Conditioning systems by radiant surfaces: comparative analysis of thermal ceramic panels versus the conventional systems in a museum

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Abstract

Radiant surface systems for heating and cooling operated by circulating water through capillary tubing provide for the user high comfort levels and significant energy savings. Compared to conventional air conditioning systems, radiant systems reduce up to six times the energy needed for distribution, a better comfort feeling as It does not need to impulse air at uncomfortable speeds, a low acoustic level and a reduction of thermal loads as it is allowed an average inner air temperature with a smaller thermal gradient with the outer air temperature. The performance of these systems is analyzed through a case-study, the Museum of the University of Alicante, where a radiant surface, integrated on a ceramic panel, is placed at the inner layer of the façade of the building. The research results show how important the thermal bridges are in the global energy performance of the building and it is possible to appreciate the energy savings versus the traditional systems.

Keywords: energy efficiency, healthy climate control, eco-friendly, thermal bridges, interior air quality, sound level.

1 Introduction

Conditioning systems by radiant surfaces are being used in buildings for decades. Systems that use water for energy exchange have become more energy efficient and a smaller payback period than those using electricity through the joule effect [1]. The fact of using water at moderate temperatures between 40–45°C in winter and 10–17°C in summer allows the use of solar, geothermal,

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heat pump systems or chemical energy for lithium chloride [2]. Furthermore, the first can be conditioned during the first annual cycle, while the latter would be usable only during winter.

The first systems used throughout water distribution circuits were closed off with copper tubing or plastics, which were mainly cross-linked polyethylene. The most common pipe diameters were available between 16 and 20 mm. with separations of between 10 and 30 cm, which mainly provided easy implementation for underfloor heating, these systems were known as “fat pipes”. From the mid-eighties thin tube systems or “capillaries” were used. [3]. These systems, in polypropylene tubes of 3 mm. in diameter, were designed in tube frames with spacings of about 10 mm. Thus, by greatly increasing the area and decreasing the thickness of the pipes, a higher efficiency was achieved in energy exchange with the surface materials, which was intended to cool or heat.

The ease of design, layout and installation of these facilities offered the possibility of heating and cooling through floors, ceilings and walls of any geometry. Nowadays the most common installation systems are underfloor, in makeshift ceilings suspended in plaster or metal, or in plasterboard wall linings and ceilings. Being able to create tube frame capillaries of any size, allows for prefabricated panels to be created that are connected to water distribution circuits with a simple “click and cool” joint. The thermal conductivity of the finished material influences the efficiency of the system. The higher the value, the faster the start-up and thermal efficiency of the panels can be observed [4].

Recently a research group in Technology and Sustainability in Architecture has developed a patented thermal ceramic panel [5] made from a large porcelain tile which include capillary link with polypropylene tubes connected with conductive adhesive paste. The format varies from pieces of 60 x 60 cm. for modular suspended ceilings, up to 300 x 100 cm. and 14 mm. thick, for large format ceramics of 3 mm. thick the maximum weight is 25 kg/m^2. This light panel can be placed easily on walls and ceilings with a metal anchor grid system, or lowered using the “baffle” method [6].

2 Physical fundamentals of conditioning systems by radiant surfaces

So that a person feels comfortable in their surroundings, you need to determine and carefully analyse parameters that determine it, mainly the temperature of dry air, relative humidity, air velocity that surrounds it, and the surface temperature of each of the surfaces that make these up [7]. Other parameters which could affect it indirectly are factors such as the purity of the surrounding air or noise and a person is subject to their own metabolism. The use of chemical energy to power processes in which work and heat is generated, an almost constant body temperature of between 36.5ºC and 37°C needs to be maintained. To create the feeling of comfort required for the maintenance of energy balance the following equation is used:

