TOWARDS AN ACTIVE, RESPONSIVE, AND SOLAR BUILDING ENVELOPE

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ABSTRACT

The key role of the building envelope in achieving building energy efficiency and indoor comfort for the user has been long established. The most promising—and innovative—strategy for the building envelope of the future is based on a dynamic, active and integrated solution, that is able to optimize the thermal performance, integrate the active elements and systems, and exploit energy from renewable sources.

This paper illustrates the most relevant results of a decade-long research activity carried out on active and integrated building envelopes at the Politecnico di Torino, in which numerical analyses and experimental campaigns, involving test cells and field monitoring, have been performed. The overall performances of different façade modules and the thermo-physical behaviour of various components, under different operating strategies, are presented and discussed. The analysis provides information on the contribution of each subsystem, e.g. glazing, sun-shading devices, natural and mechanical ventilation, . . . to the achieved energy efficiency and the overall performances of different typologies of Double-Skin Façades (DSFs) and Advanced Integrated Façades (AIFs).

KEYWORDS

double-skin façades, advanced integrated façades, adaptive building envelope, solar energy exploitation, sustainable architecture.

1. INTRODUCTION

Present-day façade technologies are the result of a long process that has taken place over thousands of years. However, a radical change in building envelope technologies occurred in the last century. From the Ancient times architecture to early Contemporary architecture times, people living in continental and temperate climates have often preferred massive wall constructions, where different tasks are performed by the building enclosure: thermal insulation, thermal energy storage, load transfer, etc. Over the centuries, the materials and construction details have changed and have been improved, but no radical innovations have occurred. However, at the beginning of the 20th century, Modernism theories led to a profound change in the form and technology of building enclosures, which involved the dissolution of massive envelopes. Thanks to the separation of the vertical load transfer from the other tasks of the building enclosure, it was possible to dissolve the massive wall into a light, glazed façade and to introduce the *curtain-wall*. As result, fully transparent building envelopes have become widespread realized since the fifties, and industrialized glass curtain-walls have become popular.

During the first decades of the Modernism era, architects and engineers were more interested in the formal aspects of the new architecture rather than in its energy performance and climatic behaviour, and they looked for an *International style* which totally ignored the local climate conditions and did not pay attention to the efficient use and management of the energy in buildings. As a result of this attitude, buildings usually suffered from unacceptable indoor comfort conditions (due to the high energy loss in winter, the excessive thermal gain in summer, the poor natural ventilation, and the visual discomfort caused by the absence of shading devices) and

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relevant energy consumption (related to the HVAC systems, which were necessary to provide suitable indoor conditions).

The consciousness of the environmental costs of construction, the evidences of the relationship between inefficient façades and energy consumption and some practical problems (e.g. the protection and maintenance of the external shading devices, the exploitation of natural ventilation in the case of high rise buildings) determined another step forward in the innovation of the building envelope. *Double-skin façades* (DSFs) were created by adding an external layer of glass and providing the façade with a certain *dynamicity*, which allowed the heat loss to be lowered in winter (thanks to the thermal buffer in the façade gap) and the thermal gain to be reduced in summer (because of the ventilated cavity). The dynamic envelope is not a new concept, since Le Corbusier invented *"mur neutralizant"* (1929), the first concept of a ventilated wall, composed of two membranes and a gap with a warm/cold air flow.

DSFs became very popular in the nineties (Oesterle, 2001; Compagno, 2002) and were usually associate with the high-tech architecture, because of their highly transparent look and structural expressionism. However, the advantages of this technology, with respect to a more "traditional" transparent façade with external shading devices, were often not very clear and the first DSFs sometimes presented relevant drawbacks (overheating risks, condensation risks, increased construction and maintenance costs) that far overcame the positive effects of a ventilated façade. Furthermore, the potential of this technology in terms of solar energy exploitation was often poorly exploited.

Advanced Integrated Façades (AIFs) (Annex 44, IEA) can be considered the natural evolution of the DSF concept and they represent the state of the art of innovative building envelope technologies. Thanks to the more complex integration between the building envelope and building services, AIFs enhance the dynamic features and active behaviour that were in part introduced by DSFs, and are a further step towards the development of a multifunctional building envelope, which will be able to continuously change characteristics and functions, in order to suit the occupants' demand and to reduce energy consumption. Mike Davies' *"polyvalent wall"* (1981) may be considered the basic (and first) concept of a building enclosure, where several incorporated functional layers are required to perform different tasks (e.g. sun and heat protection, energy flow regulation according to the needs and boundary conditions, exploitation of solar energy . . .). However, due to technological and economic aspects, *multi-functional façade modules* (MFMs) are not easily obtained and considerable research and development efforts are still necessary to reach sustainable solutions.

As previously mentioned, DSFs and AIFs have were adopted quite extensively over the last three decades, especially in "forefront buildings", which are considered examples of *green* or sustainable buildings. However, very little evidence of their advantages and disadvantages, compared to single façades (SFs) was available until the beginning of this century. In fact, the increasing interest in these technologies shown by architects and producers has lead to a considerable burst in research and development activities which started in the late nineties and are still in progress.

This work summarises the findings of a research activity, on active and integrated building envelopes, that has been carried out by the TEBE Research Group at the Politecnico di Torino. The activity was started in 2000 and different typologies of multilayer transparent building skins have been evaluated through experimental campaigns and numerical analysis. The aims of the research was to assess of the overall performances of the façade technologies and the thermo-physical behaviour of the various components, ant to optimize of each façade configuration. This research is not focused on the evaluation of the influence and contribution of multilayer transparent façade technologies on the overall building energy consumption, which is focused on the component level.

2. OVERVIEW OF THE RESEARCH ACTIVITIES AND METHODS

Over the last decade, different façade typologies have been tested under different boundary conditions. The analyzed façade typologies were:

1. *Double-skin façade* (see 3.1)
   a façade made of two glazed layers, separated by a naturally ventilated cavity (air flow path: outdoor air curtain; thermal buffer), with a shading device placed inside the façade cavity.
2. *Climate façade* (see 3.2)
   a façade made of two glazed layers, separated by a mechanically ventilated cavity (air flow path: indoor air curtain) connected to an HVAC system, with a venetian blind placed inside the façade cavity.
3. *Highly integrated façade* (see 3.3)
   a façade made of two glazed layers, separated by a mechanically ventilated cavity (air flow path: modified exhaust air) closely connected to an HVAC system and RES (ground coupling), with a roller blind placed in the façade cavity.
4. *Hybrid Ventilated DFS* (see 3.4)
   a façade made of two glazed layers, separated by a naturally and fan assisted ventilated cavity (air flow path: outdoor air curtain, supply air; thermal buffer), with a shading device placed in the façade cavity. This type of façade integrates different technologies to exploit RES (PV cells).

