Article

Experimental Validation of Water Flow Glazing: Transient Response in Real Test Rooms

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Abstract: The extensive use of glass in modern architecture has increased the heating and cooling loads in buildings. Recent studies have presented water flow glazing (WFG) envelopes as an alternative building energy management system to reduce energy consumption and improve thermal comfort in buildings. Currently, commercial software for thermal simulation does not include WFG as a façade material. This article aims to validate a new building simulation tool developed by the authors. Simulation results were compared with real data from a scale prototype composed of two twin cabins with different glazing envelopes: a Reference double glazing with solar-control coating and a triple water flow glazing. The results showed a good agreement between the simulation and the real data from the prototype. The mean percentage error of the indoor temperature cabin was lower than 5.5% and 3.2% in the WFG cabin and in the Reference glazing one, respectively. The indoor air temperature of the WFG cabin was 5 °C lower than the Reference one in a free-floating temperature regime when the outdoor air temperature was 35 °C and the maximum value of solar radiation was above 700 W/m². WFG has energy-saving potential and is worthy of further research into the standardization of its manufacturing process and its ability to increase building occupants’ comfort.

Keywords: building energy simulation; water flow glazing; experimental validation

1. Introduction

Energy consumption in buildings shows a growing trend worldwide and is of primary concern for the world population [1]. Over the last decade, nearly 60% of total net electricity consumption in Organization for Economic Co-operation and Development (OECD) economies, was in the building sector, both residential and commercial [2]. The residential building sector is responsible for more than half of the electricity consumption in developing countries [3].

In the frame of the Paris agreement in 2015, 195 countries adopted 17 sustainable development goals (SDGs) as the outcome of the UN’s inclusive and comprehensive negotiations in the frame of the 2030 agenda [4]. The seventh goal states that using clean and sustainable energy sources is an opportunity to transform economies and lives, especially in developing countries.

Annual power consumption depends on the use of the building, construction year, number of floors, building structure, and building location [5]. When it comes to heating and cooling consumption, the heating, ventilation, and air conditioning (HVAC) system, exterior walls, and glazing are the
essential elements [6,7]. Building energy management systems (BEMS) and energy-saving measures are aimed at reducing buildings’ energy requirements for heating and cooling [8–10].

In countries with a hot, humid climate, the excessive use of inefficient cooling systems leads to an increase in electricity consumption and causes pollution [11–13]. The energy performance of a building also depends on the solar radiation and the correlation between cooling/heating loads and the colors of surfaces [14].

In hot climate areas, the glazing solar heat gain coefficient (SHGC) must be low, and it is more relevant than the U-value because solar radiation causes the most significant part of the cooling load [15]. In cold climate areas, the goal is to reduce the need for heating energy, making the most of solar radiation [16,17]. Heating, ventilation, and air conditioning (HVAC) systems have to be efficient in providing users with a healthy environment. When fossil fuels and oil resources run out, solar energy and other renewable sources are alternatives to overcome the clean-energy demand growth [18,19]. The annual solar irradiation ranges between 100–200 W/m² as an average in Mediterranean countries, so the potential of solar energy is more than enough to provide as much energy as the building consumes [20].

Solar energy is aligned with the concept of “Regenerative Design.” It implies a proactive attitude of the building beyond the traditional sustainable design practice. Regenerative buildings reduce their energy consumption to zero, and can recollect, generate, and distribute renewable resources [21]. Glass is a fundamental element in the design of regenerative buildings. Still, its extensive use has increased the heating and cooling loads. Using transparent materials requires understanding their spectral properties and developing systems to solve some of the issues regarding heat gain, heat loss, and daylight [22,23]. Accurate prediction of the performance of glazing facades has to include a thorough analysis of thermal and spectral properties that depend on the glass, spacers, coatings, and gas fillings. Solar control layers reflect and filter solar radiation, and low emissivity coatings reduce the emissivity of the glass and retain the heat charge inside [24]. Acting in the chamber can improve the insulation capacity of the double-glazed windows [25]. The chamber can also be filled with inert gas, or vacuumed, to reduce the transmittance in large glazed surfaces [26]. Thermochromic and electrochromic glazing vary in color and transparency as a reaction to light and heat excess [27]. Double-pane windows, in which the exterior photovoltaic pane produces electricity, can be designed and manufactured today [28,29]. Double-pane windows can also be developed with circulating water through the chamber, instead of inert gas, allowing the water to absorb the heat of direct and diffused solar radiation [30].

The use of the building, the orientation of the facade, and the location of the project are relevant inputs to determine the glazing composition [31]. The Fourier model does not predict variations in thermal properties as a function of time [32]. Water flow glazing (WFG) facades are considered dynamic envelopes able to react or adapt to the building’s external and internal conditions. Most of the simulation engines do not include dynamic properties, so developing new tools to calculate the impact of WFG has become a goal of researchers [33,34]. Water is opaque to the near-infrared (NIR) spectrum of light, while its visible transmittance is very high [35].

Complicated simulation engines provide the designer with multiple options, and sometimes they are not useful at an early design stage because decisions have not been made yet. Architects might find better support in simple energy simulation tools than in complicated ones [35,36]. Building information modeling (BIM) has the potential to achieve performance improvements and high-quality construction, and architecture, engineering, and construction (AEC) industries have applied BIM in construction projects over the last few decades [37]. One of the features of BIM is the energy analysis of buildings. It makes the most of a friendly interface that has been tested over decades of experience by many users. However, users have identified gaps between the expected building energy consumption and the actual measured performance [38–40]. The causes of these gaps are diverse, including behavioral habits of occupants and construction flaws [41]. The evaluation of the actual thermal properties of the
building stock from monitored data is widely considered advantageous compared to tabulated data to improve the overall quality of the building process by feeding back the measured data [42].

