

Development of a First Prototype of a Liquid-Shaded Dynamic Glazed Facade for Buildings

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Abstract: This paper will report on the development of a prototype of actively controlled facade module, which is capable of adapting its solar transmittance to changeable solar gains. Hence this new facade offers additional features with respect to the most popular currently used glass facades, which have fixed solar transmittance indeed. The novel technology is made possible by the creation of an additional 1.5-mm-thick sliding shielding liquid, which flows internally, in order to dynamically adapt the window's solar transmittance. As compared with competitive technologies, this shielding system has low manufacturing costs, is durable, is completely reversible and always transparent, irrespective of its transmittance state. Specifically, the manufacture of a full-size window prototype and the engineering of the window was carried out; moreover, glass pane bending when subject to hydrostatic pressure was eventually assessed. All this information has been used to set up the industrial process needed for its manufacturing.

Keywords: active solar control, liquid shading window, smart buildings.

1. Introduction

The careful use of energy in buildings is becoming increasingly important as they are responsible for a great percentage of the total energy consumed. Furthermore, in industrialized countries, about half of the total carbon dioxide emissions comes from the building sector [1]. Windows and glazed facades strongly influence energy consumption due to lighting, cooling and heating. Considering that energy requirements generally vary over the four seasons, the same solar gains, which must be shielded in summer, should be maximized in winter. Summer solar gains contribute to conditioning loads, which should be kept as low as possible, while winter solar gains positively add to the comfort provided by heating systems.

This paper reports a new technology, currently being developed, which integrates a switchable liquid shielding system in order to make windows and glazed facades dynamically adaptable, in terms of visual and thermal properties, to external conditions. The novel liquid-shaded dynamic system is made possible by the

creation of an additional 1.5-mm-thick layer, hosting a sliding shielding liquid, which flows internally, in order to constitute an infrared radiation barrier adaptable to real needs. In both configurations the proposed solution maintains its transparency but can act either as a shield to sunlight, when put in the low solar transmittance state, or as a clear transparent envelope, when operated in its high solar transmittance configuration.

Previous research focused on physical-chemical problems in order to identify the most suitable liquid mixture and kind of glass, in terms of durability, high temperatures resistance, elimination of interstitial condensation, minimizing fluid-glass adhesion. Solar properties were estimated to be comparable to, and in some cases even better than, some other commercial glass stratifications. Recent experimental measurements of solar transmittance on this technology, performed by means of a spectrophotometer and a Fourier transform IR spectrometer, have shown that the proposed triple glass stratification with no liquid has a solar transmittance of about 50%, which, when the liquid

rises, drops to about 15% [2]. Similar results derived from reduced scale experiments [3].

In this paper the manufacture of a full size window prototype will be presented (Fig. 2). During that process the whole engineering of the window was carried out, which includes the choice of the frame, the design of micro-circuits for deploying the shielding liquid, the assembly of all components and particularly the assessment of the glass pane bending when subject to hydrostatic pressure. This research allowed us to demonstrate the technological feasibility of the system and to make possible assumptions to solve glass deformation problems due to hydrostatic pressure.

In the next section relevant references from the current state of the art are reported, while in Section 3 the set-up and the changeable functional models of this technology are described. Section 4 and Section 5 focus on the manufacturing process of the prototype, describing all its specific components. Laboratory tests and related results are described in following Section 6. Conclusions are reported in the final section of this paper.

2. Related Scientific Background

Traditionally, shading systems are classified according to their position in relation to the glass: external shading, internal shading devices and integral (between-glass) shading systems [4]. Some options for external shading are roof overhangs, awnings, exterior louvers, shading screens. Other alternative solutions reside in internal and integrated devices, such as Venetian blinds or shading rollers, located inside glass panes or in the air gap of double or triple glass stratifications.

In addition, glass coatings that can modify the optical and thermal properties of glass are generally adopted. Relevant examples, which are also being widely marketed, are solar-control and low-emission glass stratifications. Successful installations have demonstrated their high reliability, although their thermal and optical

parameters cannot be varied dynamically. The use of switchable windows may determine day lighting control, which allows major energy saving and reduction of glare discomfort [5, 6].

