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Environmental, economic and energy analysis of double glazing with a circulating water chamber in residential buildings

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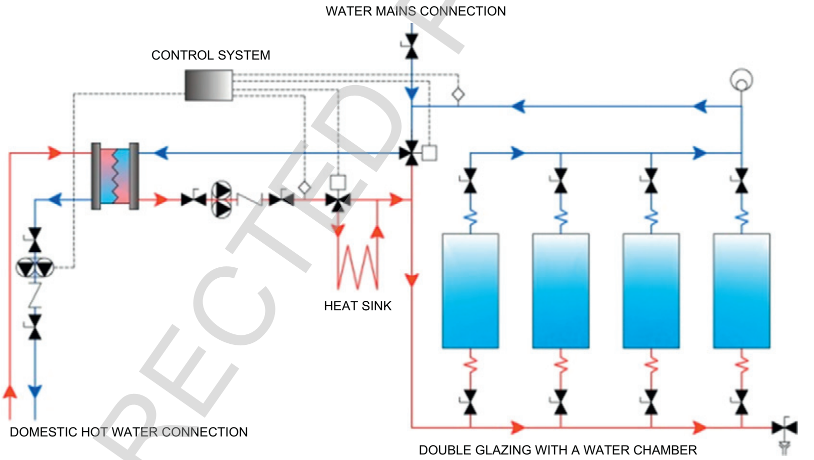
HIGHLIGHTS

- ▶ Glazed façade area is the part that produces greatest energy losses and gains.
- ▶ A potential for energy savings has been detected in residential buildings.
- ▶ Active glazing comprising two laminated glass panels with a circulating water chamber.
- ▶ Analysis of energy performance, economic viability and impact on carbon footprint.
- ▶ Natural gas condensing boilers is the less contaminating and more efficient option.

GRAPHICAL ABSTRACT



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ABSTRACT

In general, the glazed façade area of a building is the part that produces the greatest energy losses and gains. The basic aim of this work is to achieve a more efficient heat control in closed spaces. To this end, an exhaustive study has been made of active glazing comprising two laminated glass panels with a circulating water chamber. Not only has the energy consumption been analysed but also the energy efficiency according to fuel type, the amount of CO_2 emitted into the atmosphere and the economic cost. The results of this study, from the points of view of economic feasibility and energy efficiency, show that the solution of double glazing with a circulating water chamber is a less polluting and more efficient option than the systems currently used. This solution is able to reduce the energy losses and gains that are produced through the glazed façade of a building by 18.26% for calorific and frigorific energy compared to the total consumption of the building. The layout of the proposed installation facilitates its integration into any type of residential building, either under construction or being renovated. Moreover, its zero visual impact means it can even be implemented in places with strict town-planning regulations.

1. Introduction

Various studies have shown that, during a large part of the year, the windows available (either dynamic or static), do not help to achieve the thermal efficiency currently demanded [1,2].

The Adaptation of the European Directive 2010/31/EU on the Energy Efficiency of Buildings [3] aims to introduce the concept

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of "Passive Building" or "Almost Zero Consumption Buildings", and limit the maximum annual energy consumption to 15 kW h/m^2 for heating and cooling. It is also believed that the Directive will rule that all new buildings will be required to have almost zero consumption by the 31 December 2020[1].

Due to the low emission requirements for CO_2, glazed façades are being subjected to extensive continuous research, as indicated by Chow et al. [4].

Diverse techniques are capable of transforming static windows into dynamic windows, called chromogenic windows, the most marked of which are liquid crystal, electrochromic, gasochromic or suspended particle windows [5,6].

Since the 1970s, various researchers, the most outstanding being from the LBNL (Lawrence Berkeley National Laboratory), one of whom is Stephen Selkowitz, have been studying the thermal and luminous performance of electrochromic windows (the most commercially developed technology), and state that they perform better from both a luminous and a thermal point of view [7].

Weather-resistant electrochromic windows are capable of controlling infrared or thermal radiation (long wave-length $\lambda > 0.7$ μm), which to a large extent is responsible for heating the interior environment [8]. Being able to regulate thermal radiation leads to lower cooling costs in the summer and lower heating costs in the winter [9]. On the other hand, regarding luminosity, glare is reduced and the entry of visible light can be controlled if there is exposure to direct sunlight, thus reducing the need for solar protections. However, the high marketing cost of these windows, the difficulty in adapting them to the user [10], and the long colour correction time (often minutes), makes it difficult to find an opening on the market. In short, these kinds of windows have failed to satisfactorily meet their purpose.

Other researches indicate that advanced transparent super insulation materials could satisfy both requirements, which are a high thermal insulation and a high light transmittance. Aerogel is a promising transparent insulating material, due to its low thermal conductivity (down to 0.010 W/m^2 K), high solar factor, high daylight transmittance and remarkable light weight, and could be interesting especially in very cold areas where it is necessary to reduce heat transmission [11,12].

Another system that is still in its early stages commercially, that can be placed in the category of dynamic or smart windows, is a window comprising two laminated glass panels with fluid circulating in the chamber between both panels. This solution leads to better thermal comfort due to the way this fluid is processed. Of all the fluids that can be used, water has the following benefits: low cost, it is easily available (on new construction sites as well as in renovation work), it is highly opaque to infrared radiation and highly transparent. In the same way that some authors have analysed the visual comfort and daylighting designs in different glazing systems [13–15], Fig. 1 clearly shows the transparency of the glazing as well as the undistorted image achieved by the proposed system [5].

Various researchers have developed test methods to evaluate heat gain and heat loss in indoor spaces, and more specifically in the field of the energy efficiency of different types of glazing. Grimmer states that small test boxes can be a very useful tool for the thermal modelling of buildings [16]. Álvarez, Palacios, and Flores developed a test method to measure the thermal performance of glazed windows [17]. They propose a laboratory-developed procedure that lets any glazing composition be compared with another. Around 1990, the Lawrence Berkeley National Laboratory (LBNL) of the University of California (USA) developed a mobile system for the outdoor testing of advanced glazing called MoWiTT (Mobile Window Thermal Test), aimed at making exact measurements of the thermal performance over time of different glazing types when exposed to real weather conditions [18]. Basing his opinion on analytical calculations and various tests, Chow concludes that windows with a circulating water chamber are able to reduce heat gain, and therefore, energy consumption [19,1,20].