The experimental campaigns were performed in two different locations in Northern Italy (lat. 45° N). Both the locations are characterized by hot and humid summers and dry and cold winters.

TWINS (Testing Window INnovative System) is a test rig which is located in the Department of Energetics at the Politecnico di Torino and it has been developed to test responsive building envelope elements integrated with HVAC systems (Serra *et al.* 2010) (Fig. 1).

This test ring consists of two identical Test Cells, whose internal sizes were chosen in order to install a typical façade module for office buildings (internal sizes: 1.6 m wide, 3.6 m long and 2.5 m high (false ceiling)). One cell is used for reference purposes and adopts a single-skin façade (SF) made of double glazing (8/15/6 mm) with an external reflective pane and a clear internal pane; the other cell is designed for different DSFs and AIFs. The use of a reference test cell allows one to compare different configurations and to perform sensitivity analyses, even though the weather and boundary conditions are not exactly the same during the tests. The Test Cells are located on the roof of the laboratory in a position that prevents any shading problems. They can be rotated to change the façade orientation, but the experimental assessments on the DSFs and AIFs were all realized with the tested technology and the reference SF facing the south. A full air system, with a tolerance of 1°C, is used to control independently the indoor air temperature of the two Test Cells. During the experimental activity on the DSFs and AIFs, the temperature setpoint of both the Test

FIGURE 1. The TWINS facility.

Cells was fixed at 26°C in summer, 23°C in the mid-seasons and 20°C in winter.

As a general rule, the measurement apparatus usually has several sensors (e.g. thermocouples, heat flux meters, pyranometers…) connected to a data logger, in order to collect physical quantities related the thermal and fluid dynamics phenomena. The measurement chain (sensors coupled to the data logger acquisition channel) of each sensor was first calibrated and verified. Particular care was taken to reduce the influence of the direct solar radiation on the measurements of the temperatures and heat fluxes as much as possible (Corgnati *et al.* 2007, Kalyanova *et al.* 2007).

The thermal analysis of DSFs and AIFs is not an easy task since their performance, in terms of energy savings, cannot be evaluated using traditional ''static'' parameters (e.g. U-value, G-value). Dedicated parameters therefore need to be adopted, with the aim of describing the capability of the façade to pre-heat the ventilation air during the winter and the ability of the façade to remove part of the solar load during the summer. The hourly profiles of the heat fluxes and daily energies have also been considered. The performance of the façade, in terms of the thermal comfort, has primarily been evaluated through an analysis of the inner glazing surface temperature. Assessments of the PMV and the PMV* indexes have also been performed, but for the sake of brevity these analyses are not illustrated in this paper.

A detailed list of the main performance parameters and the physical quantities is presented hereafter.

- The "surface" heat fluxes $\dot{q}_{surf}$ (W/m^2) and the "total" heat fluxes $\dot{q}_{tot}$ (W/m^2) through the façade.

  The term "surface" indicates the heat flux exchanged at the indoor surface of the glazing with the indoor environment. It includes the convective heat flux and the long-wave radiative heat flux. The term "total" indicates the convective heat flux plus the long-wave radiative heat fluxes, plus the short-wave radiative heat fluxes $I_{s,t}$ (Eq. 1):

$$\dot{q}_{tot} = I_{s,t} + \dot{q}_{surf} \tag{1}$$

- The "daily" energy E_d (Wh/m^2) (Eq. 2):

$$E_d = \int_{08:00}^{20:00} \dot{q}_{tot}(\tau)d\tau \tag{2}$$

- The normalized "surface" heat fluxes ϕ_{surf} (-) (Eq. 3), the normalized "total" heat fluxes ϕ_{tot} (-) (Eq. 4) and the normalized daily energy Σ_d (-) (Eq. 5) through the façade (Perino *et al.* 2007).

$$\phi_{surf} = \frac{\dot{q}_{surf,faç} - \dot{q}_{surf,ref}}{\dot{q}_{surf,ref}} \tag{3}$$

$$\phi_{tot} = \frac{\dot{q}_{tot,faç} - \dot{q}_{tot,ref}}{\dot{q}_{tot,ref}} \tag{4}$$

$$\Sigma_d = \frac{E_{d,faç} - E_{d,ref}}{E_{d,ref}} \tag{5}$$

  The normalized parameters represent the normalization of the physical quantity ($\dot{q}_{surf}$, $\dot{q}_{tot}$, Σ_d) measured on the multilayer transparent façade compared to the corresponding physical quantity measured on the reference SF. The normalized parameters allow one to assess the improvement in the performance of the tested façade, compared to the performance of the conventional one. As a general rule, the multilayer transparent façade performs better than the reference one during the winter if ϕ_{surf}, ϕ_{tot}, $\Sigma_d > 0$, and during the summer if ϕ_{surf}, ϕ_{tot}, $\Sigma_d < 0$.
- The dynamic insulation efficiency ε (-) (Eq. 6), as defined by Corgnati *et al.* (2007).

$$\varepsilon = \frac{\dot{Q}_R}{\dot{Q}_{IN}} \tag{6}$$

  This represents the amount of the total thermal load that heats the façade $\dot{Q}_R$ which is removed by the ventilation air, with respect the total heat flux $\dot{Q}_{IN}$, through the external glazed pane of the double-skin façade. The dynamic insulation efficiency is therefore a parameter that represents the performance of the ventilated façade during summer and the mid-seasons, when the HVAC system is in cooling mode.
- The pre-heating efficiency η (-) (Eq. 7), as defined by Di Maio and van Passen (2001), where T_{exh} is the temperature of the air extracted

from the façade, T_{inlet} is the temperature of the air entering the façade, T_i is the temperature of the indoor air and T_o is the temperature of the outdoor air.

$$\eta = \frac{T_{exh} - T_{inlet}}{T_i - T_o} \tag{7}$$

This represents the ratio between the enthalpy flux related to the air flowing in the gap and the enthalpy flux required to pre-heat the ventilation air, if a heat recovery is adopted. The pre-heating efficiency is therefore a parameter that represents the performance of the façade in winter and in the mid-seasons, when the HVAC system is in heating mode and $T_i > T_o$. When $\eta > 1$, the façade is able to completely recover the ventilation losses; when $0 > \eta > 1$, the façade is able to partly pre-heat the ventilation air; when $\eta < 0$, the façade does not recover energy, but the air flow through the façade is cooled during the passage through the façade cavity ($T_{exh} < T_{inlet}$), with possible negative effects on the energy performance.

