Applied innovation: Technological experiments on biomimetic façade systems and solar panels

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Abstract. The most advanced technological concepts aim to obtain an "organic" behaviour of the building envelope, which consequently becomes "dynamic" and variable because it is sensitive and self-adapting with respect to external environmental conditions. In this highly innovative context, solar shielding devices become important and, in some cases, they can be integrated with special types of glasses or with "active" components, such as solar panels. Instead, the orientation systems of solar devices, described below, use only the thermal expansion to self-regulate, combining the reduction of energy consumption with minimum environmental impact, without the aid of motors, computerised devices or external energy sources, overcoming some critical issues of the self-adaptive envelopes used to date.

Keywords: Façade systems; biomimetics; solar panels; thermal expansion; sunblind.

Introduction

The recent rapid evolution of the building envelope made it the undisputed protagonist of contemporary architecture. In this case, the idea was born from the observation of how nature, in the case of sunflowers, "solved" the problem with a progressive orientation towards the sun of the "corolla", exploiting the differential thermal expansion of another part of the plant, the fibres of the stem. In a similar way, the proposed self-adapting systems are able to modify the inclination of elements forming the external "skin" of the building envelope during the year without the aid of engines or solutions that require the use of external energy sources, exploiting only the force generated by natural thermal expansion. These systems are composed of two main parts: the expanding elements and the mechanisms of multiplication and transformation of movement. These are connected to the elements to be handled, according to the different possible applications. At the basis of the development of the technological systems, mathematical models have been developed to describe the temperature and, therefore, the expansion of the "expanding elements", according to the hourly climatic data. These models consider all the components that determine the heat exchange with the environment: conduction, convection and radiation. The mechanisms designed and tested can move both active and passive façade devices and solar panels on independent supports. The systems can be calibrated in order to optimise solar tracking (photovoltaic panels), or to allow the penetration of solar radiation in the colder periods of the year, and to reflect it in the summer period (in the case of sunblinds or system shielding integrated with air solar panels). The systems have been tested through a series of experiments related to the expanding elements and with the realisation of some prototypes. Four application proposals are illustrated. Three leverage a mono-axial actuator system (Warm Motion system, or WM), while another application consists of a passive biaxial solar tracker (Biomimic Solar Tracker - BST), which allows you to move individual solar panels located at the top of an independent structure. The research has already had significant recognition in regional and national Star Cups. The experimentations were completed on vertical elements by the research team of the DPIA of the University of Udine, as part of the international research project "Biomimic Solar Tracker. Eureka Eurostars, project 65103".

The WM mono-axial system, thermodynamic model, experimentations and prototypes

The attention of the research was focused on the development of a mono-axial solar tracker system composed of the following elements: a frame, the expanding elements, a movement multiplication system and the elements to be handled according to the different possible applications, i.e., photovoltaic panels, sunblind or shielding elements integrated into passive solar systems. The expanding elements act as the engine of the façade system. They are made up of elongated aluminium bars, easily available at a low cost, painted in black, a few metres long and with a flat section. The thermal variations become thermal deformations (a few mm), which are amplified by a movement multiplication mechanism, which transforms them into the rotation of elements to be moved (Fig. 1).

The expanding elements are exposed outdoors: the convective component is always present and tends to make the temperature of the elements the same as that of air, while the radiative component, due to solar radiation, varies with solar height, changing seasons and with the passing of the hours. The technological systems were developed based on a thermodynamic model capable of describing the temperature and, therefore, the expansion of the "dilating elements", according to the hourly climatic data. The equilibrium temperature of the dilating elements was calculated with a global balance of radiative and convective heat exchanges, referring to the surface unit. A first series of experiments concerned the horizontal arrangement of the dilating elements. To analyse their behaviour in relation to the atmospheric agents, a test bench was built on which three bars of the same size and with the same surface treatment were installed (Fig. 2). We used Aluminium bars Al_Mg_Si 6060 T6 "Anticorodal" section 50x2 mm. Each of these was thermally insulated from the frame by means of PVC rods and constrained at one end, remaining free to expand and withdraw, due to thermal action, on the other side. Throughout the course of a calendar year, the temperature variations of the bars and the deformation differences between the bench and bars were recorded by means of potentiometric transducers.

