests (1931) versus CFD simulation (2015)

C. Ramírez-Balas, J.J. Sendra *, R. Suárez*, E.D. Fernández-Nieto**, G. Narbona-Reina***

** Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla*

*** Departamento de Matemática Aplicada I, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla*

Abstract: *At the same time as the initial development of air conditioning systems for indoor climate control in buildings were occurring in USA, Le Corbusier and Lyon made truly innovative proposals for different projects he was working on in Europe. These served to generate homogenous thermal environments and focused on the combined effect of his mur neutralisant and respiration exacte. The clearest example of their shortcomings is the City of Refuge in Paris (1930-33). Given the technological and economic mistrust towards these proposals, as it was impossible to execute these according to the original plan these were not pursued. CFD simulations carried out by our research team confirm that the mur neutralisant and respiration exacte for the City of Refuge in Paris would have functioned together if they had been executed following the original plans. The main aim of this paper is to confirm the validity of the mur neutralisant as an active thermal system for buildings. Firstly, the results of the tests carried out by the engineers of Saint Gobain are compared to the results of the CFD simulations. Based on the comparison of the results from the physical models tested in Saint Gobain laboratories and CFD energy model simulations, a possible calibration is proposed for CFD which might prompt the establishment of other operation hypotheses.*

Keywords: *Le Corbusier; mur neutralisant; The City of Refuge; Active Façade System; Computational Fluid Dynamics (CFD); Numerical Simulation.*

1. Introduction

In the 20th century, air conditioning systems gained success first in the United States and then in Europe, and their use became increasingly widespread throughout the century. In contrast, the proposals from Le Corbusier and Lyon, based on the combination of the *mur neutralisant* and *respiration exacte* (figure 1) as an active thermal system, only provoked technical and financial mistrust so that they were not followed up and could not be executed as planned. However, in the late 20th century these reappeared as predecessors of active façade systems. The best-known example of their failure is the City of Refuge in Paris (1930-33), designed as Salvation Army accommodation for between 500 and 600 homeless people.

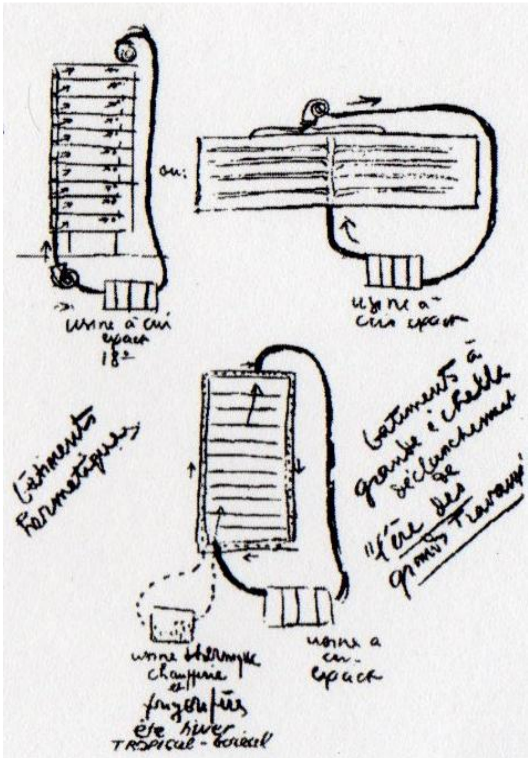
However, simulations carried out by our research team using Computational Fluid Dynamics (CFD) programs confirm the combined effect of the *mur neutralisant* and *respiration exacte* on the temperature control of the main dormitory in the City of Refuge of Paris if the system had been executed following the original designs of Le Corbusier and Lyon[1]. The main aim of this study is to establish the suitability of the *mur neutralisant* as an active conditioning system for buildings. In the 1930s Saint Gobain engineers Lebel and Le Barbier carried out

[1] Ramírez Balas, C.; Fernández Nieto, E.D.; Narbona Reina,G.; Sendra, J. J.; Suárez, R. "Numerical simulation of the temperature evolution in a room with a mur neutralisant. Application to 'The City of Refuge' by Le Corbusier". *Energy and buildings*. 2015. 86. pp. 708-722.

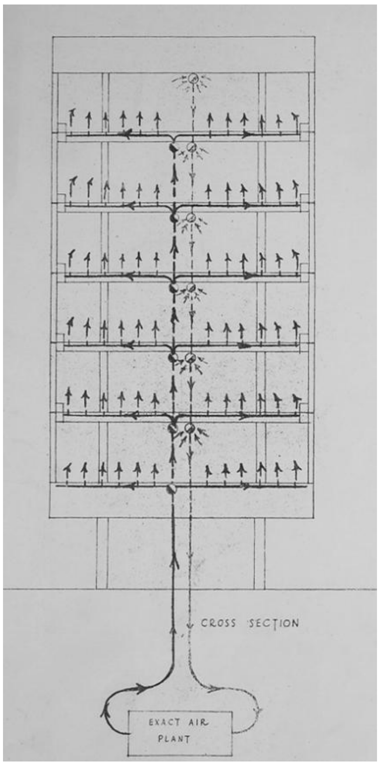
This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

laboratory tests on physical models to ascertain the suitability of the *mur neutralisant* as an active heating system in extreme outdoor temperatures and without solar radiation[2] [3] [4] [5]. Our research group has compared these with the results obtained in 2015 using energy models and CFD simulations of the same operation and outdoor environmental conditions.

Following the comparison and adjustment of both models, other hypotheses have been established regarding the operation of the energy models and subsequent CFD simulation of the design of a south-facing *mur neutralisant* for the main dormitory in the City of Refuge. The operation of the *mur neutralisant* has been assessed as an active heating system for cold winter days with and without sunlight, including the influence of solar radiation, which was neglected in the Saint Gobain tests, and as an active cooling system on hot summer days, an operation mode which Saint Gobain also failed to test.



1a. Diagram by Le Corbusier of the operation of the *mur neutralisant*[6].



1b. Drawing by Le Corbusier of the *mur neutralisant* and *respiration exacte*[7].

1. Proposal by Le Corbusier for the *mur neutralisant* and *respiration exacte.*

---

[2] Le Braz, J. "La transmission de la chaleur gràverâ travers le verre: Des idées nouvelles sur le chauffage des habitations." *Glaces et Verres*. 1933. Nº 20. pp. 13.

[3] Brian Brace, T. "Le Corbusier, the city of refuge, Paris 1929-33". Chicago: University of Chicago Press. 1987.

[4] Cuadernos de Postgrado. La respuesta de la American Blower Corporation. 24 January 1930.

[5] Bryan, Harvey. "Le Corbusier and the 'Mur Neutralisant': An Early Experiment in Double Envelope Construction." Proceedings of the Ninth International PLEA Conference. 1991. pp. 257–62.

[6] Le Corbusier. El edificio hermético. "Croquis de Précisions".

[7] Foundation Le Corbusier. FLC 15720. ©FLC-ADAGP.

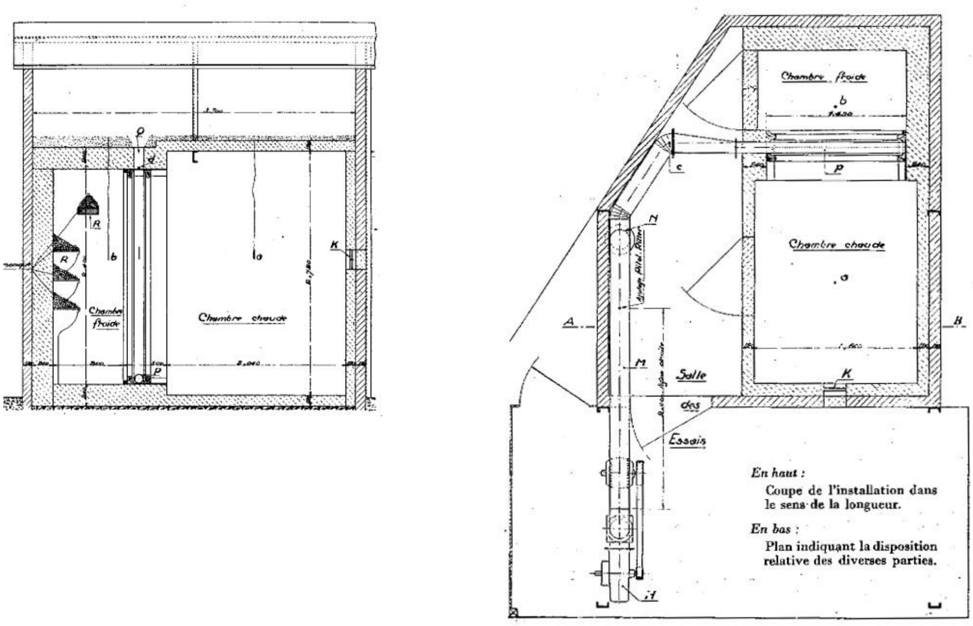
This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

2. Saint Gobain tests

On Le Corbusier's instructions, Saint Gobain engineers carried out numerous tests over a two-year period, recording them in two documents on 25 June 1931[8] and 11 March 1932[9].

The test room (figure 2) consisted of two rooms with a 0.5 m intermediate space and 7 mm double glazing in a wooden frame with an air cavity varying between 3 and 20 cm in width. The room known as the hot room representing the interior space, measured 2.04 x 1.64 m and was 2.72 m high. It needed to maintain an indoor temperature of 18 ºC to ensure minimum thermal comfort conditions in winter. Another "cold" room, measuring 0.8 x 1.4 m and 2.4 m high, represented the outdoor space. The temperature in this cold room could be maintained at different low winter levels.

