Experimental and numerical assessment of breathing walls performance for the improvement of air quality and comfort indoors

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Highlights
This study focuses on “breathing” envelope as an alternative to “tight” envelope in nZEB to reach energy efficiency and IAQ targets. Breathing envelope lets the air enter through a dynamic thermal insulation able to preheat and filter it from possible pollutants. The filtration effectiveness of two dynamic insulation materials was experimentally assessed with an optical particle counter. The thermal performance was evaluated by finite elements simulations under transient conditions in three Italian climatic areas. Results obtained are very promising for the high effectiveness in pollutants filtration and thermal transmittance reduction.

Abstract
The construction of airtight building envelopes within nearly Zero Energy Buildings is likely to generate thermo-hygrometric discomfort indoors, that needs to be managed with air-conditioning and ventilation systems. In counter trend, some researches developed in northern Europe countries focused on the construction of “breathing” building envelopes that let in the air (passively or with mechanical devices) through dynamic thermal insulations able to preheat and filter it from possible pollutants. This study reports the results of experimental and analytical assessments of dynamic insulation systems, aimed to the design of a breathing wall system for the application in building renovation interventions.

Keywords
Breathing envelope, Dynamic insulation, Nearly Zero Energy Building, Indoor Air Quality, Filtration

1. INTRODUCTION

This paper reports the preliminary results of a study aimed to the design and performance assessment of a wall system with air filtration capacity for the improvement of health conditions in nearly Zero Energy Buildings (nZEB). The research draws inspiration from the fact that in the past two decades the construction industry focused in the creation of more and more energy-efficient buildings, but paradoxically carriers of problems connected to the indoor air quality (IAQ) that fall within the so-called “sick building syndrome” [1]. The “radicalization” of the building energy performance, assumed as the primary objective, instead of reducing the risks to human health (real aim of the European Directives EPBD [2] and EPBD recast [3]), is in fact leading to a paradox. The reduction of heat losses by transmission and ventilation through the building envelope, obtained with a progressive

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In recent decades, some authors proposed alternative strategies for buildings ventilation, related to the use of “breathing” envelope. Numerous studies, mainly related to the work of Taylor and Imbabi developed since the 90s, deepen the technology, mainly through heat and mass transport models in the air flow.
stationary conditions and in temperate climates of northern Europe [4,8–13]. In breathing envelopes, during the heating season, the cold outdoor air is conveyed (passively by pressure difference, or actively with mechanical systems) within the building envelope featured by a dynamic fibrous insulation, before being introduced in the indoor environment, preheated and filtered [10]. DI s can work in “pro-flux” mode if the airflow and heat have the same direction; if the direction is the opposite, they work in “contra-flux” mode. The latter way, the most widespread and investigated, is typical during the heating season. From the energy balance point of view, the system is based on the fact that the heat lost by conduction through the envelope is recovered by ventilation through the air introduced, which penetrates into the insulation perpendicularly to the conductive heat flux [8,12] (Figure 1). The mentioned studies show the effectiveness of breathing envelopes mainly in terms of energy performance, due to the reduction of the thermal transmittance compared to a tight envelope, which occurs in “contra-flux” mode. The term “dynamic” insulation comes right from the system’s ability to vary its thermal transmittance in situ due to the airflow (“dynamic” thermal transmittance), while “breathing” envelope refers to its filtering capacity. The effectiveness of the system in terms of heat recovery and filtration is a function of the airflow volume and increases with it [12]. Only some more recent works have analysed the use of breathing walls in warmer climates, however, always in stationary conditions models [14–16]. Recently Ascione et al. investigated the performance of a DI under transient conditions in synergy with a night ventilation strategy, focusing on the cooling season [17]. The analysis of the heat and vapour flows on a wall with dynamic insulation was performed with a finite differences method. During the cooling period, when the outdoor temperature is lower than the internal one (for example, during summer nights), the outside air is introduced into the room through a mechanical ventilation system and then expelled through the porous insulation. In this way DI works in “pro-flux” mode, namely with the same direction of the air and the heat flow (outgoing). In this condition, the authors demonstrated the dynamic insulation effectiveness in speeding up the night cooling process and consequently in reducing internal temperatures. The use of DI during cooling seasons in “contra-flux” mode, with heat flow from outside to inside (typical situation of summer days, when the outdoor temperature is generally higher than the inner one) and air flow in the opposite direction, is not investigated by the authors and constitutes a research field of great interest, in order to establish the effectiveness of the technology during all the seasons of the year in hot and temperate climates.
3. METHODOLOGY