Application of the WM system in the "solar panel" mode

If the mono-axial system is designed according to the "solar panel" mode, the aim is to guarantee the orthogonality of the panel with respect to the direction of the sun rays. In the winter season, for

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example, starting from an initial vertical position (night position), a progressive increase in heat exchange with the environment causes the expansion of the dilating element, allowing the solar panel to rotate according to the height of the sun. It is possible to calibrate the mechanism so that it corresponds to the maximum temperature of the dilating elements in an almost horizontal position (zenith sun position-summer). In the event the sky remains cloudy, the radiative component will be lower, with a prevalence of diffuse radiation, and the temperature of the bar will be closer to the air temperature, still guaranteeing an effective rotation of the photovoltaic panel. In the experiments carried out with horizontal dilating elements (Fig. 2), the measured values were: the air temperature, the temperature of the bars and the differential deformation between the bars and the frame on which they were mounted. The theoretical model was confirmed by the results of the experiment. There were slight deviations in the maximum values of temperatures (higher values in reality than in the mathematical model), due to the fact that the measured values are instantaneous, while the model is based on average hourly values. The system is able to operate autonomously by orienting a surface towards the sun (Fig. 3). This shows the various positions taken by a small solar panel moved by the WM system during a typical day of the autumn season. In addition to the movement check, a comparison was also made in order to verify the production of electric current between three small photovoltaic panels. One of these was mounted on the WM system, while the others were set in a fixed position, with an inclination of 0° and 90° in relation to the horizontal plane. The production of electric current of a PV panel mounted on the WM system was greater than a fixed panel arranged vertically by 25% while, compared to a horizontal one, the increase was equal to 40%.

Application of the WM system in "solar shading" mode

According to the "solar shading" mode, the requirements to be satisfied are more complex, regarding both the lighting aspects and the thermal values. Two possible applications have been studied: an integrated system with air-powered solar panels or with ventilated façades, and a sunscreen system. In the first case, it is possible to design the mechanism in order to maximise winter energy supplies and to nearly cancel summer ones, making sure that the panel can be reached by solar energy in winter, while being shielded during the hottest periods. The "Daily" variability is not considered important, but rather a behaviour linked to the external air temperature. By shielding the vertical dilating elements from direct radiation, it can be considered, as a first approximation, that their temperature is equal to that of the air. This hypothesis allows, among other things, to consider the dilating elements, which are completely "integrated" into the façade, placed inside the support frames of façade systems. The essential geometric elements of the system (Fig. 4), are the angle of inclination of the slats (β) and the profile angle of the sun's rays (ω). The mechanism generates a rotation of the sunscreen blades through the exploitation of the difference in thermal expansion (ΔL) between the steel frame and the dilating elements, made up of aluminium sheets, with a length equal to the frame and tied in the lower part by a hinge. Their upper part is connected to a first level lever, with the fulcrum hinged to the frame and the opposite end linked to a connecting rod that controls the rotation of the slats. A façade system is created by a connection between the self-adapting device of mobile slats and air solar panels. This can transform the building envelope from a static element to a dynamic skin capable of self-adaptation and of varying its characteristics in order to guarantee internal comfort and reduce energy consumption. The system is applicable in new or existing buildings, in energy recovery-requalification processes. This allows the entry and exploitation of all solar radiation available in the winter months, and the almost complete reflection of the same during the summer months. It also allows to remove heat, during the summer months, by natural convection. The system consists of a set of pre-assembled modules essentially composed of the following layers: an external self-adaptive "skin" made up of adjustable venetian blinds and protected by a transparent glass surface; an air solar thermal collector (CSTA) integrated with a thermal storage system; an insulation panel placed in the rear; a ventilation device and interface with the environments to be conditioned. The function of the thermal storage integrated in the solar collectors is to stabilise the temperature peaks reached in the central hours of the day, at certain times of the year, to accumulate heat when it is available and to make it available to heating systems, when needed. The combination of the heat pump with the CSTA, therefore, reduces many of the disadvantages of each of the two technologies. In winter, in fact, the heat pump uses air at a higher temperature than it would take from the outside, increasing its COP. During the summer, the slats are arranged in such a way as to reflect the solar radiation almost completely, totally shielding the solar thermal panels with air. During the night the outside air, starting to cool off, is let in through the lower vent of the façade system. Concerning the application to the sunblinds, by selecting the cut-off angle as an operating parameter, and with a mechanism similar to the one previously described for air solar panels, the lighting requirements can be satisfied, but with excessive summer overheating. To allow external vision, while intercepting direct radiation, a considerable amount of radiation reflected inward is introduced. Paying more attention to the thermal aspects and leaving the user the possibility of installing other internal systems (e.g. curtain) to avoid any winter glare, the maximum and minimum temperatures were, instead, considered to carry out normal daily activities both in winter and in summer. It has been observed that for external temperatures below 18°C it is better to direct the sunblinds at the angle of solar incidence, in order to maximise direct transmittance for heating purposes. For temperatures above 18°C, in summer, it is advisable to tilt the shielding elements according to the orthogonal angle of incidence of the sun rays to stop them, while possibly also avoiding any inward reflections. For intermediate situations with respect to those just described, an intermediate regulation can be assumed, counting on the inward reflection in the colder periods and on partial shielding in the warmer ones.