Electrochromic windows vary their optical and thermal properties due to the action of an electric field and change back again when the field is reversed [7]. These windows run on very low voltage (1–3 V) and require energy only when their condition must be changed, but not to hold any particular state. Electrochromic panes consist of a thin, multi-layer assembly that is typically sandwiched between traditional glazing. The two outer layers of the assembly are transparent electronic conductors which encase a counter-electrode layer and an electrochromic layer, with an ion conductor layer between them. A low voltage can be applied across the conductors, moving the ions from the counter electrode to the electrochromic layer, thereby tinting the assembly. Reversing the voltage moves the ions from the electrochromic layer back to the counter-electrode layer, restoring the device to its previous clear state [7, 8]. However, electrochromic glazing for architectural applications is not able to reach a lifetime longer than 20 years, according to a number of aging tests, due to fast degradation under cycling. In addition, current research is ongoing to improve UV stability of the system, as, in the past, there were few indications on decomposition and delamination of some electrochromic glass prototypes by UV radiation [9]. Another drawback is given by the high manufacturing costs of large electrochromic glass panes [10].

Other technologies are presently under development. Among the most important ones, we cite liquid crystal switchable glazing, which are also controlled electronically [11]. This laminated unit contains two PVB films enclosing a thin film encasing tiny liquid crystals, and wired to a power supply. When there is no power to the glazing, the liquid crystals are randomly scattered and light is diffused in all directions. When an electric current is applied between the two conductive

coatings, the liquid crystals align neatly and light passes through it relatively unobstructed. Although useful for privacy control, liquid crystal glazing does not provide energy filtering.

Inserting silica aerogel granules through an automated and reversible mechanical device between glass panes, combines a very low U-value with a high visual transmittance [12]. The size of the aerogel granules is between about 0.001 and 0.002 m. However this method prevents transparency and preliminary tests have shown that it is not completely reversible, because aerogel granules leave powder inside glass cavity when they are removed to rise U-value or improve visibility.

Inserting Phase Change Materials (PCM) between glass panes was shown to perform better as a passive technology than absorbing gases filling air gaps [13].

More complex stratifications of a different kind for active windows have also been presented, made up of three layers and two cavities: the first ventilated with air and the second shaded with Venetian blinds [14].

Climate facades with a mechanically ventilated air gap have been tested by comparing their performance with that of a reference facade built with clear glass [15]. A sensitivity analysis showed that the ventilated air gap is effective mostly for enhancing summer conditioning, leading to load reductions higher than 30%. On the contrary, ventilation should be stopped in the winter mode and only the insulation potential used.

In addition, water-flow windows, hosting a stream of water flowing upwards within the space between two glass panes, have been presented. A numerical study estimated water-flow windows to be advisable for temperate climates where there are no extreme outdoor conditions [16].

The solution proposed in this paper provides the advantages of preserving glass transparency in both its working modes (i.e. high and low solar transmittance states), being fully reversible, durable, requiring short switching time to change from high to low solar

transmittance and being of rather low cost. In addition, it exhibits very low g-values when kept in its shading mode, as shown by the comparison with other commercially available transparent stratifications.

3. Functional Models of the Liquid-shaded Module

The presence of a switchable liquid layer calls for a slight change in the window configuration, due to the need to insert a cavity to host the liquid layer in the stratification and some devices to store and deploy the liquid in the frame. As depicted in the middle part of Fig. 2, to pursue such a goal the window was designed with the following stratification (from the exterior to the interior):

- one shielding liquid repellent glass layer;
- a cavity which holds the shielding liquid characterized by a low viscosity and weak chemical bonds with glass (about 0.0015 m thick);
- another shielding liquid repellent glass layer;
- standard air cavity (about 1 cm thick);
- standard glass layer towards the interior.