- the temperature and the normalized temperature θ_{gi} (-) (Eq. 8) of the surface of the inner glazing.

$$\theta_{gi} = \frac{T_{gi,faç} - T_{gi,ref}}{T_{gi,ref}} \tag{8}$$

The normalized temperature represents the normalization of the internal surface temperature of the tested multilayer transparent façade compared to the reference façade. The multilayer transparent façade performs better than the SF in winter and in the mid-season if $\theta_{gi} > 0$, and in summer, if $\theta_{gi} < 0$.

3. EXPERIMENTAL ACTIVITIES

3.1 Double-Skin Façade

The *Double-Skin Façade*, tested in the TWINS facility, was equipped with operable lamellas at the inlet and at the outlet openings of the ventilated cavity. It should be noted that, although the tested DSF adopted the same functional strategies as a "traditional" DSF (which first appeared in the seventies), its design and construction materials reflected the state of the art of the technology (i.e. low-e glass, high performance roller screens . . .).

From the construction point of view, the DSF (Fig. 2) was made up of:

- an external single clear glass (8 mm);
- a naturally ventilated air gap (260 mm wide) incorporating an aluminium venetian blind, with micro perforated lamellas, or a glass fibre + PVC roller blind, with a reflecting coating towards the outdoor environment;
- an internal double glazing (6/12/6 mm) with a low-e coating (emissivity $\varepsilon = 0.04$) and argon.

In winter, the DSF concept is based on the exploitation of solar energy to provide the façade with a thermal buffer. The air contained in the space between the glass layers is heated by the solar radiation which heats the shading devices contained in the cavity. Therefore, the façade behaves like an air solar collector, and increases the temperature of the air enclosed in the gap. The resulting "surface" heat flux entering the indoor environment through the

FIGURE 2. The DSF tested at the TWINS facility.

façade is always far higher that that of a single-skin façade. On the contrary, if an air flow is generated thorough the DSF cavity, the profile of the "surface" heat flux is very similar to that of the reference façade (Fig. 3a). The lower heat loss at night can be explained considering the high performance low-e DSF glass (the reference façade has a conventional double glazed unit). If the thermal buffer configuration is adopted, the surface temperature of the indoor glazing is also increased, with an almost 3°C higher peak value than the reference façade (Fig. 3c). This fact has a positive effect on the thermal comfort of the inhabitants, as it reduces the discomfort risk caused by radiant temperature asymmetry. If the façade gap of the DSF is ventilated, the positive effect does not occur, because of the higher energy loss and lower surface temperature.

In summer and the mid-seasons, when a stack driven ventilation occurs through the façade cavity, both the "surface" and the "total" heat fluxes are reduced, compared to a conventional single skin-façade (Fig. 3b). The temperature of the air and the shading devices contained in the façade gap may reach critical values (Fig. 3d) during the central hours of the day (more than 40°C and 50°C, respectively) and dedicated strategies must be adopted in order to avoid the risk of overheating (e.g. low-e glass, increased natural ventilation . . .).

DSF is a "simple" adaptive building envelope technology, which does not integrate with the HVAC. The critical issues of the design and implementation of such a technology mainly concern the adoption of high performance subsystems (glass and shading device) and an increase in the stack effect. Problems pertaining to overheating must be correctly addressed and carefully considered during the design phase.

3.2 Climate Façade

The *climate façade* typology was studied in two different experimental campaigns, one performed in-situ (Corgnati *et al.* 2007) and the other at the TWINS facility (Serra *et al.* 2010).

The in-situ façade monitored during actual operating conditions (Fig. 4), was a modular commercial system that consists of:

- an external clear double glazing (8/16/6 mm);
- a ventilated air gap (140 mm width) containing an aluminium venetian blind;
- an internal clear single glazing (8 mm).

The façade monitored at the TWINS facility was made up of:

- an external clear double glazing (8/15/6 mm);
- a ventilated air gap (148 mm width) containing a venetian blind with micro-perforated aluminium lamellas or a PVC reflective roller screen;
- an internal clear single glazing (6 mm) with low-e coating on the external side.

FIGURE 3. Double-skin façade—*(a)* "surface" heat fluxes in winter conditions; *(b)* "total" heat fluxes in summer conditions; *(c)* surface temperatures of the inner glass in winter; *(d)* temperature profiles with different shading devices in summer conditions.

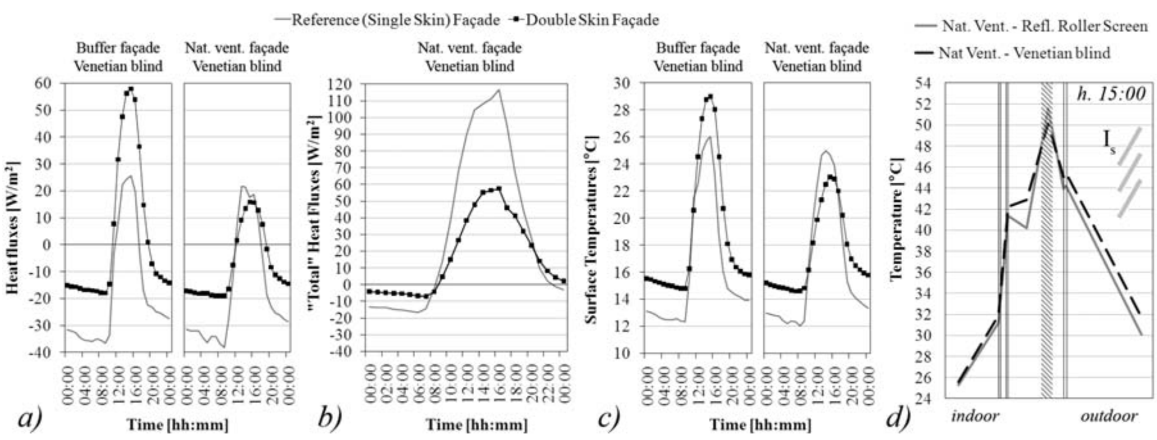


FIGURE 4. The *Climate Façade* tested in-situ.

This climate façade, which operates as an exhaust for the ventilation air, can be considered as a part of the HVAC system. The air coming from the indoor environment flows in the façade cavity, which is mechanically ventilated. The exploitation of the solar radiation is obtained from the interaction between the solar shield, which adsorbs most of the irradiance, and the air flowing in the cavity, which is heated by the solar shield. During winter, this creates a warm dynamic buffer between the indoor environment and outdoors. The heat flux absorbed by the air can also be used, through a heat recovery unit, to pre-heat the outdoor ventilation air flow (Fig. 5b).