The steady-state model is not a reliable means to analyze dynamic forms of heat transfer. Temperature, solar radiation, occupancy, and HVAC systems affect the transient state of the building envelopes. Those parameters are time-dependent and non-linear. Remote sensing systems have become indispensable in comparing the actual energy performance with simulation models and understanding the dynamic heating and cooling loads [43–45]. Cooling has represented a small share of the final energy use in buildings, but demand has been rising over the last decade [46,47]. This article considers the best available technologies (BAT) for cooling, which are innovative and economically viable [48]. The energy efficiency ratio (EER) is the parameter that measures the efficiency of cooling systems. Hydronic technologies, such as water-to-water heat pumps, are compatible with WFG and radiant floors and walls. WFG can improve the performance coefficient of cooling systems by increasing the indoor comfort temperature and the inlet temperature of the fluid through the glazing [49]. The technology of WFG has been studied in previous scientific articles. Some papers have studied the physical structure and energy performance of WFG in cooling-demand climates through numerical computation [50,51]. Recent research studied the performance of WFG compared with conventional double glazing with low-emissivity coatings. Dynamic simulation has been used to evaluate different options of glazing, and the presented simulation results concluded that improving SHGC is more efficient for thermal performance than improving the U-value [52]. Other papers have validated the numerical simulations using test prototypes. The dimensions of the tested devices varied depending on the goals of the research. Cubic boxes measuring 60 × 60 × 60 cm, with one side open, have been used to place different glass panes [53]. If the goal was to validate the performance of WFG, the prototype was designed as an adiabatic box, with high thermal insulation in the opaque walls with U values below 0.1. Other tests focused on analyzing the influence of coatings applied to the indoor surface and the heat gains by measuring the water flow rate and the inlet/outlet temperatures of WFG. These test facilities were slightly bigger (the length was 1.55 m, the width, 0.9 m, and the height, 0.9 m). In this case, the insulation of opaque walls was not relevant, and the indoor air temperature was set to 24 °C by a direct expansion cooling coil with an electrical heater [54]. The authors of the present paper have developed a set of equations to take into account the influence of multiple diffuse reflections, direct reflections between glazing and parallel surfaces, indirect reflections between the glazing, parallel surfaces, and perpendicular surfaces. These equations have been included in the simulation tool tested in the present article [55]. The simulation of the indoor air temperature and the water absorption in a transient state affected by changes in temperature and solar radiation was relevant when the test facility was bigger. In these cases, validating simulation tools with real data was essential in predicting thermal behavior and the fluctuations of indoor air temperature [56,57]. This paper aims to investigate the dynamic thermal parameters of WFG. The influence of WFG as a means of energy management was tested by comparing the indoor temperatures of two prototypes. The empirical tests under variable weather conditions and have been carried out over two years. There are three objectives in the analysis of the prototype. First, it allows for the comparison of the indoor temperatures of the WFG cabin and the Reference cabin. Second, the simulation tool based on the mathematical model to predict the performance of WFG was validated using real data. Finally, it aims to study the improvement of a water-to-water heat pump’s performance by reducing the temperature gap between the water and the indoor air. Two cases have been tested. In the first case, the water was flowing without controlling its temperature. In the second case, there was a source of energy that provided the desired boundary conditions. The thermal performances of the WFG cabin and the Reference cabin have been recorded using a proper monitoring system. Different boundary conditions based on real data are given to the mathematical models to carry out the simulation.
2. Materials and Methods

This section aims to provide a simplified model that helps designers to analyze the energy strategy of a dynamic envelope. Commercial BES tools do not include WFG as an option, so it is necessary to validate the hypothesis with data from real prototypes. The first subsection set the criteria to select the spectral and thermal parameters of the WFG. The second subsection described geometry, energy management, and the materials used in the prototype.

2.1. Simplified Model of Triple WFG

Water flow glazing (WFG) allows the flow of water between two glass panes. Water captures the solar NIR and increases its temperature through the window. The flow of the water enables the homogenization of the building envelope temperature so that designers can apply energy-saving strategies, such as energy storage or solar energy rejection. Table 1 shows the list of symbols that have been used in equations.

| Symbol | Meaning |
|--------|---------|
| $A_j$  | Absorptance of glass layers. |
| $A_w$  | Absorptance of water. |
| $A_v$  | Total absorptance of water flow glazing. |
| $h_i$  | Interior heat transfer coefficient (W/m²K) |
| $h_w$  | Water heat transfer coefficient (W/m²K) |
| $h_a$  | Air chamber heat transfer coefficient (W/m²K) |
| $h_e$  | Exterior heat transfer coefficient (W/m²K) |
| $q_i$  | Heat fluxes through the different layers of the glazing |
| $i_0$  | Normal incident solar irradiance (W/m²) |
| $g^{OFF}$ | Solar heat gain coefficient without flow rate. |
| $g^{ON}$ | Solar heat gain coefficient with high flow rate. |
| $\theta_i$ | Interior temperature (K) |
| $\theta_e$ | Exterior temperature (K) |
| $\theta_j$ | Temperature of the glass layer (K) |
| $\theta_{IN}$ | Inlet temperature of the water chamber (K) |
| $\theta_{OUT}$ | Outlet temperature of the water chamber (K) |
| $\theta_{STAGNATION}$ | Temperature of the water when $\dot{m} = 0$ (K) |
| $U$ | Thermal transmittance (W/m²K) |
| $U_i$ | Interior thermal transmittance (W/m²K) |
| $U_e$ | Exterior thermal transmittance (W/m²K) |
| $U_w$ | Thermal transmittance (water chamber–interior) (K) |
| $T$ | Transmittance of the glazing |
| $R$ | Reflectance of the glazing |
| $\dot{m}$ | Mass flow rate (kg/s m²) |
| $c$ | Specific heat of the water (J/Kg K) |
| $P$ | Heat gain in the water chamber (W) |

Figure 1 shows the heat flux and the temperature distribution when the outdoor temperature ($\theta_e$) is higher than the indoor ($\theta_i$) through a triple WFG. The thermal transmittance, $U$, is the parameter that explains the heat transfer. The European Standard determines its value and a calculation method [58,59].
Previous studies explained the thermal and spectral properties of WFG and its behavior [60,61]. This research used a simplified set of equations from those studies, along with data from commercial software, to assess the performance of the prototype defined in Section 2.2. Equations (1) to (10) show the heat fluxes through the different layers of the glazing. They consider the energy balance at each layer and the Newton’s definition of heat flux.