$$\sum q = q_{met} - q_{ev} \pm q_{ci} \pm q_{cvi} \pm q_{rdi} = 0 \tag{1}$$

Determining the ideal conditions of temperature and relative humidity to ensure regular running of indoor activities for individuals is a complex task [8] that has motivated numerous studies [9]. The American Society of Heating and Air Conditioning Engineers (ASHRAE) developed an interesting graph to approach the issue, which is set on the abscissa the dry bulb temperature and the ordinate the wet bulb temperature. The effect of temperature on comfort is mainly manifested in the transfer of heat experienced by the individual through convection and radiation as the transfer of heat by conduction is a lower magnitude. Heat loss by convection is obtained by the equation:

$$q_{cvi} = h_c (T_p - T_a) \qquad (2)$$

The h_c convection factor is directly related to air speed, and the position in which the individual is located. Typically this said factor has an average value of 3.5 W/m^2°C, with an air velocity of 0.1m/s and 4.5 W/m^2°C, with an air velocity of 0.2 m/s [7, 10].

Radiation losses are more difficult to obtain. They are based on the Stefan-Boltzmann law, according to the fourth powers of the surface temperatures of the individual and walls that make up their surroundings. When working with finite planes in different positions on the individual, the determination of radiation heat transfer becomes extremely complex. Experimentally, usual dimensions for spaces with surfaces of between 20 and 30 m^2, and heights of approximately 2.6 m to 3 m the distance factors from floor to ceiling and wall to floor or ceiling are about 0.4 and 0.15 respectively [8, 10].

Since the various surfaces of the surroundings of the individual will usually be at different temperatures, the individual exchanges heat by radiation variably in every direction. The problem is simplified by establishing a mean radiant temperature, which also takes into account the effect of the form factor, in the equation:

$$T_{rm} = \frac{T_s + 0{,}15 \cdot \left(T_{p1} + T_{p2} + T_{p3} + T_{p4}\right) + 0{,}4 \cdot T_t}{2} \qquad (3)$$

Through the average radiant temperature obtained and the value of skin temperature and/or the clothing of the individual experimentally can get the value of heat transfer by radiation, by knowing that the coefficient of radiation losses h_r adopts approximate values of 4.7 W/m^2°C with estimable human body temperature of 30°C.

$$q_{rdi} = h_r (T_r - T_{rm}) \qquad (4)$$

Once the experiment has been determined with sufficient approximation and the coefficients of convection and radiation losses, the operating temperature for comfort can be obtained. The human body, could be defined as “a uniformed temperature within an imaginary enclosure, in which, the body exchanges the same dry heat (disregarding the latent charge) by radiation and convection in the same real environment” [11].

$$T_o = \frac{h_r T_{rm} + h_c T_a}{h_r + h_c} \tag{5}$$

The interpretation of this expression is relevant to understand how the air conditioning systems work for radiant surfaces. The individual's feeling of comfort in enclosed spaces, if we consider a priori control of relative humidity and air velocity through the benchmark established by the RITE (between 40 and 60%, and from 0.15 to 0.24 m/s respectively, depending on whether it's winter or summer), depends on the temperature of the surrounding air as the surface temperature of those surfaces also make up the temperature in the space. Moreover, in a similar, or even slightly more relevant proportion, in regard to the mean radiant temperature T_{rm}. This results that, in radiant surface systems, the variation of the surface temperature of one of the surfaces produces a sense of optimum comfort while maintaining a higher air temperature in summer and lower in winter. This significant difference from convective systems (radiators) and solutions of forced air affects a significant reduction in peak heat charges, improved comfort with moderate, homogeneous temperatures, imperceptible air speed, and helps to maintain wellbeing through a reduction of excessive heat, imperceptible resonant levels, and no dust or bacteria moving in the ambient air.

In effect, the thermal heat charge by heat transfer through the walls, according to Fourier's law, are diminished significantly with decreasing temperature differences between the air inside and outside. In summer, the indoor air can get 3ºC warmer than forced air systems, a decrease of these thermal charges of around 25% [12]. Something similar happens in winter, being the lowest temperature in the convective and forced air systems.