Walls, ceilings and floors were built using 12 cm thick expanded cork insulation panels in the hot room, while those used in the cold room were 24 cm thick. On two of these walls the panels were in contact with a brick enclosure. All openings were sealed and a 22 x 22 cm window (K) was used to review the installation without opening the door. Figure 2 shows the following elements: a 2.5 m long conduct, used to measure the fan-driven airflow, which varied between 0 and 150 l/s; an air heater consisting of a series of electric resistances which could bring the temperature up to 50 ºC; a device consisted of a shell with holes on top, placed at the bottom of the air cavity between both glass panes and distributing air inside the cavity. The hot air passing between both glass sheets was expelled through a hole at the top of the air cavity. Finally, four temperature sensors were placed: (a) at the centre of the hot room; (b) at the centre of the cold room, 1.22 m from the glass; (c) in the hot air conduct, prior to air entry to the cavity; and (d) at hot air outlet, at the top of the air cavity.



2. Horizontal and vertical section of the Saint Gobain test room[10].

---

[8] Lebel, H.; Le Barbier, M. Société Anonyme des Manufactures des Glaces et Produits Chimiques de Saint-Gobain, Chauny et Cirey. Note sur les essais de transmission de la chaleur à travers les glaces, efectués à l'Annexe du Comptoir de Vente, 23 rue Boucry, Paris du 3 Avril au 8 Mai 1931. Letter of 25 June 1931.

[9] Lebel H.; Le Barbier, M. Société Anonyme des Manufactures des Glaces et Produits Chimiques de Saint-Gobain, Chauny et Cirey. Note sur la seconde série d'essais effectués pour la mesure de la transmission de la chaleur à travers les glaces à l'Annexe du Comptoir de Vente, 23 rue Boucry, Paris du 23 Novembre au 21 Décembre 1931. Letter of 11 March 1932.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

Various tests proposing different hypotheses were carried out on a 7 mm double glazed *mur neutralisant*. The width of the air cavity, airflow and duration of the test were modified. The main aim was to obtain a low transmission coefficient (Q) for the *mur neutralisant* in winter with a view to maintaining an indoor room temperature of 18ºC in very low outdoor temperatures with no solar radiation.

Between 3 April and 8 May 1931 an initial series of tests was carried out for three air cavity widths: 20 mm, 70 mm and 120 mm, with no hot airflow through the cavity (table 1). The Q values obtained were 2.80, 3.36 and 3.92 kcal/h m^2 ºC, respectively. Accordingly, the decision was made to continue the tests with a hot airflow of 100 l/s into the air cavity (active chamber), at different temperatures and cavity widths between 11 and 12 cm. An initial run of three tests on the 12 cm active chamber was carried out with different airflow temperatures suited to the cold room temperature (case 1, table 2), followed by a second three-test run with the same airflow, varying the cavity widths to 11 cm (case 2, table 3), and with cold room and hot airflow temperatures also differing from earlier ones. In both cases the hypotheses were numbered following the chronological order of tests.

	13 April	15 April	14 April
Test duration	2h 30'	2h 45'	2h 30'
Active chamber width	12 cm	7 cm	2 cm
Mean T hot room: Tc	+18 °C	+18 °C	+18 °C
Mean T cold room: Tf	-7.5 °C	-22.5 °C	-15.5 °C
Mean ambient T: Ta	+12.8 °C	+13 °C	+12.2 °C
Value of Q (kcal/hm^{2}ºC)	2.80	3.36	3.92

Table 1. Tests on *mur neutralisant* with different chamber widths and no heating.

Case 1: 12 cm	**Hypothesis 1**	**Hypothesis 2**	**Hypothesis 3**
	27 April	28 April	29 April
Test duration	1h 30'	1h 15'	2h 45'
Active chamber width	12 cm	12 cm	12 cm
Mean T hot room: Tc	+19 °C	+16.2 °C	+16 °C
Mean T cold room: Tf	-6 °C	- 8.8 °C	- 17.5 °C
Mean ambient T: Ta	+14 °C	+15 °C	+13.5 °C
Inlet T *mur neutralisant*	+20.25 °C	+20.2 °C	+22.7 °C
Outlet T *mur neutralisant*	+17.5 °C	+16.5 °C	+17.5 °C
Airflow	100 l/s	100 l/s	100 l/s
Value of Q (kcal/hm^{2}ºC)	5.95	6.78	6.70

Table 2. Test on 7+120+7 mm *mur neutralisant* with hot airflow inside the active chamber and with the same flow.

Case 2: 11 cm	**Hypothesis 1**	**Hypothesis 2**	**Hypothesis 3**
	8 May	8 May	8 May
Test duration	50'	4 h 15'	55'
Active chamber width	11 cm	11 cm	11 cm
Mean T hot room: Tc	+18 °C	+18 °C	+18 °C
Mean T cold room: Tf	-28 °C	-20 °C	-13 °C
Mean ambient T: Ta	17°	17°	17°
Inlet T *mur neutralisant*	+38 °C	+31.5 °C	+27.5 °C
Outlet T *mur neutralisant*	+28.5 °C	+24 °C	+22 °C
Airflow	100 l/s	100 l/s	100 l/s
Value of Q (kcal/hm^{2}ºC)	6.60	7.00	6.60

Table 3. Test on 7+110+7 mm*mur neutralisant* with hot airflow inside the active chamber and with the same flow.

[10]Le Braz, J. "La transmission de la chaleur gràverâ travers le verre: Des idées nouvelles sur le chauffage des habitations". *Glaces et Verres*. 1933. Nº 20. pp. 13.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

Between 23 November and 21 December another three tests were carried out with different flows and hot airflow temperatures in the 12 cm active chamber, depending on the temperature of the cold room (case 1, table 4).

Case 1: 12 cm	**Hypothesis 4**	**Hypothesis 5**	**Hypothesis 6**
	26 November	18 December	18 December
Test duration	1h	1h 30'	1h 45'
Active chamber width	12 cm	12 cm	12 cm
Mean T hot room: Tc	+17.2 °C	+18.1 °C	+18 °C
Mean T cold room: Tf	-11.5 °C	-11.8 °C	-10.5 °C
Mean ambient T: Ta	+13 °C	+7.5 °C	+8 °C
Inlet T *mur neutralisant*	+35.7 °C	+35.5 °C	+43.7 °C
Outlet T *mur neutralisant*	+29.2 °C	+29.7 °C	+32.5 °C
Airflow	150 l/s	120 l/s	85 l/s
Valueof Q (kcal/hm^{2}ºC)	6.98	6.34	5.35

Table 4. Test on 7+120+7 mm *mur neutralisant* with hot airflow inside the active chamber and with different flows.

On 12 December 1931 a test was carried out using an electric radiator inside the 13 cm cavity in order to determine the influence of hot air convection within this active chamber (case 3, table 5).

Case 3: 13 cm	12 December
Test duration	1h 30'
Active chamber width	13 cm
Mean T hot room: Tc	+18.5 °C
Mean T cold room: Tf	-10.2 °C
Mean ambient T: Ta	+2.7 °C
Mean T cavity	+42.1 °C
Value of Q (kcal/hm^{2}ºC)	5.49

Table 5. Test on 7+130+7 mm *mur neutralisant* with intermediate heating from electric radiator.

Finally, in late 1931 a further two tests were executed with a *mur neutralisant* configuration consisting of three 7 mm panes, with a 65 mm separation between the outer glazing and the intermediate glazing, and 120 mm between the intermediate and the inner glazing, with no hot airflow in the two air chambers (table 6).

	1 December	16 December
Test duration	1h 26'	2h 3'
Width of cavity between inner glazing and intermediate glazing	12 cm	12 cm
Width of cavity between intermediate glazing and outer glazing	6.5 cm	6.5 cm
Mean T hot room: Tc	+17.6 °C	+18 °C
Mean T cold room: Tf	-10.9 °C	-11.5 °C
Mean ambient T: Ta	+6.2 °C	+7.4 °C
Value of Q (kcal/hm^{2}ºC)	1.65	1.71

Table 6. Tests on 7+65+7+120 +7 mm *mur neutralisant* without heating.

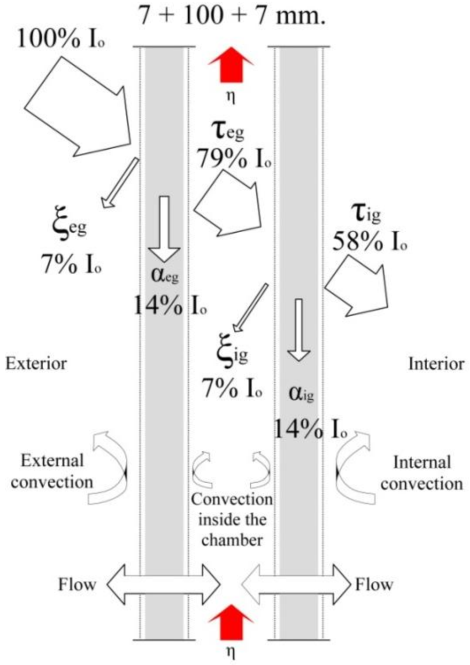
3. Numerical model proposed for the simulation of the *mur neutralisant*

Current CFD energy simulation systems make it possible to evaluate the energy behaviour of the *mur neutralisant* solution proposed by Le Corbusier. In fact, our research group has developed a CFD model not only reproducing the behaviour of Le Corbusier's *mur neutralisant*, but also its behaviour when combined with

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

respiration exacte[11]. The numerical calculation model drawn up using mathematical codes and ways of resolution was implemented and subsequently simulated using FreeFem++ (hereafter FF++)[12].

Figure 3 clearly shows the energy flows within the *mur neutralisant*, which were taken into account in the design of the model. Of the total incident solar radiation (I_o), 7% was reflected to the exterior (ξ_{eg}) and 14% absorbed by the outer glazing (α_{eg}). The remaining 79% of energy incides on the inner glazing (τ_{eg}), with 7% transmitted to the air cavity through reflection (ξ_{ig}), 14 % absorbed by the inner glazing (α_{ig}) and finally, 58% of incident solar energy which is transmitted to the room (τ_{ig}).