In winter and on sunny days, the presence of the warm buffer results in a "surface" heat flux entering the indoor environment. The air flow and the "surface" heat gains are inversely proportional: an increase in the air flow leads to a reduction in the entering heat flux (Fig. 6a). The dynamic buffer also affects the temperature of the inner glazing: the temperature is always higher in a climate façade compared to a single-skin façade. The surface temperatures are also negatively influenced by an increase in the air flow: an higher flow rate makes the performance of the façade worse. Because of the close connection between the façade and the HVAC system (the façade acts as an exhaust for the ventilation air), a balance need to be found between the ventilation requirements and the thermal comfort requirements.

As for the heat fluxes, also for the temperatures a higher air flow rate worsens the performance of the façade, and, therefore, in winter conditions its value must be set according to the needs for ventilation purposes (Serra et al., 2010). The pre-heating efficiency (Fig. 7b) shows that the façade cools the air

FIGURE 5. Operating strategy of the climate façade—*(a)* summer and the mid-seasons; *(b)* winter.

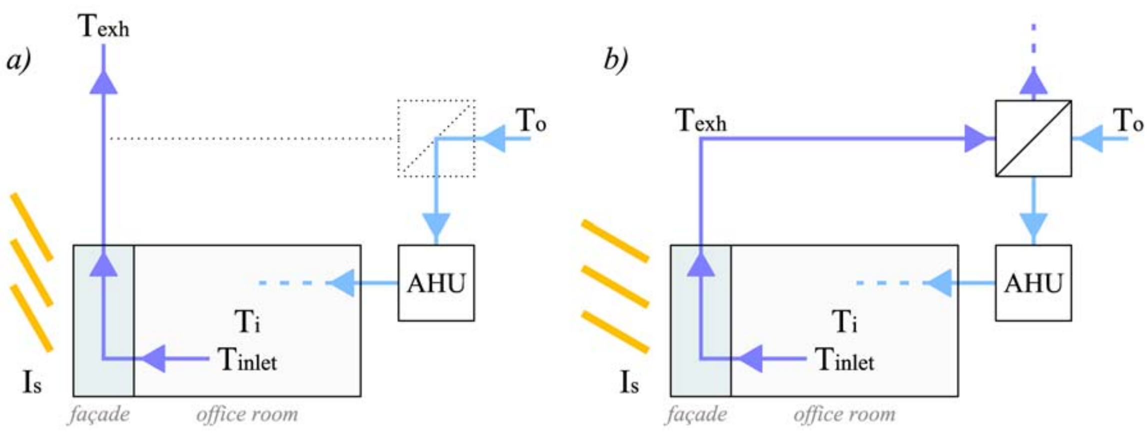


FIGURE 6. Climate façade—*(a)* “long wave” heat fluxes in winter conditions, configuration with venetian blind, and different air flow rates; *(b)* normalized surface temperature of the inner glass in summer conditions, configuration at 56 m^3/h with different shading devices.

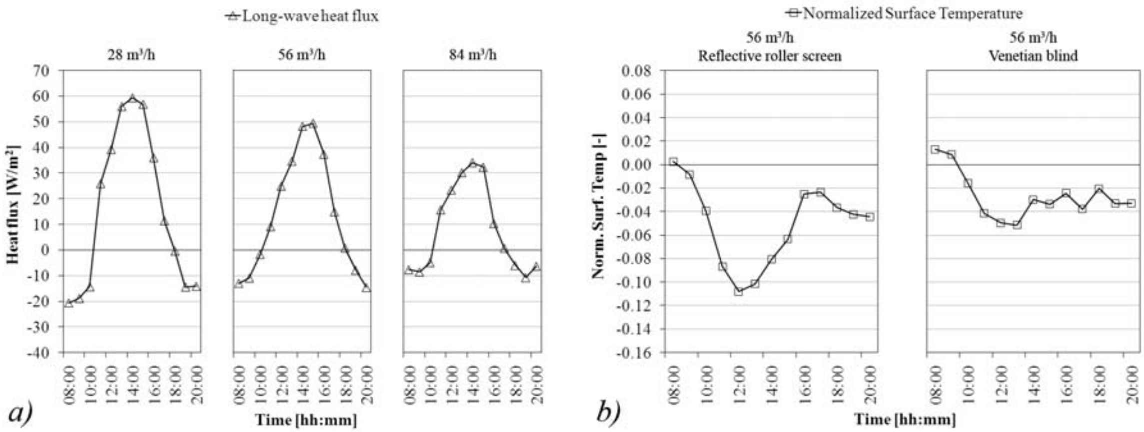
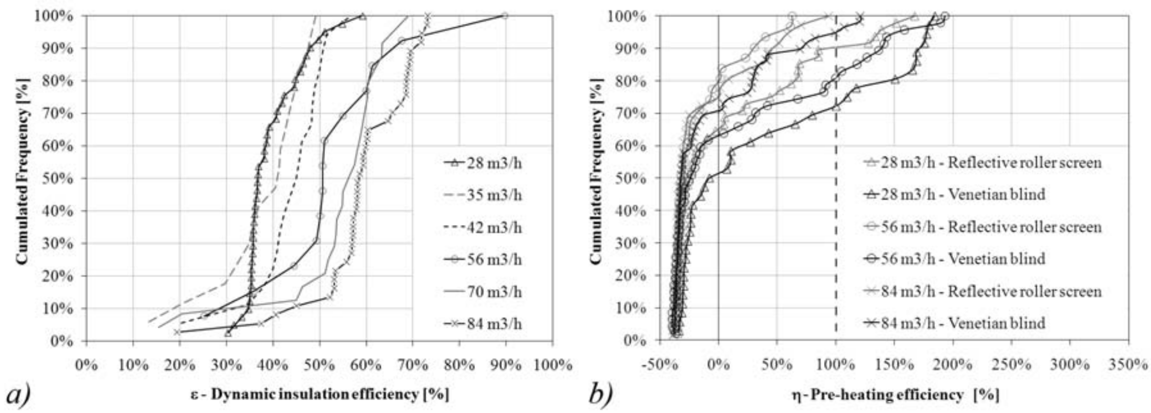


FIGURE 7. Climate façade—*(a)* dynamic insulation efficiency in summer conditions at different air flow rates; *(b)* pre-heating efficiency in winter conditions at different air flow rates and with different shading devices.



flowing through the gap, instead of heating it, for at least 50% of the operative time. This means that an energy efficient use of the façade as air solar collector is possible, but it is important to control the temperature of the air exhausted by the façade, and to decide whether to use it in combination with a heat exchanger. A shading device with a high solar absorption (an aluminum venetian blind instead of a PVC reflecting roller screen), provides a higher pre-heating efficiency, as well as a lower air flow rate.

In summer conditions, the aim of the climate façade is to collect most of the solar radiation in the ventilated cavity, and to remove a part of this heat load through the exhaust air, which by-passes the heat recovery system and is discharged directly into the outdoor environment (Fig. 5a).