The breathing wall analysed in this work is configured as an internal wall for the energy retrofitting of existing buildings, and consists of several functional layers: an interior finishing plasterboard, an air gap, the DI, a second air gap adjacent to the original building structure (that can be variously shaped). The outside air inlet in the envelope is ensured by openings installed at the base of the wall (openable vents), while inside openings are placed in the upper part of the plasterboard panel. In this study, we compared the filtration performance of two different porous materials to be used as possible DI: cellulose and polyester fibre.

Both permeable insulating materials have a fibrous nature, which makes them ideal candidates for the filtration of particulate matter (PM) in the volume of air for the internal ventilation. The filtration effectiveness of the two insulating materials was assessed through a continuous analysis using an optical particle counter (OPC) Fluke 983 with a 50% counting efficiency for particles of 0.3 \( \mu \)m and 100% for particles >0.45 \( \mu \)m. The OPC returns the cumulative sum of the particles, according to their equivalent diameter, contained in 2.83 litres of air drawn in a minute. A synthetic powder composed of talc, zinc oxide, hydrated silica, liquid paraffin was realized as a source of particulates with equivalent diameter of 2, 5, 10 \( \mu \)m. Insulating samples 47 cm x 47 cm were positioned on special wooden frames within a test chamber, connected to a system of air supply and suction with a speed of 10-2 m/s. Through the air supply, a controlled precipitation of the synthetic powder was realized using a funnel dispenser. At the centre of the test chamber, the air sampling tube of the OPC was positioned. During a first experimental phase, 5 measurements with controlled dust concentration were carried out to register the amount of PM in the test chamber before the installation of the filter. During a second phase, after the filter installation, 5 new measurements were carried out to detect via...
optical counter the concentration of particulates

The thermal performance of a breathing wall with cellulose DI was assessed through a two-dimensional modelling with the simulation program for the calculation of heat and air transport Delphin 5.6.8 [18], calibrated against experimental results obtained on a DI small prototype using a Hot Box test facility. Details on the experimental tests carried out and on the model calibration results are reported in a previous publication of the authors [5].

<table>
<thead>
<tr>
<th>Materiale</th>
<th>Spessore s [m]</th>
<th>Conduttività termica λ [W/mK]</th>
<th>Capacità termica c [J/KgK]</th>
<th>Densità ρ [Kg/m³]</th>
<th>Permeabilità Ψ [s]</th>
<th>Resistenza al vapore μ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parete esistente (forati di laterizio)</td>
<td>0.35</td>
<td>0.385</td>
<td>833.761</td>
<td>1200</td>
<td>-</td>
<td>45</td>
</tr>
<tr>
<td>Intercapedine d'aria</td>
<td>0.08</td>
<td>0.278</td>
<td>1000</td>
<td>1.29</td>
<td>0.1</td>
<td>0.35</td>
</tr>
<tr>
<td>Cellulosa - isolante</td>
<td>0.12 (Bolzano)</td>
<td>0.038</td>
<td>2544</td>
<td>45</td>
<td>0.000068556</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0.10 (Ancona)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.08 (Palermo)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intercapedine d'aria</td>
<td>0.08</td>
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<td>1000</td>
<td>1.29</td>
<td>0.1</td>
<td>0.35</td>
</tr>
<tr>
<td>Cartongesso</td>
<td>0.012</td>
<td>0.2</td>
<td>850</td>
<td>850</td>
<td>-</td>
<td>10</td>
</tr>
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</table>

Figure 2. Main thermal properties of the materials in the simulated breathing wall.

The breathing wall analytical model was compared with a traditional wall (with the same materials layers, but in absence of vents for the air inlet), and in transient weather conditions in the Italian cities of Bolzano, Ancona and Palermo. Coherently with the different climatic zones, the DI thickness was established to ensure a stationary thermal transmittance under the limits imposed by the actual Italian law D.M. 26/06/2015. Details on the stratigraphy of the wall modelled are shown in Figures 2 e 3.
The values of temperature and relative humidity within the environment were fixed at 20°C and 60% respectively. The values of the external atmospheric pressure were established constant, while the internal air pressure was calculated considering the contributions of stack effect, wind pressure on the wall, and the pressure drops in the vents and through the permeable material.