\[ q_1 = h_e(\theta_e - \theta_1), \]  
\[ q_2 = q_1 + A_1\dot{i}_0, \]  
\[ q_2 = h_g(\theta_1 - \theta_2), \]  
\[ q_3 = q_2, \]  
\[ q_4 = h_w(\theta_2 - \theta_w), \]  
\[ q_4 = q_3 + A_2\dot{i}_0, \]  
\[ q_5 = h_w(\theta_w - \theta_3), \]  
\[ q_5 = q_4 + A_w\dot{i}_0 + \dot{m}c(\theta_{IN} - \theta_w), \]  
\[ q_6 = h_i(\theta_3 - \theta_1), \]  
\[ q_6 = q_5 + A_3\dot{i}_0. \]  

The \( U \) values depend on the interior heat transfer coefficient, \( h_i \), the exterior heat transfer coefficient, \( h_e \), the air chamber heat transfer coefficient, \( h_g \), and the water heat transfer coefficient.

\[ \frac{1}{U_e} = \frac{1}{h_e} + \frac{1}{h_g} + \frac{1}{h_w}. \]
\[
\frac{1}{U_i} = \frac{1}{h_i} + \frac{1}{h_w}. \tag{12}
\]

\(A_1\) is the absorptance of the exterior glass pane, \(A_2\) is the absorptance of the middle glass pane, and \(A_3\) is the absorptance of the interior one. \(A_w\) is the absorptance of the water chamber. The absorptance, \(A_v\), depends on the energy absorbed by the glass panes and by the water:

\[
A_v = A_1 \left( \frac{U_e}{h_e} \right) + A_2 \left( \frac{1}{h_i} + \frac{1}{h_e} \right) U_e + A_3 \left( \frac{U_e}{h_i} \right) + A_w. \tag{13}
\]

Solving the Equations (1) to (10) and using the values of Equations (11) to (13):

\[
\theta_{OUT} = \frac{i_0 A_v + U_i \theta_i + U_e \theta_e + mc \theta_{IN}}{mc + U_e + U_i}. \tag{14}
\]

Water heat gain is a power magnitude, and it is measured in watts (W). Equation (2) shows the analytical expression.

\[
P = mc(\theta_{OUT} - \theta_{IN}), \tag{15}
\]

where \(P\) is the power absorbed by the water, \(\theta_{OUT}\) and \(\theta_{IN}\) the temperature of water leaving and entering the glazing, respectively, \(\dot{m}\) is the mass flow rate, and \(c\) is the specific heat of the water. The mass flow rate is a measurement of the amount of mass passing by a point over time. The goal of absorbing the same power, \(P\), can be achieved with a high \(\dot{m}\), which results in a low-temperature increase or a low \(\dot{m}\), which results in a high-temperature difference between the inlet and outlet. Equation (16) results by combining Equations (14) and (15).

\[
P = \frac{mc}{mc + U_e + U_i} (i_0 A_v + U_i(\theta_i - \theta_{IN}) + U_e(\theta_e - \theta_{IN})), \tag{16}
\]

where \(\theta_e\) and \(\theta_i\) are, respectively, the temperature outdoors and indoors of the room. Analyzing the Equation (16), the power absorbed by the water varies with \(\theta_{IN}\). Considering the rest of the equation as a constant, \(P_0\), \(P\) linearly decreases with slope \((U_i + U_e)\). Figure 2 shows that at a specific value of \(\dot{m}\), there is a maximum absorbed power, \(P\), depending on \(\theta_{IN}\).

\[
P = P_0 - \theta_{IN}(U_e + U_i). \tag{17}
\]

If boundary conditions do not change with time, the solution becomes constant when the system reaches a steady state. In this set of test cases, sunrays are perpendicular to the glazing. This assumption eliminates uncertainties associated with the dependence of each layer’s absorptance with the angle of incidence. Two case studies are considered: (a) and (b). Table 2 defines the outdoor and indoor boundary conditions. Case (a) studies the influence of \(\theta_{IN}\) with a fixed absorptance, and case (b) considers the impact of the absorptance when \(\theta_{IN}\) is fixed.

| Glazing | \(i_0\) (W/m²) | \(U_e\) (W/m²K) | \(U_i\) (W/m²K) | \(c\) (J/kg ◦C) | \(\theta_i\) (◦C) | \(\theta_e\) (◦C) | \(\theta_{IN}\) (◦C) | \(A_v\) |
|---------|----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|--------|
| Case (a) |
| 800     | 1.08           | 6.89            | 3600            | 25             | 30             | 15             | 0.5            |
| 800     | 1.08           | 6.89            | 3600            | 25             | 30             | 20             | 0.5            |
| 800     | 1.08           | 6.89            | 3600            | 25             | 30             | 25             | 0.5            |
| Case (b) |
| 800     | 1.08           | 6.89            | 3600            | 25             | 30             | 20             | 0.4            |
| 800     | 1.08           | 6.89            | 3600            | 25             | 30             | 20             | 0.5            |
| 800     | 1.08           | 6.89            | 3600            | 25             | 30             | 20             | 0.6            |

Figure 2 illustrates the power variations with water flow rate, \(\dot{m}\). There is a maximum water heat gain when \(mc >> U_e + U_i\). The maximum power absorption occurs when \(A_v\) is high and \(\theta_{IN}\) is low.
If the goal is to reject the solar energy, \( A_v \) must be as low as possible, with solar control coatings in the outermost glass panes. In this case \( (\eta c \gg U_e + U_i) \), the absorbed power \( (P) \) is the maximum power \( (P_{max}) \)

\[
\begin{align*}
P_{\text{max}} &= i_0 A_v + U_i (\theta_i - \theta_{IN}) + U_e (\theta_e - \theta_{IN}), \\
P_{\text{max}} &= i_0 A_v + U_i \theta_i + U_e \theta_e - \theta_{IN} (U_i + U_e).
\end{align*}
\]

(18)

(19)

\[\text{Figure 2.}\] Power absorbed by the water chamber of the WFG: (a) constant \( A_v \) at different inlet temperatures \( (\theta_{IN}) \); (b) constant inlet temperature \( (\theta_{IN}) \) with different \( A_v \).

