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Assessment of Void Insulation Panels for innovative thermal insulation of apartments in heritage buildings

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Abstract. Void Insulation Panels (VIP) or Vacuum Insulation Panels are a technology that allows a sufficient thermal resistance for walls, floor or roof with a small thickness. The solution is more expensive than traditional ones but in historic centres of large cities with high value apartments, it could be an innovative solution for improving thermal comfort and reducing energy consumption. Different configurations of insulation with VIP in historical buildings in Bordeaux and Paris, two of the most expensive cities in France, are studied. The results show a great interest but moisture risk, especially in Bordeaux where the climate is wet due to the Atlantic coast. Special care for the thermal bridges and for the plaster hourdis between the beams of the floor are needed and the vapour barrier has to be continuous on top of the VIP complex plus insulation filler.

Keywords – Innovative thermal insulation; hygrothermal risks; void insulation panels; vacuum insulation panels; attics

1. Introduction

Improving energy efficiency of existing buildings has become a real concern to reduce significantly the impact of the building sector in terms of energy consumption and greenhouse gas emission. To achieve low energy consumption and comfort, more and more traditional buildings are undergoing thermal insulation and airtightness improvement. In buildings with architectural and cultural values, external thermal insulation is not an option most of the time. In this paper, the focus was placed on historical buildings in cities with very high financial value per square meter such as Paris. Void Insulation Panels (VIP) or Vacuum Insulation Panels are investigated as a solution for thermal insulation of classic apartments and also for the ones under roof slopes. Insulation of the roof in this kind of top floor old "maid's room" (example in figure 1 and 2) is an important issue for summer and winter comfort in a small volume. Just in Paris, the French Statistical Institute (INSEE) reported in 2011 more than 114 400 of these so-called maid's room. 50 000 of them are available to rent because they are larger than 9 m² and 20 m^3 that is the legal minimum. Only 17 000 are occupied because of substandard housings and comfort problems.

The thermal comfort in this kind of place is usually very bad and considering classic insulation solutions, the loss in volume in the room would made the thermal retrofitting a huge expense as the value of one square meter of liveable area (i.e. with at least 1,8 meter from floor to ceiling in French law) is higher than 10 k€. That is why innovative solutions such as super-insulation products could be considered in such cases. Research on those solutions [1] [2] led to several products on the market [3] and it is reasonable to project the future spread of the technology.

Concerning historical building, in addition to energy performance and cultural heritage preservation, EN 16883:2017 "Conservation of cultural heritage. Guidelines for improving the energy performance of historic buildings" recommends to assess the following criteria: "energy performance, cost control, indoor climate, air quality, preservation of the building fabric and sustainability". The table 1 presents arguments for those criteria for VIP.

Figure 1. Top floor old "maid's room" before retrofitting

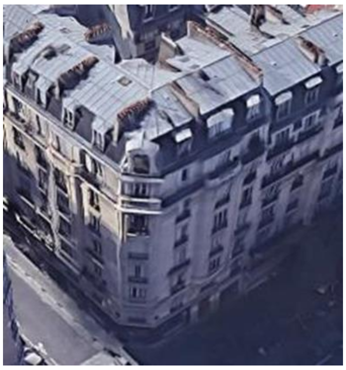


Figure 2. External view of the top floor in Haussmannian Building

Table 1. EN 16883:2017 Criteria for VIP

Criteria	Arguments
Energy performance	The literature is clear on good performance for VIP to insulate the envelope of buildings : an additional thermal resistance from 3,05 to 8.8 m².K/W.
Cost control	Volume savings in small apartment of high value allow high retrofitting cost.
Indoor climate	Air permeability improvement and better insulation improve summer and winter comfort.
Air quality	An effective ventilation system should always go with air permeability improvement.
Preservation of the building fabric	The humidity issue need to be assess as excessive level of moisture in building leads to construction disorders [4]. This point is developed in the next sections.
Sustainability	Life cycle analysis have been studied in [5]. Moreover the VIP have to be protected against all kind of drillings.

2. VIP applications in historical buildings

2.1. Insulation with VIP on vertical walls

Depending of the architectural particularities and the heritage conservation issues of historical buildings, the insulation process could take place from inside or from outside. The latter technique is the most efficient, when it is possible. Applying interior insulation will modify the hygrothermal behaviour of the wall and may induce a risk on interstitial condensation, frost damage or mould growth. In most cases with building with heritage significance, interior insulation is the only possible solution as in Paris and Bordeaux.