The biomimic bi-axial system: features, experiments and prototypes

The system allows to amplify small deformations caused by the difference in thermal expansion of 3 vertical dilating elements, oriented differently in space (with an angle between them of 120°), which are subject to different thermal expansions generated by the motion of the sun. The BST system consists of four main elements (Fig. 5): the stem, the HRE (Heat Responsive Elements) dilating elements, the MTU (Motion Transmission Unit) and the support platform for the PV panels. The stem, made of a steel tube, supports the system and all elements are fixed onto it. The HRE dilating elements act as both sensors and actuators of the system. They consist of flat black aluminium bars arranged on three sides of the stem, hinged on it in the lower part and connected above the MTU. This consists of three articulated elements arranged at 120° between them and connected to the support platform by means of spherical joints. It transmits the weight of the PV panels in such a way that the stress is constantly tensile. When an HRE is irradiated by sun rays, it heats up. The amount of heating depends on the angle of incidence of the sun. The consequent thermal expansion modifies the tensional state of the system, causing it to reach a new equilibrium position, placing the solar panel orthogonally with respect to the sun's rays. Simplifying the description, the PV panel tilts towards the "hottest" bar (Fig. 5).

The inclination increases in relation to the temperature difference between the hottest and coldest bars. In addition, the system places the PV panels in a horizontal position when the three bars present the same temperature. This occurs in the following three cases: at night, in the case of overcast skies (where energy production is maximised because the diffused light mainly comes from the zenith), and in case of strong wind, when the panel is placed in a safe position to avoid the sailing effect. The system is totally passive, so it has zero energy consumption and does not require electricity from either external energy sources or from motors or sensors.

It has lower production costs than its competitors, and its maintenance costs are significantly reduced due to potentially usable elements.

Tests were carried out relating to the evaluation of the effects of surface treatments on the HRE and mechanical tests in the proximity of the south wall of the Official Laboratory Materials and Structural Testing (DPIA-UNIUD). Sixteen aluminium samples, with different surface treatments, were tested for the HRE. The samples were exposed externally on special supports and the sensors measured their surface temperatures, comparing them with the climatic data collected by a weather station installed nearby. The samples were arranged with different orientations. The experiment allowed to select the materials with the best characteristics as well as to verify the correspondence of the mathematical model with the experimental data. It has been verified that the model slightly underestimates the temperature values, compared to the real data (the differences are in the range of 6°-8°). These differences have been caused by the albedo coefficient of the surrounding areas, which may change depending on the effects of solar reflection either on adjacent walls or on other surfaces (for example parked cars). The temperature difference between the 3 bars arranged on east, south and west has been proven to be able to guarantee an optimal system operation. The experimental equipment related to the mechanical verification of the system (with reference to Fig. 6) consisted of a steel frame (C)

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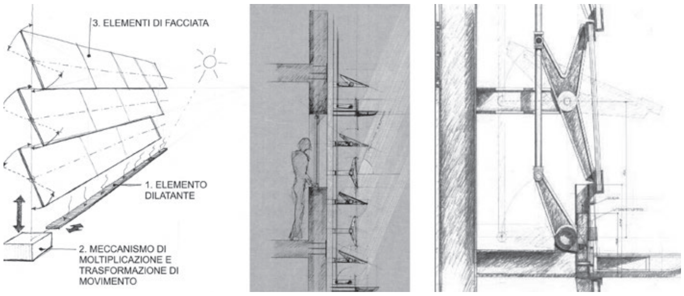

01 | On the left and centre: hypothesis of operation of the WM system applied to a generic façade. On the right: an example of axperimental apparatus.