When attempting to find a thermal source for a large surface in these systems, the floor, ceiling or wall surface temperatures emitting heat or cold are more moderate, resulting in the same emission power in the other systems, and similarly, operating temperature. This difference leads to substantial energy savings, and allows the use of alternative energies such as solar or geothermal energy.

3 Hydronic capillary tube systems

HVAC systems through capillary tubes use water as energy transport. The water distribution temperatures are moderate: 15ºC to 17ºC in summer, 29ºC to 35ºC in winter, although the latter depends on the needs of the surroundings studied and the installed capillary surface. The power units, through a primary circuit, are connected to a heat exchange, normally of plate type, and heat or cool the water in the secondary circuit to transport the energy to the surfaces that are to be conditioned through the capillary tubes.

The capillary tubes are made of polypropylene with a diameter of 2 to 3 mm. and arranged within a frame in which the tubes are spaced 10 to 30 mm, depending on the model and the use for which they are intended. Contained in these frames is a return tube of approximately 20 mm in diameter. The dimensions of the frames are variable, allowing widths of between 150 mm to 1,210 mm and lengths of 600 mm to 6000 mm.

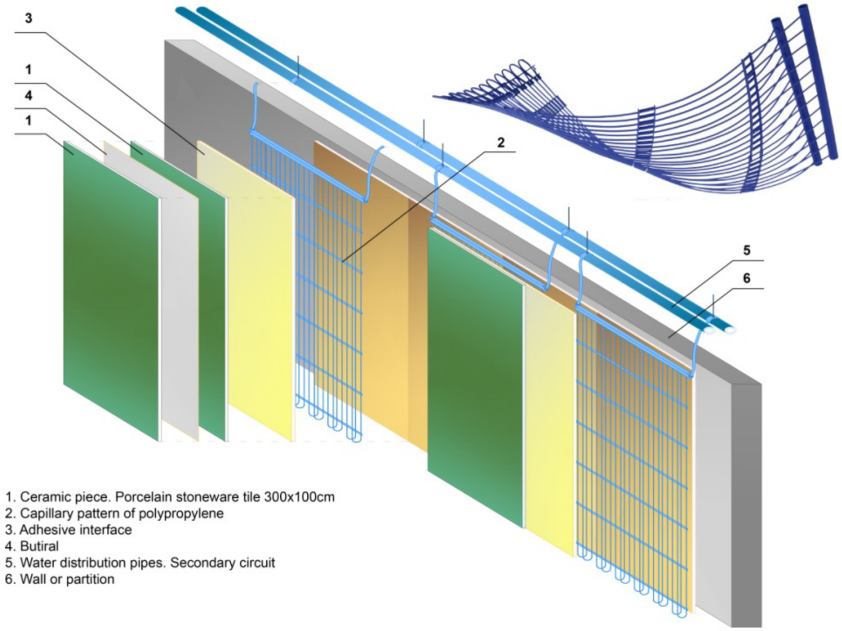

Figure 1: Patent Application No. P201001626. Thermal Ceramic Conditioning Panel.

The flexibility of these frame supports allows the positioning of many different systems. They can be placed directly onto the receiving surface, in order to later place plaster or lime (applications on ceilings and walls) on to. One can also place makeshift metal removable roof plates (prefabricated climatic plates) on to them. Another possibility is to arrange them between the necessary secondary grid to form a continuous ceiling of dry gypsum board to solve the later cladding finished with a conventional plasterboard. This same implementation can be done in plasterboard walls. Of course, the capillary links are applicable to flooring for creating much more effective underfloor heating and building height less than conventional thick tubes. The solutions are varied, having made prefabricated panels of a large size ceramic wall and ceiling [5], including the trusses in the soul polypropylene capillary tube.

Feeding hot or cold water to the framework of capillary tubes, despite each installation being custom and being able to adapt to the needs of each project, can be done in three main ways: centralised distribution, distribution manifolds and loop type distribution. This research herein has adopted centralised distribution technique. Here, we gather together in a hydraulic substation all the necessary elements such as a plate heat exchanger, a water distribution pump, an expansion vessel, a safety valve, a full and empty steam trap, and also the supply and return manifolds (Fig. 6). From this hydronic substation distribution pipes are lined to each circuit capillary links. These pipes are usually 20 mm in diameter and have a return circuit.