Combining Equations (14) and (19), the value of \( \theta_{OUT} \) is:

\[
\theta_{\text{OUT}} = \theta_{\text{IN}} + \frac{P_{\text{max}}}{mc + U_e + U_i}.
\]

(20)

\( \theta_{\text{STAGNATION}} \) is the temperature of the water when the mass flow rate is stopped. Figure 3 illustrates the relationship between \( \theta_{\text{OUT}} \) and \( \dot{m} \) in two cases: (a) and (b). Case (a) shows that \( \theta_{\text{STAGNATION}} \) is the same if the water absorption \( A_v \) does not change; case (b) shows the variations of \( \theta_{\text{STAGNATION}} \) with different conditions of \( A_v \). When \( \dot{m} \) is close to zero, then \( \theta_{\text{OUT}} \) gets the maximum value, which is \( \theta_{\text{STAGNATION}} \). When \( \dot{m} \) is very high, then \( \theta_{\text{OUT}} = \theta_{\text{IN}} \).

\[\text{Figure 3.}\] Outlet temperature \( (\theta_{\text{OUT}}) \) of the WFG: (a) constant \( A_v \) at different inlet temperatures; (b) constant inlet temperature \( (\theta_{\text{IN}}) \) with different \( A_v \).

Equation (21) shows the total heat flux, \( q \):

\[
q = gi_0 + U_i (\theta_i - \theta_e) - U_w (\theta_i - \theta_{IN}),
\]

(21)
where \( g \) describes the proportion of solar energy transmitted indoors, \( U(\theta_e - \theta_i) \) expresses the heat exchange between the room and outdoors, and \( U_w (\theta_e - \theta_{IN}) \) represents the heat exchange between the water chamber and indoors. As per Equations (34) and (35) in [50]:

\[
U_w = \frac{U_{inc}}{mc + U_{e} + U_{i}'},
\]

\[
U = \frac{U_{e}U_{i}}{mc + U_{e} + U_{i}}.
\]

Since the WFG is a dynamic envelope, the \( g \) factor depends on the flow rate. When the water flows, the \( g \) factor decreases, and when the water flow stops, the solar energy enters the building, and the \( g \) factor increases. The thermal transmittance, \( U_i \), is almost zero when the flow rate is the design flow rate because the water chamber isolates the building from outdoor conditions. When the water flow stops, the thermal transmittance depends mainly on the components that make up an insulated glass unit: the glass panes, coatings, spacer, sealing, and the gas filling the sealed space.

### 2.2. Description of the Prototype

A prototype has been built to compare the thermal performance of WFG with a double-glazing solution. It is located near Madrid, Spain (latitude 41°22′ N, longitude 3°29′57″ W, altitude 1037 MAMSL). Conceptually, this mock-up is a mobile and autonomous prototype consisting of two cabins named WFG and Reference. The prototype design allows both the primary and secondary circuits to be housed within the demonstrator structure, although in independent sectors. Besides, the mock-up has four wheels at the bottom of the structure for easy transport and orientation.

The prototype has two levels: the lower level of 500 mm high and the upper level of 1000 mm high. The lower level holds the primary circuit, which is composed of a “Peltier” unit, and a lithium battery that feeds it. The upper level includes the two cabins. Finally, a photovoltaic panel has been installed on the roof allowing to store electric energy in the battery for the operation of the cooling device. A circulating device is made up of a 10 W solar pump. The primary circuit connects the circulating system with a “Peltier” device. The secondary circuit goes from the circulating system to the WFG, with a design flow rate of 0.5 L/min. Figure 4 illustrates a schematic of the prototype with its main components, and Figure 5 shows the layout of the prototype. It consists of two semi-detached insulated cabins, one with WFG facing South and the other with a Reference glazing in the same orientation. The dimensions of the windows are 1 m × 0.5 m.

![Figure 4. Schematics of the prototype. 1. Solar Pump 10 W, 2. “Peltier” Thermo-Electric Liquid Cooler 184 W, 24 V, 3. Battery 12 V (2 units serial connection), 4. PV Panel Polycrystalline cells. 236 W 24 V, 5. Flow meter, 6. Control unit, 7. Temperature sensors, 8. Pyranometer.](image-url)
Regarding the construction materials, the prototype is made up of a steel structure formed by welded tubular profiles. Furthermore, for the cladding of the opaque parts, a white aluminum sandwich panel with 100 mm of XPS has been selected. Hence, for the glazed facade, a high selective double glazing has been chosen for the Reference cabin and a highly selective triple glazing with a water chamber towards the inside, for the WFG cabin. Figure 6 shows the configuration of both glazing facades.

The prototype has undergone an exhaustive commissioning process from the design stage to the manufacturing, factory assembly, on-site assembly, and commissioning of all the systems involved. Hence, high reflective WFG is chosen to reject sun energy and use the water chamber of the glazing facing indoors to eliminate heat loads when required. Since the energy absorption should be minimized, a high reflective coating (Xtreme 60.28) is positioned close to the outer glass pane (face 2). This coating allows for the reduction of the $U$-value because it can be considered a low emissivity coating at the same time (Planitherm XN). The maximum g value ($g^{OFF}$) and the minimum g value ($g^{ON}$) are almost the same and around 0.2. Table 3 shows the spectral and thermal properties of the glazing defined in Figure 6. WFG presents different values of $U$ and $g$, depending on the mass flow rate. $U^{ON}$ and $U^{OFF}$ have been calculated with the equation (23) using $\dot{m} = 1$ L/min m² and $\dot{m} = 0$ L/min m², respectively. The steady values of the reference glazing have been placed on the columns $U^{OFF}$ and $g^{OFF}$.
The WFG was selected to eliminate internal heat loads by circulating cool water through the water chamber facing indoors. This cool isothermal envelope allows insulating the building from external boundary conditions. Furthermore, the “Peltier” device connected to a buffer tank produces cool water for the glazing. To minimize the electrical consumption of the “Peltier” device, the temperature of the buffer tank should be close to the cool water of the glazing. When the outdoor conditions made it possible, evaporative cooling and cooling by night were considered to cool down the buffer tank. Besides, the prototype allows the understanding of the real issues of glass facades, analyzing deep concepts such as overheating and thermal mass.