Past research focused on the development of a proper shielding liquid, capable of sliding up and down inside the inner cavity without leaving fragments (such as drops, powder, etc.) on the inner surfaces of the encasing glass layers. The liquid was obtained by blending different substances that would assure it to work properly under cycling and repellent glasses to its main component were individuated. Additives were added to lower as much as possible the solidification temperature and raise the evaporation temperature [3]. Properties and colour of the liquid may also be adaptable within a certain range, according to the specific context and climatic area.

In the bottom side of the window frame, a hydraulic pump is inserted to pump liquid from the storing tanks to the window cavity when solar shielding is needed, and pumping it back when solar gains should be maximized. Overflows are left not only above the liquid tanks, but also above the liquid layer of the window. A gas is

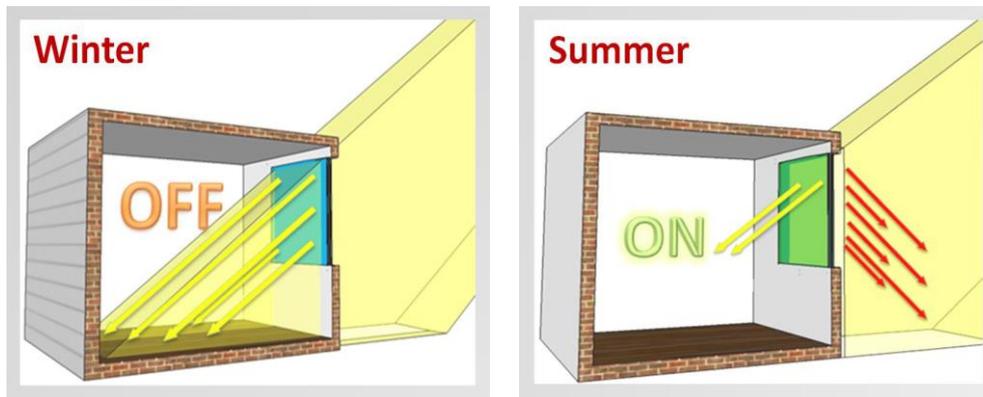


Fig. 1 Winter (left side) and summer (right side) behaviour of the smart window: in winter the liquid is stored in the tank and the stratification is clear, while in summer the window is filled with liquid, which is able to shade solar energy and sunlight.

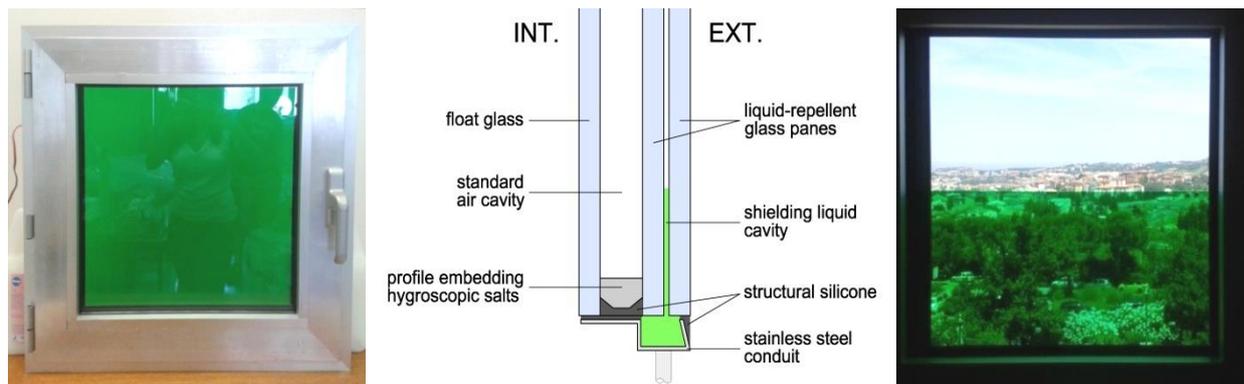


Fig. 2 Cross-section showing the basic window stratification (in the center) and the window in operation (on the left and on the right).

inserted in the circuit to compensate for the liquid, e.g. the gas is stored in the tank when the interlayer is full of liquid. The switchable nature of the technology proposed can then be exploited to optimize the window's behaviour, according to the conditioning needs of the building.