4 Energy savings compared to other air conditioning systems

There are numerous studies and publications that show reductions of between 20% and 30% in energy consumption of radiant systems to forced air systems [12, 13]. We also found cases in which these consumption savings can reach up to 40% with capillary solutions, when compared to a system of variable air volume [14].

4.1 Water as a means of energy transfer

If we consider two values of the physical properties of water compared with air, we found that the specific heat of water is four times the specific heat of air. This means that, to carry a certain amount of heat with the same thermal energy, more air is required and thus more power from the electromechanical element.

The second number to compare would be the density. The density of air at 25°C is about 1.19 Kg/m^3 (this depends on the exact composition of the air) and water at the same temperature is 1000 kg/m^3. This means that when you decide to carry a certain amount of energy, the necessary volumes require 1000 times more air than water. As a result, the electrical energy we need to move motors and fans in a forced air system is 80% higher than would be necessary with a radiant system [15].

This is one of the main reasons to be able to use water at moderate temperatures in order to achieve high energy efficiency. Moreover, if we value the operation in cooling mode it has limited the dew-point temperature flow, which not only gives us energy savings compared to other systems of forced convective and radiant air, but allows us to achieve powers of between 75–90 W/m^2 in cooling mode, other radiant systems are not able to achieve.

4.2 Reduction of peak charge

The capillary radiating systems are active solutions which constantly act not only on the air containing the stay, but on all the walls of the room, changing its temperature through radiant elements. This leads to an effect on peak charges meaning peak needs are dampened and reduces its value by 27% over “full air” systems [12]. A properly executed heating system saves energy and reduces peak charges and consumption compared to air systems. These values may vary depending on the local climate [16], and so forth, but the range for peak charge varies between 20% and 40%.

4.3 Thermal performance of the installation

The temperatures at which you need to prepare the water for use in capillary networks are very moderate (about 15°C for operation in cooling mode and 35°C for use in heating mode) and this allows us to improve the performance of the power production against other systems with higher needs preparation [9]. If the source selected is a heat pump (geothermal or aerothermal for example), we will see less use as we will improve the COP of the machine which can push water at more moderate temperatures than with other systems. That is we will get better thermal performance than other systems [17, 18]. We can also maximise the overall performance of the system from a major use of alternative energy [19, 20].

5 University of Alicante Museum

In 2000 the University of Alicante Museum, Spain, project (MUA) was completed. The building consists of several exhibition halls, the most emblematic box 54 x 22.4 m and 11.3 m in a single space. The enclosures are stadip glass around the perimeter to a height of 2.45 m and the rest is a sandwich skin type panel made of Bakelite and rockwool, a *naya* (an enclosed space between the two skins) 1.4 m wide, and a second skin based at the DM interior panel of 16 mm. thick, and the structure is metallic. The outer shell suffered damage from improper disposal of the panels, which caused resting moisture inside, severely damaging the panels [21]. The building was restored in 2010, featuring new ventilating facade panelling made of Bakelite, thus reducing thermal bridging with greater energy efficiency. The transmittance value reduction facade *U* disclosed in Table 1, with a resulting reduction of 43%.

Figure 2: Aerial photograph of the Museum with water surrounding it.

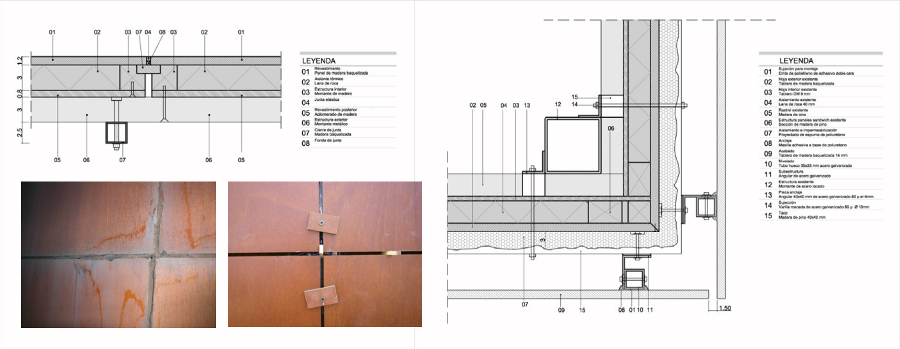

Figure 3: Construction plan detailing restored original facade.

