Thermal-physical behavior and energy performance of air-supported membranes for sports halls: A comparison among traditional and advanced building envelopes

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1. Introduction

Pressostatic envelope systems are tensile membrane structures supported by air, where the fabric layer is stabilized by a positive differential pressure between the inner and outer sides, in order to maintain their form under external loads. This building technology has been developed since the end of the 1950s, while recently it has been updated more and more through a wide variety of durable and translucent technical textiles (i.e. PVC coated polyester) and self-cleaning, transparent films (i.e. fluoro-polymeric foils of ETFE) [1].

Traditionally pressostatic envelopes provide the location for temporary events, although in the last decade the range of uses has been extended to a wider variety of typologies [2]. Permanent, seasonal or ephemeral buildings can be mainly distinguished, where a pneumatic or inflatable skin is able to protect courtyards in educative and residential buildings, to cover sports halls during the winter season, or even to perform a temporary pavilion for shorter service life [3]. Especially in permanent or semi-permanent applications HVAC systems are often required to maintain hygro-thermal comfort conditions. In this regard the air inflation system can also serve as the heating/cooling system.

Following this emerging trend, more and more attention should be paid to the membrane envelope thermal-physical properties in order to improve indoor comfort conditions and to reduce climatization energy consumption. Thus envelopes made up of double or multiple layers pneumatic cushions are increasingly used instead of single layer envelopes. Although translucent double skins made of technical textiles are quite common as a permanent building (e.g. the Serpentine Sackler Gallery by Zaha Hadid in Fig. 1), the transparent skins performed by ETFE foil cushions (e.g. the Khan Shatyr Entertainment Centre by Foster and Partners, Fig. 2) are mainly investigated [4–7]. For the pneumatic cushions a center-of-the-cushion thermal transmittance can be identified. As it happens in glazing systems, the thermal transmittance or *U*-value is dominated by surface thermal resistances in the single layer case, and by air gaps resistances in the multiple layers situations. By passing from single to double layers cushions the *U*-value

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Fig. 1. Zaha Hadid Studio, Serpentine Sackler Gallery, London. Permanent building with double textile membranes roofing system integrated with glazing eyes on the top. (Copyright reproduced courtesy of Architen Landrell Associates.)

roughly halves, passing from about 6 to 3 $W/(m^2 K)$. Knippers et al. [1] conclude that the choice of the U-value calculation method is not critical, but rather the horizontal/vertical installation of the cushion, determining the direction of the heat flow and thus the natural convection effectiveness. Thermal bridges at the cushion edges, due to the clamping or to the welding, usually increase the heat transfer across the cushion. In order to avoid thermal bridges effect a new generation of pressostatic double layers envelopes has recently been proposed. In this case a gap is created between the two envelopes and an air flow rate is continuously injected into the gap in order to keep the two membranes separated.

Although the structural behavior of fabric envelopes is well established, a few studies [8–10] focused on their overall thermal-physical behavior. According to [8], membranes enclosures are highly sensitive to changes in outdoor environment due to their low thermal inertia. Moreover they may be affected by indoor air thermal stratification, caused by the large air volumes and by the internal surface temperature difference between the membrane and the more massive components such as the floor.

Summer behavior of a test membrane open to the environment was analyzed both experimentally and numerically by He and Hoyano [9]. They show that solar transmission is one of the key factors affecting the thermal environment of the space under the membrane structure and that simulation tools can be used to quantitatively predict the impact of materials properties on it. As a further step, He and Hoiano [10] propose to couple the thermal simulation with computational fluid dynamics (CFD) in order to evaluate the effects of a passive cooling strategy based on an evaporative cooling pavement.

Fig. 2. Foster & Partners, Khan Shatyr Entertainment Center in Astana, Kazakstan, 2012. An elliptical tent with a 200 m base and 150 m height, with a structure made of steel cables and an envelope of ETFE transparent pneumatic cushions, screen-printed with aluminum powder. (Copyright reproduced courtesy of Vector Foiltec.)

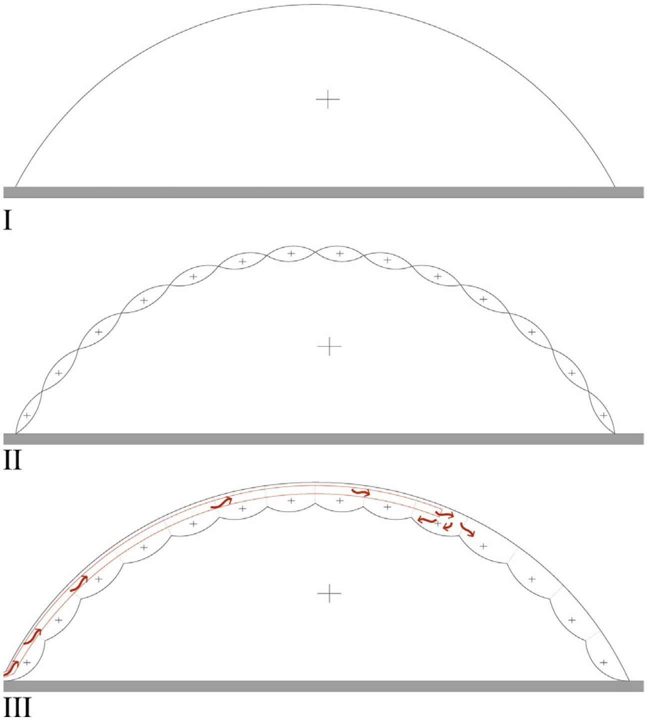

Fig. 3. Schematic section of 1st, 2nd and 3rd generation.

However to the best of the authors' knowledge no comparative assessment of the energy performance of the different kinds of membrane envelopes, namely single layer (referred in this paper as 1st generation), double layer made up of cushions (in this paper referred as 2nd generation) and double layer based on a continuous air gap (3rd generation), has ever been carried out. Therefore the present study aims at investigating the thermal-physical behavior of those three main kinds of envelopes (see Fig. 3), assessing the thermal comfort conditions and the condensation risk and finally quantifying the energy saving achievable passing from single to double layers constructions. Moreover, further energy saving strategies are proposed and analyzed. The case study consists of a sport hall adopting an air-supported fabric envelope for winter operation in Milano, Northern Italy.

The methodology adopted consists of:

- site surveys on running sports hall adopting the analyzed envelopes, in order to measure some relevant parameters and to verify some simplifying hypotheses on the thermal-physical behavior;
- set up of simulation models for the three envelope generations and dynamic simulations performed with ESP-r tool [11].