3. Scope and detail of physical phenomena in the *mur neutralisant*.

The numerical model proposed resolves the following system of partial differential equations:

$$\begin{cases} (\rho c V)_f \dfrac{\partial T_f}{\partial z} = -\eta c \dfrac{\partial T_f}{\partial z} + U_c A(T_{eg} - T_f) + U_c A(T_{ig} - T_f) \\ (\rho c V)_{eg} \dfrac{\partial T_{eg}}{\partial t} = U_{ext} A(T_{ext} - T_{eg}) + U_c A(T_f - T_{eg}) + \sigma \varepsilon_{eg}(T_{ext}^4 - T_{eg}^4) + \alpha_{eg} I_o + Q_{eg} \\ (\rho c V)_{ig} \dfrac{\partial T_{ig}}{\partial t} = U_{int} A(T_{int} - T_{ig}) + U_c A(T_f - T_{ig}) + \sigma \varepsilon_{ig}(T_{int}^4 - T_{ig}^4) + \alpha_{ig} \tau_{eg} I_o + Q_{ig} \end{cases}$$

with $z \in [0, L]$, L is the length of the *mur neutralisant* and $t \in [t_0, t_M]$ time.

[11] Ramírez Balas, C.; Fernández Nieto, E.D.; Narbona Reina,G.; Sendra, J.J.; Suárez, R. "Numerical simulation of the temperature evolution in a room with a mur neutralisant. Application to 'The City of Refuge' by Le Corbusier". *Energy and buildings*. 2015. Vol. 86. pp. 708-722.

[12] FreeFem++ v.-3.37-1. Available from: http://www.FreeFem.org/ff++/ (22.05.15).

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

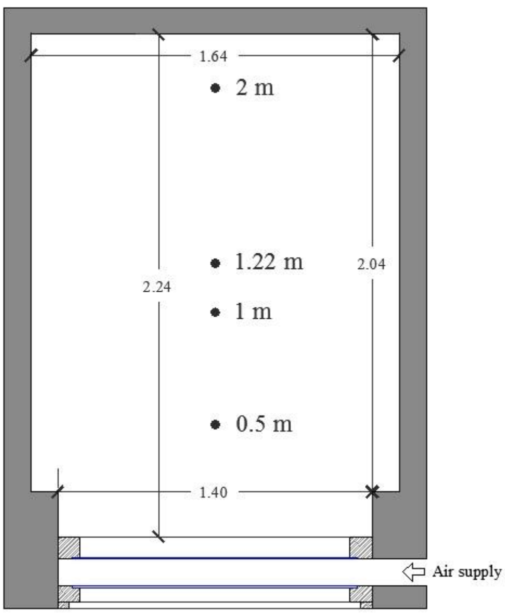
The model designed can calculate in both winter and summer conditions as it makes it possible to introduce the absorption, transmission and reflection of solar radiation and the convection flows in the glazing due to incidence of solar radiation and exterior temperature.

The model was validated with the models proposed by Ismail and Henríquez[13][14][15]. This research focused exclusively on the study of the effects of the *mur neutralisant*. The complete development of the numerical model can be consulted in[16].

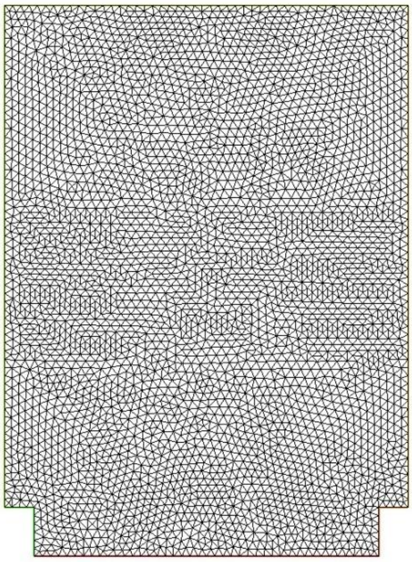
4. Numerical model vs. Saint Gobain tests

The initial proposal was the comparison of the results of the 1930s Saint Gobain tests (hereafter SG) with the FF++ simulation results of the Computational Fluid Dynamics numerical models design (hereafter CFD), with only the *mur neutralisant* in operation.

The CFD model reproduces the Saint Gobain test room, respecting the measurements and characteristics of the room and the *mur neutralisant* under study (Fig. 4). The mesh density in the CFD model was adjusted to ensure reliable results and a minimum margin of error (Fig. 5).



4. Dimensions and points of measurement for the SG room.



5. Density of the SG room mesh for CFD model.

---

[13] Ismail, K.A.R.; Henríquez, J.R. "Modeling and simulation of a simple glass window", *Solar Energy Materials & Solar Cells.* 2003. 80. pp. 355–374.
[14] Ismail, K.A.R.; Henríquez, J.R. "Two-dimensional model for the double glass naturally ventilated window", *International Journal of Heat and Mass Transfer*. 2005. 48. pp. 461–475.
[15] Ismail, K.A.R.; Henríquez, J.R. "Simplified model for a ventilated glass window under forced air flow conditions". *Applied Thermal Engineering*. 2006. 26. pp. 295–302.
[16] Ramírez Balas, C.; Fernández Nieto, E.D.; Narbona Reina,G.; Sendra, J. J.; Suárez, R. "Numerical simulation of the temperature evolution in a room with a mur neutralisant. Application to 'The City of Refuge' by Le Corbusier". *Energy and buildings*. 2015. 86. pp. 708-722.

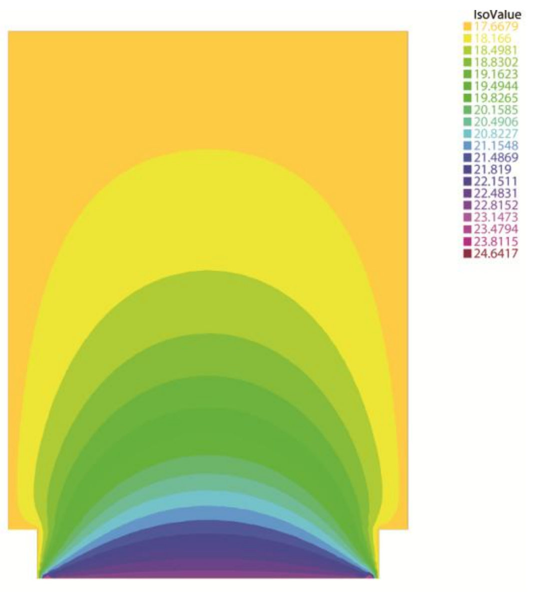
This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

Test 2, with a 7+110+7 mm *mur neutralisant* in the Saint Gobain hypothesis, was taken as reference for the comparison of the results of both models for two main reasons. It was the test with the longest duration, 4 h 15 m, to maintain the room at 18 ºC and it established an air flow of 100 l/s in the chamber. Saint Gobain established this value after analysing the effect of different flows, such as 120 l/s and 150 l/s. It was shown that with the reduction of airflow to 100 l/s there was a considerable reduction in the heat transmission coefficient due to less turbulence in the air chamber and less active exchanges between the hot air and the cold outer glazing.

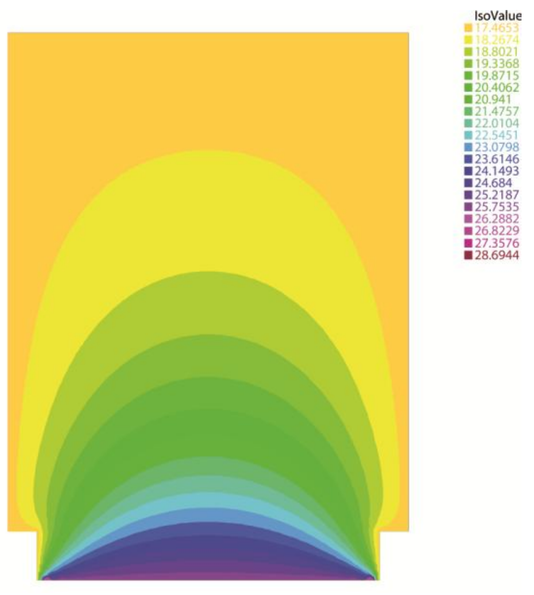
Table 7 shows the results of the CFD model simulation at hourly intervals from the first to the fourth hour, recording the evolution of the different temperatures both in the room and the *mur neutralisant* itself. As with the SG model, the simulation was carried out in the absence of solar radiation. In addition, figure 6 shows the output of the results of the CFD model for the same hourly intervals. Based on these results, a graph was produced to show the distribution of the indoor room temperature in relation to the room depth (Fig. 7).

		Test duration FF++ (CFD)			
Room under study		60 min	120 min	180 min	240 min
0.5 m Room temperature	T 0.5 m	20.15	21.50	22.29	22.74
1 m Room temperature	T 1 m	18.82	19.35	19.65	19.82
1.22 m Room temperature	T 1.22 m	18.53	18.87	19.07	19.18
2 m Room temperature	T 2 m	18.07	18.12	18.15	18.16
Mur neutralisant		60 min	120 min	180 min	240 min
Exterior glazing temperature	Teg	-3.38	3.76	6.41	7.41
Interior glazing temperature	Tig	21.89	25.24	27.10	28.47

Table 7. Temperatures of the room and *mur neutralisant* following CFD simulations with air heating.

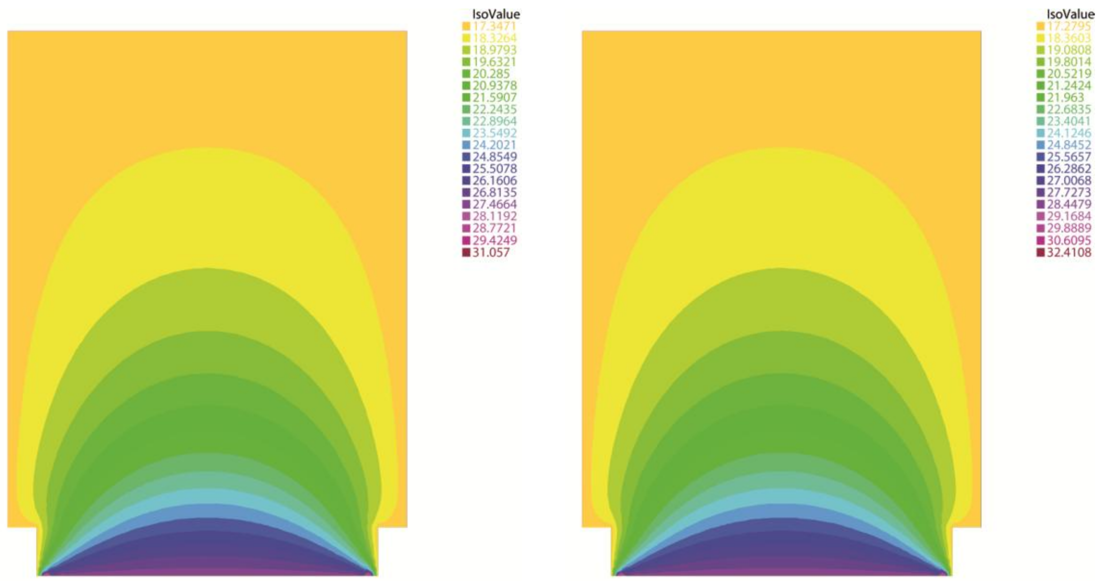


6a. 60 min.