5.1 Reduction in energy demand due to the absence of thermal bridges

The restoration solution with a new ventilating facade has made a significant improvement to the energy efficiency of the museum. Through the simulation tool Antherm the coefficient L^{2D} was calculated and the linear thermal transmittance of the thermal bridges of MUA 1 and MUA 2, according to eqn. (6) and (7).

$$L^{2D} = U_m \cdot l \tag{6}$$

$$\psi = L^{2D} - U \cdot l \tag{7}$$

A reduction in transmittance has been obtained found in the facade-roof by 43%, and in thermal bridges and wooden frameworks by 32%.

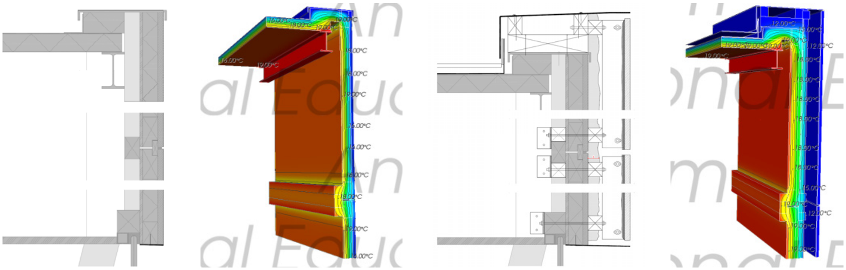

Figure 4: Construction details of the enclosure and restored original roof. Heat flows.

Table 1: Thermal transmittance values for U and Ψ for MUA 1 and MUA 2.

	Enclosures			Found in enclosure-roof		
	U w/m^{2}k	L^{2D}	Ψ w/m^{2}k	U w/mk	L^{2D}	Ψ w/mk
MUA 1 (2000) Air System	0.794	1.324	0.228	0.794	1.334	0.177
MUA 2 (2010) Air System	0.452	0.754	0.130	0.452	0.915	0.149

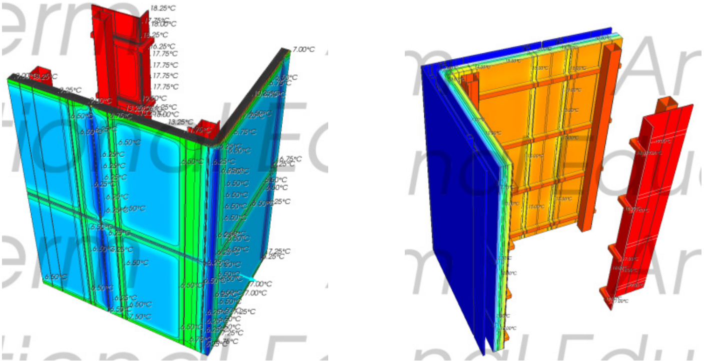

Figure 5: Heat fluxes in original and restored facade. Surface temperatures.

5.2 Application of ceramic panels with capillary links

Recently a patented for a large format ceramic panel has been issued incorporating polypropylene capillary links inside [5]. A study to incorporate these ceramic panels has been carried out replacing the existing DM panels in the original project. Thus, replacing the climate control system for the air conditioning system with one of an evaporating/condenser style which is water based. We proceeded to evaluate the HVAC system by radiant surface of the walls of the MUA versus the original air convection system. A primary circuit distributes hot or cold water into two substations in which, through a heat plate exchanger, distribution to ten secondary circuits controlled by thermostatic balancing valves occurs. Four types of dehumidifiers have been incorporated which is a fan-coil system for the summer periods which receive cold water from the primary distribution circuit. The possibility of solar vacuum tube has been contemplated in order to meet demand on sunny winter days and to reduce the energy consumption in summer through a solar cooling system by chemical chloride lithium [14, 22], through which water cools the primary circuit.