Fig. 1. Transparency of the glazing.

Given the complexity of its analysis, there is currently no comparative research on the economic and energy feasibility of this system compared to more conventional solutions like windows with an air chamber. It would appear that new models need to be produced that allow analysing the energy and cost savings over a representative period of time, as well as the environmental impact.

The aim of this research is to compare a conventional double glazing system with an air chamber with another system with a water chamber, the purpose of which is to check its energy efficiency, its repercussion on the environment and its economic feasibility. The two types of glazing compared are: 6 mm thick double glazing with an 8 mm thick air chamber (due to its being one of the most common in the building industry) and glazing comprising two 6 mm thick glass panels (stadip 3 + 3 glass) with water circulating through an 8 mm thick chamber between the panels.

2. Material and methods

2.1. Description of the proposed system

A glazing solution that is standard in the building industry was chosen, which, by incorporating circulating water in the chamber considerably reduces thermal transmittance (*U*), increases the capacity to block infrared radiation (responsible for interior overheating) and preserves the transparency of the glass.

As the water circulates inside the chamber, the transmittance and the solar factor of the assembly vary, among other properties, depending to a large extent on the temperature of the circulating water. The finite element method used specifically takes account of this variation in the model's properties according to temperature.

The heating system and water circulation system through the chamber, which is made of two glass panels, consists of two circuits: primary and secondary (Fig. 2).

- The primary circuit comprises the inlet and outlet connections from the mains corresponding to the building's domestic hot water supply and the circulation pumps.

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[1] For buildings belonging to public administrations, this date will be brought forward to 31 December 2018; and for existing buildings, the deadline will be 31 December 2050.

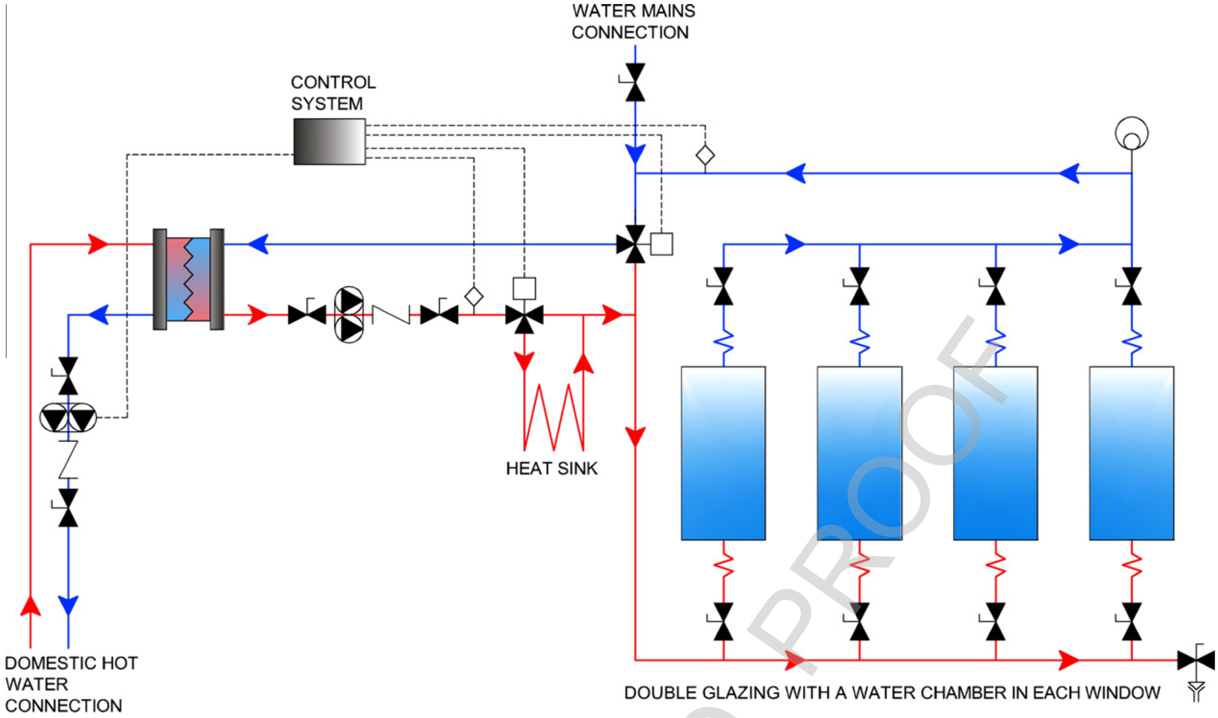

Fig. 2. Layout of the facility.

- The secondary circuit is closed and supplies the water to the terminal units (double glazing with a water chamber), aided by the circulation pumps, and has a heat sink (cooling tower, geothermal sink, inertial tank, etc.) and a by-pass, both with a three-way motorised valve. This circuit is connected to the water mains (filling) and the waste pipe (emptying). It keeps the water circulating at an approximate velocity of 0.3 m/s so that the thermal load is effectively transferred, thus avoiding any turbulence that might reduce the transparency of the glass.

As the water circulates at a very low velocity, the load loss of the secondary circuit is low and therefore the pumps can be low-powered (10 W).

There is also a plate heat exchanger where the heat energy is transferred from the water flowing in the primary circuit to the water flowing in the secondary circuit. The function of the primary circuit is to supply the energy required to the fluid circulating inside the chamber.

The secondary circuit water temperature control is performed by a centralised control system that activates the three-way motorised valves and their primary circuit pumps according to the signals sent from the corresponding sensors.

The system for distributing the water to the thermal units is an inverse return system to improve the circuit's hydraulic balance. It is supplied by pipes that are integrated into the frame supporting the glazing. When the glazed surface is not fixed but moveable, the joint between the main secondary circuit and the integrated pipes in the frame is made with flexible pipes.