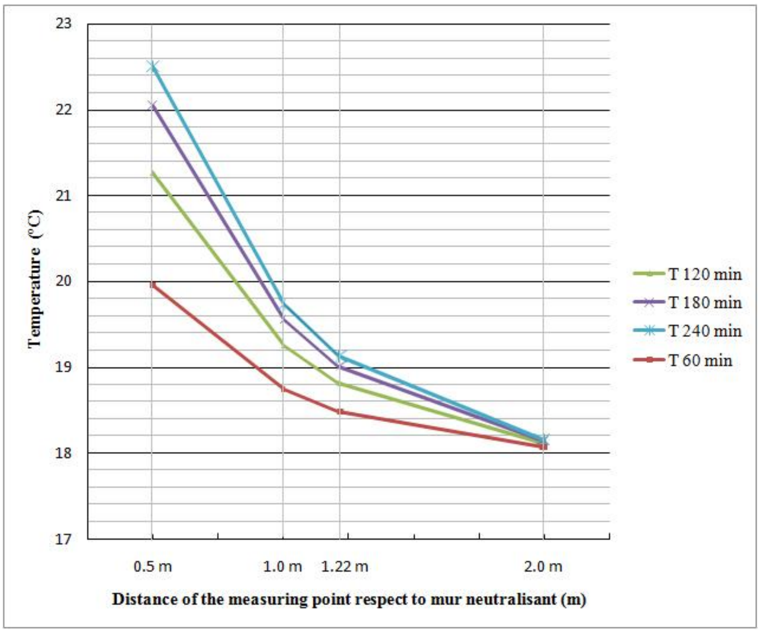
6b. 120 min.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)



6c. 180 min. 6d. 240 min.

6. Results of the CFD simulation at hourly intervals (horizontal model section) with air heating.



7. Evolution of indoor temperature at different points of the room over 4 hours with air heating.

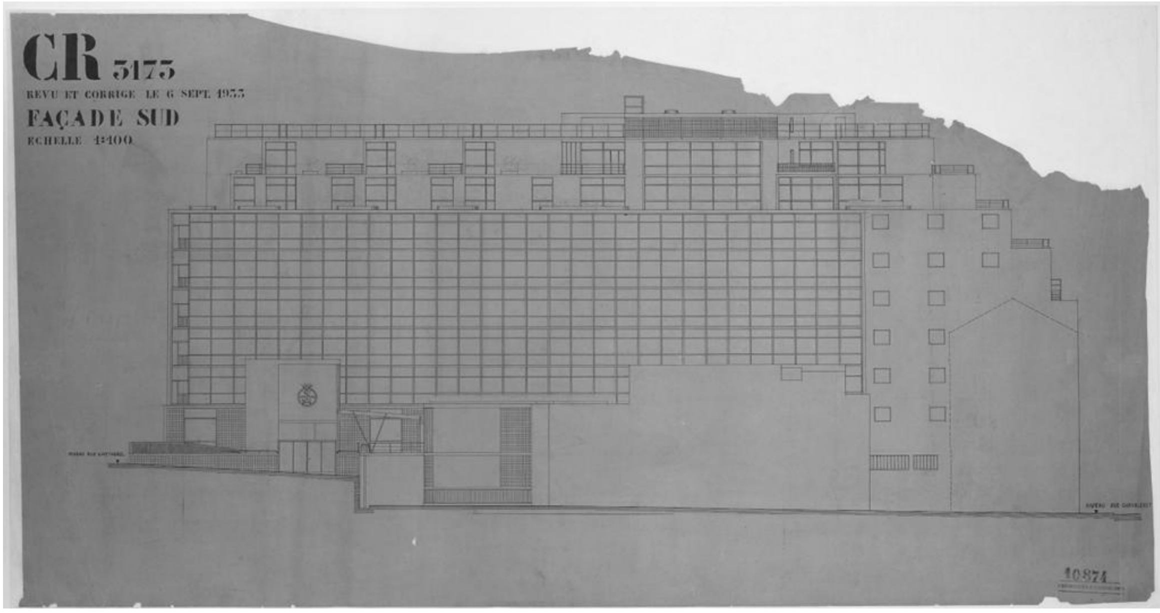
Figure 7 shows that with the same flow temperature in the active chamber as the SG model, 31.5 ºC, and the mass flow from the same airflow in the chamber, 100 l/s, the temperature 1.22 m deep where Saint Gobain placed temperature probes is around 19 ºC, a degree higher than that of SG. Convergence at 18 ºC takes place 2 m from the *mur neutralisant*. Therefore, with this temperature and flow the values occurring in the room are similar to those Saint Gobain regarded as comfort level in winter, or even slightly higher.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

As is to be expected the indoor and outdoor surface temperature of the glazing in the *mur neutralisant* evolve over time, increasing perceptibly to values around 7º C outdoors and 28.4 ºC indoors. Therefore, given that the difference in temperature between both models is around 5%, it can be considered that in winter conditions without solar radiation there is adjustment between them.

5. Establishment of other hypotheses on environmental conditions and the operation of the *mur neutralisant*

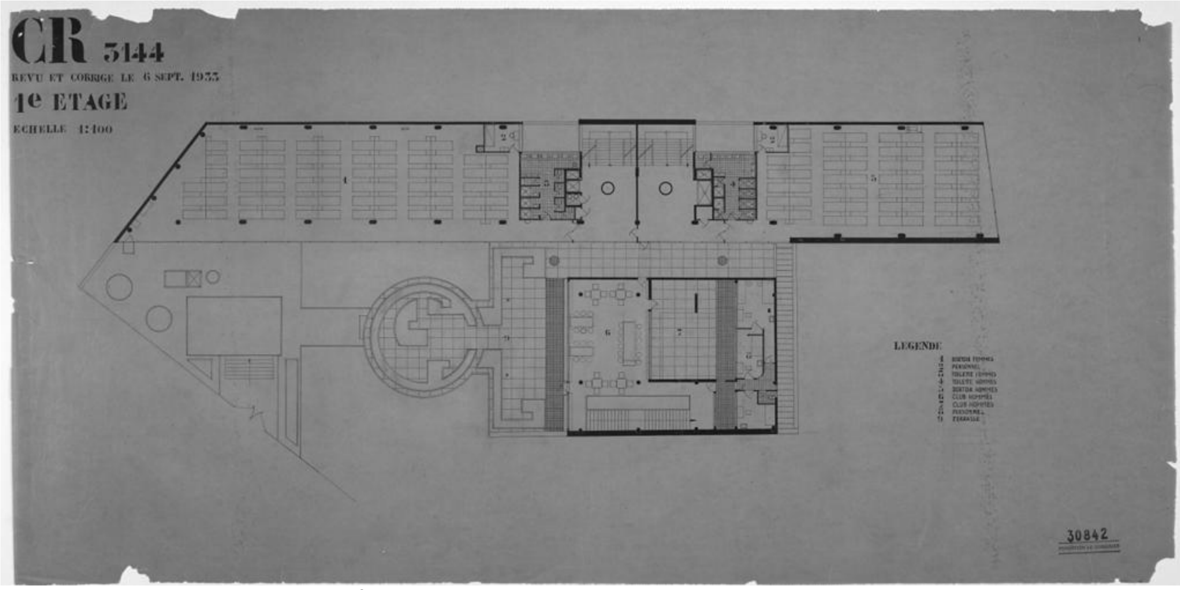
Once the adjustment between both models was established, different hypotheses were proposed for environmental and operation conditions of the *mur neutralisant*, but the CFD model of the test room was replaced with a model of the main dormitory of the City of Refuge (figure 8) (hereafter CR model), with a surface area of 297.67 m^2. Figure 9a shows this model and figure 9b shows the meshing applied to it. The south-facing façade of the Parisian CR model is a *mur neutralisant* 37.20 m long and 2.80 m high, with a surface area of 104.16 m^2 and a 110 mm cavity with 7 mm double glazing (7+110+7).



8a. South façade of the City of Refuge[17].

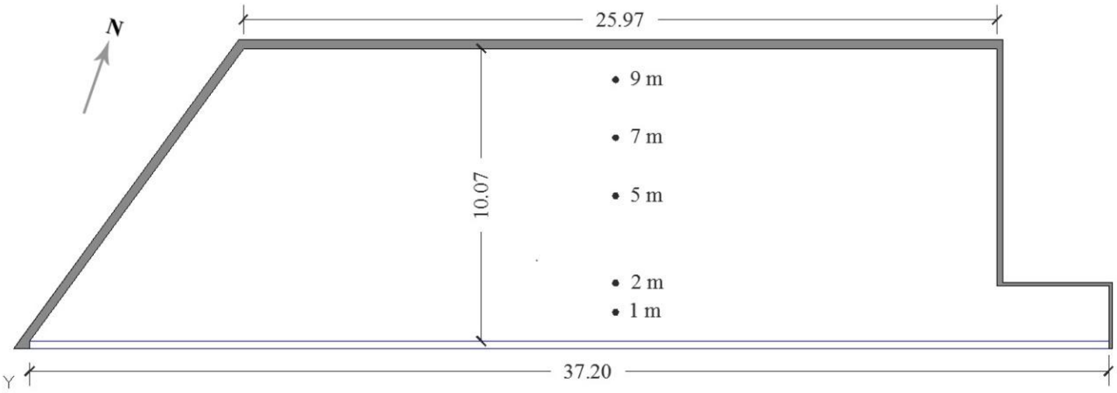
[17]Fundation Le Corbusier. CR 3173. FLC 10874. ©FLC-ADAGP

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)



8b. First floor of the City of Refuge[18].