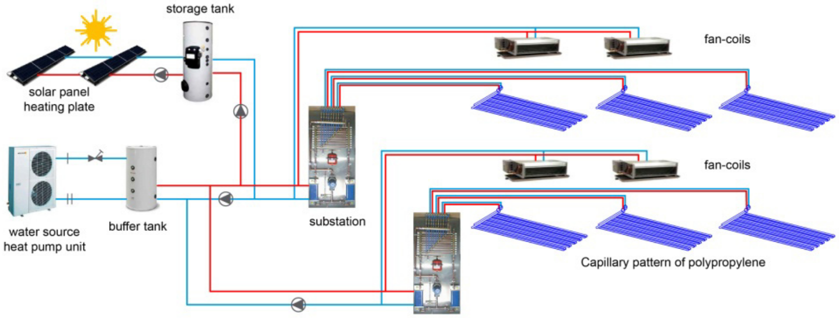

Figure 6: Installation diagram of two tubes with substations.

6 Comparison of comfort and energy between the two systems

We proceeded to perform calculations of thermal behaviour of the museum in three different scenarios: in *MUA 1* with the solution of the original panels, in *MUA 2* solution facade panels ventilation space after rehabilitation and in *MUA 3* solution in which incorporating ceramic panels at the entire inner surface of the museum. In the first two cases the HVAC system is all compact machine with air pump air to air heat. In the third system, a heat pump air-water distrubutes water into the capillary links (Fig. 6). The surface temperature of the ceramic thermal conditioning panel is 17ºC, which cannot fall in any case, as surface condensation would occur.

Table 2: Comparison of energy and power consumption.

	Heating power		Cooling power	
	W/m^2	kW	W/m^2	kW
MUA 1 (2000) Full air system	73.02	86.53	60.52	71.72
MUA 2 (2010) Full air system	70.44	83.47	57.08	67.64
MUA 3 (Panels) Radiant system	58.49	69.31	52.41	62.10

	Heating consumption		Cooling consumption		Annual energy consumption	
	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh
MUA 1 (2000) Full air system	17,19	20370	31,48	37303	49,65	58835
MUA 2 (2010) Full air system	14,91	17668	27,38	32445	40,33	47788
MUA 3 (Panels) Radiant system	10,34	12253	21,06	24958	31,40	37211

We proceeded to evaluate the performance of the building by energy and environmental simulation software “Design Builder” in three stages , with regard to energy consumption for cooling and heating as required by the heat pump machines during peak demands, and the comfort experienced by the individual. For the simulation of the thermal behaviour of the constructive solutions of the surroundings, monthly climate data from the provincial capitals listed in Table G.2, the *T* dry bulb and the *HR* Document Basic Energy Saver HE CTE have been taken into account. Therefore, it was deemed advisable to consider the most extreme outdoor average temperature considering that the same basic document measures an indoor air of 20ºC in winter and 24ºC in summer. This corresponds to the average outside temperature estimated in January T_{med} = 11.6°C. To calculate the thermal resistance of the air chambers is taken into account in Table E.2. “Thermal resistance of air chambers $m^2 \cdot K/W$” HE CTE DB [23]. As noted, the annual energy consumption has decreased by 18.8% due to the restoration solution of a new ventilating facade, and is reduced by 22.13% when ceramic panels were used.

Subsequently, a simulation was performed using the module fluid dynamics CFD available to the programme to evaluate indoor comfort conditions that provide both air conditioning systems. Sensible heat losses have been calculated by convection and radiation from a person who was standing at the geometric centre of the room, as the speeds and temperatures of indoor air and surface temperatures obtained in situ, which have helped to calibrate the simulation, as shown in Table 3. We used the eqns. (2)–(5).