2.2. Input data

In order to be able to compare the energy efficiency of a conventional double glazing system with an air chamber with another system with a water chamber, some real conditions were taken as the starting point (outside temperature and solar radiation) throughout a 1 year time period. The outside temperature and solar radiation taken into account every hour was furnished by the AEMET [21].

The temperature of the water circulating in the chamber was set close to the comfort temperature. Comfort temperature was set at 21 °C in winter and 25 °C in summer, which are the mean temperatures recommended by the Building Technical Code [22].

The output data are the variation in temperature in the interior of a theoretical habitable space located in the city of Madrid (Spain). For a residential building located in Madrid, the dimensions of a standard room are 3×3 m with a minimum allowable height of 2.5 m [23], with a glazed window on one of its sides facing south. It is deemed to be sufficiently insulated for the heat gains and losses to be produced solely through the glazed surface. Municipal town-planning regulations set the minimum surface area for lighting apertures is 12% of the useable surface of the living spaces [24]. The indoor temperature was calculated at a distance of 1.5 m from the glazed surface. This distance was chosen because it is the centre of 3×3 metre square room.

2.3. Defining the models

Two different models have been worked with. Firstly, an experimental model was produced by making small-sized boxes that would be easy to transport and position. Then, given the difficulty of conducting this experimental test at full scale, a theoretical model was constructed using a finite element program. Once it had been validated with the previous experimental test, the purpose of this second model was to measure the variations in the indoor temperature at the centre of the theoretical habitable space that has been previously described.

2.3.1. Experimental device

By analysing the test methods referred to in the previous chapter and using the resources available in the Department of Architectural Construction and Technology at the Madrid Higher School of Architecture (ETSAM), a part of Madrid Polytechnic

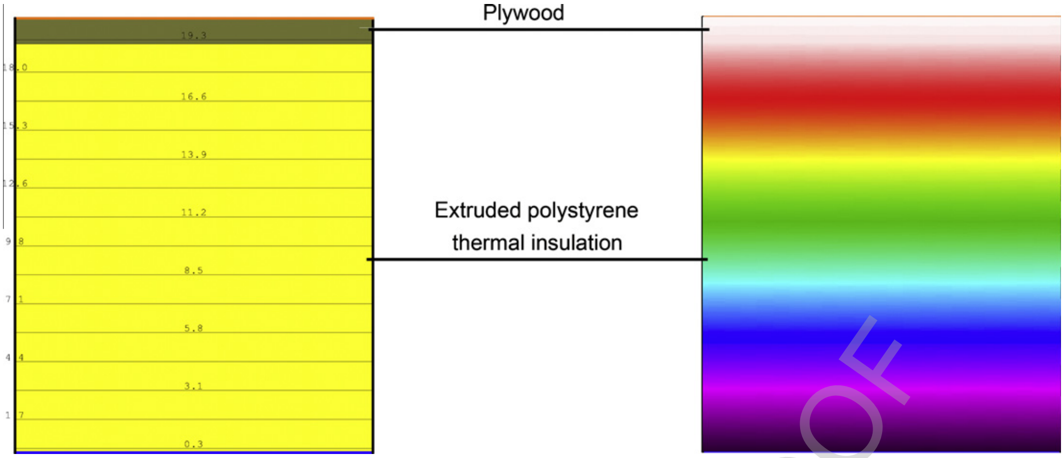

Fig. 3. Study of the flow of the isothermal lines of the test box with the Therm 5.2 (LBNL) program.

University, physical tests were performed. These consisted in assessing the heat gain and heat loss through a double glass panel with an air chamber and with a circulating water chamber [25,5].

These tests were carried out on the north terrace of the Madrid Higher School of Architecture, located at 40°25′ latitude N, 3°41′ longitude W and at an altitude of 675 m, as the boxes could be positioned facing south, with a 100% obstacle-free open sky, and this could be done any day of the year.

In order to conduct these tests two square boxes were constructed whose dimensions were 60 × 60 × 60 cm on the inside, with one of their sides being open. The different types of window to be tested were successively placed on the open side: 6 mm thick double glazing with an 8 mm thick air chamber and the glazing comprising two 6 mm thick glass panels (stadip 3 + 3 glass) with water circulating through an 8 mm thick chamber between them.

The composition of the boxes from the inside to the outside was as follows: 12 mm thick plywood with anti-damp treatment and a conductivity of 0.09 W/m K and an emissivity of 0.90; 160 mm thick extruded polystyrene thermal insulation with a conductivity of 0.033 W/m K and an emissivity of 0.90; and 4 mm thick reflective insulation comprising a 100% 8μ pure aluminium sheet + 4 mm of FR polyethylene bubble.

The transmittance of the complete enclosure was 0.178 W/m^2 K, according to its simulation using the Therm 5.2 (LBNL) program. The surface thermal resistances corresponding to the interior and exterior air used in the program were measured in accordance with the position of the enclosure, the direction of the heat flow and its location in the building according to the Spanish legislation currently in force (Building Technical Code). The exterior boundary conditions are: temperature 0 °C and film coefficient 25 W/m^2 K while the interior conditions are: temperature 20 °C and film coefficient 7.69 W/m^2 K. Fig. 3 represents the flow of the isothermal lines.

To collect data, datalogger Hobo temperature and humidity sensors[2] were used with the Hobo Temperature, RH © 1996 ONSET model for the interior, and the HOBO pro series Temp, RH © 1998 ONSET for the exterior, calibrated for a two-year period. Measurements were taken at 15 min intervals, taking the interior and exterior temperature. The sensor to measure the temperature of the water circulating inside the chamber was placed in the chamber itself.

The interior temperature measurement sensors were placed on the opaque wall opposite the window, 45 cm from the floor, so that the measurement would not be affected by direct solar radiation.