4. RESULTS

Figure 4 represents the percentage collection efficiency of the DI tested (cellulose and polyester fibre), in relation to the diameter of PM particles. A very good performance of both materials can be observed. The polyester fibre shows a better behaviour in the capture of PM10 (100%) compared to cellulose (99.94%); the intermediate particle diameters are captured from both samples with a 99.95% efficiency (points B and E). However, the most significant difference on the filtration efficiency occurs for PM2, which is the most dangerous particulates to human health. Cellulose is able to guarantee an efficiency equal to 99.94%, while polyester reaches 99.41%. Consequently, cellulose, which provides a high filtration performance for all PM diameters, was established as DI of the breathable wall model simulated.

The simulations in dynamic conditions allowed obtaining the heat flux through the wall and the temperatures at all points. From these data, we calculated the “in situ” thermal transmittance values of the breathing wall in comparison with the traditional wall, using the Average Method reported in standard ISO 9869:1994.
The graphs in Figure 5 show the trends of the thermal transmittance and their average values, obtained in the breathing and the traditional wall, during a typical winter week in the three climatic zones considered. They highlight how the breathing wall allows obtaining transmittance values substantially lower than the traditional wall. Figure 6 summarizes the mean values obtained and the percentage differences. Especially in the colder climate zone (Bolzano), the breathing wall allows to obtain a reduction of the stationary transmittance of about 55%.

Figure 5 Trends of the external air temperature (Test) and of thermal transmittances (U-value) of the breathing wall (Udyn) and of traditional wall (Ust) and their average value (respectively, Udyn* e Ust*), in each climatic area, during a typical winter week.
5. CONCLUSIONS

This paper reports the results of experimental and analytical assessments of dynamic insulations, aimed at the design of a breathing and filtering wall system for the application in buildings renovation interventions. The filtration effectiveness of two fibrous insulating materials, cellulose and polyester fibre, was experimentally assessed through a continuous analysis using an optical particle counter. The thermal performance of a breathing wall with cellulose DI compared to a traditional wall was assessed in transient conditions, in three different Italian climatic areas, using a finite elements simulation software, preliminarily calibrated with the experimental results obtained on a prototype with Hot Box tests. The results obtained are very encouraging, both in terms of efficacy of pollutants filtration (over 100% for PM10, over 99% for PM2 and PM5), both in terms of thermal performance during the heating season with the “passive” use (reduction of the thermal transmittance of the traditional wall among 28% and 55%, depending on the climatic area).

However, the performance of the breathing wall must be further investigated in order to declare such technology really effective even in hot and temperate climate contexts. Future studies should especially investigate:

- the thermal performance in summer phase in “contra-flux” mode (incoming heat flow, outgoing airflow through the wall), when outdoor temperatures are higher than internal ones;
- the thermal performance in summer phase in “contra-flux” mode (outgoing heat flow, incoming airflow through the wall), when outdoor temperatures are lower than internal ones.

Moreover, this work has not intended to deepen some practical aspects related to the application of technology (method of assembly and installation, maintenance, management of the fans for the air inlet system, hygrometric issues), focusing on the only aspects related to the filtration and the theoretical thermal performance. These issues should certainly be the subject of future analytical and experimental research works.

<table>
<thead>
<tr>
<th>Zona</th>
<th>Comune</th>
<th>GG gradi giorno</th>
<th>Udyn* [W/m²K]</th>
<th>Ust* [W/m²K]</th>
<th>Differenza percentuale [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
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<td>601 - 901</td>
<td>0,232</td>
<td>0,325</td>
<td>28,62</td>
</tr>
<tr>
<td>D</td>
<td>Ancona</td>
<td>1401 - 2101</td>
<td>0,163</td>
<td>0,233</td>
<td>30,04</td>
</tr>
<tr>
<td>F</td>
<td>Bolzano</td>
<td>&gt; 3000</td>
<td>0,105</td>
<td>0,232</td>
<td>54,74</td>
</tr>
</tbody>
</table>
6. REFERENCES