2. Case study

The dimensions of the analyzed sport hall are 36 m×36 m with a maximum height of 10 m at the center. The total indoor volume and plan surface are 8940 m^3 and 1888 m^2, respectively. The hall is provided with an air heating system mixing fresh air from outside

Table 1
Thermal-physical properties for the three generations envelopes.

Envelope generation	T_{sol}	$R_{sol,front}$	T_{vis}	$R_{vis,front}$	ε	Horizontal heat flow U (W/m^2 K)	Vertical upwards heat flow U (W/m^2 K)
1st	0.10	0.75	0.08	0.85	0.86	5.75	6.96
2nd	0.02	0.79	0.02	0.89	0.86	3.15	3.47
3rd	0.02	0.79	0.02	0.89	0.86	–	–

with return air from the inside. The design total flow rate is about 5.1 Air Changes per Hour (ACH) and the outside air design flow rate is 1.2 ACH. An indoor temperature setpoint of 18 °C is maintained from 9 a.m. to 11 p.m. The heating system provides also the necessary pressure difference between indoor and outdoor. In the case of the 2nd and of the 3rd generations, a small fraction of the warm air flow rate is used to keep in form the cushions and the air gap, respectively.

The three envelope generations are made up of PVC coated PES. In Table 1 the main thermal-physical properties of the three generation envelopes are reported. Regarding optical properties, solar and visible transmissivity T and reflectivity R are shown. For the single layer envelope they are based on the manufacturer data, while for the two layers envelope they are calculated according to the technical standard [12]. It can be noticed that solar transmittance decreases from 10% to 2% by passing from single membrane to double ones and therefore less solar gains can be expected in the latter cases. It is also possible to notice that the material emissivity ε, taken from [13], is high. Concerning thermal transmittance, winter conditions are adopted for the calculation and the two limit situations for horizontal heat flow (corresponding to vertical orientation of the membrane) and vertical upwards heat flow (corresponding to horizontal orientation of the membrane) are given. For the 2nd generation a center-of-the-cushion U-value is reported, calculated considering a typical air gap of 20 cm between the two layers in the cushion. Compared to the 1st generation, the 2nd generation U-value is lower by 45–50% depending on the heat flow direction. However, the 2nd generation U-value reported in Table 1 does not take into account the thermal bridges due to the cushion edges. Therefore, thermal bridges have been estimated by means of the numerical tool THERM [14]. In this regard the example of a real 2nd generation sport hall located in Milano has been considered (Fig. 4), where cushions with a width of 3 m and lengths ranging from 6 to 22 m are adopted. On the overall membrane surface the thermal bridges are thus estimated to increase the center-of-the-cushion U-value by 9%. In turn no U-value is reported at this stage of the analysis for the 3rd generation, since in the presence of a continuously ventilated and warmed air gap the thermal transmittance can become meaningless. In all the cases the floor is a typical synthetic tennis floor, made up of a 2 cm polyurethane resin layer on bitumen and mortar layers, resulting in a U-value for downward heat flow equal to 2.2 W/(m^2 K).

Fig. 4. Example of a 2nd generation sport hall.

3. Site surveys and measurements

In order to get the necessary data for the modeling, two measurement campaigns in some sports halls located in Milano have been performed. A site survey was made to clarify the existence of significant thermal gradients in the indoor air volume. Firstly spot air temperature measurements moving horizontally in a 2nd generation sports hall were carried out, resulting in temperature variations below the sensor accuracy equal to 0.5 °C. Secondly the vertical thermal stratification in the indoor environment was checked. Five thermal probes were located at different heights, namely 0.1, 1.7, 3.5, 6.6, 9.6 m from the floor in the central part

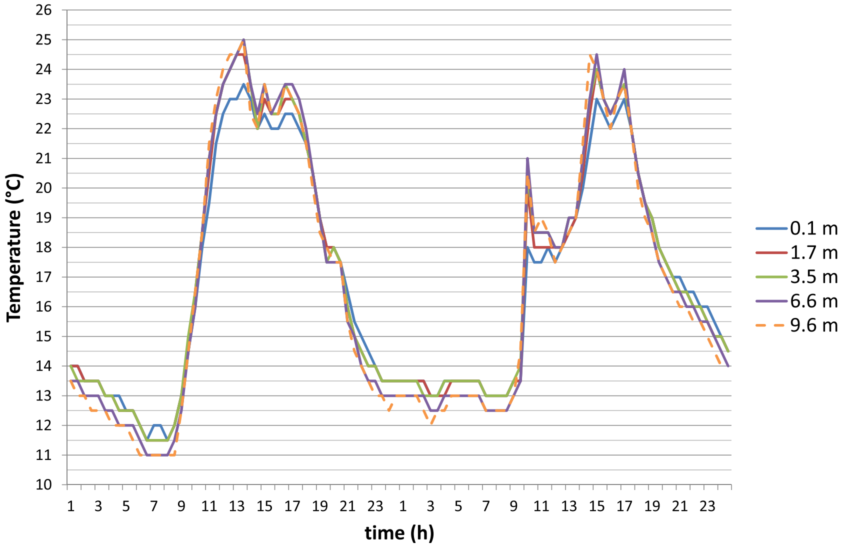

Fig. 5. Measurement campaign in 2nd generation sport hall: air temperature at different heights in two representative days.

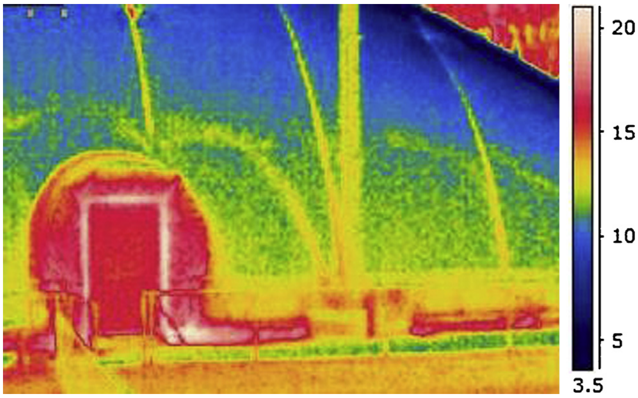

Fig. 6. 2nd generation sport hall: thermographic image from the outside showing air flows from the basement and the door.

of the sports hall. Measurements were carried on for 1 week. In Fig. 5 the results regarding two representative days are shown. It can be recognized that when the heating system is on, either in the early morning or in the late afternoon (since the period is at the end of the winter season), the temperature difference along the height of the hall is less than 1.5 °C and the thermal gradient is mainly concentrated in the first 2 m from the floor. A modest thermal stratification was then found, probably due to the presence of mechanical ventilation. Therefore in the next simulations the simplifying assumption of a well-mixed air volume has been adopted for the indoor environment.