In the heat gain tests performed with windows with a circulating water chamber, the closed circuit supplying the chamber with water was connected to the cold water mains and fitted with a pump and a heat sink that incorporated an air fan as a heat exchanger. A thermostat connected to the pump was placed inside the box to set the reference temperature at 25 °C. When the temperature inside the box rose above the set reference temperature, the thermostat activated the fan and the pump, making the water re-circulate through the chamber.

The heat loss test was similar to the previous one but the heat exchange was done through a thermotank that could supply hot water at 35 °C. The water circuit inlet to the chamber was connected to a pump, the reference temperature being set at 25 °C. When the temperature inside the box fell below the set reference temperature the pump was activated, pumping hot water into the window from the thermotank.

2.3.2. Fine element model

Two models were made using the Straus 7.4.2. finite element program. Both attempted to simulate the test performed using double glazing with an air chamber and double glazing with a water chamber.

The data fed to the program were as follows:

- The exterior daytime temperature measured every 15 min, furnished by the State Meteorological Agency (AEMET) [21], part of the Ministry of the Environment, and Rural and Marine Environment, and the test time period.
- The solar radiation at 40° N latitude measured every 15 min throughout the day, furnished by the State Meteorological Agency (AEMET) and the test time period.
- The initial temperature inside the box at the start of the test, measured at the same distance from the glazed surface.
- The temperature of the water circulating in the chamber for the window with the water chamber test, measured every 15 min by the sensor inside the chamber.

A non-linear calculation was made using the Transient Heat module of the program. 90 steps were calculated at 900 s intervals (15 min) so as to be able to compare the test measurements taken.

With the purpose of verifying the developed models and proceeding to their validation, the interior temperatures obtained at

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[2] The dataloggers comprise a programmable processor, a memory and input ports with one or several channels to connect the different sensors. The measurement data are received through the sensor. An analogue-digital converter converts the data into electronic data and records them in the memory. The recorded data are transmitted through the ports and analysed by the software.

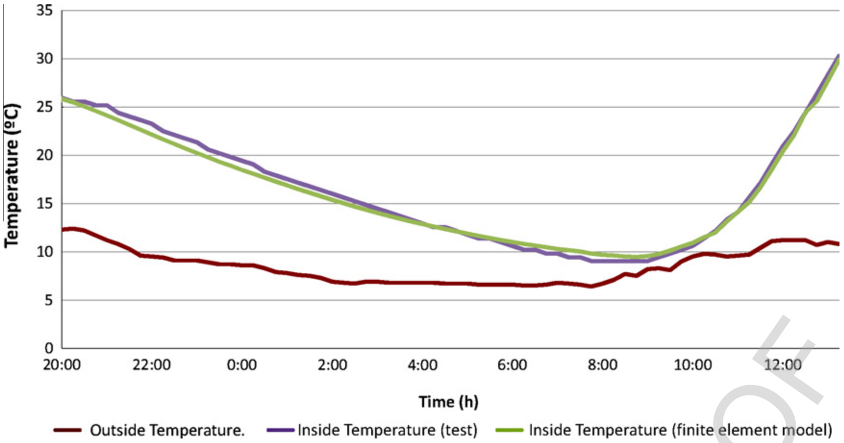

Fig. 4. Double glazing test with air chamber (03–04/05/10).

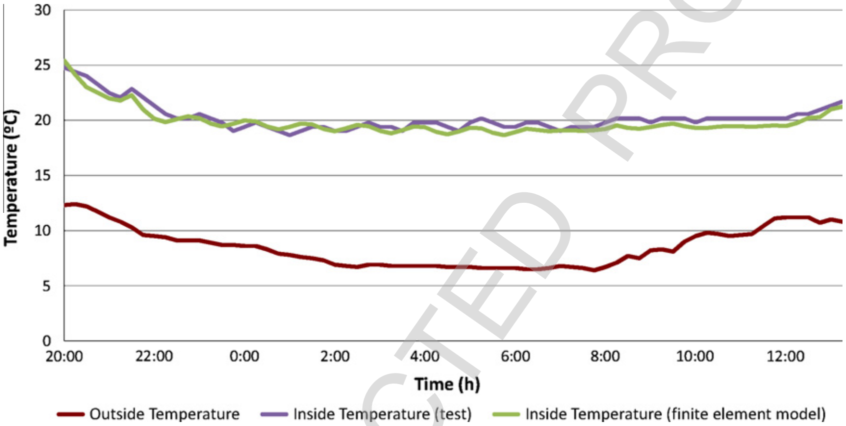

Fig. 5. Double glazing test with water chamber (03–04/05/10).

a same point from May 3rd to 4th 2010, throughout 18 h were compared (a cycle with a loss and gains period). This was done for both the experimental tests as well as for the finite element models. Then, every 15 min the interior temperatures measured by the sensor inside the box were superimposed on those given by the finite element program according to the exterior temperature, solar radiation and the temperature of the water circulating through the chamber. Fig. 4 shows how the interior temperatures evolved for the double glazing with an air chamber, and Fig. 5 for the double glazing with a water chamber.

By analysing both figures it can be deduced that the difference between the temperature measured inside the box tested and the simulation was less than 1.2 °C, in every case (90 measurements taken in the case studied). For the test with the water chamber, the graph depicts the periods when the pump supplying the chamber with hot water was activated. These periods are also reflected in the simulation performed. The difference between the temperature measured inside the box tested and the simulation temperature was less than 0.7 °C. Therefore, the models obtained through the finite element program were deemed to be sufficiently precise to develop this research.

2.4. Theory

The analysis was carried out in four stages.

2.4.1. Analysis of the indoor temperature in two representative periods

The variation in the indoor temperature in the two most representative periods was analysed: winter and summer. The days chosen as being representative of the two periods analysed were the winter solstice (21 December) and the summer solstice (21 June), when the outside temperatures and solar radiation are close to maximum and minimum.

The indoor temperatures were calculated every hour using the finite element model, by taking the actual outside temperature and solar radiation without the use of any additional heating or cooling systems. The initial indoor temperature was measured in every case, as was the comfort temperature (recommended by the Building Technical Code). The temperature of the water circulating in the chamber was set close to the comfort temperature at 21 °C.