In [6], a retrofitting project with VIP on the exterior of the façade for a listed traditional building in Sweden was studied by monitoring and simulation. The VIP thickness is 20 mm and glass wool filled the gap between panels and around windows. An additional 60 mm glass wool layer covers the VIP. The overall U-value of the wall insulated is 0.40 W/(m².K) while the original was 1.1 W/(m².K). A wood cladding finishes the walls. In this application, the monitoring and the simulations showed that the insulation did not increase the water content in the walls. On the contrary, in [7] with VIP on the inside of the brick walls in an historic building, the conclusions are that it provides a great thermal behaviour but there is a risk of moisture damages such as frost in the exterior part of the brick, especially in Bergen climate, and risk for wood beam ends inside the wall.

Both techniques, interior and exterior insulation with VIP on vertical walls, are well described in technical documentation.

2.2. Case of top floor apartment in traditional building in Paris and Bordeaux with attics

Contrary to vertical walls, insulation with VIP in attics is not really described in technical documentation.

The objectives would be to allow a sufficient thermal insulation for the walls of the apartment and in this "maid's room" cases. Part of these walls are made with wood structure and metal cladding or tiles. In table 2, a comparison is made between VIP and PU for this insulation. The VIP solution allows a good thermal resistance with a very thin thickness on the rafters of the roof.

Table 2. Thermal resistance for the attics part of the walls

Insulation combination	R ($m^2.K/W$)
6 cm PU between rafters and 3.1 cm for VIP solution on rafters	2.7 + 4 = 6.7
6 cm PU between rafters and 3.1 cm PU on rafters	2.7 + 1.4 = 4.1
6 cm PU between rafters and 8 cm PU on rafters	2.7 + 3.6 = 6.3

To adapt a retrofitting scenario in attics with VIP panels, the most feasible solutions would be install a first layer of insulation with a classic material between the rafters. Then, a solution has to be planned to secured the VIP on the rafters and in the same time, the plaster board has to be fixed on top of the VIP covered by an appropriate vapour barrier. The figure 3 present such a configuration, on the left part a current section and on the right part the part close to the floor. The figure 4 show the global configuration with identification of the moisture risks.

The problem with this solution is that for the wooden structure of the roof, which crosses the insulation layer, the vapour barrier is not continuous.