A thermographic survey has also been carried out on the same sport hall where thermal gradient was measured. The thermographic image in Fig. 6 shows a portion of the outside surface of the envelope including the door. Warm areas can be noticed around the door and along the basement, where the envelope is attached to the ground. Therefore the thermographic assessment allowed to highlight the presence of critical areas where warm air from the inside flows to the outside.

The third site survey has been performed on a 3rd generation membrane to measure the air flow rate which is blown from the heater to the top of the membrane and then into the air gap.

Fig. 7 shows the entrance of the two ducts, where the air flow rate is blown into the air gap. The air flow rate has been measured by inserting an anemometer in a section of the ducts. The air flow rate can be adjusted manually by means of a butterfly valve. In the usual valve position an air flow rate of about 580 m^3/h per duct has been measured. When it snows, in order to enhance the snow melting on the top of the dome, the valve can be completely opened in order to increase the air flow rate. With the valve completely open a flow rate of about 850 m^3/h has been measured. These figures were adopted as inputs for the 3rd generation simulation model.

4. Simulation models

ESP-r is a transient energy modeling program allowing to simulate buildings and plants [11]. One or more zones within a building are defined in terms of geometry, construction and usage profiles. The plant network is then defined by connecting individual components. And, finally, the multi-zone building and multi-component plant are connected and subjected to simulation processing against user-defined control. An air flow network (AFN) approach is also possible within ESP-r, since the work by Cockcroft [15] and Hensen [16]. In AFN modeling [17] pressure nodes are attributed to the air volume within each building thermal zone and to the control volumes in the mechanical ventilation systems. Pressure at exterior nodes is usually a boundary condition, related to wind pressure around the building. The pressure nodes are linked by connections, representing windows, doors, cracks, fans, ducts and so on. A simple nonlinear relationship between the flow through a connection and the pressure difference across it can be established. Conservation of mass for the flows into and out of each node leads to a set of simultaneous nonlinear equations which has to be solved. ESP-r solves the equations using a guess-and-correct iterative procedure. Different simulation time step is used for thermal and air flow calculation to guarantee the accuracy [18].

First of all, in order to model the sport hall into ESP-r, the curved geometry of the membranes had to be converted into a proper arrangement of plane elements, preserving as much as possible at the same time the membrane area and orientation. A detailed geometry made up of 386 triangles was initially created. However, due to the constrain that in ESP-r the maximum number of surfaces for one thermal zone is around 80, this geometry required to divide the indoor environment into at least 8 fictitious thermal zones. Therefore a simpler geometry was preferred, allowing to model the indoor environment as a single thermal zone bounded by 18 surfaces (see Fig. 8). Despite its simplicity, the final geometry adopted proved to be accurate, since the corresponding indoor volume and membrane surface differ from the real ones by only 0.7% and 1.1%, respectively.

As already mentioned, in the 1st and 2nd generation simulation models a single thermal zone has been adopted to represent the indoor environment. In turn, for the 3rd generation envelope model an AFN approach has been implemented in order to describe the airflow into the air gap between the two membranes and therefore a multizone model has been created.

The PVC coated polyester thermal-physical properties were given as inputs to ESP-r. For the 2nd generation envelope, the

Fig. 7. 3rd generation sport hall: ducts for the air flow rate into the air gap between the two envelopes (left) and view of the air gap between two membrane layers (right).

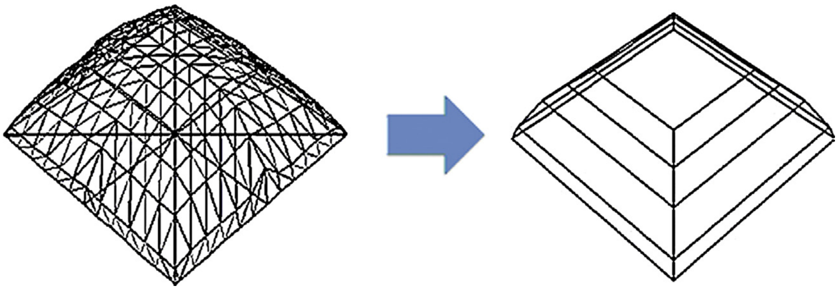

Fig. 8. Geometrical model of the sport hall: from detailed (left) to simplified (right).

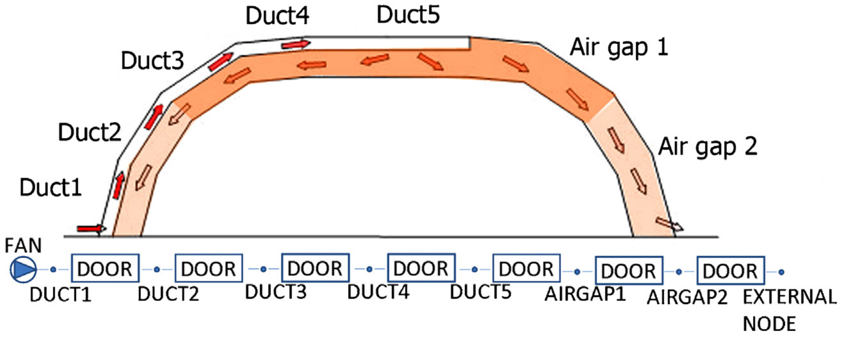

Fig. 9. 3rd generation model: air flow network and thermal zones.

cushions were described in terms of an equivalent stratigraphy made up of an external fabric layer, an air gap layer and an internal fabric layer. The air gap thermal resistance was adjusted in order to achieve a *U*-value of the stratigraphy equal to the overall *U*-value of the cushions calculated in Section 2, namely taking into account the cushion thermal bridges effect. An ideal air heating system maintains the indoor set point temperature, namely 18 °C, from 9 a.m. to 11 p.m., by means of 1.2 ACH.

The 3rd generation model is shown schematically in Fig. 9. The AFN describes the air flow from the air heater into the ducts, through the air gap and then toward outside. In order to better understand how the temperature decreases from the inlet to outlet, each duct is split into five branches. Each branch represents a thermal zone and a pressure node. The same approach is applied to the air gap: it was divided into two parts, named air gap 1 and air gap 2, to understand better the temperature profile. Each part consists of two parallel membrane layers with air in between. A constant air flow rate equal to 580 m^3/h (see Section 3) flows into the AFN: when the heating system is switched on, the inlet temperature is set to 50 °C; when the heating system is switched off, the inlet temperature results from the mixing between outdoor and indoor air. The indoor environment thermal zone is controlled as in the 1st and 2nd generation models.