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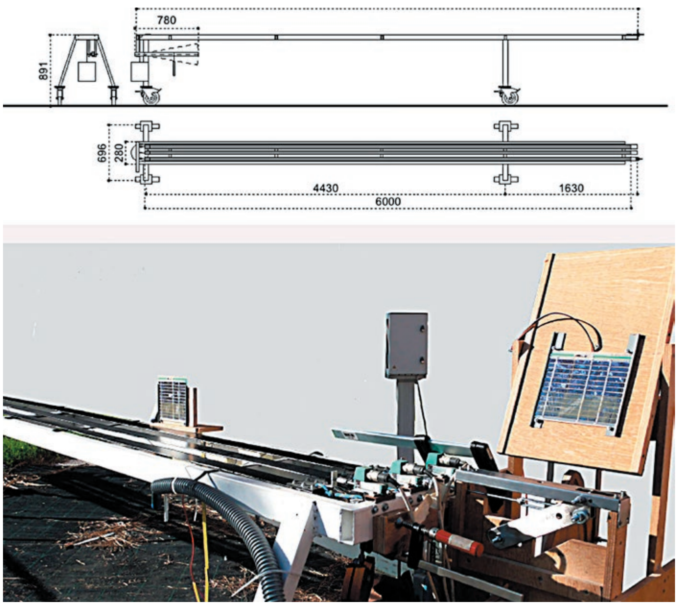

02 | Experiments with horizontal arrangement of the dilating elements. Above: diagram of the test bench. Below: prototype of the WM system and experimental apparatus.

03 | Left: photographic sequence of the various positions taken by the test photovoltaic solar panel during a day in October. Right, from above: theoretical trend of the temperature of the dilating elements in relation to the air temperature of a typical year; the measured trend of the temperature of the dilating element (bar in Fig. 2) in relation to the air temperature detected during the year of experimentation: the excellent quality correspondence is noted; comparison between the electricity production of a fixed photovoltaic panel, in horizontal and vertical position, and of the self-adapting panel

04 | On the left: geometrical diagram of the position of the adjustable slats and their inclination (β) in relation to the incoming and reflected radiation, and the angle of incidence profile of the solar radiation (ω). Right: geometrical diagram of the operation of the passive slat angle control mechanism

05 | Operating principles of the Biomimic system. In the upper part of the image on the left: the system; in the centre: relationship between the expansion of the dilating elements (HRE), the position of the sun and the position of the upper platform supporting the solar panel. Top right: detail of the transmission mechanism of the HRE movement to the platform. On the right, in the centre: temperature differences between the dilating elements (HRE) exposed to the east (blue) to the south (red) and to the west (green) with respect to the air temperature (purple). In the lower part of the image: example of the movement induced in the solar panel by dilation of the dilating elements (HRE)

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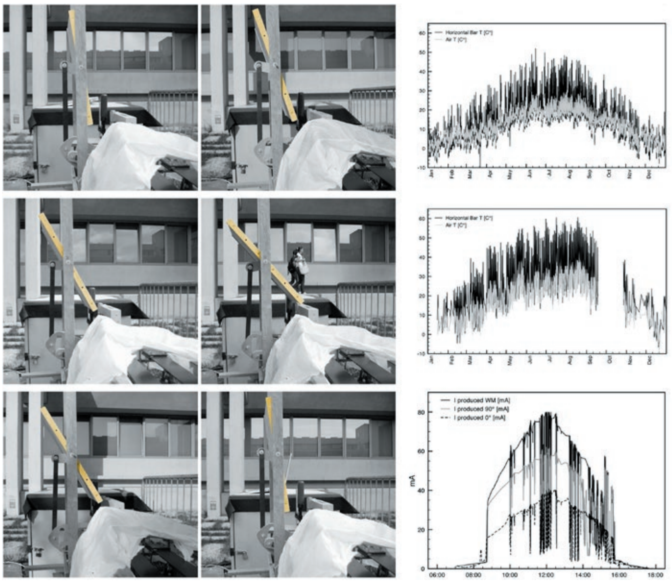

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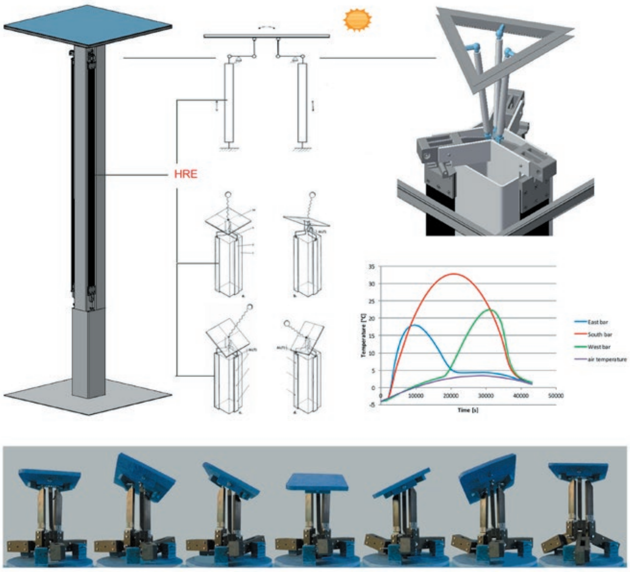