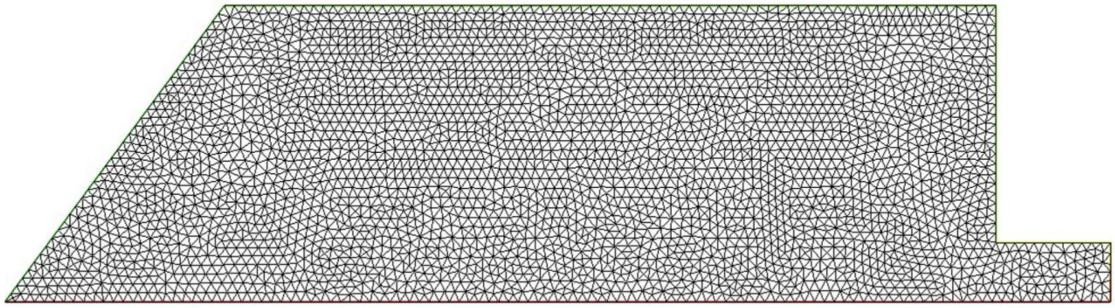
8. Drawings of the City of Refuge. 6 September 1933.



9a. Dimensions and points of measurement in the room in the City of Refuge.

[18]Fundation Le Corbusier. CR 3144. FLC 30842. ©FLC-ADAGP

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)



9b. CFD mesh density in the room in the City of Refuge.

9. CFD Model.

5.1 CFD simulations in the City of Refuge model in winter with absence and presence of solar radiation

Simulations were carried out on the CR model from the 27 to 31 December, but the only results specified here are those of the third and coldest day, 30 December, with an outdoor temperature ranging from – 6 ºC at 8:00 h to 1 ºC at 15:00 h (table 8), once the operating conditions of the thermal system were stabilised. Both the presence and absence of solar radiation -not included by Saint Gobain in the tests- were simulated, in order to assess solar incidence on the evolution of indoor temperatures. The airflow used in the cavity was 100 l/s per metre along the *mur neutralisant*, as recommended by Saint Gobain engineers following the tests. The heat coefficient value (Q) used was the same as that calculated by Saint Gobain engineers for this configuration of *mur neutralisant* and airflows. The following formula, proposed by Lyon, and based on outdoor temperature was used to calculate airflow temperature:

$$\theta_E = 21.6 - \frac{Tf}{5}$$

where θ_E equals airflow temperature and T_f the outdoor temperature, both in ºC.

However, unlike constant airflow temperature criteria followed in the Saint Gobain tests, a simplification which could be considered as valid given the test duration, our simulations have considered a variable airflow temperature based on outdoor temperature, with no variation given the limited thermal inertia of the *mur neutralisant*. These calculations were spread out over four days, with day-night thermal oscillations, and a maximum value of 7 ºC was reached on the third day (30 December). Therefore, applying Lyon's formula to each hour of these days, the airflow temperature varies depending on the outdoor temperature.

5.1.1 Simulation with solar radiation

Table 8 shows the results for simulations with solar radiation. The fifth and sixth columns show the respective surface temperatures of the outer and inner glazing of the *mur neutralisant*. The fourth column of the table gives the variable hot airflow temperature in the active chamber, values oscillating from 22.8 ºC at 8:00 h to 21.4 ºC at 15:00h. These are relatively low values given the outdoor temperatures and the relatively low airflow, 100 l/s per metre along the *mur neutralisant*, and provide an idea of the efficiency of the thermal system.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

Figures 10 and 11 show the results in a horizontal section at 8:00 h and 15:00 h, when the respective minimum and maximum outdoor temperatures are reached. In addition, figure 12 includes a series of graphs of the evolution of the temperature inside the room on the third day at hourly intervals depending on the distance from the *mur neutralisant* as well as its relationship to the outdoor temperature.

As can be seen, the maximum indoor temperatures are reached at 15:00 h and the minimum ones at 7:00 h. The temperatures reached at the same distance from the *mur neutralisant* are fairly uniform throughout the day, with temperature differences between the two test hours of 1.14 ºC at 1 m, 0.95 ºC at 2 m, 0.49 ºC at 5 m, 0.26 ºC at 7 m and 0.09 ºC at 9 m. This uniformity of temperature therefore increases throughout the day with the distance from the *mur neutralisant*. The thermal uniformity on the outdoor glazing of the *mur neutralisant* is also significant. Although outdoor temperature varied by 7 ºC on that day, the superficial temperature of the outdoor glazing only varied by 2.58 ºC.

As was to be expected, there is less thermal uniformity in the room, although all its points fall within the temperature comfort band during the day, with a maximum temperature value of 23.73 ºC, at 1 m from the *mur* at 15:00 h, and a minimum value of 18.49 ºC, at 9 m from the *mur* from 7:00 to 9:00 h. At 15:00 h the difference in temperatures 1 m from the wall and 9 m from the wall (end locations in the room) is 5.15 ºC, and at 7:00 h it is 4.10 ºC. The difference in the half of the room closest to the *mur neutralisant* is more pronounced, as the differences in temperature 5 m from the *mur neutralisant* and 9 m. from the *mur neutralisant* are 2.41 ºC at 15:00 h and 2.01 at 7:00 h.

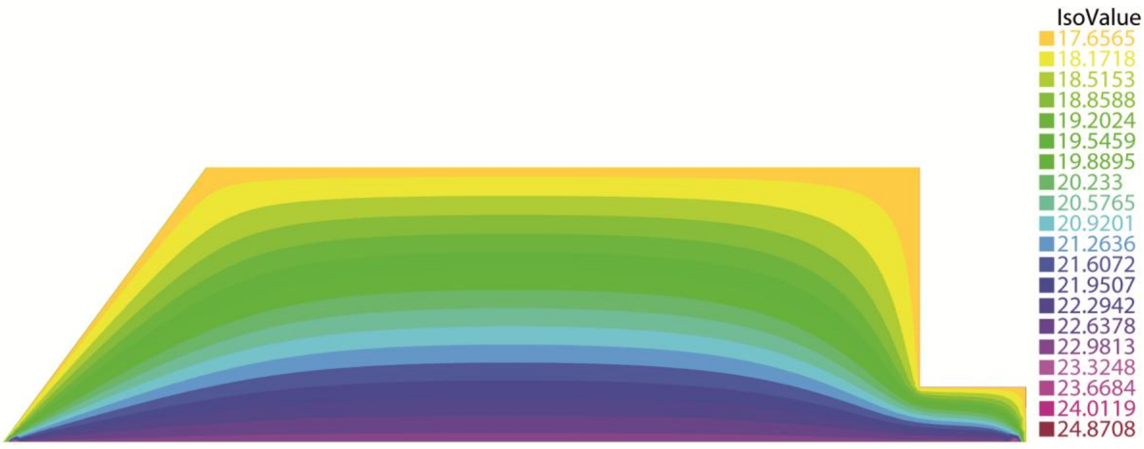
As stated by our research group in the CFD simulations using a numerical model of the combined effect of the *mur neutralisant* and *respiration exacte*, the function of *respiration exacte* is not merely limited to improving indoor air quality but also contributes to greater thermal uniformity in the room, thus improving the comfort conditions of the thermal system[19].

[19]Ramírez Balas, C.; Fernández Nieto, E.D.; Narbona Reina,G.; Sendra, J. J.; Suárez, R. "Numerical simulation of the temperature evolution in a room with a mur neutralisant. Application to 'The City of Refuge' by Le Corbusier". *Energy and buildings*. 2015. 86. pp. 708-722.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

30-Dec	Io W/m²	Text ºC	Timp ºC	Teg ºC	Tig ºC	T (1 m) ºC	T (2 m) ºC	T (5 m) ºC	T (7 m) ºC	T (9 m) ºC
1:00	229	-3.8	22.36	11.92	22.53	22.68	22.16	20.58	19.54	18.51
2:00	228	-4	22.4	11.78	22.5	22.66	22.13	20.56	19.53	18.51
3:00	232	-3	22.2	11.73	22.47	22.62	22.11	20.55	19.52	18.51
4:00	227	-4.2	22.44	11.61	22.45	22.61	22.09	20.53	19.51	18.50
5:00	228	-4	22.4	11.53	22.44	22.59	22.07	20.52	19.50	18.50
6:00	224	-5	22.6	11.39	22.44	22.59	22.07	20.51	19.49	18.50
7:00	225	-4.8	22.56	11.29	22.44	22.59	22.07	20.50	19.49	18.49
8:00	221	-6	22.8	11.13	22.47	22.61	22.08	20.50	19.49	18.49
9:00	226	-5	22.6	11.11	22.49	22.63	22.09	20.51	19.49	18.49
10:00	287	-4.3	22.46	11.31	22.64	22.71	22.14	20.52	19.50	18.50
11:00	628	-4	22.4	11.72	22.95	22.92	22.28	20.56	19.51	18.50
12:00	865	-2	22	12.34	23.30	23.20	22.50	20.64	19.55	18.51
13:00	1017	-0.1	21.62	12.98	23.59	23.46	22.72	20.76	19.61	18.53
14:00	932	0	21.6	13.44	23.78	23.65	22.91	20.89	19.68	18.55
15:00	861	1	21.4	13.69	23.78	23.73	23.02	20.99	19.75	18.58
16:00	531	0	21.6	13.60	23.62	23.66	23.01	21.05	19.80	18.59
17:00	279	-1	21.8	13.34	23.41	23.51	22.92	21.06	19.82	18.60
18:00	237	-2	22	13.05	23.23	23.37	22.80	21.02	19.81	18.60
19:00	236	-2.3	22.06	12.80	23.09	23.24	22.69	20.96	19.78	18.59
20:00	240	-3	22.2	12.56	22.98	23.14	22.59	20.89	19.74	18.58
21:00	244	-4	22.4	12.30	22.91	23.07	22.52	20.84	19.70	18.57
22:00	250	-3.6	22.32	12.13	22.84	23.00	22.46	20.79	19.67	18.56
23:00	257	-3	22.2	12.04	22.78	22.94	22.40	20.75	19.65	18.55
24:00	261	-2	22	12.05	22.71	22.87	22.34	20.71	19.63	18.54