Table 3: Temperatures of the walls, and air temperature and velocity.

Average surface temperatures of the walls							
		P1	P2	P3	P4	S	T
Winter	MUA2	18.68 (18.84)	18.81 (18.87)	22.25 (19.96)	18.89 (18.87)	18.67	19.78
	MUA3	26.75	26.82	26.64	26.74	21.52	23.64
Summer	MUA2	29.15 (24.59)	29.44 (24.57)	25.82 (24.59)	30.00 (25.03)	21.32	24.80
	MUA3	18.63	18.52	18.34	18.92	21.10	22.26

Speed and temperature at 2m heigh in the centre of the room			
		Air speed (m/s)	T ºC
Invierno	MUA2	0.10	22.50
	MUA3	0.03	20.50
Verano	MUA2	0.12	24.30
	MUA3	0.05	26.80

Factors were determined to shape the surfaces of the panels, as experienced adopted by M. Ortega and A. Ortega [10], whereby the shape of floor to ceiling factor is 0.4, the roof to wall is 0.15, and that of the ceramic wall panels is 0.10, given that they do not occupy the entire surface of the facade but only one-sixth. We could obtain the mean radiant temperature in summer in both cases, eqn (3).

The results of the mean radiant temperature was 21.9°C for the convective system, and 19.8°C for the heating system being T_{pc} 18°C $n = 1$.

For h_r ratio, radiation losses of the individual, we have estimated a value of 4.7 W/m2ºC for both HVAC systems [10]. The surface temperature of the human body has been estimated at 30ºC. Thus the heat exchanges by radiation of the human body surfaces are, in the summer environment, per square metre of body surface, according to eqn. (4), 38.07 W/m^2 and 47.89 W/m^2 respectively. Where we can conclude that the efficiency of conditioning by radiating surfaces of the user is 125% over traditional convective systems.

With respect to convection losses of the individual we can determine the heat transfer factor h_c which, in both cases, does not depend on the geometry of position of the panels:

$$h_c = 8{,}3 \text{ x } 0{,}12^{\,0{,}24} = 4{,}98 \text{ W/m}^2\,{}^{\circ}\text{C} \tag{8}$$

$$h_c = 8{,}3 \text{ x } 0{,}05^{\,0{,}24} = 4{,}04 \text{ W/m}^2\,{}^{\circ}\text{C} \tag{9}$$

To determine the convective heat flow per m^2 q_{cvi} the value of the air temperature according to the conditions described above was analysed. As shown in Fig 7 and 8 for summer air temperatures in the occupied zone are higher for the heating system. We have determined the average temperature in the occupied zone in two different positions, depending on proximity to glass: the first 2 m in separation, and the second in the middle, at 11.2 m in separation. The temperatures obtained by simulation are 27.35°C and 26.84°C respectively compared to 25.20ºC and 24.35°C in the convective system. Considering that the body temperature is 30°C and average temperatures measured, could determine the value and body heat flow per square metre of body surface area by convection according to eqn. (2). The results are 27.9 W/m^2 and 12.9 W/m^2 respectively. We conclude that the convective heat flux is higher for the conventional system compared to heating, depending on the individual located farthest or nearest the glazing.

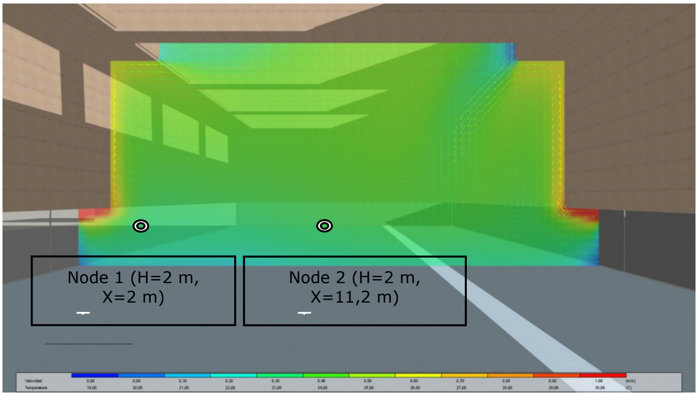

Figure 7: Image of air temperatures in the central section of the Museum. Radiant system.