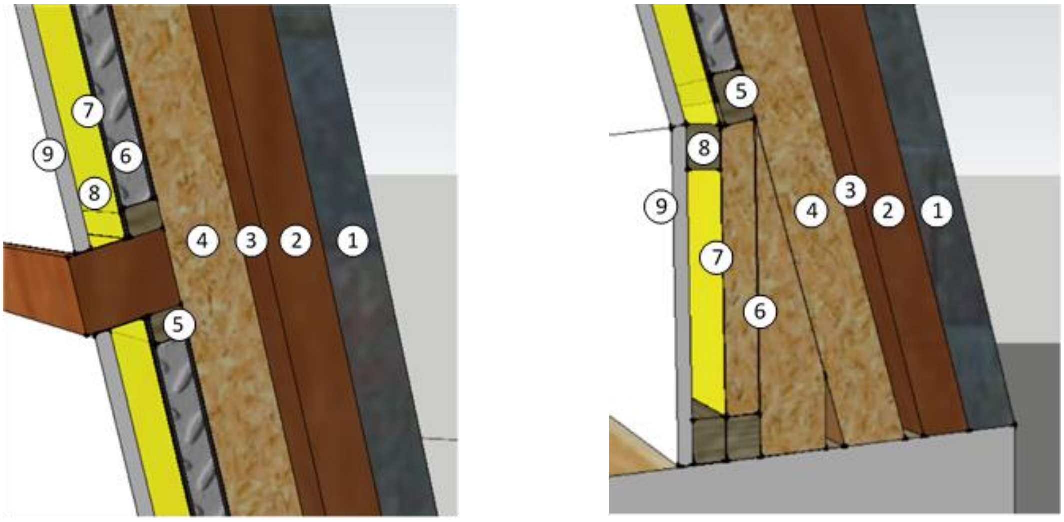
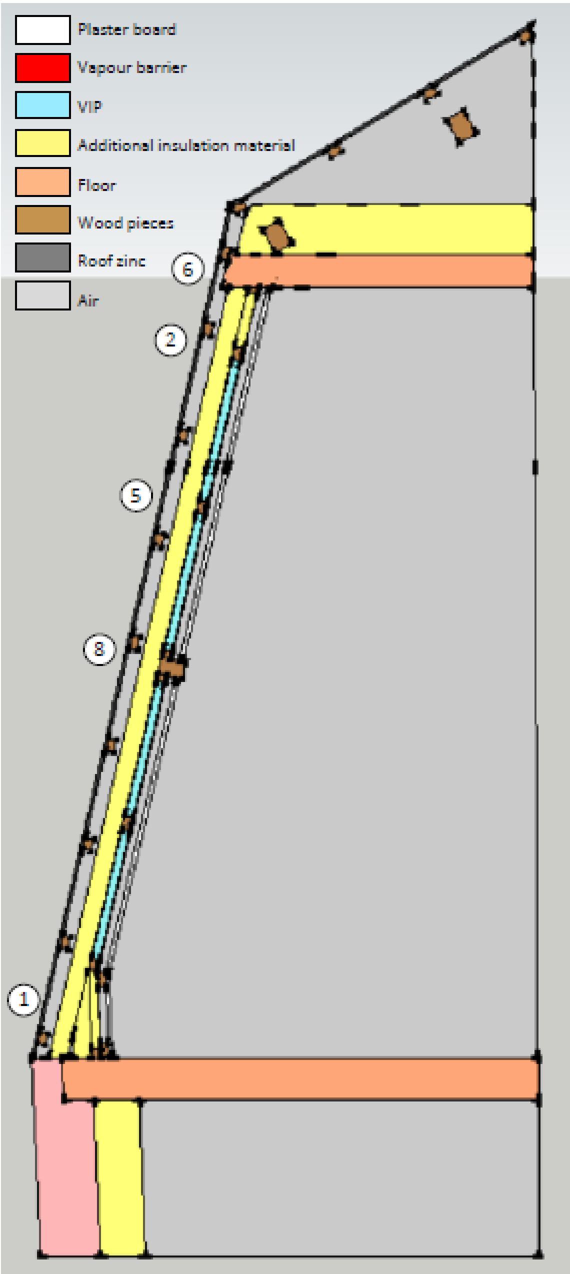


Figure 3. Configuration of insulation with VIP in attics using wooden structure

In figure 3, the numbers represent:

- 1: roof coating
- 2: battens (represented as a continuous plan for simplification here)

- 3: air gap 2 cm
- 4: insulation between rafters PU or wool (60 mm thick)
- 5: horizontal wood structure (18 mm thick)
- 6: VIP or insulation material used as filler (18 mm thick)
- 7: vapour barrier
- 8: wooden counter-lathing and technical air gap (18-20 mm thick)
- 9: plaster board (13 mm thick)



1: Thermal bridge with the floor
2: Furring or horizontal cleat between VIP and additional insulation material
3: Thermal bridge with inner bearing wall
4: Thermal bridge with windows (not on the figure)
5: Furring or horizontal cleat between two VIP
6: Link between ceiling about wall insulation
7: Link between rafters and insulation material (not on the figure)
8: Horizontal purlin under rafters

Figure 4. Configuration of insulation with VIP in attics : Identification of moisture risks analysis focus

This solution presents theoretically less air leakage risks than a solution with a classic metal structure perpendicular to the rafters because the vapour barrier is stuck between structural pieces when it is discontinuous except for the purlins

3. Moisture risk analysis when retrofitting historical buildings with VIP in Paris and Bordeaux

3.1. General literature statements

The IEA-EBC annex 65 reports "Long-Term Performance of Super-Insulations – Practical Applications" [7] studied VIP application in 22 reals buildings from historic ones to more recent. A common simulation-based procedure was introduced to identify potentially critical hygrothermal conditions, which were identified as main drivers of the ageing effect. The study highlights that some physical phenomena (such as thermal bridging effects, the influence of temperature on the thermal conductivity and the decay of performance over time) should be carefully evaluated during the design phase. As general guidelines, a list of recommendation is proposed:

- The protection of VIP with thin traditional insulation layer is always encouraged.
- The application of VIP behind heater determines high value of surface temperature field which could potentially lead to a fast degradation of the panel. A possible solution to mitigate the severity of the boundary conditions could be the coupling of VIP with a radiant barrier, or the protection of VIP with thin insulation layer when it is possible.
- In presence of wall subjected to high driving rain, it is preferable to adopt ventilated façade working as rain-screen to prevent the water absorption.