Figure 7 shows the prototype and the position of sensors. A short description of the monitoring devices is listed below:

- Pyranometer: The Delta Ohm LP PYRA 03 Pyranometer measures the irradiance on a horizontal surface (W/m²). The measured irradiance is the sum of the direct irradiance of the sun and the diffuse irradiance.
- One wire temperature probe: The DS18B20-PAR uses Dallas’ exclusive 1-Wire bus protocol that implements bus communication using one control signal.
- Flow meter: TacoSetter Inline 100 Potermic: Balancing valve made of brass with female thread 3/4” × 1/2”. Measuring range 0.3–1.5 L/min), Kvs 0.25 (m³/h).

**Table 3.** Thermal and spectral properties of the reference glazing and the WFG.

|        | R   | T   | \(U^\text{ON}\) (W/m²K) | \(U^\text{OFF}\) (W/m²K) | \(\delta^\text{ON}\) | \(\delta^\text{OFF}\) |
|--------|-----|-----|--------------------------|--------------------------|----------------------|----------------------|
| Reference | 0.433 | 0.252 | -                        | 1.017                   | -                    | 0.27                 |
| WFG     | 0.433 | 0.215 | 0.061 \text{1}            | 0.977 \text{2}          | 0.22                 | 0.26                 |

\text{1} Equation (23) with \(\dot{m} = 1\) L/min m²; \text{2} Equation (23) with \(\dot{m} = 0\) L/min m².

![Figure 6](image-url) Glass configuration for the Spanish mock-up. (a) Water Flow Glazing (WFG), (b) Reference glazing.
3. Results

The empirical tests, conducted by the experimental setup, were run over the years 2018 and 2019 to collect data in all the possible weather conditions. Some logged parameters were used as input data to the simulation tool, and other measurements compared the performance of the selected glazing and its importance on the indoor temperature. Continuous experimental data were taken to reflect the influence of variable weather conditions. The experimental data logging time step was set at 1 min.

3.1. Analysis of the Prototype. Free-Floating Temperature Regime

In 2019, the “Peltier” device was switched off, in a free-floating temperature regime. Figure 8 presents the interior temperature of both cabins and the exterior temperature over the last week of April, May, June, July, September, and October of 2019. In all the cases, the interior temperature of the WFG cabin ($T_{w\text{-air}}$) was 5 °C below the internal temperature of the Reference cabin ($T_{r\text{-air}}$) and reached similar or slightly lower values compared to the outside temperature ($T_{\text{ext1}}$). When analyzing 27/04/2019, $T_{w\text{-air}}$ almost reached 20 °C, while $T_{r\text{-air}}$ was 25 °C. Likewise, during the night on that day, the minimum $T_{w\text{-air}}$ remained at 7 °C, while $T_{r\text{-air}}$ dropped to 3 °C when the outdoor temperature reached 0 °C. Furthermore, in July, the maximum values for $T_{w\text{-air}}$ were below $T_{r\text{-air}}$ and $T_{\text{ext1}}$. The minimum temperature inside the WFG cabin did not drop as much as that inside the Reference cabin. On 24/07/2019 the graph shows that the maximum $T_{w\text{-air}}$ was 34 °C, while the $T_{r\text{-air}}$ reached 40 °C, and $T_{\text{ext1}}$ remained at 38 °C. During the night, $T_{w\text{-air}}$ reached 25 °C, while $T_{r\text{-air}}$ was 21 °C, when $T_{\text{ext1}}$ dropped to 18 °C.

Besides, Figure 8 shows the curve of the indoor temperature of the WFG cabin as a damped wave shape compared to the interior temperature curve of the Reference cabin or the outside temperature. The temperature difference between day and night inside the WFG cabin did not exceed 10 °C in most cases. However, the temperature difference between day and night inside the Reference cabin was around 20 °C. Analyzing the same parameters on 24 July 2019, it can be observed that the difference between the maximum (34 °C) and the minimum (25 °C) temperature inside the WFG cabin was 9 °C, while the difference between the maximum (40 °C) and the minimum (21 °C) temperature inside the Reference cabin was 19 °C. However, the difference between the maximum (38 °C) and the minimum (18 °C) outside temperature was 20 °C. The interior temperature curve of the WFG cabin is flatter than the reference glazing one.

Figure 7. Set up of the Spanish mock-up and schematic of sensors distribution of the cabins. Sensors nomenclature and position for the WFG cabin and the Reference cabin.
Besides, Figure 8 shows the curve of the indoor temperature of the WFG cabin as a damped wave shape compared to the interior temperature curve of the Reference cabin or the outside temperature. The temperature difference between day and night inside the WFG cabin did not exceed 10 °C in most cases. However, the temperature difference between day and night inside the Reference cabin was around 20 °C. Analyzing the same parameters on 24 July 2019, it can be observed that the difference between the maximum (34 °C) and the minimum (25 °C) temperature inside the WFG cabin was 9 °C, while the difference between the maximum (40 °C) and the minimum (21 °C) temperature inside the Reference cabin was 19 °C. However, the difference between the maximum (38 °C) and the minimum (18 °C) outside temperature was 20 °C. The interior temperature curve of the WFG cabin is flatter than the reference glazing one.

Figure 9 presents the indoor temperature of both cabins ($T_{w\text{-air}}$, $T_{r\text{-air}}$), the outdoor temperature ($T_{ext1}$), and solar radiation from 24 July 2019 to 30 July 2019. The maximum value of solar radiation was above 720 W/m$^2$, almost every day. Despite these high values of solar radiation, the interior temperature of the WFG cabin remained under 35 °C on 24 July 2019, while the Reference cabin temperature was above 40 °C.
The next step was to analyze a typical summer day in both cabins. Figures 10 and 11 show the glazing temperatures, measured in different points. There is a little difference between the surface temperatures of the outer glass pane in the WFG cabin ($T_{w, extU}$ and $T_{w, extD}$) with the Reference cabin ($T_{r, extD}$). The effect of the water flowing through the glazing affected the indoor surface temperatures in both cabins. Figure 10 illustrates that the measured indoor glass surface temperatures in the Reference cabin ($T_{r, up}$, $T_{r, down}$) are remarkably variable during the daily hours, according to the relevant variations of the outdoor thermal conditions and the low thermal inertia of the glazing. However, there is no difference between $T_{r, up}$ and $T_{r, down}$. The indoor surface temperatures in the WFG was measured at the bottom and the top of the indoor glass pane. The water heats up as it moves through the glazing, and the figure explains the influence of the water flow in the temperature distribution.