on which four HRE (D) (length equal to the real system) were fixed, subjected to different load conditions (E). For each HRE, the temperature and expansion were measured by potentiometric transducers. The weather station (A) compares the actual temperature of the bars with that theoretically calculated from external climatic data. In all cases, the angular movements of the mechanisms presented an almost perfect correspondence with the theoretical data, showing differences within an error margin of 2.5° (Fig. 7).

The effects of friction were addressed both theoretically and in the field of tests where the dissipative phenomena were mitigated by two different types of elements: the roller bearings with internal ring (mechanism C in Fig. 6) and the bushings self-lubricating and flanged composite material (mechanism D in Fig. 6). The "precision" of the system was assessed in the experiments: to what extent it always responds in the same way to similar conditions; the presence of relaxation phenomena due to the failure of the connections or the effects of friction. However, these settlements are relatively limited, as they are less than 0.6° of rotation over a month. There are no appreciable differences in behaviour between the two mechanisms mentioned above. It has occurred that the relaxation phenomena gradually decrease with time, after an initial period of settling. As far as the precision of the system is concerned, a higher dispersion in position measurements can be observed for temperature values equal to 30°C, compared to those relating to the position of the levers at 20°C.

Conclusions and possible developments

Since the results of the research have given positive feedback, after the experiments it was considered possible to create prototypes in order to monitor their operation and to verify and refine the mathematical model. In summary, possible future developments may be: optimi-

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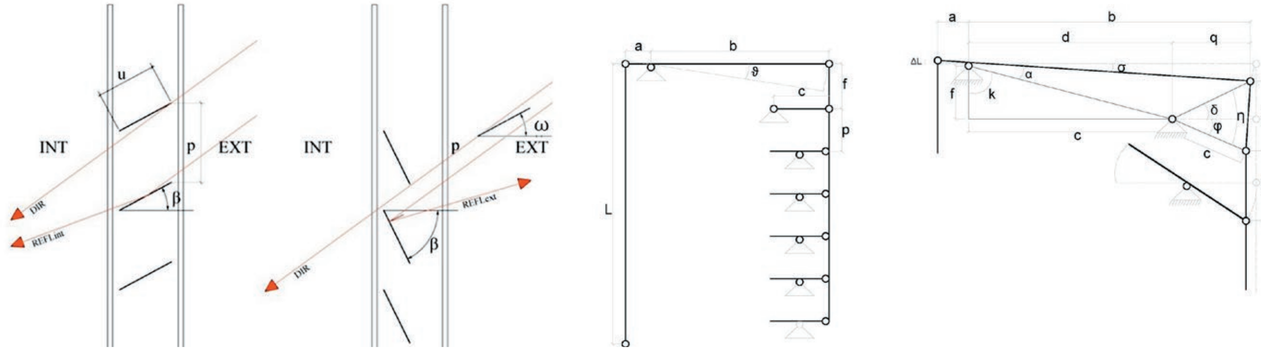

06 | Experimental apparatus built at the DPIA laboratory of the University of Udine. With reference to the photo in the centre, the following are highlighted: (A) weather station, (B) rack for supporting samples of dilating elements characterised by different surface treatments, (C) supporting frame, (D) dilating elements (aluminium bars), (E) levers and counterweights to put the HREs in traction by simulating the operating conditions. Left: the apparatus that allowed to test different movement transmission mechanisms with loads comparable to the operating ones obtained through suitable levers (B - direct load of 25.3 kg; A - maximum expected work load equal to 231.5 kg; C - equivalent load of 231.5 kg obtained from a second degree lever with hinges equipped with roller bearings; D - equivalent load of 231.5 kg obtained from a second degree lever with sliding type bearings). Right: details of the linkages