The ability of the façade to remove part of the solar loads is represented by the dynamic insulation efficiency (Fig. 7a). It increases with the air flow: if the air flow rate varies from 28 m^3/h to 84 m^3/h, the reduction in the entering load varies from 37% to 58%, for at least 50% of the time. The corresponding dynamic insulation efficiency is proportional for intermediate air flow rate values. The adoption of a continuous reflecting shading device (a PVC reflecting roller screen instead of an aluminum venetian blind) affects the fluid dynamics phenomena that occur in the cavity, and improves the performance of the façade. With the same boundary conditions, the energy heat loads entering through the climate façade are about 37–46% lower than those entering through a single skin façade, depending on the configuration adopted for the climate.

A possible problem related to this typology is the overheating of the cavity, which in fact leads to a possible overheating of the inner glass and to radiant asymmetry problems. In the presence of high solar radiation, the inner glass temperature reaches values of up to 39°C. These values can create discomfort for the occupants. The performance of the climate façade is still better than that provided by the SF (Fig. 6b), and there is a reduction in the temperature values of between 2% and 10%. A higher reduction, and therefore a better performance, is obtained at high air flow rates while adopting a continuous and less absorbing shading device (a PVC reflecting roller screen instead of an aluminum venetian blind).

3.3 Highly Integrated Façade

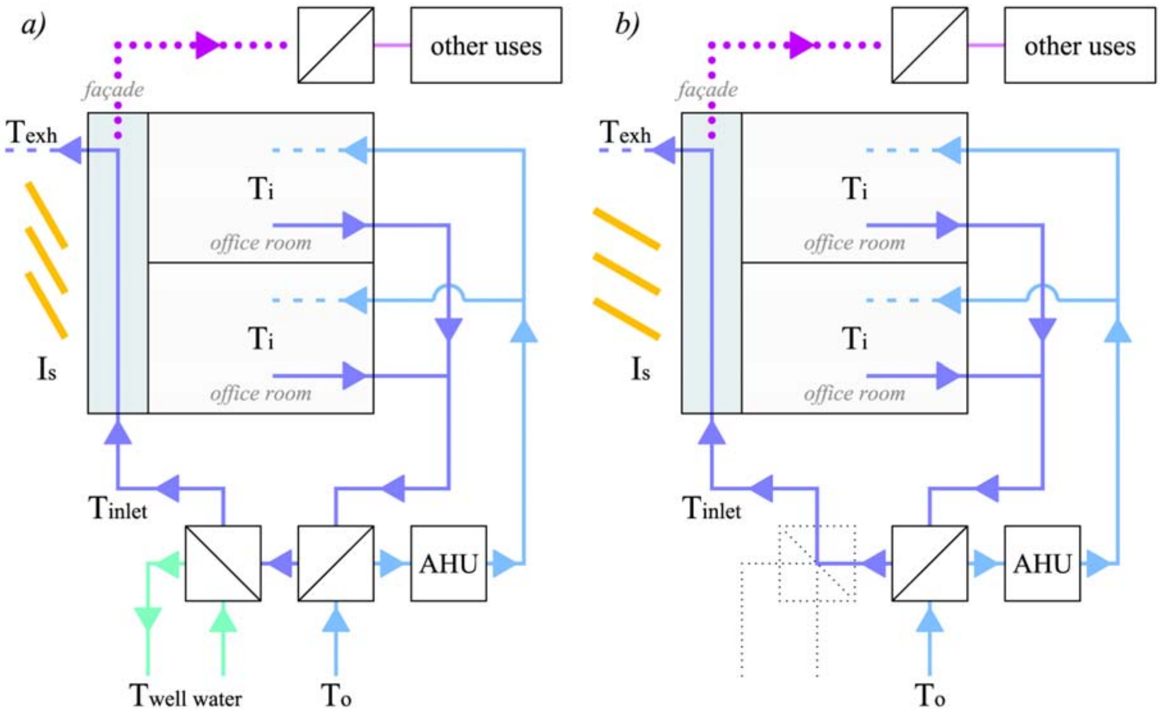
A façade with a higher integration with the building services (called *Highly Integrated Façade*) has been monitored in-situ. The monitored component was a two storey façade (8 m high), composed of 9 adjacent glazed modules for a total width of about 17 m; the monitoring concerned one module and was conducted all along its height (Fig. 8). The layer structure of the façade module was:

- an external single glazing (12 mm);
- a ventilated air gap (714 mm width) with a reflective roller blind, positioned at 112 mm from the outer glazing;
- an internal double extra clear glazing (5+5/15/8 mm) filled with argon, with a low-e coating and a PVB layer (which also contributes to acoustic insulation).

Exploitation of the solar radiation is similar to that of climate façades: the ventilation cavity functions as a solar collector, creating a dynamic warm buffer in winter and removing part of the solar loads in summer. In this case, however, the façade is not a direct exhaust for the ventilation air: the exhaust air from the indoor environment is sent to a heat exchanger (air-air) to pre-heat (in winter) or to pre-cool (in summer) the fresh air. In winter (Fig. 9b), the air is then sent to the plenum placed in the lower part of the façade. The air, after flowing along the façade, is extracted in the upper part of the cavity and is exhausted outdoors. In summer and in the mid-seasons (Fig. 9a), a second heat exchanger (air-water) can be activated and the air is pre-cooled before it enters the ventilated cavity of the façade. The suitable heat exchanger makes use of well water, at 14°C. This heat exchange can be activated when

FIGURE 8. The *Highly Integrated Façade.*

FIGURE 9. Operating strategy of the highly integrated façade—*(a)* summer and the mid-seasons; *(b)* winter season.

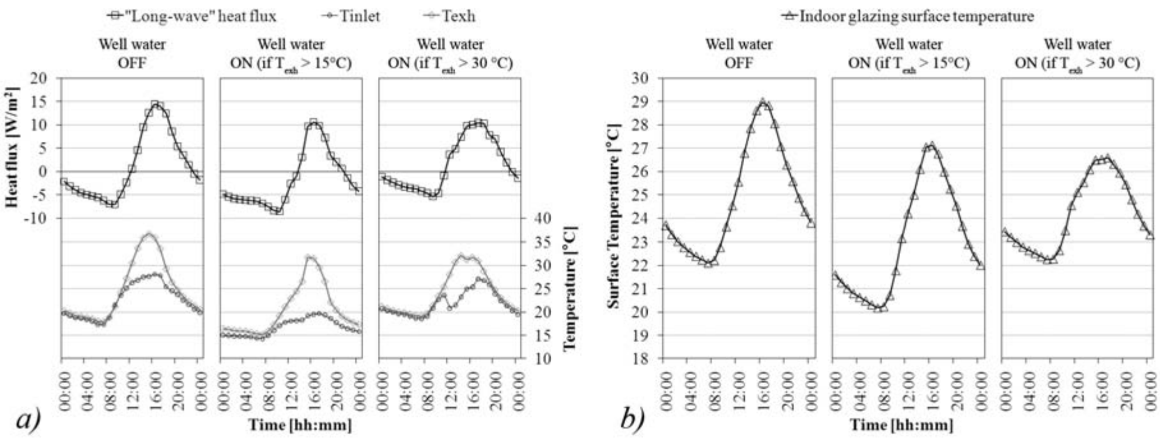


the temperature of the air at the façade exhaust exceeds a value that is set according to the season. The air exhausted in the upper part of the façade, in each operational strategy, could potentially be sent to an additional heat exchanger to exploit the related enthalpy flux.