Figure 10. Temperatures of the Reference glazing, both on the outside ($T_{r, extD}$) and the inside face of the glazing ($T_{r, up}$, $T_{r, down}$). Sample day 25 July 2019.

Figure 11 shows the surface temperatures of the WFG facade, both on the outside and the inside face of the glazing. The external pane reached temperatures above 41 °C, while the maximum surface temperature on the inner pane was 34 °C. There was no significant difference between $T_{w, extU}$ and
When it comes to the interior pane, the water absorbed part of the solar radiation as it flowed. There were two sensors in the upper part ($T_{w_{up}, L}, T_{w_{up}, R}$) and two sensors in the lower part ($T_{w_{down}, L}, T_{w_{down}, R}$). A 2 °C difference was observed between the lower and upper probe of the inside surface of the glazing. The lower part of the inner glass reaches a maximum temperature of 32 °C, while the upper part reaches 34 °C.

![Temperatures of the WFG facade, both on the outside ($T_{w_{ext}, U}, T_{w_{ext}, D}$) and the inside face of the glazing ($T_{w_{up}, L}, T_{w_{up}, R}$ for the upper probes, $T_{w_{down}, L}, T_{w_{down}, R}$ for the lower ones). Sample day 25 July 2019.](Figure-11.png)

**Figure 11.** Temperatures of the WFG facade, both on the outside ($T_{w_{ext}, U}, T_{w_{ext}, D}$) and the inside face of the glazing ($T_{w_{up}, L}, T_{w_{up}, R}$ for the upper probes, $T_{w_{down}, L}, T_{w_{down}, R}$ for the lower ones). Sample day 25 July 2019.

### 3.2. Analysis of the Prototype. “Peltier” Device ON

Figure 12 shows the interior temperature of both cabins and the exterior temperature from 22 July 2018 to 27 July 2018. The “Peltier” cell was in operation according to a simple control logic based on the interior temperature programmed in the monitoring control unit. It was set to operate every summer day from 12:30 to 20:00. The goal was to keep the inlet temperature between 15 and 17 °C to test the indoor air conditions inside the WFG cabin. The mean maximum temperature reached inside the WFG cabin ($T_{w, air}$) was 26.5 °C, with a mean maximum solar radiation of 720 W/m². However, the mean maximum temperature of the Reference cabin ($T_{r, air}$) exceeds 37 °C, when the mean maximum outdoor temperature ($T_{ext}$) is 34.5 °C. Therefore, there were more than 10 °C of difference inside both cabins. The Reference glazing replicated the thermal oscillations of the outside temperature, generating discomfort inside the building and contributing to overheating. The same behavior was observed when analyzing the minimum temperatures. The minimum value of $T_{r, ext}$ was 10 °C, while the Reference cabin remained at 12 °C, and the WFG cabin reached 15 °C. Therefore, the thermal inertia that characterizes the WFG facade managed to dampen the oscillation of the interior temperature. The temperature oscillations of the Reference cabin were similar to the outside temperature. Hence, the WFG cabin allowed for the bringing of the maximum and minimum values close to the comfort temperature. Specifically, analyzing 23 July 2018, the mean value between the maximum $T_{w, air}$ daytime temperature (26.5 °C) and the mean minimum value of night time temperature (16.5 °C) was 21.5 °C, which was very close to the comfort temperature.
4. Discussion

When the glazing is part of an insulated room, the thermal problem of the glazing is coupled with the thermal problem of the room, and the indoor temperature should be determined. The indoor boundary condition disappears to be part of the solution to the thermal problem. The prototype was a rectangular room with glazing facing south. The dimensions of the room, the near and far-infrared absorption \( \alpha_{\text{NIR}}, \alpha_{\text{FIR}} \), and the thermal transmittance of the opaque envelope are defined in Table 4.

| Reference cabin | Height (m) | Length (m) | Width (m) | \( U_{\text{wall}} \) (W/m\(^2\)K) | \( \alpha_{\text{NIR}} \) | \( \alpha_{\text{FIR}} \) |
|-----------------|------------|------------|-----------|----------------------------------|----------------|----------------|
| WFG cabin       | 1          | 0.6        | 0.5       | 0.3                              | 0.4            | 0.9            |

In these following test cases, outdoor temperature and solar irradiance varied during the day, and thermal performances depended on time. The indoor temperature was unknown, and it should have been obtained at the same time as the glazing temperature profile. Regarding the water flow glazing, the flow rate and the inlet temperature were constant values given by Table 5.

| Glazing | \( \dot{m} \) (l/min m\(^2\)) | \( \theta_{\text{IN}} \) (°C) | \( h_g \) (W/m\(^2\)K) | \( h_{\text{up}} \) (W/m\(^2\)K) | \( c \) (J/Kg K) |
|---------|---------------------------------|------------------|------------------|------------------|----------------|
| WFG     | 1                               | 18–22            | 1.16             | 50               | 3600           |

Transient behavior occurred when the outdoor temperature and solar irradiance varied during the day. Besides, each wall had a different temperature due to the luminance of the direct beam solar radiation. Since the WFG was facing south, the north indoor wall absorbed solar radiation. The rest of this energy was diffusely reflected and created the indoor diffuse irradiance. Later, this irradiance was absorbed in each indoor surface. Hence, in this test case, the water flow glazing absorbed extra energy from the indoor irradiance. Figure 13 shows the validation of the Software Tool using real data from both cabins. The figure illustrates six days, from 22 July 2018 to 27 July 2018, in which we can see how the measured curves replicate the simulation curves in all the cases.
Table 4. Dimensions of the cabins with thermal and spectral properties of opaque walls.

|                  | Height (m) | Length (m) | Width (m) | Uwall (W/m² K) | αNIR | αFIR |
|------------------|------------|------------|-----------|----------------|------|------|
| Reference cabin  | 1          | 0.6        | 0.5       | 0.3            | 0.4  | 0.9  |
| WFG cabin        | 1          | 0.6        | 0.5       | 0.3            | 0.4  | 0.9  |

In these following test cases, outdoor temperature and solar irradiance varied during the day, and thermal performances depended on time. The indoor temperature was unknown, and it should have been obtained at the same time as the glazing temperature profile. Regarding the water flow glazing, the flow rate and the inlet temperature were constant values given by Table 5.