A range of internal gains related to occupants and lighting was identified, leading to the low and high internal gains schedules reported in Table 2.

The energy simulations were performed for a complete heating season in Milano, namely from 15th October to 15th April, adopting standard weather data. In order to take into account both energy and environmental aspects in the comparison among the different generation envelopes, an ideal heating demand was calculated and at the same time thermal comfort analysis and condensation risk analysis were carried out.

Regarding the evaluation of the comfort conditions, the well-known Fanger's approach based on Predicted Mean Vote (PMV) and Percentage of Dissatisfied Persons (PPD) [19] was considered. A metabolic rate equal to 3.5 Met, corresponding to an intense sport activity, and a clothing resistance equal to 0.8 Clo, corresponding to a light sport clothing, were chosen. At every simulation time step t_i, indoor hygro-thermal parameters were obtained from ESP-r and used to calculate PMV_i e $PPD(PMV_i)$. An indoor environment falling into Category III according to EN 15251 [20] was adopted. It means that the PMV can lie between −0.7 and +0.7 and thus the PPD can reach 15%. In order to perform an evaluation on the whole heating season, one of the long-term indices proposed by [20] was adopted, namely the PPD weighted criteria. According to this approach a discomfort index is defined through Eqs. (1) and (2):

$$\text{discomfort index} = \sum_{i=1}^{N} wf_i \cdot \Delta t_i \tag{1}$$

Table 2
Internal gains schedules.

Item	Time (h)	Low internal gains (4 people, 20 lamps)		High internal gain (20 people, 24 lamps)	
		Sensible heat (W)	Latent heat (W)	Sensible heat (W)	Latent heat (W)
People	0–9	0	0	0	0
	9–23	740	1360	3700	6800
	23–24	0	0	0	0
Lighting	0–18	0	0		0
	18–24	8000	0	9600	0

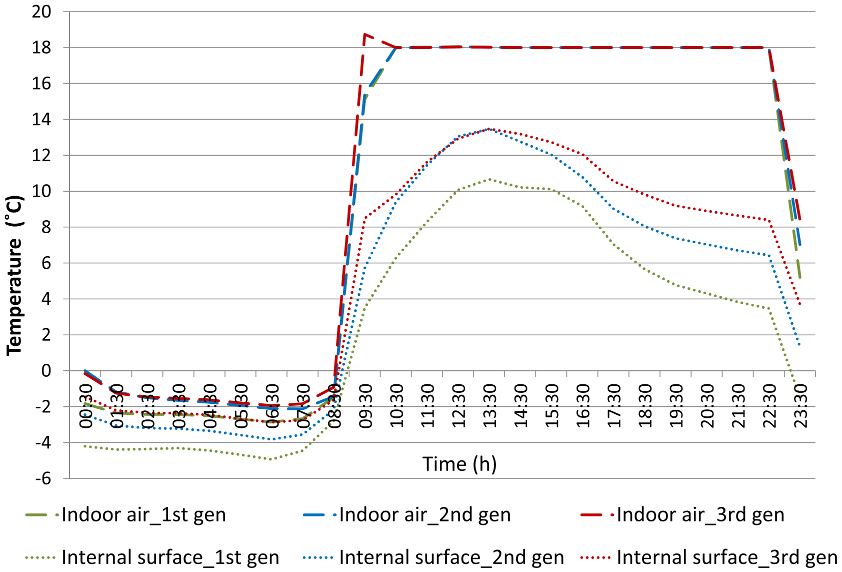

Fig. 10. Typical winter day: indoor air and membrane inside surface temperatures for the three generations of envelopes.

$$wf_i = \begin{cases} 0 & \text{if } \left|\mathrm{PMV_i}\right| \le \mathrm{PMV_{max}} = 0.7 \\ \dfrac{\mathrm{PPD}\,(\mathrm{PMV_i})}{\mathrm{PPD}\,(\mathrm{PMV_{max}})} & \text{if } \left|\mathrm{PMV_i}\right| > \mathrm{PMV_{max}} = 0.7 \end{cases} \tag{2}$$

where Δt_i is the time interval and wf_i is the corresponding weighting factor. As the definition shows, the discomfort index is obtained by a sum over the whole season of the time intervals during which the actual PMV exceeds the comfort boundaries, weighted by a factor function of the PPD.

As far as the condensation risk is concerned, at every simulation step the presence of condensation on the membrane inside surface and on the floor was checked. Then the number of condensation hours over the entire simulation period for each surface was calculated.

5. Simulation results and remarks

5.1. Thermal-physical behavior

A typical winter day (3rd December) is chosen to demonstrate the thermal-physical behavior of the three kinds of envelopes. It can be seen from Fig. 10 that during daytime in all kinds of membranes the indoor air temperature set point equal to 18 °C is satisfied. Due to the negligible thermal inertia of the envelopes, the indoor temperature drops down quickly after the heating system switch off at 11 p.m. The increasing insulation obtained passing from 1st to 2nd and then to 3rd generation means that the membrane inside surface is kept increasingly warmer: for the 2nd generation, it is about 2 °C higher than for the 1st; for the 3rd generation in the late afternoon it is more than 4 °C higher than the 1st. It has to be mentioned that the membrane inside surface temperatures reported are a weighted area average over the 17 surfaces adopted in the geometrical model (Fig. 8, right).

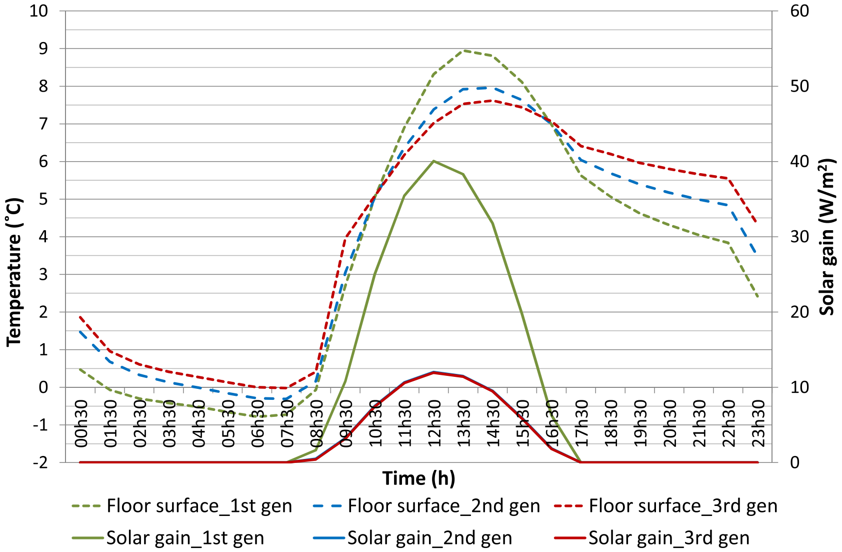

Fig. 11. Typical winter day: floor inside surface temperatures and specific solar gains on the floor for the three generations of envelopes.