3.2. Assessment of humidity risks in traditional buildings in Paris and Bordeaux when retrofitting with VIP by inside.

As the literature warned us about thermal bridges, driving rain and freezing risks in the retrofitted walls, these points have been investigated by hygrothermal dynamic simulation with Wufi 2D [8]. A parametric study was performed on the parameters in the table 3.

Table 3. Parameters for the simulation

Climatic data	Paris and Bordeaux weather files, orientation north
Type of façade	Limestones
Type of floor	Iron beams and plaster ceiling (hourdis) between the beams
Insulation solution	VIP with mineral wool filler and vapour barrier / VIP with PU filler / both cases with and without air leakages through the vapour barrier

The geometry of the model represents the configuration shown in figure 4 for the attics and the model in figure 5 for the vertical walls as part of the attics could be side walls.

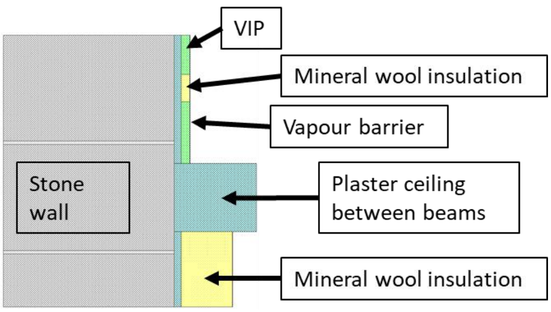


Figure 5. Configuration for limestones walls and plaster ceiling between beams in the simulation

The vapour barrier is present in the cases with mineral wool as a filler. The model for the VIP in the simulation is presented in table 4. It is an average of 3 different products available on French market, all of them with a silica heart in the panels.

Table 4. VIP model for the simulations

Bulk Density [kg/m3]	200
Porosity [m3/m3]	0.001
Specific Heat Capacity. Dry [J/kgK]	800
Thermal Conductivity. Dry. 10°C [W/mK]	0.0055
Water Vapour Diffusion Resistance Factor [-]	24000
Water content W80 [kg/m3]	/
Water Absorption Coefficient [kg/m2s1/2]	/

The properties of the VIP panels were considered stable. And for the simulations of the air cavity, in the approach of this project, no air change linked to the exterior have been implemented in the model. The results of the simulations have been analysed with five indicators presented in table 5.

Table 5. Indicators for risk analysis

Indicators	Position	Limits
A: Water content in porous materials (existing walls)	A1: Average in a current section A2: highest value on a thermal bridge	Less than 2% of increase on a yearly basis comparing year 9 and year 10 of simulations. Continuous minimum of 95% relative humidity for more than 24h.
B: Water content in the insulation material (when it is mineral wool)	Most critical part of the grid, highest value	99% of relative humidity
C: Mould risk development in the plan between the existing plaster and the insulation layer	In the first node of the mesh in the existing plaster.	98% of relative humidity for more than 6 straight hours
D: Freezing risk in the mortar, bricks or stones	The first node of the mesh in the material close to the outdoor boundary	Relative humidity value of 98% when temperature is negative
E: Wood decay in beams end	Node of the mesh in the wood in contact with the wall	Relative water content in mass higher than 20% for more than 8 weeks in a year (French standard)

Details about beam end treatment could be found in [9]. Perfect airtightness of the insulation material, composed of PU panels or insulation with a vapour barrier is not realistic. WTA 6-2 [10] proposes a method to calculate a realistic moisture source behind the insulation layer when the insulation work has been done with “normal care”. The average air permeability of the building envelope in these calculation is considered at a level of 5 $m^3/(m^2.h)$ under 50 Pa. It represents an average n50 of 3,5 h^{-1} for a building with a compactness of 1,4 and so a French Q4 of 1 $m^3/(h.m^2)$ under 4 Pa.