As depicted in Fig. 1, in the summer, when the sun is high in the sky and external temperatures are rather high, given that buildings usually need to shield solar contributions and reduce the thermal load to be extracted by the conditioning system, windows are likely to be shielded so that solar energy cannot enter. This configuration will dramatically reduce the solar gains in order to keep indoor temperatures close to the comfort level range [3]. The opposite should be done in winter, leaving the liquid down in order to increase the solar gains as much as possible and to reduce the thermal load to be supplied by the heating system.

These two basic functional modes will be selected according to the specific conditioning requirements of the building. By way of an example, in mid-season the best combination will be strongly dependent on the changeable weather conditions, such as sun intensity and outdoor temperatures. Hence it is reasonable for a control system to drive the window behaviour according to transient indoor and outdoor conditions.

4. Overview of the Manufacturing Process

Referring to the involved professional figures, we envisaged the following manufacturing steps:

1. assembly of the glass stratification;
2. production and integration of the deployment and actuation apparatus in the frame;
3. fitting of glass stratification in the window frame.

In the first step, the presence of the liquid layer required to add another liquid-repellent glass panel to a

standard double glass with air layer. The two panes embedding the shielding liquid were of liquid repellent type and sealed through structural silicone. Two spacers were inserted on the long sides to create the 1.5-mm-thick liquid layer and two steel conduits were fixed at the bottom and top sides, in order for the liquid to be evenly distributed in the cavity.

In the second step an “intermediate assembler” provides the realization of deployment and actuation apparatus, composed by the hydraulic circuit, the electrical circuit and the pumping system. The hydraulic circuit was made up of two 1.0-mm-thick PVC tanks placed inside the window post, a peristaltic pump (12V) placed in the lower part of the frame, a liquid deployment system consisting of polyurethane pipes (\varnothing 6 - 4 mm) and three-way taps in order to permit the maintenance of each element separately. The system was powered by a low voltage electrical circuit which allows the passage of electricity only if window is closed thanks to a hidden contact.

Finally, the third step is up to a “frame assembler” who closes the window frame ensuring the inclusion of all components previously manufactured. A (0.5 by 0.5) m operable window was assembled, in order to check what modifications to the frame (drilling and milling) were necessary for the subsequent inclusion of the actuation system.

5. Development of the Full-scale Prototype

The phases of the production process, such as metalworking and assembly of glass, were carried out with the cooperation of local companies specialized in specific areas and identified through market analyses.

5.1 Glass Stratification

The components of the glass stratification are as follows:

- no. 2 glass panes, 50 x 50 cm, 6-mm-thick each, with liquid-repellent treatment;
- no. 1 float glass, 50 x 50 cm, 6-mm-thick;
- no. 4 anodized aluminum spacers for the 1.5-mm-

thick liquid cavity;

- no. 2 stainless steel conduits, 1-mm-thick, on top and bottom of the glass stratification, provided with a central hole and graft to allow the connection with the polyurethane pipes; the one at the bottom was provided with a double inner slope of 2%, made by pouring epoxy resin, to facilitate the outflow of the liquid during the draining of the cavity.

The production steps required first to produce the three glass panes, the two stainless steel conduits and two anodized aluminum spacers. Then, the realization of the dual-slope into the conduit by pouring epoxy resin, after checking the contact compatibility with the liquid used. Again, the construction of a traditional glazing consisting of two panes and the assembly of the third pane by means structural silicone and spacers. Finally, gluing of the steel conduits to the triple glass stratification using structural silicone was made.

5.2 Liquid Storage and Deployment

The necessary elements for the realization of the liquid storage and deployment system are as follows (Fig. 3):

- elastollan 1.0-mm-thick polyurethane pipes (1), \varnothing 6 mm and 0.65-mm-thick polyamide pipes, \varnothing 4 mm;
- no. 4 three-way taps (2) for medical use, to allow the system to be closed/emptied for transport/maintenance and no. 4 brass linear fittings with automatic clutch for 6 mm pipes, geared to connect pipes coming from the PVC tanks (5) with the hydraulic circuit.
- no. 2 brass T-fittings (3) with automatic clutch for 6 mm pipes, the lower one for the connection to the peristaltic pump (6) and the upper one acting as overflow;
- no. 1 brass silencer (4) for compressed air with porous bronze, grafted on a polyamide pipe, acting as a filter for ventilation;
- Loxeal 32 instant glue (ethyl-cyanoacrylate), used to connect polyamide pipes with three-way taps;
- plastic coated iron wire used to connect 4-mm-thick pipes to 6-mm-thick ones;
- shielding liquid [2].