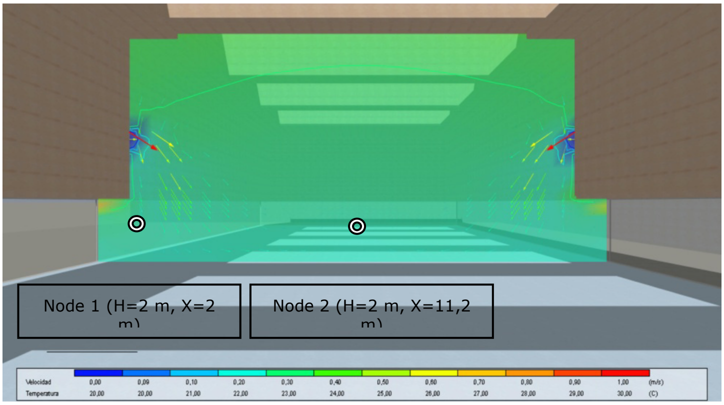

Figure 8: Image of air temperatures in the central section of the Museum. Convective system.

A summary of the results is given in Table 4, in which the flow of sensible heat from the individual are determined by both radiation and convection. It can be seen that for the space type studied, the sum of these two flows remains almost unchanged. Considering the small effect that heat flow transmitted has on total heat dissipation from the individual, and that the effect of evaporative heat flow through breathing and perspiration, there are similarities in both systems, due to the relative humidity controlled by means dehumidification found in some low power fan-coils. We conclude that the radiant system provides a satisfactory fitting with lower air speed and therefore more comfortable surroundings, with energy savings of over 20%.

Table 4: Calculating the power dissipation of heat in summer.

	T_p	T_s	T_{rm}	v	h_c	h_r	T_a	q_{rdi}	q_{cvi}	$q_{rd}+q_{cv}$ W/m^2
Full air system o convection	21.5	21	21.9	0.12	4.98	4.7	24.3	38.0	27.9	65.9
Radiant ceramic panels system	17	20	19.8	0.05	4.04	4.7	26.8	47.9	12.9	60.8

7 Conclusions

Restoration of surroundings by means of a ventilating facade system carries significant decreases in thermal transmittance values, linear thermal transmittance in thermal bridges and energy consumption of buildings. In the case analysed, the University of Alicante Museum, the value of the transmittance *U* has been reduced by 43%, in linear transmittance of thermal bridges by 32% and in annual energy consumption by nearly 19%.

The thermal conditioning system for large format ceramic panels incorporating polypropylene capillary links are very effective in achieving a quiet, clean air, with proven energy savings. The system supports available in the ceiling, walls and floors, compared with conventional systems, a radiant system brings significant reductions in annual energy consumption especially in summer due to the higher value of air the temperature inside, resulting in a lower inside/outside air temperature drop. The thermal charges are thus reduced by transmission. This fact, coupled with the efficiency of the water distribution system compared with air, due to the energy transport capacity per unit volume is almost 1,000 times more, it makes it ideal for application in architecture. In the present case, the arrangement of ceramic heat panels inside the museum, through the simulation tool “Design Builder”, represents a reduction of the annual energy consumption of 22%. Ceramics are presented as a good material in panels because of the high thermal conductivity which favours transmission of heat to the water flowing through the capillary links.

With respect to the feeling of comfort in summer, the loss of sensible heat from the individual is quite similar in both cases. Although in the case of the air cooling impulsion it is an 8% higher requirement, with the radiant system typical values at 60W, for individual metabolic dissipation. Furthermore, excessive convection losses due to the higher air velocity, means the individual is less satisfied. It should be noted that in both cases a minimum air dehumidification is required, according to the RITE-sets through a fan-coil derived from the distribution of cold water, due to the fact that the capillary link system itself is unable to do so.

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