Table 5. Parameters of WFG.

| Glazing       | ṁ (l/min m²) | θIN (°C) | hg (W/m²K) | hw (W/m²K) | c (J/Kg K) |
|---------------|--------------|----------|------------|------------|------------|
| WFG           | 1            | 18–22    | 1.16       | 50         | 3600       |

Transient behavior occurred when the outdoor temperature and solar irradiance varied during the day. Besides, each wall had a different temperature due to the luminance of the direct beam solar radiation. Since the WFG was facing south, the north indoor wall absorbed solar radiation. The rest of this energy was diffusely reflected and created the indoor diffuse irradiance. Later, this irradiance was absorbed in each indoor surface. Hence, in this test case, the water flow glazing absorbed extra energy from the indoor irradiance. Figure 13 shows the validation of the Software Tool using real data from both cabins. The figure illustrates six days, from 22 July 2018 to 27 July 2018, in which we can see how the measured curves replicate the simulation curves in all the cases.

Figure 13. Indoor air temperature. Real results and simulation of the Reference cabin and the WFG cabin. Sample summer days 22 July 2018 to 24 July 2018.

The software tool tested in this article is an open software code written in modern Fortran, with a graphic user interface. The functionalities are grouped visually and logically into thematic units. There are libraries of spectral and absorption properties with different glasses and coatings. These libraries can allow developers to integrate WFG in existing building energy simulators. A thermal simulator of zones with glass and opaque envelopes includes properties such as thermal mass and reflections inside the zone. Some papers on the functionality of this tool have been published to present the design approach [62].

4.1. Analysis of the Reference Cabin

The reference glazing is considered a high-performance transparent envelope. It is made up of glass panes with coatings and gas cavities. Figure 14 illustrates real data and simulated indoor temperatures of the Reference cabin. In both measured and simulated curves, the interior peak temperature is slightly above 40 °C between 03:00 and 10:00 on 23 July 2018. Equation (24) represents the mean error (ME), which is the difference between the measured value and simulation results. Equation (25) represents the mean percentage error (MPE), with a total number of measurements of \( n = 1440 \).

\[
ME = \frac{1}{n} \sum_{i=1}^{n} |T_{Si} - T_{Ri}|, \quad (24)
\]

\[
MPE = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{T_{Si} - T_{Ri}}{T_{Ri}} \right| 100. \quad (25)
\]

where \( T_{Si} \) is the simulated value, and \( T_{Ri} \) is the measured value. By computing ME and MPE, the sample summer day, 23 July 2018, MEs and MPEs of the indoor temperature of the Reference cabin, \( T_{r,air} \), were lower than 0.6 °C and 3.2%, respectively. Predictions of \( T_{r,air} \) were more accurate because the boundary conditions were more suitable to predict.
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\[
\text{Equation (24)} \quad \text{ME} = \frac{1}{n} \sum_{i=1}^{n} |T_{Si} - T_{Ri}|
\]

\[
\text{Equation (25)} \quad \text{MPE} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{T_{Si} - T_{Ri}}{T_{Ri}} \right| \times 100.
\]

where \( T_{Si} \) is the simulated value, and \( T_{Ri} \) is the measured value. By computing ME and MPE, the sample summer day, 23 July 2018, MEs and MPEs of the indoor temperature of the Reference cabin, \( T_{r\text{air}} \), were lower than 0.6 °C and 3.2%, respectively. Predictions of \( T_{r\text{air}} \) were more accurate because the boundary conditions were more suitable to predict.

4.2. Analysis of the WFG Cabin

Two different mechanisms appeared to modify the thermal performances of the WFG. The first one was the value of the indoor temperature, which can be very high, depending on the wall insulation. The second one was the absorbed back irradiance. Depending on the insulation of the walls and the near-infrared absorptances, the water heat gain can differ when compared to the water heat gain of isolated glazing. Figure 15 shows the comparison between real data and simulation over the same day, 23 July 2018. MEs and MPEs of the indoor temperature of the WFG cabin were lower than 1.2 °C and 5.5%, respectively.

Figure 14. Indoor air temperature. Real results and simulation of the Reference cabin. Sample summer day 23 July 2018.

Figure 15. Indoor air temperature. Real results and simulation of the WFG cabin. Sample summer day 23 July 2018.
Figure 16 illustrates the time histories of indoor and outdoor air temperatures and the solar irradiance in W/m² on the outdoor horizontal roof surface on a sample summer day (23 July 2018). The indoor air temperature of the Reference cabin \( (T_{\text{inlet}}) \) varied according to the solar irradiance and the outdoor temperature \( (T_{\text{exit}}) \). The measured inlet temperature \( (T_{\text{inlet}}) \) was input in the simulation tool as boundary conditions. By considering the activation of a solar fed “Peltier” device, the inlet temperature was set between 18 and 22 °C. The operation schedule for the cooling system activation was from 12:30 to 20:00. Figure 16 reports the results of the daily analysis. The thermal effect of the “Peltier” device kept the indoor temperature below 27 °C over the hottest hours of the day.