2.4.2. Energy balance analysis

The energy balance was calculated throughout 2010. To be more exact, the heating and cooling consumptions were differentiated. This process enabled the energy saving of the double glazing with a water chamber to be ascertained compared to the double glazing with an air chamber.

Firstly, the indoor temperatures were calculated, using the finite elements model, from the actual outside temperatures and solar radiation by taking the data furnished by AEMET.

The thermal step between the comfort temperature and the previously obtained indoor temperature was found for each hour.

$$\Delta T = T_c - T_i \tag{1}$$

where: ΔT is the rise in temperature every hour, T_c the comfort temperature and T_i the indoor temperature obtained for every hour.

Table 1a
Technical specifications of the boilers.

Name	Type of complimentary boiler		
	Diesel boiler and condenser TRISTAR	Electric boiler General	Modular gas condensation MODULEX
Boiler option number	1	2	3
Fuel source	Diesel-C	Mains electricity	Natural gas
Seasonal efficiency	0.94	0.98	0.97
Boiler heat losses	0.10	0.20	0.10
Carbon coefficient for primary fuel source (kW h/kW h)	1.081	2.603	1.011
Calorific potential of the fuel	10,650 kW h/m^3	1.00 kW h/kW h	10.42 kW h/m^3

Table 1b
Specifications of the reference boilers.

	Reference boilers	
	Mains gas boiler Reference for options 1 and 3	Mains electricity Reference for option 2
Seasonal efficiency	0.80	0.98
Heat loss	0.25	0.40
Carbon coefficient	1.011	2.603
Calorific potential	10.42 kW h/m^3	1.00 kW h/kW h

The heating and cooling energy required to bypass the thermal step found for each hour is directly proportional to the mass and the variation in temperature.

$$Q = m \cdot c \cdot \Delta T \tag{2}$$

where Q is the energy (J), m is the mass (kg), c is the specific heat (J/kg K) and ΔT is the rise in temperature (K).

For a unit of volume the energy required in kW h/m^3 will be:

$$Q_u = \rho \cdot c \cdot \Delta T/1000 \cdot 3600 \tag{3}$$

where Q_u is the energy per unit of volume (kW h/m^3) and ρ is the density (kg/m^3).

By taking the above values, the monthly calorific and frigorific value can be found. For the double glazing system with a circulating water chamber, the energy consumed by the water pump was taken into account.

2.4.3. Analysis of energy consumption and CO$_2$ emissions

The energy consumed and the amount of CO$_2$ emitted was determined by considering three types of high efficiency boilers with different fuels: electricity, natural gas and diesel. Biofuel and biomass boilers were not considered as they fail to attain high efficiency apart from the fact that there are some localities where it is difficult to find a supply of this energy.

Table 1a lists the technical specifications of the three boilers chosen [26,27]. In order to assess their performance, they had to be compared to a standard boiler. Two reference boilers were used, the specifications of which are shown in Table 1b.

The boiler's annual energy consumption was found by multiplying the energy demand, shown in the previous section, by (1 + the boiler losses). The energy demand by boiler type was found by multiplying the boiler's annual energy requirements by the coefficient of the primary energy used. The system's total annual energy consumption will be equal to the energy demand according to fuel type divided by the calorific potential and the seasonal efficiency.

The amount of CO$_2$ emitted can be found by multiplying the energy demand according to fuel type by the carbon conversion factor. The carbon produced by each boiler was calculated using the reference coefficients taken from the CALENER program, approved by the Spanish Government [28,29].

2.4.4. Economic feasibility analysis

A 20 year period was analysed, since it is the usual period required to recoup the cost of a facility. The same energy saving was taken into account for each year. The facility's economic feasibility study took account of the boiler type, fuel costs and inflation. The economic indicators used were those habitually used in economic studies for projects requiring a capital investment [30,26]. Fuel costs have been estimated with an annual estimated increase of 3.47%, as well as the operating and maintenance costs estimated at 50 euros per year with an annual estimated increase of 1.4% in this case. In order to obtain reliable data, the time required to recoup the cost of the facility was taken into account, as well as the calculations made by the gas and electricity companies, so as to be able to calculate the bills.

The facility costs for a new residential building have been taken into account. Glazing costs have been estimated at 7.2 €/m^2 for double glazing with an air chamber and at 9.6 €/m^2 for double glazing with a water chamber [31].

3. Results and discussion

3.1. Analysis of the indoor temperature in two representative periods

Fig. 6 shows the results obtained for the winter solstice. Loss of temperature was less in the double glazing with the water chamber than in the conventional double glazing, due to the lower transmittance of the first solution and in spite of the period having less solar radiation (winter). In both cases, the initial indoor temperature was set at 21 °C (winter comfort temperature). At the end of the day, the indoor temperature was 19.04 °C in the window with the water chamber and 8.46 °C in the window with the air chamber.

Bearing in mind that in a standard building the percentage loss through the windows fluctuates between 13% and 24% in respect of the total loss [32,33], if we take a mean value, the daily energy requirement to ensure an indoor temperature equal to the comfort temperature (21 °C) is 0.09 kW h/m^3 for the interior air for the double glazing with a water chamber, and 0.41 kW h/m^3 for the interior air for the conventional double glazing. Therefore, in the first case, the energy saving is 78.22% compared to the second case.

Fig. 7 shows the results obtained for the summer solstice. As in the previous case, the temperature loss is less in the double glazing with a water chamber compared to the conventional double glazing, due to the lower transmittance of the former. In spite of the initial indoor temperature having been set at 25 °C in both cases (summer comfort temperature), the indoor temperature at the end of the day was 26.14 °C in the double glazing with a water chamber and 37.72 °C in the double glazing with an air chamber.