This method was applied and moisture sources were calculated and integrated into the gypsum plaster just behind the insulation material. These sources are reasonably small, as they represent only small flaws in the airtightness and not major defects such as a small break in the vapour barrier or the lack of joining tape between panels.

The results of the simulations for the configuration presented in figure 5 are presented in table 6 for 4 cases with a wall to the north. The first case with mineral wool as a filler for the VIP and a smart vapour barrier (between 0,2 and 26 m for Sd) in Bordeaux climate, the second case is the same in Paris climate, the third case is in Bordeaux and with PUR in place of mineral wool and the forth case is the same but without the moisture source representing air infiltration.

Table 6 : Presentation of the results for 4 simulations on the indicators

Case	A1	A2	B	C	D	E
1	3% increase in the wall behind the VIP	HR>95% for 1059 h in the stone in contact with the plaster ceiling	HR<99% everywhere in the mineral wool	2552 h in the year over the limit behind the VIP.	Always below the limit	Iron beam
2	0% increase	HR>95% for 6 consecutive days in the stone in contact with the plaster ceiling	HR<99% everywhere in the mineral wool	2408 h in the year over the limit behind the VIP.	Always below the limit	Iron beam
3	3,2% increase in the wall behind the VIP	HR>95% for 1059 h in the stone in contact with the plaster ceiling	HR<99% everywhere in the PUR	1036h in the year over the limit behind the PUR and 2634h behind the VIP	Always below the limit	Iron beam
4	0% increase	HR>95% for 1059 h in the stone in contact with the plaster ceiling	HR<99% everywhere in the PUR	Always below the limit	Always below the limit	Iron beam

For all the configurations, the indicators B and D, moisture content in the mineral wool and freezing risks did not show any risks. The indicator A, moisture content in structural materials is good for all configuration in Paris and show risks for a configuration in Bordeaux with PU as filler. The element with water accumulation is the wood joist of the floor when a humidity source is added to the model to represent air leakage. For the configuration with plaster ceiling (hourdis) between the beams, in Bordeaux the results for A2 shows some risks of high moisture levels. The indicator C reveals that all configurations with sources could be subject to mould. In Bordeaux even without sources, the different configurations could be subject to mould.

The climate in Bordeaux is more humid than the climate in Paris and it has a strong impact on risk analysis for the different configurations of buildings with VIP. Concerning the insulation filler between VIP, the results with mineral wool and vapour barrier are always better in terms of moisture risks than the results with PU. It seems that a vapour barrier is always needed. A precise installation with great care for the vapour barrier would ensure the lowest moisture risks. It is particularly sensible in the Bordeaux climate. The façade with heavy driving rain should avoid internal insulation with VIP without a dedicated study. A moisture risk was identified for the plaster ceiling (hourdis) of the floor because of the thermal bridges due to the interruption of the VIP insulation between two storeys. This problem is common to all internal insulation retrofitting scenarios but as the VIP brings strong thermal resistance in thin layer, the thermal bridges are more important.

3.3. Perspectives on moisture risk analysis in attics with VIP

The work will continue with the study of moisture risk when using the configuration 2 presented in figure 4. The different points of interest have been identified:

- Thermal bridge with the floor;
- Furring or horizontal cleat between VIP and additional insulation material;
- Thermal bridge with inner bearing wall;
- Thermal bridge with windows;
- Furring or horizontal cleat between two VIP;
- Link between ceiling about wall insulation;
- Horizontal purlin under rafters.

4. Conclusions

The scientific literature on VIP show that it's a promising solution and it could be used in several configurations in historical buildings. Research on these innovative products now lead to available products on the market and in several countries, applied research program and real scale tests are performed. However, historical buildings need great care when dealt with and several studies have showed the sensitivity to moisture accumulation due to internal insulation. It is also the case in the results of this study with the climate of Paris and Bordeaux. The driving rain and higher humidity rate in Bordeaux showed potential moisture problems in limestone buildings with VIP on the internal side of the walls. Nonetheless, work should continue on VIP in attics as it is a real issue for comfort in small volume under roofs. The works on the project will continue with brick façades, half-timbered façades on courtyards and floor with wood beams and the west orientation for the driving rain, especially in Bordeaux climate.

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