The façade shows a good thermal and comfort performance compared to a single-skin façade, with lower heat losses in winter and lower cooling loads in summer. This good performance is related to the high performance level of the various components (low-e double glazing, roller screen with a low-e coating) of the façade, to the air flow in the cavity and, in summer, to its ability to lower the temperature of the air entering the ventilated cavity. The highly integrated façade has a lower warm dynamics buffer in winter and less ability to remove part of the solar loads in summer, compared to the climate façade (as the heat recovery occurs before the air enters the ventilated cavity). In these cases, the façade presents very good behaviour, and the overall energy performance of the HVAC-façade integrated system seems to be better than that of the climate façade.

The integration between the façade and the well water cooling system leads to lower temperature values in the ventilated cavity, and this increases the ability of the façade to remove part of the solar loads. In mid-season conditions, the pre-cooling effect is useful to lower the cooling loads that enter in the afternoon. However, if it is activated during the morning hours, it may increase the heat losses (Fig. 10a). A correct choice of the control temperature value is therefore essential, and a set-point value of 25°C (similar to the indoor air temperature) has proved to be a good compromise. In summer conditions, pre-cooling lowers the temperature of the air flowing in the gap by about 5°C, and this allows the "surface" and the total cooling loads entering the indoor environment to be reduced by about 19% and 6%, respectively. Interaction with the well water, in summer conditions, is therefore always advisable during the daytime.

FIGURE 10. Highly integrated façade, mid-seasons conditions—*(a)* "surface" heat fluxes, inlet and exhaust temperature; *(b)* temperature of the inner glass surface.



As far as thermal comfort issues are concerned, the high performance level of the components leads to temperatures of the inner glazing that are higher than 16°C in winter and lower than 30°C in summer, even when the pre-cooling system is not activated: these values do not cause any possible risk of discomfort due to radiant asymmetry. The effect of the activation of the well water is to lower the glazing temperature (to 1.5°C in summer and 2.5°C in the mid-season), and to further improve the performance of the façade (Fig. 10, Tab. 1).

When considering the Highly Integrated Façade, it is probably more appropriate to evaluate the performance of the complex system that is represented by the façade and the HVAC system, rather than the performance of the façade itself. This system is potentially very efficient and can provide good performances, but a very good and precise regulation of each part of the system is essential for its good functioning, and an error in the regulation may cause undesirable effects.

TABLE 1. "Surface", total daily cooling loads and peak temperatures of the inner glass in summer conditions.

Configuration	"Surface" cooling loads [Wh/m²]	*Total cooling loads* [Wh/m²]	*Peak temperature of the inner glass* [°C]
Pre-cooling at 25°C	87	254	29.3
No pre-cooling	107	271	28.5

3.4 Hybrid Ventilated Double-Skin Façade

The experimental campaign on the so-called *Hybrid Ventilated DSF* (Fig. 11) was performed using the TWINS apparatus and the performances of the façade were compared with those of a traditional SF (Serra *et al.* 2009).

The façade module was made up of:

- an external single clear glass (8 mm);
- a fan-assisted ventilated air gap (260 mm width) containing an aluminium venetian blind, with micro perforated lamellas or a glass fibre + PVC roller blind, with a reflecting coating towards the outdoor environment;
- an internal double glazing (6/12/6 mm) with a low-e coating (emissivity $\varepsilon = 0.04$) and argon.

In a similar manner to a "traditional" DSF, the HV-DSF operates as an outdoor air curtain in the summer season in order to reduce the cooling loads. An integrated PV panel powers up to 6 fans, which enhance the ventilation through the façade cavity (Fig. 12a). In the winter season, a thermal buffer is

FIGURE 11. The *Hybrid Ventilated DSF*.

obtained, in the façade gap, by exploiting solar radiation (Fig. 12b). In winter and the mid-season, the HV-DSF can perform as a supply-air façade, exploiting solar radiation to pre-heat the fresh air which is directly released into the indoor environment (12c). In these conditions, the HV-DSF can be considered as a façade that is partially integrated with the building services.

In winter and with the thermal buffer configuration, the behaviour of the HV-DSF is comparable with that of the tested DSF, with an increased "surface" heat flux and energy entering the indoor environment, as well as a more comfortable surface temperature of the inner glazing. Considering the supply-air configuration, it is important to investigate the ability of the HV-DSF to heat the air that flows in the cavity and which is subsequently released to the indoor environment. The façade is able to heat the air flow for almost 100% of the time (despite the fact that days with both high and low solar radiation were used to evaluate the pre-heating efficiency). Regardless of what shading devices is adopted (venetian blind or roller screen), a value $\eta > 1$ is obtained for long periods (35–40% of the time), which means that the façade is able to heat the incoming fresh air to a higher temperature than the indoor air temperature. Therefore, in these conditions, the heat loss due to the natural ventilation of the indoor environment is fully compensated.

As far as the summer behaviour is concerned, the performance of the HV-DSF was compared with a conventional single-skin façade, a DSF, and with a climate façade. It is possible to notice that, compared to the DSF, the obtained hybrid (fan assisted) ventilation (directly coupling the fans with the PV panels placed on the façade itself) is capable of reducing the "surface" heat flux through the façade

FIGURE 12. Operating strategy of the hybrid ventilated DSF—*(a)* summer season; *(b)* winter season; *(c)* air supply in the winter and mid-seasons.