As this period of summer has high solar radiation, it can be seen how the double glazing with the water chamber performs better. The screening effect provided by the double glazing with a water chamber was measured to analyse the interior rise in temperature caused exclusively by solar radiation. With the double glazing with

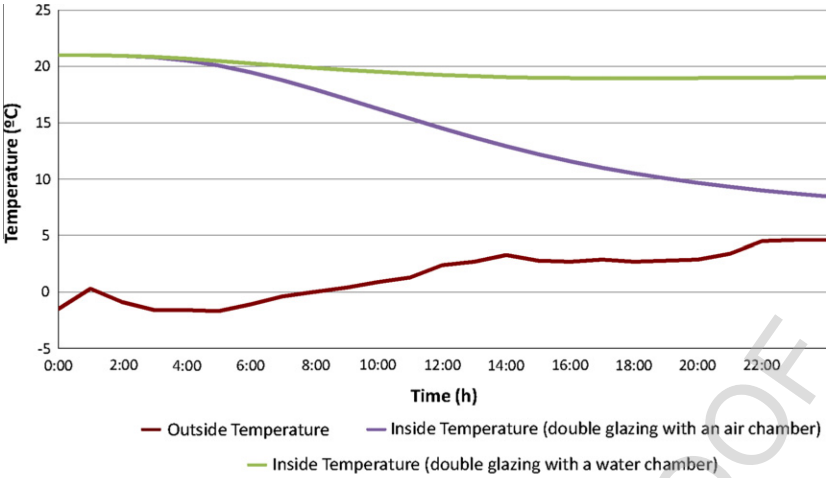

Fig. 6. Evolution of inside temperature (21/12/10).

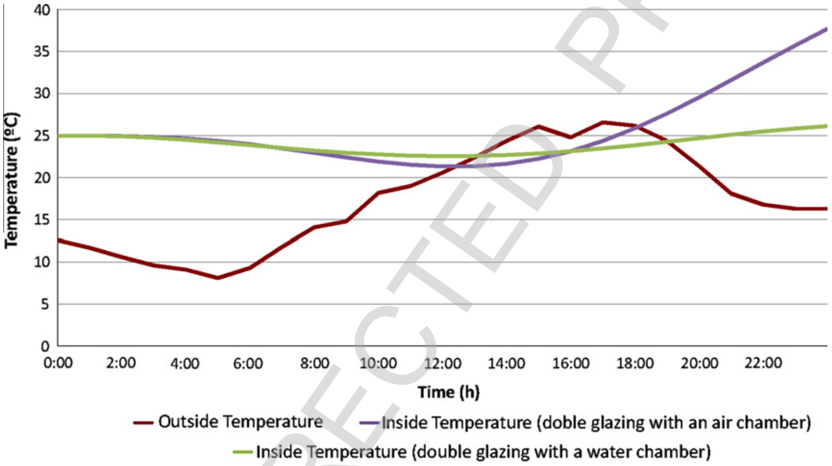

Fig. 7. Evolution of inside temperature (21/06/10).

a water chamber, the rise in temperature at the end of the day exclusively due to solar radiation was 4.49 °C, compared to 17.29 °C for the double glazing with an air chamber. That is, the rise in temperature due exclusively to solar radiation was 36% less for the double glazing with a water chamber compared to the double glazing with an air chamber.

Taking into account the same percentage loss as in the case above through the windows of a conventional building, the daily energy requirement to ensure an indoor temperature close to comfort temperature (21–25 °C) is 0.08 kW h/m^3 for the interior air with the double glazing with a water chamber and 0.87 kW h/m^3 for the interior air for a conventional double glazing. Therefore, in the first case, the energy saving is 90.45% compared to the second case.

3.2. Energy balance analysis

As Table 2 illustrates, the annual energy consumed was calculated per cubic metre of indoor air.

Based on the characteristics of the standard room previously set out, the energy required per unit of useable surface in the living spaces can be calculated (Table 3).

As Table 3 shows, if only the energy consumed to reach comfort temperature is taken into account, the annual energy saving in heating and cooling, compared to the whole building, is 18.26% if double glazing with a water chamber is used compared to double glazing with an air chamber. If only the annual energy saving in heating and cooling is taken into account, regarding the energy gains and losses through the apertures of the building, this figure is 68.99%.

Table 2
Monthly energy demanded by glazing type.

	Energy demanded by glazing type (kW h/m^3)			
	Double glazing with an air chamber		Double glazing with a water chamber	
Month	Heating energy	Cooling energy	Heating energy	Cooling energy
January	9.07	0.00	7.11	0.00
February	10.20	0.00	8.14	0.00
March	3.72	0.00	2.93	0.00
April	1.93	0.44	1.53	0.42
May	0.92	3.82	0.74	3.38
June	0.00	4.19	0.00	3.83
July	0.00	7.50	0.00	6.38
August	0.00	6.81	0.00	5.74
September	0.00	1.47	0.00	1.29
October	4.52	0.00	3.54	0.00
November	6.51	0.00	5.12	0.00
December	12.63	0.00	10.11	0.00
Annual energy required	49.50	24.23	39.21	21.05
	73.73		60.26	

Table 3
Annual energy demanded by glazing type.

	Energy demanded by glazing type			
	Double glazing with an air chamber		Double glazing with a water chamber	
	Heating energy	Cooling energy	Heating energy	Cooling energy
Annual energy required (kW h/m^3)	49.50	24.23	39.21	21.05
	73.73		60.26	
Annual energy required (kW h/m^2)	14.85	7.27	11.76	6.31
	22.12		18.08	
Energy saving in heating (%)	20.78			
Energy heating in cooling (%)	13.12			
Energy saving (%)	18.26			

Table 4
Comparison of energy consumed with the limit set by the Adaptation of the European Directive 2010/31/EU.

	Annual energy required	
	Double glazing with an air chamber	Double glazing with a water chamber
Heating and cooling energy (kW h/m^2)	22.12	18.08
Passive building 2010/31/UE (kW h/m^2)	15.00	
Excess energy (kW h/m^2)	7.12	3.08
Excess energy compared to 15 kW h/m^2 (%)	47.46	20.52

The Adaptation of the European Directive 2010/31/EU on the Energy Efficiency of Buildings [3], shortly to come into force, aims to set a maximum value for a building's annual heating and cooling energy consumption (15 kW h/m^2 year). This type of building will be called a "Passive Building" or an "Almost Zero Consumption Building" [34].