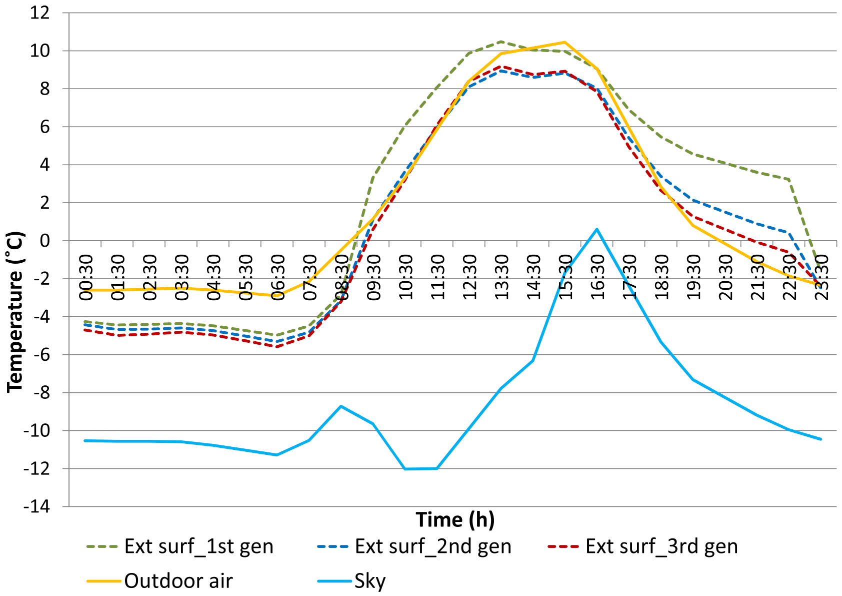

Fig. 12. Typical winter day: membrane outside surface temperatures for the three generations of envelopes, outdoor air and sky temperatures.

In Fig. 9 the floor inside surface temperatures in the three cases are reported for the same winter day. It can be noticed that from the late morning to the early afternoon the floor of the 1st generation envelope is warmer. This result is coherent with the higher solar transmissivity of the 1st generation (Table 1), resulting in larger solar gains on the floor, as also shown in Fig. 11. In the late afternoon it can be observed that the floor temperature for the 3rd generation is about 1 °C higher than for the 2nd, possibly due to the long wave radiation heat transfer with the warmer membrane inside surface (Fig. 10). The simulations show that during occupation period, by taking into account the floor and the membrane inside surfaces, the indoor mean radiant temperature in double layers membranes is higher than in the 1st generation membrane, which has an impact on thermal comfort conditions as will be discussed in Section 5.3.

The membrane outside surface temperature is shown in Fig. 12 together with outside air and sky temperatures. It can be noted that the more the envelope is insulated the lower is the outside surface temperature during daytime. It is also interesting to observe that during nighttime the outside surface temperature drops below outdoor air due to the effective heat transfer with the sky. Actually due to the large view factor between the membrane and the sky, radiative heat transfer generally dominates over convective heat transfer at the external surface, as shown in Fig. 13. Moreover, while radiative heat flows are always losses, convective heat flows may change in sign. By passing from 1st to 2nd and then 3rd generation the radiative and the convective heat losses are reduced.

The thermal-physical behavior of the 3rd generation envelope is analyzed in detail in Fig. 14. The air temperature decreases by more than 20 °C passing from the bottom (Duct 1) to the top (Duct 5) of the air ducts, before being injected into the air gap between the two layers. When the heating system is switched on, the air gap temperature (either in the upper part, namely Air gap 1, or in the lower part, namely Air gap 2) is lower than the indoor temperature. Therefore there is no heat gain from the air gap toward the indoor environment, as it would happen if the air gap was warmer than the indoor space. In turn the heat flows from the inside to the outside

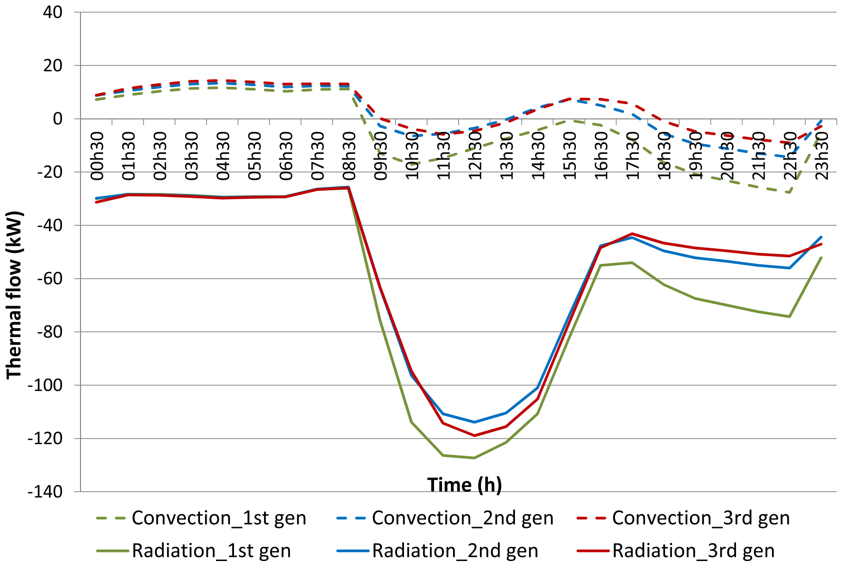

Fig. 13. Typical winter day: convective and radiative flows at the external membrane surface for the three generations.