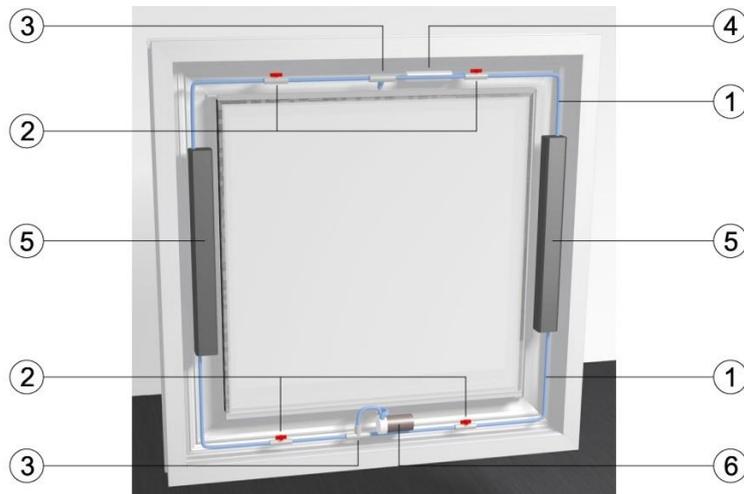


Fig. 3 Location of the system's components inside the window frame; (numbers are mentioned in the text).

For the proper operation of the device two tanks were used, connecting them to the peristaltic pump, using a T-fitting and two three-way taps. Other two taps and one T-fitting were inserted in the upper part of the circuit to connect the upper conduit with the two tanks, acting as overflow. Aeration provided for the system has the important and not negligible task to ensure that all the liquid flowing operations take place at atmospheric pressure, thus avoiding possible unwanted overpressures between glasses. The vent will be properly protected by a filter, made with a silencer for compressed air, to prevent the access of foreign matter into the system. The hydraulic circuit was realized by means of polyurethane pipes, \varnothing 6 mm, while polyamide pipes, \varnothing 4 mm, were used for the connection of pump and taps to the circuit. This flexible pipes allow accentuated bending, after heating, with considerable savings in space.

5.3 Electrical circuit

The 12V electrical circuit necessary for normal operation of the system, was achieved by a specific transformer connected to the activation control. Contact between the fixed frame and the mobile one occurs through a special spring contact allowing the operation when the window is closed.

5.4 Window Frame

The frame required some milling on the top and

bottom of the casing and the drilling of the mounting brackets to allow the passage of the tubes. All openings are designed to be closed by means of the frame rails commonly used for scrolling the closing boards activated by handle. In this way maintenance operations will be made possible simply sliding the covers. Tanks and connections between electrical parts, cables, pipes, taps, filter, fittings, pump were included in the frame and all the related links were run. Finally, glass stratification was inserted, the frame closed, handle mounted, pump wrapped with sound absorbing material and all the accessible openings were closed.

6. Laboratory Tests of the Prototype

6.1 Operation and Reversibility Tests

The test was prepared by placing the frame in a vertical position, the two tanks were filled with liquid, through the bottom taps, using a syringe and keeping the window open. Providing power to the circuit, the prototype was also submitted to some cycles in order to record the time required for filling and emptying. Using a 7.5V actuation, fluid takes 7 min to go up and 8 min to completely go down. If the pump operates at full power (12V), the time reduces to 3.10 min for filling (Fig. 4) and 3.45 min for emptying (Fig. 5). Even with reduced voltage, prototype shows filling and emptying times perfectly compatible with common dynamic shielding requirements.