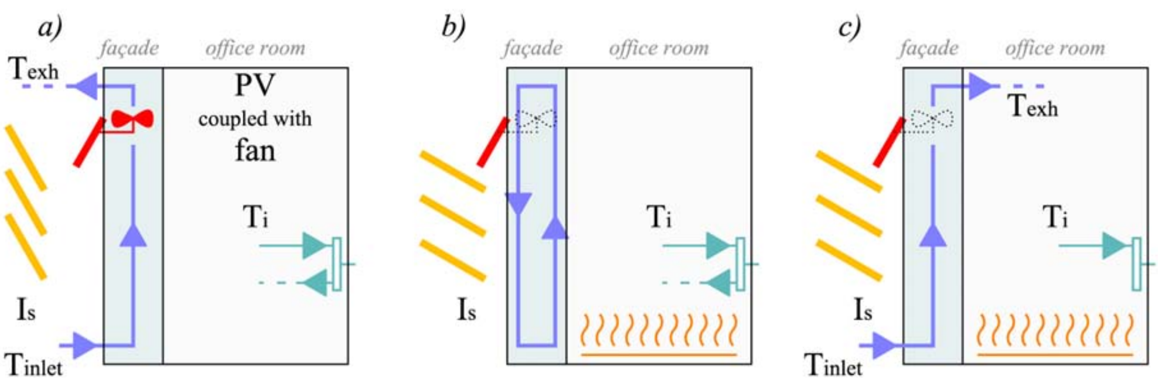
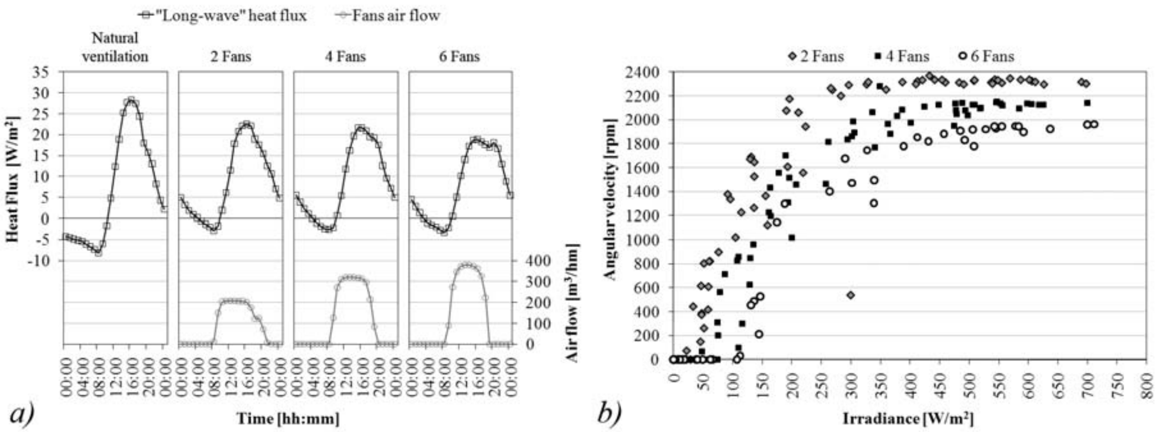


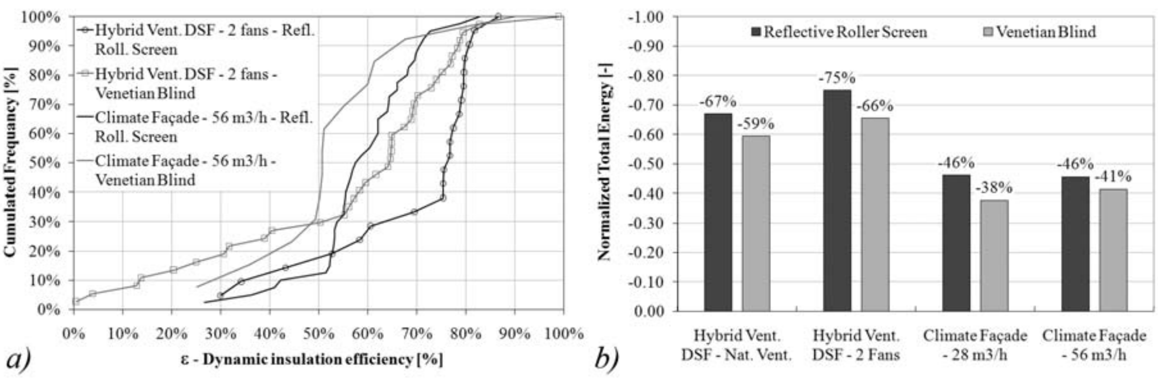
FIGURE 13. Hybrid ventilated DSF—*(a)* "surface" heat fluxes with different ventilation strategies, in summer conditions; *(b)* relationship between the angular velocity of the fans and irradiance.



(Fig. 13a). The configuration with two operating fans seems to be the most promising, as the addition of other fans (4 or 6) does not produce any relevant improvement. The relationship between the angular velocity of the fan and the irradiance on the façade is presented in Fig. 13b. It can be noticed that the fans are usually activated when the solar irradiance is above 70 W/m^2.

In order to evaluate the energy efficiency of the façade in the summer season, the dynamic insulation efficiency of the HV-DSF was compared with that of the climate façade. The HV-DSF is able, thanks to the air flow, to remove more than 75% (if equipped with a reflective roller screen) and 60% (if equipped with a venetian blind) of the "total heat" flux reaching the façade, for more than the 60% of the time (Fig. 14a). When considering the normalized total daily energy (Fig. 14b), it can be noticed that the HV-DSF with 2 fans reduces the energy gain to about one-quarter that of a conventional single-skin façade. Moreover, it is more efficient than the DSF (total energy gain of about –10%) and than the climate façade (total energy gain of about –60%). It should be pointed out that, while the better performance than the DSF can be explained above all considering the increased ventilation, the comparison with the climate façade is affected to a great extent by the technologies of the two façades

FIGURE 14. Hybrid ventilated DSF and climate façade, in summer conditions—*(a)* dynamic insulation efficiency; *(b)* normalized total daily energy.



(different glazed layers and positions, different integrations with the HVAC system . . .).

The HV-DSF is slightly more complex than a conventional DSF, and it allows a certain integration with the building services. Moreover, the incorporation of a technology (PV panel) to directly convert the solar energy allows the façade to be provided with a certain electric power which can be used directly by the façade itself. In this configuration, the power is used to increase the ventilation during the hot season, thus reducing the risk of overheating (which may occur in a conventional DSF) and increasing the efficiency of the façade to remove potential cooling loads.

4. FURTHER DEVELOPMENT: THE ACTRESS FAÇADE CONCEPT

Starting from first-hand experience and a literature survey, a new façade module has been conceived, named *ActResS*—Active, Responsive and Solar—*façade module*. The weak spots of current AIF were considered during the design phase, in order to develop a new module which may represent a step forward in the field of adaptive and dynamic building envelopes. Among others, the following critical issues were considered:

- the poor thermal inertia of the current lightweight and transparent façades, which negatively influences the passive control of the heat fluxes that cross the façades;
- the disproportion between the transparent and the opaque surface in AIF, which affects the behaviour of the façades to a great extent (e.g. glazing still presents lower thermal resistance than opaque materials).
- the possibility of incorporating technologies (PV and solar panels) to increase the direct exploitation of solar energy.