Consequently, the priority objective of this research is to make a contribution to increase a building's energy efficiency through a reduction in the energy demand and through a more efficient design of the facilities. A second objective would be to equip the building with the technology to generate the energy required from renewable sources.

Energy demand can be reduced with passive or bioclimatic strategies. Table 4 compares the energy consumed using double glazing with an air chamber and double glazing with a water chamber. This measure reduces the excess energy demand from 47.46% to 20.52%. However, this measure on its own does not manage to reach the limit value. It therefore needs to be accompanied by other passive measures (better insulation in the building envelope, control of solar radiation, use of natural ventilation, ...).

Efficiency in the facilities is achieved by using high-efficiency energy systems. These will be studied in the following section.

3.3. Analysis of energy consumption and CO_2 emissions

Considering that the analysed case is double glazing with a circulating water chamber, the amount of carbon dioxide emitted per unit of surface of acclimatised dwelling varies from 4.10 kg/m^2 (natural gas) to 36.65 kg/m^2 (electricity), depending on the type of fuel used (Table 5). If the same case were double glazing with an air chamber, the carbon dioxide emissions per unit of surface

Table 5
Energy consumed and carbon emitted according to boiler type.

	Annual energy consumed and CO_2 emitted according to boiler type					
	Diesel boiler and condenser		Electric boiler		Modular gas condensation	
Name	TRISTAR		General		MODULEX	
Boiler option number	1		2		3	
Fuel source	Diesel-C		Electrical emersion heater		Natural gas	
Type of glazing	Air chamber	Water chamber	Air chamber	Water chamber	Air chamber	Water chamber
Energy demand (kW h/m^2)	22.12	18.08	22.12	18.08	22.12	18.08
Energy consumption by boiler (kW h/m^2)	24.33	19.89	26.54	21.69	24.33	19.89
Energy consumption from the fuel (kW h/m^2)	26.30	21.50	69.09	56.47	24.60	20.11
Total energy consumed by the system (/m^2)	0.002627 m^3/m^2	0.002147 m^3/m^2	70.499 kW h/m^2	57.623 kW h/m^2	2.434 m^3/m^2	1.989 m^3/m^2
Total carbon emitted (kgCO_2/m^2)	7.36	6.02	44.84	36.65	5.02	4.10

Table 6
Annual cost according to boiler type.

	Annual cost according to boiler type (€/m^2)					
	Diesel boiler and condenser		Electric boiler		Modular gas condensation	
Name	TRISTAR		General		MODULEX	
Boiler option number	1		2		3	
Fuel source	Diesel-C		Electrical emersion heater		Natural gas	
Type of glazing	Air chamber	Water chamber	Air chamber	Water chamber	Air chamber	Water chamber
Fuel cost	2.27	1.86	4.09	3.34	1.95	1.59
Installation cost	0.00	4.27	0.00	4.27	0.00	4.27
Glazing cost	7.20	9.60	7.20	9.60	7.20	9.60

Table 7
Evolution of the saving of the water glazing compared to the air glazing system, according to boiler type.

	Evolution of saving according to boiler type (€/m^2)		
	Diesel boiler and condenser	Electric boiler	Modular gas condensation
Name	TRISTAR	General	MODULEX
Boiler option number	1	2	3
Fuel source	Diesel-C	Electrical emersion heater	Natural gas
Annual saving	0.42	0.75	0.36
5-year saving	2.22	4.00	1.91
10-year saving	4.86	8.75	4.17
15-year saving	7.99	14.38	6.85
20-year saving	11.70	21.05	10.02
Time to recoup the cost of the facility (years)	13	8	15

vary from 5.02 kg/m^2 to 44.84 kg/m^2 depending on the type of fuel used. Therefore, for the analysed case, installing double glazing with a circulating water chamber in the façades reduces CO_2 emissions by 81.74%.

3.4. Economic feasibility analysis

Table 6 shows the economic costs of the three boilers studied for the glazing with an air chamber and for the glazing with a water chamber.

Table 7 shows the annual saving in energy supply company bills. If a natural gas boiler is chosen for the water chamber glazing compared to a diesel boiler, an annual saving of 14% can be attained and 52% compared to an electric boiler.

The same table shows the time calculated required to recoup the cost of the facility of glazing with a water chamber compared to the standard solution.

4. Conclusions

Installing double glazing with a circulating water chamber in a residential building, as a replacement for double glazing with an air chamber (currently used), reduces the heat losses and gains produced through its glazed façade, maintains transparency and does not deform the image. For the habitable space studied, which conforms to the usual size and characteristics of a residential building, the calorific and frigorific energy consumption is reduced by 18.26% in respect of the total consumption of the building.

The layout of the proposed facility, without any need for an additional energy source (only the building's domestic hot water mains supply), facilitates its integration into any type of residential building, either under construction or being renovated. Moreover, its zero visual impact means it can even be implemented in places with strict town-planning regulations (historical parts of town, specially protected areas, ...).

This system has the capacity to make use of solar energy to supplement the main energy source, but does not lose its efficiency when solar energy is lacking. Based on the analyses performed during different seasons, in similar climate zones where the amount of solar energy is low as well as in zones where it is high, the proposed system continues to be efficient.

The indicators usually used to assess the feasibility of any potential investment in projects are not appropriate for analysing high energy efficiency systems whose main purpose is to reduce energy consumption and environmental pollution. The proposed solution is justified by its capacity to reduce carbon dioxide emissions (81.74% can be reduced depending on the energy used) and, consequently, by raising the building's energy rating. This is a very important issue for existing buildings since it is not viable to make the majority of the systems used in their construction more efficient. Taking the economic study undertaken as a basis, this facility takes from 8 to 13 years to pay for itself depending on the energy used.