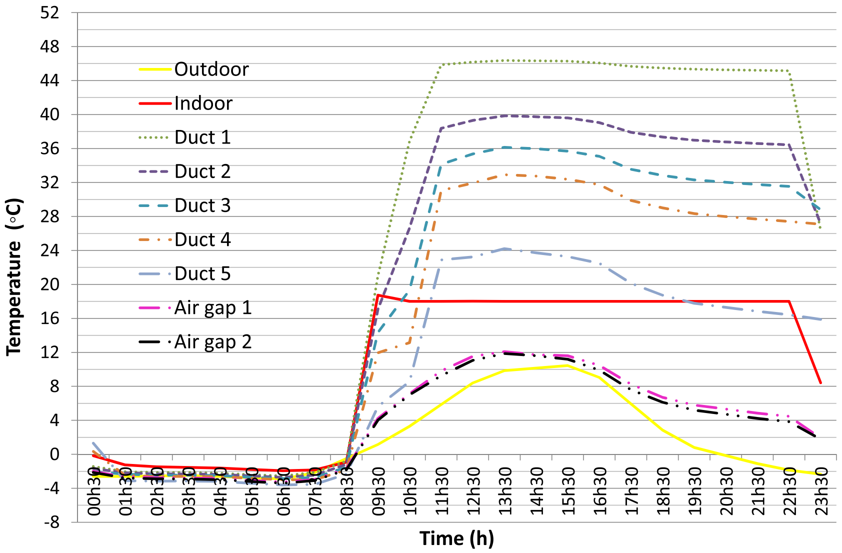

Fig. 14. Typical winter day: temperature distribution in the air duct and in the air gap for 3rd generation envelope.

across the air gap. We can then conclude that, to a first approximation, the *U*-value concept is still valid to describe the heat transfer across the 3rd generation envelope.

5.2. *Energy performance assessment*

By calculating the heating demand for the complete heating season, we can see that, passing from the 1st to the 2nd generation, the heating demand reduces from 253 to 224 MWh, i.e. by 11%. A further reduction to 208 MWh is obtained by adopting the 3rd generation envelope, resulting in 18% saving in respect to the 1st. In Fig. 15 the various terms contributing to the energy balance are shown, namely the convective heat losses at the internal surfaces, the infiltration losses and the convective portion of the gains generated by occupants and lighting. For the 3rd generation only, the energy needed to heat the air flowing into the gap has to be added to the indoor zone heating demand, resulting in a 5% more. Fig. 15 shows that the heating demand is dominated by the losses and that convection and infiltration losses are substantially equally important. The different energy demands for the three generations derive from the different entity of the convective losses.

If the external surfaces heat losses are then analyzed, radiative losses toward the environment, convective losses to outdoor air and conductive losses through the floor toward the ground are obtained (see Fig. 16, where the energy losses are calculated, as in Fig. 15, considering only the occupation period, i.e. when the heating system is active). A clearer picture is given that long wave radiation to the environment is the most important loss. By passing from 1st to 3rd generation such loss is reduced by 20%. Convective losses also decrease (by 62%), but their role is less important. Conductive losses slightly increase (by 8%) but similarly their role is marginal. By comparing directly the 2nd and 3rd generation the effect of removing the cushions thermal bridges can be quantified: the overall losses at the external membrane decrease by 7%.

A sensitivity analysis to the internal gains, considering the two scenarios reported in Table 2, was carried out. By passing from the low to the high internal gains case the 1st generation heating demand decreases only by 3%. Therefore the conclusion can be derived that the considerations on the energy demand comparison performed above are not influenced significantly by the hypothesis on the internal gains.

5.3. *Thermal comfort and condensation risk assessment*

The thermal comfort assessment results are reported in Table 3. In the base situation, where an indoor air temperature set point equal to 18 °C is considered, the discomfort index (see Eq. (1)) results in 4869, 5085 and 7390 h for the 1st, 2nd and 3rd generation, respectively. The worst performance achieved by the double layers envelopes is because at increasing envelope insulation the membrane internal surface temperature increases (see Fig. 10). Therefore the indoor mean radiant temperature increases and, with a high metabolic rate, a warm sensation for the occupants is easily reached. These results lead to investigate the possibility to lower the indoor air set point temperature in double layers envelopes by keeping constant or possibly improving comfort conditions with respect to single layer. As it is shown in Table 3, by lowering the set point of the 2nd generation from 18 to 17 °C, the discomfort index decreases to 4842 h, a value quite similar to the discomfort index for the 1st generation with 18 °C. This strategy results in a decrease in the energy demand, that passes from 224 to 206 MWh. By taking the 1st generation energy demand (253 MWh) as a reference, the energy saving is thus equal to 19%. If the set point in 2nd and 3rd generation is changed to 14 °C, lower discomfort indexes equal to 3709 and 3811 h, respectively, are reached, that means people playing sports inside would feel much comfortable. As reported again in Table 3 this strategy would result at the same time in considerable energy savings, equal to 42% and 49% for the 2nd and 3rd generation, respectively, compared to the 1st generation with 18 °C case.

Condensation is likely to occur on the membrane inside surfaces during winter, due to poor insulation and low surface temperatures. Then an improvement is expected in advanced envelopes because

Table 3
Discomfort index and heating demand depending on envelope generation and indoor set point temperature.

Envelope generation	Indoor air set point temperature (°C)	Discomfort index (h)	Heating demand (MWh)
1st	18	4869	253
2nd	18	5085	224
	17	4842	206
	14	3709	148
3rd	18	7390	208
	14	3811	129

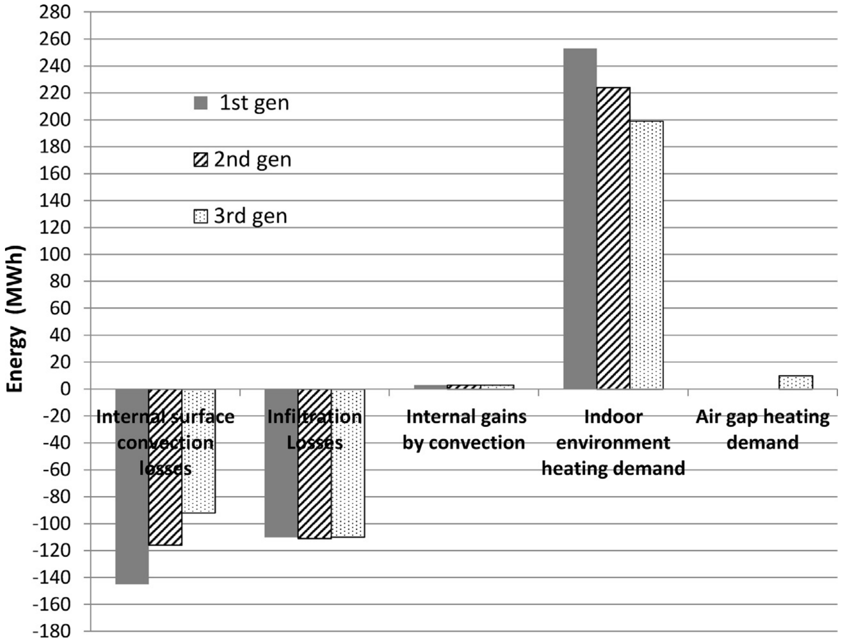

Fig. 15. Winter energy balance for the three generations.