4.1 Module design

Unlike the "traditional" DSF and AIF configurations, the façade module presents a balance (50-50) between the transparent and the opaque surface (which is not usual in DSFs) in order to increase the heat capacity of the building envelope and to reduce the heat loss due to the low thermal resistance of the glazed layers. The non-transparent sub-module performs like an Opaque Ventilated Façade (OVF), with fan-forced ventilation. Moreover, the opaque surface allows PV devices to be incorporated for direct solar energy conversion. A highly insulating VIP layer is placed behind the cavity, and this is coupled to a PCM panel (facing the indoor environment), in order to store the thermal energy and moderate the indoor microclimate. The transparent submodel is similar to a conventional single skin-façade: it is made up of a triple glazed unit with low-e coating (indoor). A high reflective, low-e coated venetian blinds is placed in the outer cavity of the glazing, to control the solar and light transmission.

4.2 Functional strategies

As far as the natural and forced ventilation is concerned, the prototype allows the potential of the façade module to be tested adopting different functional strategies (e.g. exhaust air façade, supply air façade, outdoor air curtain . . .), which correspond to different integration levels with HVAC systems. Among others, the following functional strategies will be evaluated through experimental analysis.

- In summer, the ActResS module is expected to work as an outdoor air curtain façade or as an exhaust air façade. After the air is heated inside the cavity, it is released into the outdoor environment or into a duct for further use (e.g. heat exchanger…).
- In winter, the ActResS module is expected to work as a supply air façade or to provide a thermal buffer to reduce heat losses. Different configurations may be also tested (e.g. exhaust air façade, coupled to a centralized heat recovery device).

As far as the direct conversion of solar energy thorough the PV panel is concerned, the following behaviour is expected.

- In summer, the PV panel provides power to activate the ventilation fans and to control the shading devices (which have both a direct relationship with the amount of solar radiation); the extra current is released to the electric system.
- In winter, the current generated by the PV panel is expected to heat a PCM layer, contained in the OVF sub-module, by means of a heated carpet.

4.3 Experimental test rig and future plans for the measurement campaign

An experimental campaign has been planned at the Department of Energetics—Politecnico di Torino, in order to assess the potentials of the ActResS façade module. The prototype, which is currently under construction, will be tested using the TWINS test cell apparatus. The themo-physical behaviour, the energy efficiency and the thermal and visual comfort performances of the ActResS module will be compared to a conventional single-skin façade (placed on the reference test cell) by means of the continuous measurement of the transmitted irradiances, heat fluxes and temperatures for both the façades. The experimental campaign is planned to start in Winter 2010.

5. CONCLUSIONS

Although the dynamic and active building envelope concept has long been established, the research and innovation necessary to obtain a polyvalent and multifunctional building skin, still require considerable efforts. The technological evolution of multilayer transparent building skins may represent a possible pass towards the multifunctional façade concept. The lessons learned from both first-hand experience and from a literature review allow to assess the influence of each subsystem and the role of the integration strategies between the building skin and the building services, in order to achieve the best performance, both in terms of energy efficiency and indoor environmental comfort.

Considerable improvements have been made since the first DSF appeared, both concerning the subsystem components and the interaction between these elements. Such improvements have lead to an increase in the performances of the transparent dynamic façades, but few innovations have appeared as far as the functional strategies are concerned. A greater exploitation of solar energy (direct conversion via PV devices) represents an interesting perspective, which may allow the efficiency of the façade to be increased and new building skin concepts to be explored, on the basis of the direct use of electrical power within the façade itself.

The negative aspects of AIF also need to be considered to improve these building skins. "Conventional" AIFs are usually conceived for worldwide applications, while different climatic regions require individual and dedicated solutions, based on local climate conditions. The poor thermal inertia of AIFs is a clear example of this attitude. High thermal inertia is a crucial feature for building envelopes in warm and hot climates and reduces the energy efficiency of these technologies in Mediterranean and Tropical regions. However AIFs designed for buildings located in those climates show as poor thermal inertia as that designed for continental climates.

Integration between AIFs and the building services is probably the hottest topic in the field of dynamic skins. Several experiences have revealed that a fusion between the building services and the active building enclosure can enhance the features and the efficiency of the responsive building envelope. However, the higher the façade integration with the HVAC system, the more complex the design, the construction and the management of the building. In this case, it is mandatory that the integrated façade is planned together with the environmental services: the façade can be considered as a part of the HVAC system or it can even be regarded as the link between the building and the mechanical plant. It should also be observed that an integration between the building skin and services can only be obtained when economy of scale is reached and especially for some building types, such as offices, retail buildings, hotels… A stand-alone façade, based on an advanced module, that integrates different functions, can instead be considered as a promising solution which would also be suitable for small-scale buildings.

Together with the research activity on highly integrated façades, a new investigation is about to start at the TEBE Research Group at the Politecnico di Torino. This investigation is based on a stand-alone façade technology. An innovative prototype (ActResS façade module) has been conceived as part of a national research project, with the aim of improving the current technology of active and dynamic building envelopes. The main features of the façade module concern, together with the responsive behaviour, an increase in the thermal inertia of the component, a reduction in the disproportion between transparent and opaque surfaces, and the exploitation of solar energy.

NOMENCLATURE

E_d	Wh/m^2	Transmitted daily energy (08:00—20:00)
ε	-	Dynamic insulation efficiency
ϕ_{surf}	-	Normalized surface heat flux
ϕ_{tot}	-	Normalized total heat flux
η	-	Pre-heating efficiency
I_s	W/m^2	Solar irradiance heating the façade
$I_{s,t}$	W/m^2	Transmitted solar irradiance
$\dot{q}_{surf}$	W/m^2	Surface heat flux
$\dot{q}_{tot}$	W/m^2	Total heat flux
$\dot{Q}_{IN}$	W/m^2	Total thermal load through the external glazed pane of a multi-layer façade
$\dot{Q}_R$	W/m^2	Thermal load removed by ventilation air
θ_{gi}	°C	Normalized surface temperature
Σ_d	-	Normalized daily energy
T_{exh}	°C	Temperature of the air extracted from the façade
T_{gi}	°C	Surface temperature of the inner glazing
T_i	°C	Temperature of the indoor air
T_{inlet}	°C	Temperature of the air entering from the façade
T_o	°C	Temperature of the outdoor air
τ	h	Time

Subscripts

faç	Tested multi-layer façade
ref	Reference single-skin façade

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