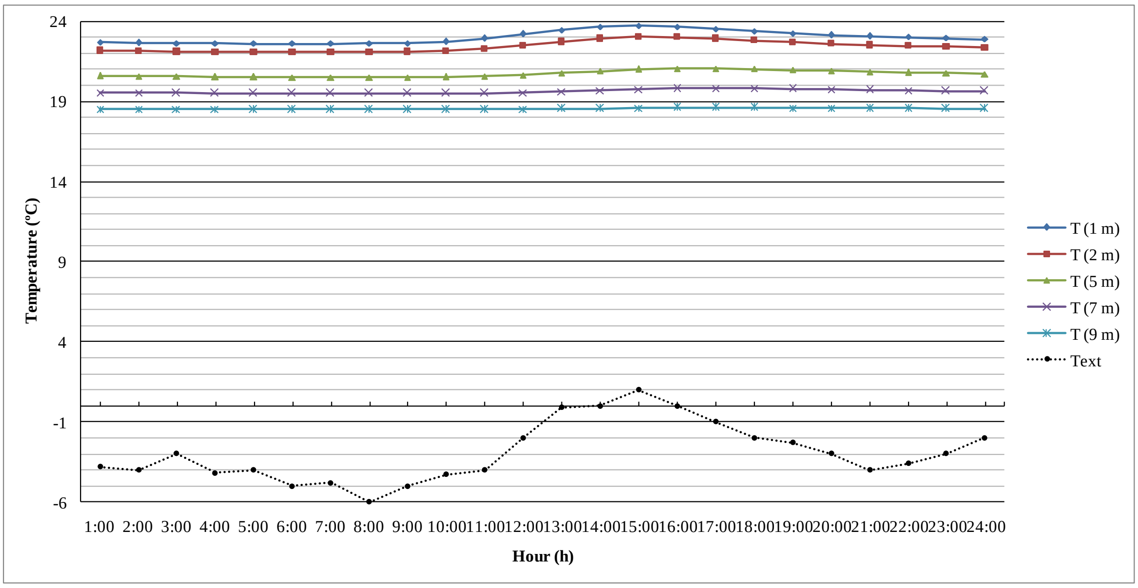
Table 8. Results of the temperatures for the *mur neutralisant* and different points of the room on 30 December, with solar radiation.



10. Results of the CFD simulation (horizontal section of the model) with air heating and solar radiation: 30 December, 8:00 h.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

11. Results of the CFD simulation (horizontal section of the model) with air heating and solar radiation: 30 December, 15:00 h.



12. Evolution of indoor temperature at different points in the room for 30 December, with solar radiation, with airflow q=100 l/s and a variable airflow temperature in the active chamber.

5.1.2 Simulation without solar radiation

Table 9 and figures 13, 14 and 15 show the same results in the absence of solar radiation, confirming the influence of solar radiation on the operation of the system. Without radiation uniformity throughout the day was very pronounced. In figure 15 the graphs showing the evolution of indoor temperatures at different distances from the *mur neutralisant* are almost straight lines. The maximum difference is 0.12 ºC at 1 m from the *mur* compared with 1.14 ºC occurring with solar radiation. Uniformity in the surface temperature of the outer glazing is also more pronounced: there is a maximum oscillation of only 0.99 ºC in the exterior surface temperature compared with the 7 ºC variation in outdoor temperature.

Equally, thermal uniformity in the room is more pronounced without solar radiation. The maximum indoor temperature is 21.18 ºC at 15:00 h and 1 m from the *mur neutralisant*, and the minimum is 18.32 ºC at 1:00 h and 9 m from the *mur neutralisant*. There is therefore a difference of only 2.86 ºC for these positions and

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

extreme hours. At 15:00 h, the difference between indoor temperature at 1 m and 9 m from the *mur neutralisant* is 2.82 ºC, compared with a difference of 5.15 ºC occurring with solar radiation.

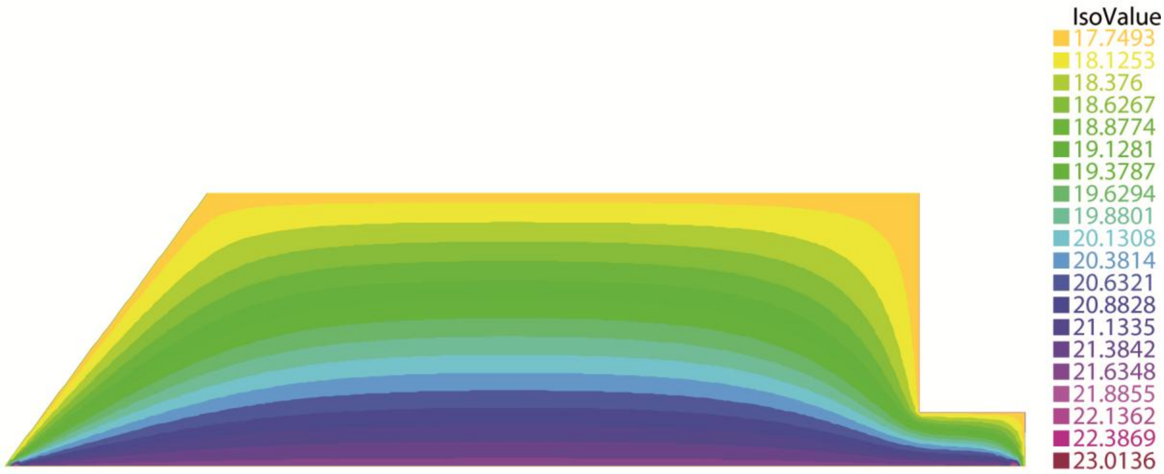
As regards the temperature values reached in both hypotheses it can be observed that at 15:00 h (day), this difference is 2.65 ºC at 1 m, 2.18 ºC at 2 m, 1.20 ºC at 5 m, 0.68 ºC at 5 m and 0.18 ºC at 9 m, while at 1:00 h (night) the difference is 1.33 ºC at 1 m, 1.20 ºC at 2 m, 0.77 ºC at 5 m, 0.46 ºC at 5 m and 0.16 ºC at 9m.

It should be noted that based on the solar radiation values extracted from the climate table, 30 December was a fairly sunny day. On an overcast day, the worst case scenario for winter, the results for both hypotheses simulated would be quite similar.

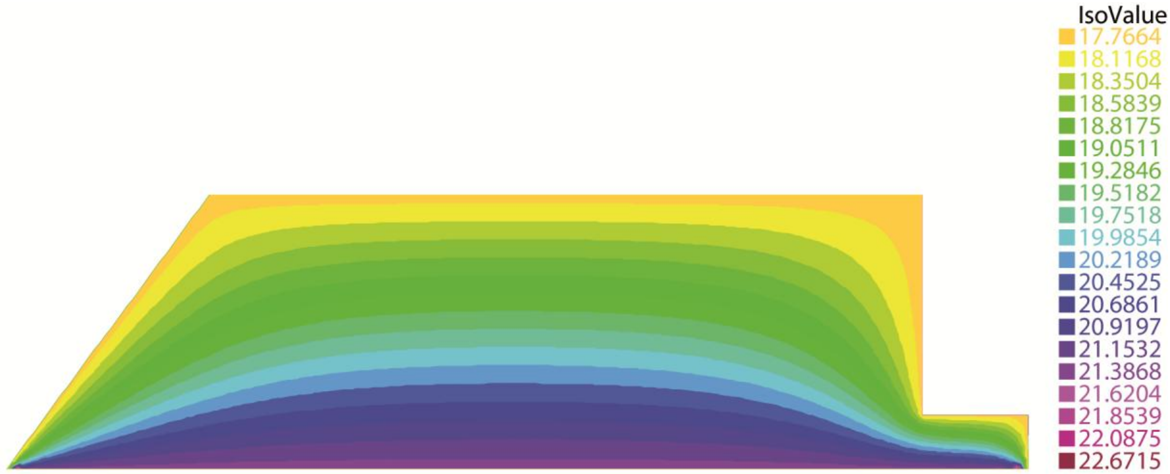
30-Dec	Io W/m²	Text ºC	Timp ºC	Teg ºC	Tig ºC	T (1 m) ºC	T (2 m) ºC	T (5 m) ºC	T (7 m) ºC	T (9 m) ºC
1:00	0	-3.8	22.36	10.82	21.52	21.10	20.72	19.65	18.98	18.32
2:00	0	-4	22.4	10.73	21.33	21.14	20.76	19.67	18.99	18.33
3:00	0	-3	22.2	10.70	21.54	21.16	20.78	19.69	19.00	18.33
4:00	0	-4.2	22.44	10.62	21.51	21.19	20.81	19.71	19.01	18.34
5:00	0	-4	22.4	10.54	21.69	21.22	20.84	19.73	19.02	18.34
6:00	0	-5	22.6	10.43	21.64	21.26	20.87	19.74	19.03	18.34
7:00	0	-4.8	22.56	10.34	21.85	21.30	20.90	19.76	19.04	18.35
8:00	0	-6	22.8	10.20	21.66	21.34	20.94	19.78	19.05	18.35
9:00	0	-5	22.6	10.17	21.53	21.38	20.97	19.81	19.07	18.35
10:00	0	-4.3	22.46	10.19	21.47	21.39	20.99	19.82	19.08	18.36
11:00	0	-4	22.4	10.24	21.21	21.40	21.00	19.84	19.09	18.36
12:00	0	-2	22	10.42	21.17	21.38	20.99	19.84	19.09	18.36
13:00	0	-0.1	21.62	10.69	21.10	21.32	20.95	19.84	19.09	18.36
14:00	0	0	21.6	10.92	21.04	21.25	20.90	19.81	19.09	18.36
15:00	0	1	21.4	11.16	20.97	21.18	20.84	19.79	19.07	18.36
16:00	0	0	21.6	11.28	21.00	21.13	20.79	19.75	19.05	18.35
17:00	0	-1	21.8	11.29	21.19	21.09	20.76	19.72	19.03	18.34
18:00	0	-2	22	11.23	21.24	21.09	20.74	19.70	19.02	18.34
19:00	0	-2.3	22.06	11.16	21.36	21.09	20.74	19.69	19.01	18.34
20:00	0	-3	22.2	11.05	21.54	21.11	20.75	19.69	19.01	18.33
21:00	0	-4	22.4	10.90	21.45	21.14	20.77	19.69	19.01	18.33
22:00	0	-3.6	22.32	10.82	21.34	21.17	20.79	19.70	19.01	18.33
23:00	0	-3	22.2	10.81	21.15	21.18	20.81	19.72	19.02	18.34
24:00	0	-2	22	10.86	21.12	21.18	20.81	19.72	19.02	18.34