of their higher insulation. In Fig. 17 the percentage of time when condensation occurs on the top part of the membrane surface and on the floor is shown for the three generations. If night time is included in the analysis, condensation on the membrane happens for 24%, 15% and 4% of the time for the 1st, the 2nd and the 3rd generation envelopes, respectively. As far as the floor is concerned, condensation happens for 7%, 6% and 1% of the time. If only the occupation time is considered, namely from 9 a.m. to 11 p.m., condensation on the membrane happens for 3% of the time for the 1st generation and never happens for the advanced envelopes. On the floor the percentage is 5% for the 1st generation, 3% for the 2nd and zero for the 3rd. Therefore it can be concluded that passing from the 1st to the 2nd and then to the 3rd generation the condensation risk on internal surfaces is dramatically reduced, becoming almost negligible in the 3rd generation.

5.4. Improving energy performance

After assessing the actual energy performance of the three generation membranes, further analyses were carried out in order to evaluate the impacts that some envelope properties may have on the heating energy demand and to critically compare them with the double layers strategy leading to design the 2nd and the 3rd generation.

Firstly, the possibility to reduce the single membrane thermal transmittance by adopting a low-emissivity coating on the inside face was analyzed. Therefore a new simulation was conducted for the 1st generation membrane by setting an internal emissivity equal to 0.20 instead of the original 0.86.

The results in Fig. 16 show that by applying a low-e coating the long-wave radiation losses to the outdoor environment and the

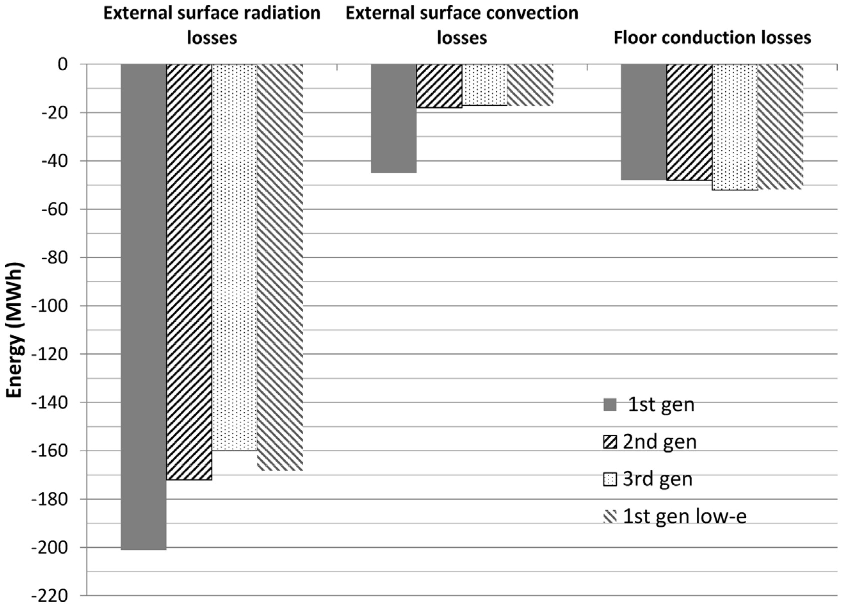

Fig. 16. External surface winter losses for the three generations and for the 1st generation with low-emissivity coating.

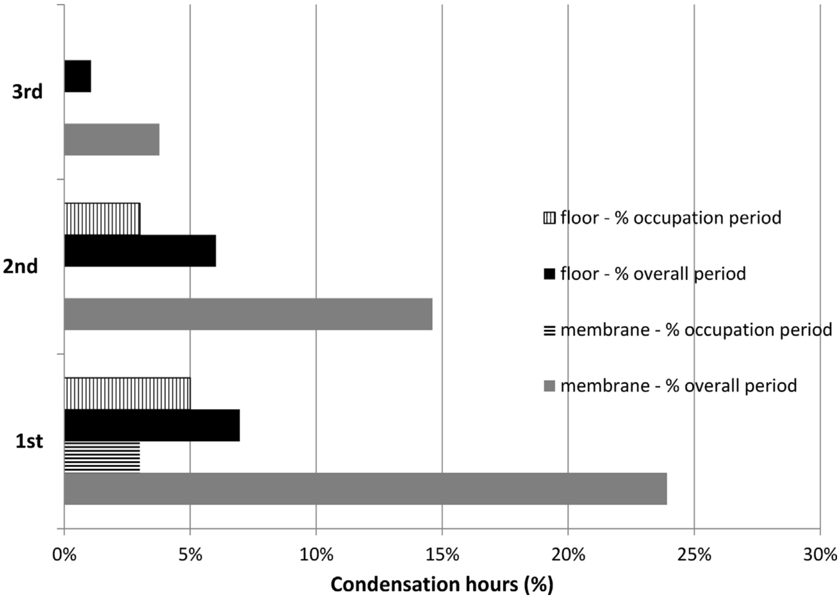

Fig. 17. Condensation on internal surfaces: percentage of condensation hours on the membrane top surface and on the floor, on the overall period and on the occupation period, for the three generations.

convective losses are reduced by 16% and 62%, respectively, compared to the base 1st generation case. Conduction losses increase by 8% possibly because, being the membrane thermal resistance higher, it is now easier for the heat to flow through the floor. The impact of the low-emissivity coating on the overall losses appears then quite similar to that due to the adoption of a double layers envelope, as it can also be noticed in Fig. 16. Globally the heating energy demand is reduced by 13%, a result in between the 2nd and the 3rd generation, though achieved with a simpler envelope that does not require any air inflation system.

As a second possibility, starting from the result that infiltration losses account for 43% of the heating demand in the 1st generation (see Fig. 15), the reduction of infiltrations was analyzed. Clearly, in order to reduce the infiltrations by keeping the same pressure difference between indoor and outdoor, the systems adopted to hang the membrane on the ground have to be carefully revised and tighter doors are to be used. Since the design of technical details is beyond the scope of the present study, it was assumed that the actual infiltration rate equal to 1.2 ACH could be halved and simulated the impact on the heating energy demand. It was found that the 1st generation heating demand would decrease by about 19%, a result similar to the one achieved by adopting a 3rd generation membrane.