07 | Comparison between the daily diagrams of the angular movements of the two levers (solutions C and D in Fig. 6) detected in the experiments on a sample day (9 August) with the theoretical movement, calculated from the differential temperature values measured at the HRE and the chassis. It is possible to verify that there is an almost perfect correspondence between the theoretical and real values. Looking at the diagrams in detail, it can be seen that the lever D (the one with sliding friction bearings) has slightly lower angular excursions than the mechanism C (needle roller bearing). These differences, however, are less than 1° of rotation. Furthermore, by enlarging the diagrams, it is possible to observe a greater reactivity of the mechanism C, compared to the mechanism D. The first mechanism, in fact, reacts to temperature variations in the range of 1 °C, while the mechanism D reacts to temperature variations of 4°C

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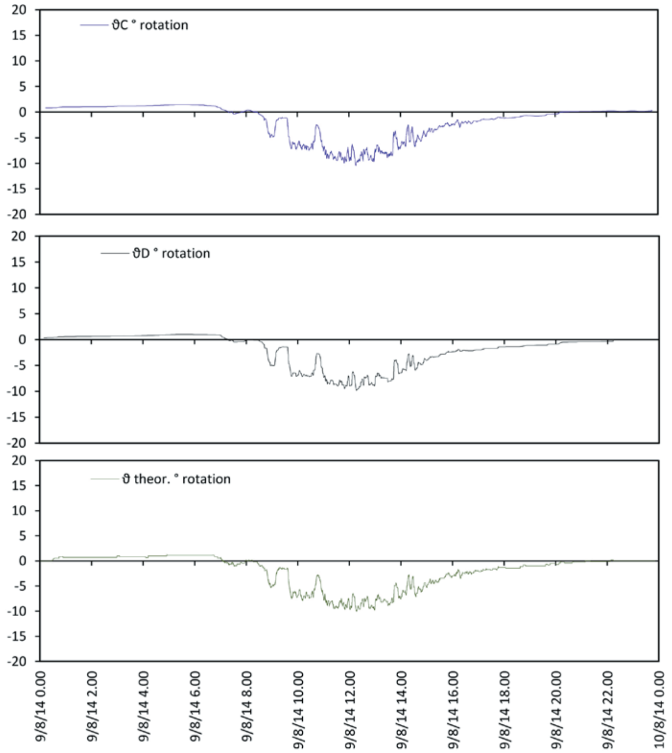

sation of the geometry of the dilating elements to maximise radiative solar input; the design, construction and installation of prototypes in order to refine the behaviour with respect to the mathematical model; the adoption of more advanced mathematical models, using finite element programmes for the calculation of the coefficients, with the variation of the physical-mechanical parameters of the systems; the optimisation of the systems in order to increase their overall efficiency by also evaluating the effects of the wind; the use of innovative materials having high coefficients of thermal expansion and surface treatments with high solar absorption and low emission; the use of other motion multiplication systems and kinematics.

REFERENCES

Bakker, L.G., Hoes-van Oeffelen, E.C., Loonen, R.C. and Hensen, J.L. (2014), “User satisfaction and interaction with automated dynamic facades: A pilot study”, *Building and Environment,* Vol. 78, pp. 44-52.

Karagiorgas, M. (2010), “Solar assisted heat pump on air collectors”, *Solar Energy,* Vol. 84, pp. 66-78.

Fulchir, F. (2009), “Progetto di un sistema di facciata autoadattante per dilatazione termica”, *Tesi di dottorato di ricerca*, University of Udine.

Karagiorgas, M. (2010), “Solar assisted heat pump on air collectors”, *Solar Energy*, Vol. 84, pp. 66-78.

Klein, K., Hutchtemann, K. and Muller, D. (2014), “Numerical study on hybrid heat pump system in existing buildings”, *Energy and Buildings*, Vol. 69, pp. 193-201.

Kramer, K.S. (2013), *White paper on Solar Air Heating Collectors*, IEA.

Moon, J.W., Yoon, S. and Kim, S. (2013), “Development of an artificial neural network model based thermal control logic for double skin envelopes in winter”, *Building and Environment*, Vol. 61, pp. 149-159.

Moret Rodrigues, A., Marques da Silva, F., Gloria Gomes, M. (2015), “Measuring and estimating airflow in naturally ventilated double skin facades”, *Building and Environment*, Vol. 87, pp. 292-301.

Wang, R. and Gerber, S. (2014), “Megnetically geared wind generator technologies: opportunities and challenges”, *Applied Energy*, Vol. 136, pp. 817-826.

Yang, M., Wang, P., Yang, X. and Shan, M. (2012), “Experimental analysis on thermal performance of solar air collector with a single pass”, *Building and Environment*, Vol. 56, pp. 361-369.