Table 9. Results of the temperatures of the *mur neutralisant* and the room at the different points measured for 30 December, without solar radiation.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

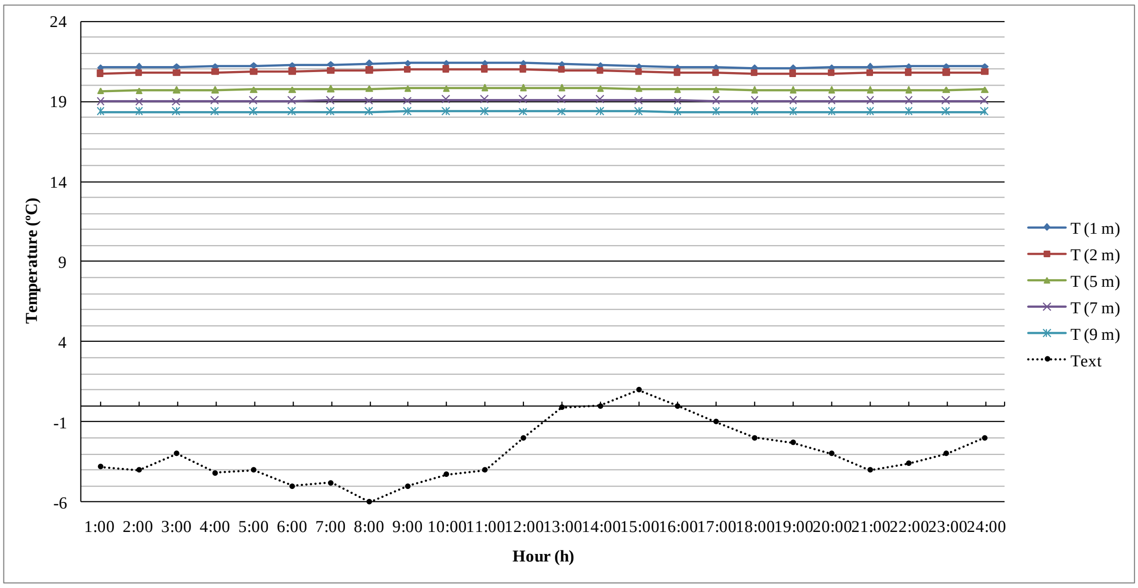


13. Results of the CFD simulation (horizontal section of the model) with air heating and no solar radiation: 30 December, 8:00 h.



14. Results of the CFD simulation (horizontal section of the model) with air heating and no solar radiation: 30 December, 15:00 h.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)



15. Evolution of indoor temperature at different points in the room on 30 December, without solar radiation, with airflow q=100 l/s and variable airflow temperature in the active chamber.

5.2 CFD simulations of the City of Refuge model in the summer

Simulations were carried out on the CR model from 29 June to 3 July, but as in the case of winter, only the results for the third and hottest day, 2 July, were specified once the operating conditions of the thermal system were stabilised. In this case only solar radiation was simulated. The airflow selected in the air cavity was also 100 l/s per metre along the *mur neutralisant*. Lyon's formula was also used to calculate the airflow temperature, which was still considered variable depending on outdoor temperature.

Table 10 shows the results for the simulations with solar radiation. The respective surface temperatures of the outer and inner glazing of the *mur neutralisant* are shown in the fifth and sixth columns. The fourth column of the table shows the variable hot airflow temperature in the active chamber, with values ranging from 18.2 ºC at 6:00 h to 15.6 ºC at 14:00-15:00 h. These are quite high values given the outdoor temperatures and relatively low airflow, 100 l/s per metre along the *mur neutralisant*, and provide an idea of the efficiency of the thermal system.

Figure 16 shows the results in a horizontal section at 15:00 h, when the maximum exterior temperature is reached. In addition, figure 17 includes a series of graphs showing the evolution of the temperature inside the room on the third day at hourly intervals, depending on the distance from the *mur neutralisant* and its relationship with the outdoor temperature.

As can be observed the maximum indoor temperatures are reached between 15:00 and 18:00 h and the minimum temperatures between 6:00 and 8:00 h. Relatively uniform temperatures are obtained throughout the day at the same distance from the *mur neutralisant*, although logically this homogeneity is less pronounced than in winter given the greater incidence of solar radiation and the greater variability in outdoor temperatures, with differences at these extreme times of 3.39 ºC at 1 m, 2.92 ºC at 2 m, 1.73 ºC at 5m, 1.01 ºC at 7 m and 0.34 ºC at 9 m. Therefore, as in winter, the uniformity of these temperatures increases throughout the day along with the distance from the *mur neutralisant*. The thermal uniformity on the outer glazing of the *mur neutralisant* is also significant. Although outdoor temperature varies by 13 ºC on 2 July, the surface temperature of the outer glazing only varies by 6.33 ºC, slightly less than half the previous value.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

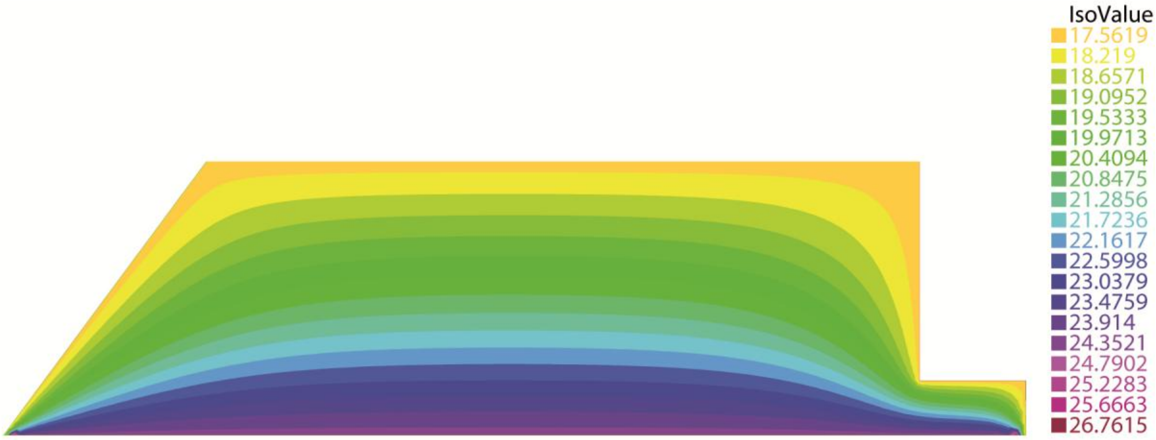
Although there was less thermal uniformity in the room throughout the day, all points in the room were within the comfort band, with a maximum temperature value of 23.80 ºC, 1 m from the *mur neutralisant* at 15:00 h, and a minimum value of 18.27 ºC 9 m from the *mur neutralisant* and from 7:00 to 8:00 h, values very similar to those obtained in winter at the same points in the room and at the same time. This shows the potential of the thermal system to maintain similar environmental conditions inside, regardless of the outdoor temperature. At 15:00 h the difference in temperatures 1 m from the *mur* and 9 m from the *mur* (extreme locations in the room) was 5.25 ºC, and at 6:00 h it was 2.13 ºC. This difference is more pronounced in the half of the room closest to the *mur neutralisant*, as the differences in temperature 5 m from the *mur neutralisant* and 9 m. from the *mur* were 2.38 ºC at 15:00 h and 1.10ºC at 6:00 h.

As was already stated in the discussion of results for winter with solar radiation, *respiration exacte* contributes to greater thermal uniformity in the room, thus improving the comfort conditions of the thermal system.