The daily cooling demands are shown in Figure 17. The daily energy that the flow of water can absorb was calculated using Equation (15). WFG prevented this energy from entering the cabin. The “Peltier” device provided the cooling power that explains the difference in temperatures between the WFG cabin and the Reference cabin. The energy absorbed by the WFG was 117.5 Wh in 0.5 m², so the ratio of energy per area was 0.235 kWh/m².
4.3. Final Energy and Cost Considerations

This section has considered best available technologies (BAT), which are innovative and economically viable [48]. Hydronic technologies are compatible with radiant systems, such as WFG and radiant floors and walls. Air-to-air heat pumps are used to compare the final energy consumption and cost of different cooling systems. WFG can be a part of hydronic HVAC systems, and it is compatible with water-to-water heat pumps. Tables 6 and 7 illustrate the final energy consumption with different energy generators. It takes into account the effect of the operative temperature of the system [63]. The performance of water-to-water heat pumps (WWHP) depends on the inlet temperature of the WFG (θ\text{IN}) and the source inlet temperature (T\text{s,i}) in the heat pump. A typical value of T\text{s,i} ranges from 20 °C in ground source heat pumps (GSHP) to 35 °C in other WWHPs. The source and load sides are relevant when it comes to calculating the performance of the cooling device. Air-to-air heat pumps (AAHP) for heat recovery on ventilation are also analyzed. The parameters that influence air-to-air heat pumps’ performance are the dry bulb exterior air temperature (T\text{e_db}) and the dry bulb interior return air temperature (T\text{r_i_db}).

Table 6. Final energy analysis. Water-to-water heat pump.

| Water-to-Water Heat Pump | θ\text{IN}(°C) | 7 °C | 18 °C |
|-------------------------|----------------|-----|------|
|                         | T\text{s,i}(°C) | 20  | 35   | 20  | 35   |
| Energy consumption (kWh/m²) | 0.235          | 0.235 | 0.235 | 0.235 | 0.235 |
| EER ¹                   | 5.93           | 3.27 | 7.11 | 4.22 |
| FE consumption (kWh/m²)  | 0.040          | 0.072 | 0.033 | 0.056 |
| NRFE consumption (kWh/m²) | 0.077         | 0.140 | 0.065 | 0.109 |
| CO₂ emissions (KgCO₂)    | 0.013          | 0.024 | 0.011 | 0.018 |

¹ Energy efficiency ratio (ERR) values are taken from Appendix A in [63].

Table 7. Final energy analysis. Air-to-air heat pump.

| Air-to-Air Heat Pump | T\text{r_i,db}(°C) | 22 °C | 26 °C |
|---------------------|------------------|-----|------|
|                     | T\text{e,db}(°C) | 35  | 40   | 35  | 40   |
| Energy consumption (kWh/m²) | 0.235          | 0.235 | 0.235 | 0.235 | 0.235 |
| EER ¹               | 3.22            | 2.94 | 2.60 | 2.90 |
| FE consumption (kWh/m²)  | 0.073           | 0.080 | 0.090 | 0.081 |
| NRFE consumption (kWh/m²) | 0.143         | 0.156 | 0.177 | 0.158 |
| CO₂ emissions (KgCO₂)    | 0.024          | 0.026 | 0.030 | 0.027 |

¹ ERR values are taken from Appendix A in [63].

PEF stands for the primary energy factor from final energy (FE) to non-renewable final energy (NRFE). The Spanish code for thermal systems in buildings (RITE) recommends a value of 1.954. The factor of CO₂ emissions for electricity was 0.331 [64]. The RITE aims to establish primary energy factors and CO₂ emission factors, for each final energy consumed by buildings in Spain and for each geographic area with a different electricity generation source.

Table 6 shows that the best performance belongs to WWHP when the inlet temperature (θ\text{IN}) is close to 18 °C, and the source inlet temperature (T\text{s,i}) in the heat pump is 20 °C. Figure 16 shows that it is possible to keep the cabin’s indoor temperature within the comfort range by setting θ\text{IN} between 18 °C and 22 °C. Other systems, such as fan-coils, need lower operating temperatures. The lower the difference between T\text{s,i} and θ\text{IN} the higher the EER coefficient. The NRFE consumption of GSHP is 0.065 kWh per m² of WFG, and the average NRFE use of air-to-air heat pumps is 0.155 kWh per m² of
When it comes to CO₂ emissions, air-to-air heat pumps generate an average of 0.027 KgCO₂, twice as much as the CO₂ emitted by GSHP.

5. Conclusions

This paper has studied a model to assess innovative building envelopes’ energy performance, such as water flow glazing (WFG), the system equations for load calculation, and the relationships with steady and transient parameters. Some of the magnitudes can be measured accurately in the prototype. The presented tool has been developed and tested by the authors. Details of the prototype and the on-site measures have been used to validate the tool. The analysis included a free-floating temperature regime and a cooling system with simple logic to keep the prototype within a comfort range. Results included simulated indoor air and glazing temperatures along with the potential final energy savings.

1. When the WFG cabin’s interior temperature was below the exterior temperature, the WFG facade cooled down the room. As the “Peltier” device was not in operation over 2019, it can be concluded that WFG working on a free-floating temperature regime, without auxiliary energy systems, results in smaller indoor temperature fluctuations.

2. Circulating water increased the temperature gap between external and internal glass panes. The outer pane reached temperatures above 41 °C, while the maximum surface temperature on the inner pane was 34 °C. The reference glazing showed a smaller gap between outer pane (41 °C) and inner pane (38 °C). The reduction of radiant temperature of indoor envelopes can improve the occupant’s comfort.

3. The damping effect on the WFG cabin’s temperature is shown in Figure 12. The WFG system provided the facade with thermal inertia, and the cabin did not suffer large thermal oscillations between day and night. This effect can increase the thermal comfort inside the building and reduce energy consumption.

4. The WFG increased the thermal inertia of the facade. Once the maximum temperature was reached, the interior of the WFG cabin cooled down more slowly than the Reference cabin did. There was a good agreement between the simulation and the real data from the prototype. MEs and MPEs of the indoor temperature in the WFG cabin, were lower than 1.2 °C and 5.5%, respectively. The simulation results of the Reference cabin were more accurate because the boundary conditions were more suitable to predict.

The weather and indoor conditions impact the efficiency coefficients of heat pumps. The EER values of the cooling systems were evaluated for different combinations of indoor and outdoor conditions.

Ground source heat pumps (GCHP) coupled with borehole heat exchangers in a closed loop are very effective and make the most of the near-constant ground temperature over the year.

Finally, if the electricity is supplied from solar cells, it is possible to use a renewable and CO₂ free energy source to provide thermal comfort.

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