5.5. *Parametric study for the 3rd generation membrane*

A specific analysis was carried out for the 3rd generation membrane, in order to understand the impact of the properties of the air flowing into the gap between the two membranes on the energy performance. Then a parametric study was performed, by varying

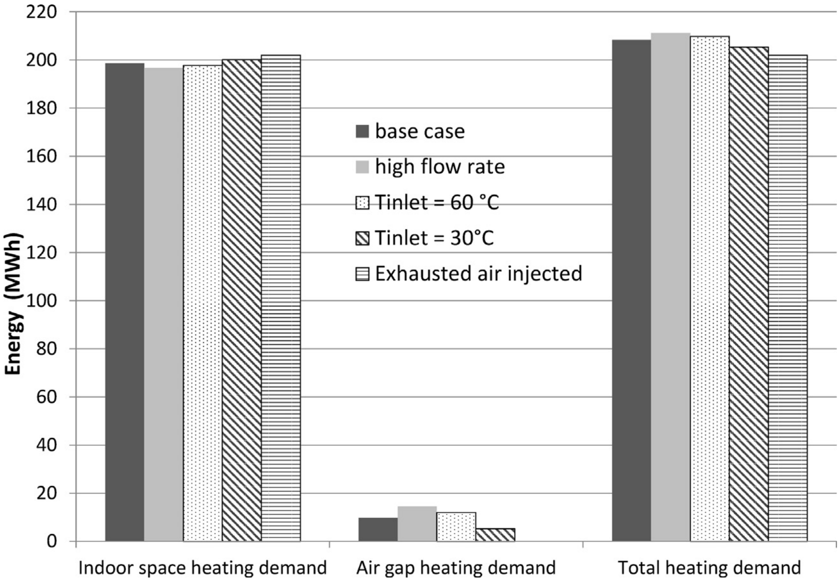

Fig. 18. Energy demand of the 3rd generation envelope by varying the air flow rate and the air inlet temperature.

the air flow rate and the inlet temperature. Regarding the flow rate, as explained in Section 3, the base value equal to 580 m^3/h can be increased to a maximum of 850 m^3/h. Therefore a simulation was carried out by adopting the maximum flow rate. Regarding the air inlet temperature into the gap, since in the base case it is equal to 50 °C, a larger (60 °C) and a smaller (30 °C) inlet temperature case were simulated.

The results of the parametric study are reported in Fig. 18 in terms of heating demand of the indoor zone, energy spent to heat the air flow and then total heating demand, obtained as the sum of the previous two.

If the maximum flow rate is injected into the air gap, the heating demand in the occupied zone decreases by 1.0% compared to the base case. In turn, more energy is needed to heat the air flow, so that in the end the total heating demand slightly increases (+1.4%). A similar result is achieved by increasing the inlet air temperature from 50 to 60 °C: the small reduction in the hall demand is overcompensated by the increase in the air flow energy demand, so that the total heating demand remains almost the same (+0.7%). An opposite trend is found when the inlet air temperature is decreased to 30 °C, so that the total energy demand slightly decreases (−3.1%). Since the last result, it was proposed to verify the impact of blowing into the gap the exhaust air from the indoor hall, being at 18 °C. In this case the energy demand to heat the air flow would be null, as shown in Fig. 18, and the overall heating demand is reduced by 3% compared to the base case. The parametric study on the 3rd generation envelope thus shows that by varying the flow rate and inlet temperature into the gap very small variations in the total energy demand are produced. The best way of operating the 3rd generation envelope is by recirculating the indoor air into the gap: in such a case 3.0% of the energy can be saved, which is a small amount that can however sum with the benefits arising from the adoption of other strategies illustrated above (lowering the indoor set point, adopting low-emissivity coating, reducing infiltrations).

6. Conclusions

The present study provides an insight into the thermal-physical behavior of air-supported envelopes made up of PVC coated PES membranes for winter covering of sports halls. Traditional single layer envelopes and advanced double layers envelopes were considered. The authors distinguished three main generations of inflatable skins for which a quantitative assessment of energy performances has to be carried out.

The analysis shows that, at least as long as a mechanical ventilation is present, the indoor thermal stratification is limited and a well-mixed volume approximation can be adopted. Further, the study shows that the indoor environment has a very low thermal inertia and its energy balance is dominated by the thermal losses, mainly long-wave radiative losses to the sky and infiltration losses. The disadvantages deriving from the reduction of solar gains in double layers envelopes are overcompensated by the advantages coming from the reduction of transmission losses. Different results could be achieved by changing the membrane materials (e.g. with high translucency materials like ETFE), as future studies could investigate.

For the first time, to the best of the authors' knowledge, a quantitative assessment of the advantages deriving from the adoption of double layers membranes compared to single ones, in terms of heating energy saving, reduction of condensation risk and improvement of thermal comfort conditions, was reported. In the climate of Milan, it was found that a double layers envelope based on pneumatic cushions, named 2nd generation, and a double layers envelope based on a continuously ventilated air gap, named 3rd generation, provide energy savings equal to 11% and 18%, respectively, compared to single layer or 1st generation. However it was shown that similar savings can be achieved with a single layer envelope either adopting a low-emissivity coating or reducing infiltration losses. In this regard, redesigning construction details to reduce the cracks between the membrane envelope and the ground should be a task for energy saving purposes.

The thermal comfort analysis revealed a higher mean radiant temperature in double layers envelopes, leading to propose a lower air temperature set point: a 2nd generation envelope with 14 °C air set point needs 42% less energy than a 1st generation envelope with 18 °C air set point, with comparable comfort conditions.

Passing to double skin envelopes allows to dramatically reduce the condensation phenomena on internal surfaces: the condensation risk becomes almost null in 3rd generation envelopes.

By means of an AFN approach coupled with thermal engine simulation, an understanding of the behavior of the continuously ventilated double layers envelope or 3rd generation was in particularly reached. It is now clear that, although warm air is injected into the air gap, to a first approximation the *U*-value concept is still valid to describe the heat transfer across the 3rd generation envelope. Moreover it was demonstrated that the main advantage in energy terms for the 3rd generation compared to the 2nd comes from eliminating the thermal bridges at the cushions edges. Finally it was shown that the energy demand of the 3rd generation is almost insensitive to air flow rates and inlet air temperature into the gap. However, the best way of operating this envelope is by recirculating into the gap the exhaust air from the sports hall, so that a further 3% of the energy can be saved.

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