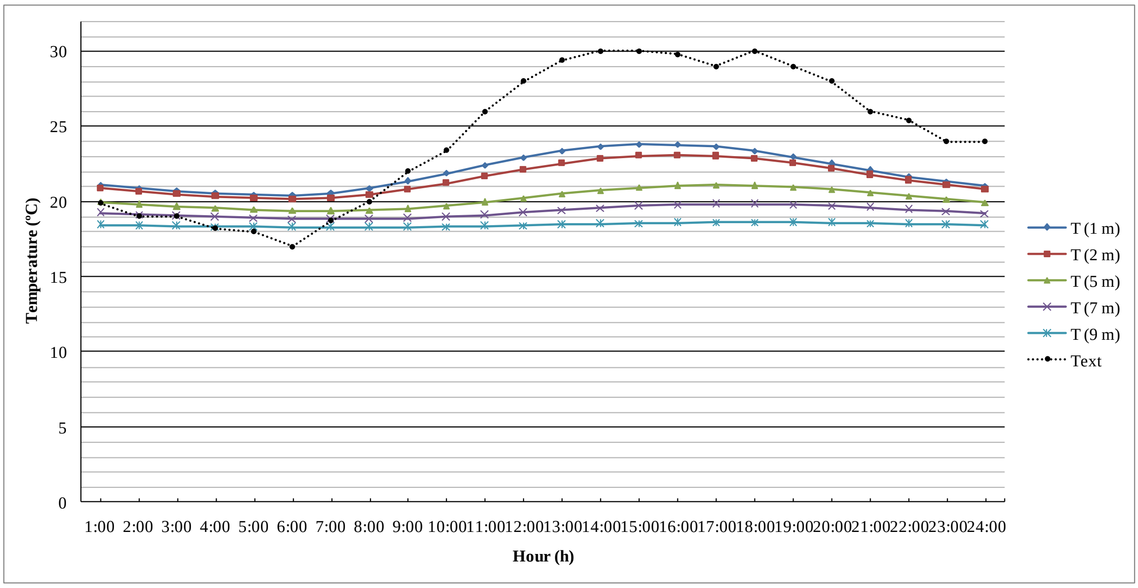
02-Jul	Io W/m²	Text ºC	Timp ºC	Teg ºC	Tig ºC	T (1 m) ºC	T (2 m) ºC	T (5 m) ºC	T (7 m) ºC	T (9 m) ºC
1:00	344	19.9	17.62	22.13	21.16	21.103	20.874	19.967	19.222	18.414
2:00	339	19	17.8	21.64	20.97	20.89	20.664	19.806	19.119	18.379
3:00	339	19	17.8	20.83	20.66	20.706	20.486	19.67	19.031	18.349
4:00	335	18.2	17.96	20.57	20.57	20.555	20.336	19.556	18.957	18.323
5:00	334	18	18	20.22	20.48	20.434	20.215	19.46	18.895	18.301
6:00	369	17	18.2	20.2	20.5	20.415	20.158	19.386	18.844	18.284
7:00	715	18.7	17.86	20.54	20.72	20.559	20.227	19.359	18.814	18.272
8:00	1127	20	17.6	21.12	21.12	20.881	20.442	19.4	18.819	18.27
9:00	1557	22	17.2	21.85	21.85	21.341	20.789	19.523	18.869	18.283
10:00	1840	23.4	16.92	22.76	22.4	21.872	21.219	19.718	18.965	18.311
11:00	2046	26	16.4	23.77	22.88	22.412	21.68	19.963	19.097	18.353
12:00	2180	28	16	24.76	23.21	22.919	22.131	20.23	19.251	18.402
13:00	2231	29.4	15.72	25.62	23.9	23.351	22.536	20.497	19.41	18.455
14:00	2138	30	15.6	26.23	23.8	23.66	22.852	20.738	19.562	18.506
15:00	1923	30	15.6	26.51	24.03	23.803	23.041	20.929	19.69	18.551
16:00	1591	29.8	15.64	26.53	24.08	23.777	23.085	21.046	19.781	18.585
17:00	1360	29	15.8	26.32	23.87	23.635	23.014	21.087	19.826	18.603
18:00	1140	30	15.6	26.04	23.12	23.362	22.832	21.056	19.828	18.607
19:00	855	29	15.8	25.57	22.84	22.976	22.542	20.955	19.788	18.597
20:00	588	28	16	24.99	22.54	22.518	22.174	20.792	19.708	18.574
21:00	411	26	16.4	24.32	22.09	22.064	21.782	20.583	19.596	18.539
22:00	384	25.4	16.52	23.76	21.37	21.654	21.413	20.358	19.466	18.497
23:00	380	24	16.8	23.21	21.01	21.307	21.087	20.139	19.334	18.453
24:00	382	24	16.8	22.78	20.79	21.004	20.802	19.94	19.21	18.411

Table 10. Results of the temperatures of the *mur neutralisant* and the room at the different points measured on 2 July.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)



16. Results of the CFD simulation (horizontal section of the model) with air heating and solar radiation: 2 July, 15:00 h.



17. Evolution of the indoor temperature at different points in the room on 2 July, with solar radiation, with airflow q=100 l/s and variable airflow temperature of the active chamber.

6. Conclusions

The combined technological innovation of the *mur neutralisant* and *respiration exacte* proposed by Le Corbusier, with the help of G. Lyon, constituted a new interpretation of the mechanisation of the environment to solve the control of indoor climate in Modern Movement. Based on the data and conclusions of the *mur neutralisant* tests carried out by Saint Gobain engineers on physical models in test rooms in the 1930s, a numerical model was validated and implemented using the CFD-based program FreeFem++. This made it possible to observe the behaviour the *mur neutralisant* in the City of Refuge would have displayed under different environmental and operating conditions had the original design been completely carried out.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

The numerical model allows the energy simulation of the south-facing *mur neutralisant*of the main dormitory in the City of Refuge. The *mur neutralisant* is made up of two sheets of 7 mm glass with a 110 mm active air chamber, a hypothesis which is very similar to that proposed in the original project by Le Corbusier. Airflow in this *mur* was 100 l/s per metre along the *mur neutralisant* at a temperature which varied according to outdoor temperature. In winter conditions, represented by a sunny winter's day in Paris, with outdoor temperatures oscillating between and -6 ºC and 1ºC on the same day, and with an airflow temperature in the chamber varying between 22.8 ºC and 21.4 ºC, notably uniform indoor temperatures occur in the room throughout the day at the same distance from the *mur neutralisant*. These temperatures decrease along with the increased distance from the *mur neutralisant* from a mean value of 23 ºC 1 m from the *mur neutralisant* to a value of 18.5 ºC 9 m from the *mur*, that is to say, at the far end of the room. Despite low winter temperatures, the fact that comfort temperatures are reached in the room with an active air chamber and relatively low airflows (for heating in winter), gives some idea of the energy efficiency of the *mur neutralisant* as a heating system.

In summer conditions, represented by one of the hottest days of the representative climate year in Paris, with outdoor temperatures which on one day oscillate between 17 ºC and 30 ºC, the airflow temperature in the chamber decreases to values between 18.2 ºC and 15.6 ºC. The increase in solar radiation entails less thermal uniformity throughout the day compared with the winter day at the same distance from the *mur neutralisant*, although the difference in the middle of the room (5 m from the *mur neutralisant*) is 1.7 ºC. The difference in temperature with respect to the distance from the *mur neutralisant* is more pronounced, with mean values ranging from 22 ºC at a distance of 1 m from the *mur neutralisant* to18.5 ºC at 9 m from the *mur*, values potentially equivalent to those obtained in winter for the same distances. This demonstrates the potential of the thermal system which results in thermal uniformity at the same distance from the *mur neutralisant* throughout the year. As in the case of the heating operation mode, the relatively low airflow and relatively low airflow temperatures (for cooling in summer) show the energy efficiency of the *mur neutralisant* as a cooling system.

Therefore, the operating conditions of the *mur neutralisant* and the indoor temperature values obtained in both winter and summer confirm that the active thermal system proposed by Le Corbusier for controlling indoor temperatures makes it possible to obtain an *isothermique* thermal environment with similar indoor comfort conditions throughout the year, regardless of outdoor temperature and solar radiation. The energy efficient integrated system of temperature control was incorporated into the building envelope. This comprehensive interpretation of the relationship between architecture and energy was practically half a century ahead of environmental control systems with active façade systems designed with a view to building sustainability and energy efficiency. Had the *mur neutralisant* been executed following the original designs of Le Corbusier and Lyon, it would probably have posed serious competition to the air conditioning systems developed in the 20th century with great success and barely any technological competition.

7. Acknowledgements

The authors wish to thank the Le Corbusier Foundation and researcher Jorge Torres from Universitat Politècnica de València for the information and documentation provided for this study.

8. References

Brian Brace, T. "Le Corbusier, the city of refuge, Paris 1929-33". Chicago: University of Chicago Press. 1987.

Bryan, Harvey. "Le Corbusier and the 'Mur Neutralisant': An Early Experiment in Double Envelope Construction". Proceedings of the Ninth International PLEA Conference. 1991. pp. 257–62.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)

Cuadernos de Postgrado. La respuesta de la American Blower Corporation. 24 January 1930.

FreeFem++ v.-3.37-1. Available from: http://www.FreeFem.org/ff++/ (22.05.15).

Ismail, K.A.R.; Henríquez, J.R. "Modeling and simulation of a simple glass window". *Solar Energy Materials & Solar Cells*. 2003. 80. pp. 355–374.

Ismail, K.A.R.; Henríquez, J.R. "Simplified model for a ventilated glass window under forced air flow conditions". *Applied Thermal Engineering*. 2006. 26. pp. 295–302.

Ismail, K.A.R.; Henríquez, J.R. "Two-dimensional model for the double glass naturally ventilated window". *International Journal of Heat and Mass Transfer*. 2005. 48. pp. 461–475.

Le Braz, J. "La transmission de la chaleur gràverâ travers le verre: Des idées nouvelles sur le chauffage des habitations". *Glaces et Verres*. 1933. 20. pp. 13.

Lebel H.; Le Barbier, M. Société Anonyme des Manufactures des Glaces et Produits Chimiques de Saint-Gobain, Chauny et Cirey. Note sur la seconde série d'essais effectués pour la mesure de la transmission de la chaleur à travers les glaces à l'Annexe du Comptoir de Vente, 23 rue Boucry, Paris du 23 Novembre au 21 Décembre 1931. Letter of 11 March 1932.

Lebel, H.; Le Barbier, M. Société Anonyme des Manufactures des Glaces et Produits Chimiques de Saint-Gobain, Chauny et Cirey. Note sur les essais de transmission de la chaleur à travers les glaces, efectués à l'Annexe du Comptoir de Vente, 23 rue Boucry, Paris du 3 Avril au 8 Mai 1931. Letter of 25 June 1931.

Ramírez Balas, C.; Fernández Nieto, E.D.; Narbona Reina,G.; Sendra, J. J.; Suárez, R. "Numerical simulation of the temperature evolution in a room with a mur neutralisant. Application to 'The City of Refuge' by Le Corbusier". *Energy and buildings*. 2015. 86. pp. 708-722.

This work is licensed under a Creative Commons 4.0 International License (CC BY-NC-ND 4.0)