Finally, it should be pointed out that new topics not yet explored in depth have emerged from this research: treating the water circulating through the chamber so that it preserves its original properties; making use of the energy surplus of the water circulating in the chamber to satisfy other demands of the building, and controlling the level of natural light and/or transparency in indoor spaces by using additives in the water circulating in the chamber. New research into these topics would seem to be required, as it will contribute new knowledge that will undoubtedly result in greater energy efficiency and better environmental protection.

References

[1] Chow T, Li C, Lin Z. The function of solar absorbing window as water heating device. Build Environ 2011;46:955–60.

[2] Gimenez-Molina C. Smart windows, analysis of application in sustainable buildings. Dyna-Bilbao 2009;84:59–63.

[3] European Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official J European Union 2010; 53:L 153–13.

[4] Chow T, Li C, Lin Z. Thermal characteristics of water-flow double-pane window. Int J Therm Sci 2010;50:140–8.

[5] Gimenez-Molina C. Alternatives for Improving the Energy Performance of Glazing: Dynamic windows. Ph.D. Thesis. Madrid: Madrid Polytechnic University; 2011.

[6] Gimenez-Molina C. Smart windows. Analysis of application in sustainable buildings. Dyna-Bilbao 2009;84:59–63.

[7] Ward GJ, Inkarojrit V, Yazdanian M. Advanced of electrochromic windows. A design guide for early-market electrochromic windows. California Energy Commission CEC-500-2006-052-AT16. Berkeley: Lawrence Berkeley National Laboratory; 2006.

[8] Larnpert CM. Chromogenic switchable glazing: Towards the development of the smart window. Presented at Window Innovations '95. Toronto, Canada. June, 1995.

[9] Kraft A, Rottmann M. Properties, performance and current status of the laminated electrochromic glass of gesimat. Sol Energy Mater Sol Cells 2009;93:2088–92.

[10] Zinzi M. Office worker preferences of electrochromic windows: a pilot study. Build Environ 2006;41:1262–73.

[11] Buratti C, Moretti E. Glazing systems with silica aerogel for energy savings in buildings. Appl Energy 2012. http://dx.doi.org/10.1016/j.apenergy.2012.03.062.

[12] Buratti C, Moretti E. Experimental performance evaluation of aerogel glazing systems. Appl Energy 2012. http://dx.doi.org/10.1016/j.apenergy.2011.12.05.

[13] Yoshimura K, Yamada Y, Bao S, Tajima K, Okada M. Preparation and characterization of gasochromic switchable-mirror window with practical size. Sol Energy Mater Sol Cells 2009;93:2138–42.

[14] Han J, Lu L, Yang H. Numerical evaluation of the mixed convective heat transfer in a double-pane window integrated with see-through a-Si PV cells with low-e coatings. Appl Energy 2010;87:3431–7.

[15] Zinzi M. Office worker preferences of electrochromic windows: a pilot study. Build Environ 2006;41:1262–73.

[16] Grimmer DP, McFarland RD, Balcomb JD. Initial experimental tests on the use of small passive-solar test-boxes to model the thermal performance of passively solar-heated building designs. Sol Energy 1979;22:351–4.

[17] Alvarez G, Palacios MJ, Flores JJ. A test method to evaluate the thermal performance of window glazings. Appl Therm Eng 2000;20:803–12.

[18] Robinson P, Littler J. Advanced glazing: outdoor test room measurements, performance prediction and building thermal simulation. Build Environ 1993;28:145–52.

[19] Chow T, Li C, Lin Z. Innovative solar windows for cooling-demand climate. Sol Energy Mater Sol Cells 2010;94:212–20.

[20] Chow T, Li C, Clarke JA. Numerical prediction of water-flow glazing performance with reflective coating. In: Proceedings of the 12th conference of international building performance simulation association. Sydney. November, 2011.

[21] AEMET. State Meteorological Agency. Spanish Government: Ministry of the Environment, Rural and Marine Environment; 2010.

[22] R.D. 1826/2009. Reglamento de Instalaciones Térmicas en los Edificios: I.T.1.1.4.1.2. Building Technical Code. Spanish Government; 2009.

[23] Madrid City Government. Plan General de Ordenación Urbana de Madrid. Normas Urbanísticas, art. 7.3.5, Madrid: Madrid City Council; 1997.

[24] Madrid City Government. Plan General de Ordenación Urbana de Madrid. Normas Urbanísticas, art. 7.3.8, Madrid: Madrid City Council; 1997.

[25] Gimenez C, Lauret B. Experimental study for the analysis of low emissivity and water cooled glazings in sustainable houses. Proceedings of the First International Conference on Construction and Building Research. Madrid. June, 2009.

[26] Gil-Lopez T, Gálvez-Huerta MA, Castejón-Navas J, Gómez-García V. Analysis of carbon impact using mix energy sources for industrial heating applications. An assessment of options to refit services in an existing building. Fuel Process Technol, In press. http://dx.doi.org/10.1016/j.fuproc.2011.11.002.

[27] Gil T, Castejon J, Galvez MA, Gómez V. Carbon impact of supplying energy to air curtains via hot water. An assessment of options to refit services in existing buildings. In: Proceedings of the International Conference on Management and Service Science. Wuhan, China. August, 2011.

[28] SAP. The Government's standard assessment, Procedure for energy rating of dwellings. BRE/DEFRA, United Kingdom Government; 2005.

[29] UNE-EN 15603:2008. Energy performance of buildings – overall energy use and definition of energy ratings. Madrid: AENOR; 2008.

[30] Word IR, Reynolds AJ. Financial evaluation of projects in management for building services engineers MSc. London: Brunel University; 2002.

[31] Madrid City Government. Price List 2011. Area de Gobierno de Urbanismo, Vivienda e Infraestructuras. Madrid: Madrid City Council; 2011.

[32] Balaras CA, Droutsa K, Argiriou AA, Asimakopoulus DN. Potential for energy conservation in apartment buildings. Energy Build 2000;31: 143–5.

[33] Schlueter A, Thesseling F. Building information model based energy / exergy performance assessment in early design stages. Automat Constr 2009;18: 153–63.

[34] P.H. Institute; 2011. <http://www.passivehouse.com>.