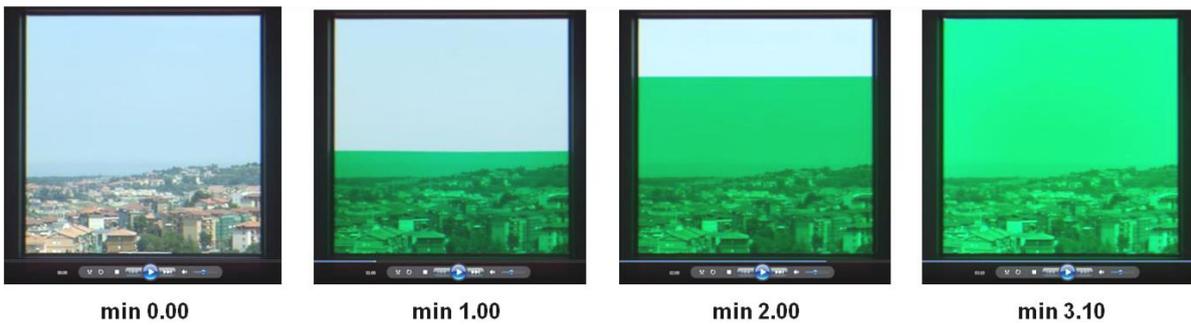


Fig. 4 Snapshots recorded during the filling in of the window's interlayer.

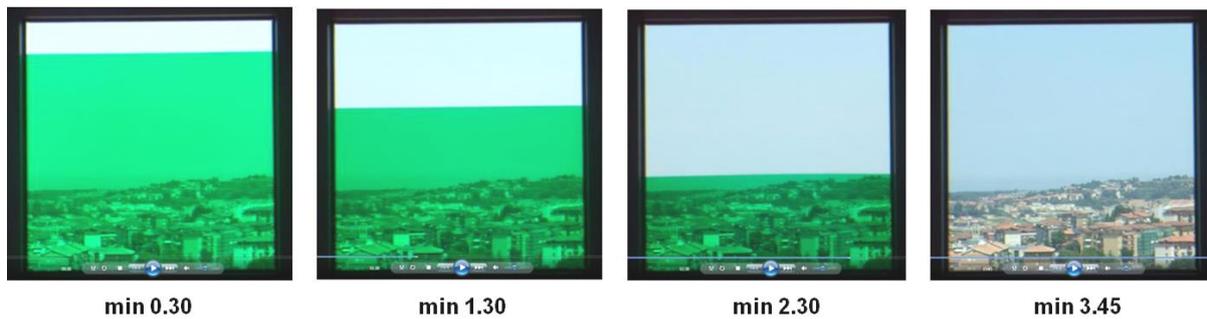


Fig. 5 Snapshots recorded during the emptying phase.

6.2 Glass Bending Tests

The pressure at a point, exerted by a fluid in static equilibrium, only depends on the height of that point and not on the horizontal dimension or characteristics of the container. As a consequence, it is extremely important to study the problem of hydrostatic pressure even considering the small cavity containing the liquid.

On previous tests on a 50 x 50 cm prototype, the maximum deflection value recorded was 1.54 mm, in correspondence of 22 cm ordinate point. Such deformation entails on the one hand a different gradation of colour due to the different thickness of the cavity, on the other hand an increase in the amount of liquid to be used, but especially it is not compatible for possible future use on larger structural facades of buildings.

The design solution tested in this research phase consists of impressing a negative strain on the glass panes, which may counteract the positive hydrostatic pressure. The idea is to use another pump to extract air from inside the air layer containing the liquid. In this way, the liquid, always introduced from below upwards,

will go up due to depression inside the cavity going to occupy the space left by the air. The prototype was equipped with both the pumping systems to be tested separately: the pump for liquid positioned below, connected with the tanks containing the liquid, and the pump for air extraction fixed on the top and connected with the upper conduit (Fig. 6). The test involved a sequence of cavity filling and emptying, taken alternately with both pumping systems. A 7.5V transformer was used for the pump operating with liquid, and a 3V transformer for the pump extracting air.

Measurements recorded during the deformability test, made by a dial gauge positioned at a height of 22 cm (maximum deflection point on previous tests) confirmed the effective positive deformation, i.e. outward, ($\delta = 0.83$ mm) produced on glass panes by the hydrostatic pressure of the liquid pumped inside the cavity (Fig. 6 left part). The glass fully recovered that deformation after the emptying phase, going back in rest condition ($\delta = 0.00$ mm) in a few minutes.

The air pumping system, instead, worked in depression and such air removal from cavity produced a negative deformation, i.e. inward, which is maximum

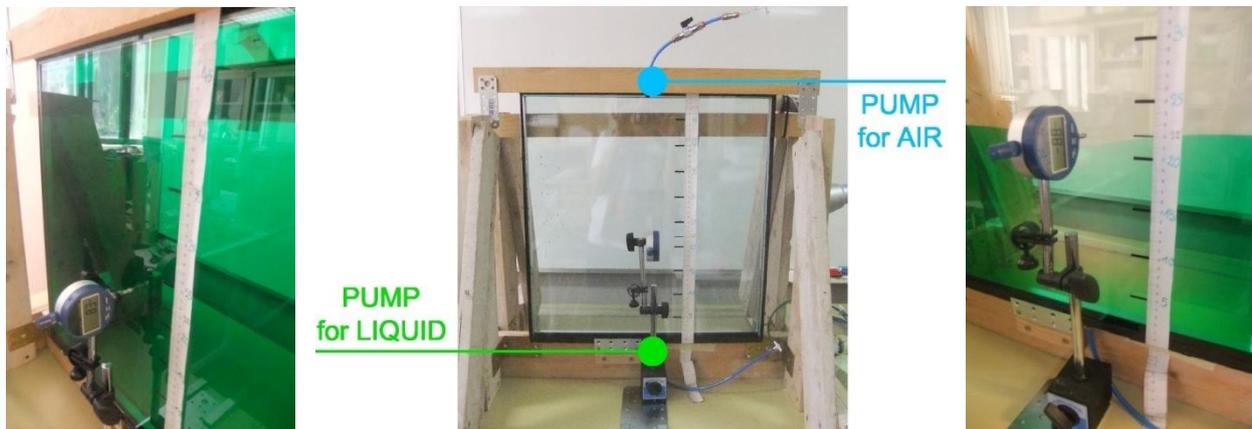


Fig. 6 Glass bending tests: maximum deformation $+0.83$ mm with cavity under pressure (on the left), maximum deformation -0.88 mm with cavity in depression (on the right).

when the sliding up liquid reached height 22 cm (position of the gauge), and then it kept constant until the complete filling of the cavity. This negative deformation value recorded ($\delta = -0.88$ mm) is therefore the peak value for the glass tested (Fig. 6 right part).

Hence, a possible solution to the excessive deformation problem may lie in an appropriate coupling of the two pumping systems. The two pumping systems tested separately, at the moment, have potentials to be installed together; so a control system might be able to set the two pumps combined work in pressure and depression on the liquid, so as to restore the equilibrium condition, with null deformation of the glass panes.

Alternatively, it is also feasible to imagine a system which provides a single pump working in depression, coupled to an electrovalve located near the bottom conduit. Depression should be generated, so as to fill even the upper conduit; once filled in, the glass cavity and the upper conduit, keeping the electrovalve close and reversing the pump action, it would be possible to regenerate the right pressure inside the cavity in order to restore liquid equilibrium condition.

7. Conclusions

Research carried out allowed to demonstrate technological feasibility of the liquid-shaded dynamic system which constitutes an effective and technologically

competitive response to the problem of protection from solar radiation, with the huge advantage due to lower production costs if compared with other dynamics shielding systems. The prototype design and construction of the novel dynamic window was developed resembling the industrial process. This approach allowed to define the guidelines for a future large-scale production.

Specific experimental tests were carried out in order to assess the glass pane bending when subject to hydrostatic pressure. The analysis of the data allowed to formulate possible hypotheses of solution to the problem of glass deformability, in fact preparing future developments.

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