Experimental Verification of the Theoretical Aging of Vacuum Insulated Panels

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Abstract. *Vacuum Insulation Panels (VIPs) encompass a higher thermal resistance per unit of thickness compared to any other kind of insulation. However, their aging has often shown some critical concerns among stakeholders. To support the broader use of VIPs in the building sector, a comprehensive analysis of the physical properties of VIPs and in particular of their thermal conductivity over long-periods is required. This research investigates the effect of the temperature and relative humidity on the service life and thermal conductivity of VIPs. The scope of this study is to validate existing aging models for VIPs. First, the experimental results of the thermal conductivity for five VIPs both in pristine and in laboratory-accelerated conditions are described. Then, an analytical aging method is employed to validate the collected data. Results show that the aging has a more significant impact on the performance of VIPs with a core of fiberglass-core than with VIPs with a core of fumed silica.*

Keywords: *Vacuum Insulation Panels, Durability, Service Life Prediction, Thermal Conductivity.*

1 Introduction

It is widely acknowledged that buildings account for more than 32% of total global energy consumption and contribute to 19% of the GHG emissions. The global energy-related CO_2 emissions from the building sector more than doubled between 1970 and 2010, and are projected to increase by another twofold by 2050 (Berardi, 2017). Several researches confirmed that the heat transfer (*i.e.* losses) through the building envelope is the most significant energy factor for building efficiency as such, significant attention exists for super-insulating materials. High-performance materials such as Vacuum Insulation Panels (VIPs) offer a high thermal resistance value with minimized thickness, thanks to their low thermal conductivity (0.003-0.005 W/mK) which is about five times lower than that of traditional insulation materials (Johansson *et al.*, 2014; Karami *et al.*, 2015). VIPs are non-homogeneous insulation materials consisting of a porous core which is evacuated from air and vapor, tightened, and then heat-sealed. VIPs materials are in the early market stages in the building sector and data about their thermal performance over the building lifetime is missing (Baetens *et al.*, 2010; Kalnæs and Jelle, 2014).

Consequently, many international research efforts have focused on the thermal properties of VIPs over time (Wegger *et al.*, 2011; Isaia *et al.*, 2017; Mac Lean *et al.*, 2017). Several works have proposed methods to predict the service life of VIPs with Fumed Silica (FS) core and on the development of models to determine their moisture content. Theoretical approaches to predict their long-term performances by means of interpreting accelerated aging tests done in laboratories have also been proposed (Table 1). The increase in pressure and humidity inside a VIP panel over time is often pointed as the main aging mechanism for VIPs (Schwab *et al.*, 2005).

The objective of this paper is to evaluate experimentally the thermal conductivity of some VIP after several aging exposures and to assess the accuracy of existing thermal conductivity aging models through verification of collected results for different core materials of VIPs.

Table 1. Literature review summary of previous studies related to the topic of the present paper.

Study	Core type	Test type	Equivalent test period	Parameters of study results	Results
Simmler et al., 2005	-	laboratory work	5.5d at 23°C/80% RH, 9h at 30°C/90% RH, 65h at 65°C/75% RH, 152h at 80°C/80% RH	Ageing mechanism with results for different temperature and humidity	Pressure increase rate is about 2.1 mbar per year, while moisture accumulation rate is 0.18 mass% per year
Wegger et al., 2011	Va-q-VIPB 2009	laboratory work	25 years	Evaluating the accelerated ageing of VIPs for various procedures	Acceptable agreement with that of the accompanying theoretical analysis
Saber et al., 2015	fumed silica	in-situ test	a year	Effects of thickness and thermal conductivity on effective thermal resistance	The thermal resistance of the wall with VIP is higher than the wall with failed VIP or XPS
Kucukpinar et al., 2015	organic nano-foam	mock-up test	More than a year	Monitoring heat flow through the panels over months	Nanoporous foam VIPs are still effective
MacLean et al., 2017	VIP	pilot wall	-	long-term thermal performance of VIPs	Confirming the good performance of the VIPs compared to XPS
Batard et al., 2018	fumed silica	laboratory work	25 years at 23 °C for 80% RH	Comparison data of linear and dynamic model	Similar results for linear and dynamic models with a comparable increase of conductivity over time
Pons et al., 2018	fumed silica	laboratory work	10 years at 23 °C and 80% RH	Mild artificial aging of six VIPs samples	- The surface hydrophilicity of core aged VIPs is twice higher than the new one

2 Theoretical Background and Research Methodology

The thermal conductivity of VIPs is a critical characteristic to study. Solid conduction, air convection, and radiations determine the primary heat transfer mechanisms that control the insulation capacity of the panel. The thermal conductivity of VIPs has been proposed as a summation of different effects as reported in Eq. (1) (Wegger *et al.*, 2010; Alotaibi *et al.*, 2014):

$$\lambda_{tot} = \lambda_s + \lambda_g + \lambda_r + \lambda_{wv} + \lambda_w + \lambda_{cop} \qquad (1)$$

where λ_s represents solid conduction through the material, λ_g shows gas conduction through the porous of material, λ_r presents radiation heat transfer between inner pore, λ_{wv} is the permeation of air and moisture through pores, λ_w is the thermal conduction over time based on adsorbed water within the core material, and λ_{cop} is the thermal conductivity accounting for second-order effects between the mentioned thermal conductivities. In Eq. (1), the λ_{wv} and λ_{cop} components have a lower value compared to other terms, and can often be neglected. The gas thermal conductivity is independent of the density, and its reduction provides a significant opportunity to improve the performance of the VIPs (Kwon *et al.*, 2009).

A different way to express the thermal conductivity of VIP is by taking into account their aging, as described by Eq. 2 (Caps *et al.*, 2008):

$$\lambda_{tot} = \lambda_{init} + \frac{\lambda_0}{1 + \frac{0.032}{p\Phi}} + bX_w(t) = \lambda_{init} + \frac{\lambda_0}{1 + \frac{0.032}{p\Phi}} + c\left(1 - exp\left(-\frac{t}{\tau_w}\right)\right) \qquad (2)$$

where λ_{int} is a summation of solid and radiation thermal conductivities, λ_0 is the conductivity of air for atmospheric pressure, p is gas pressure, and Φ is the pore size of the pores.

As evident, to fully study the behaviour of Eg (2), long periods would be needed. Consequently, accelerated aging methods are often used to find failure modes in a shorter time, which is resulted after many years at a normal temperature. In this study, exposure of VIP to elevated temperature was used to age several VIP samples. The increase of temperature could grow the kinetic reaction rate within the molecules of materials which causes chemical deprivation. For this purpose, accelerated aging temperatures of building materials are often select around 70 ˚C (Jelle, 2012; Kunic, 2012). Arrhenius law was used to calculate the time equivalent to 25 years of aging. To determine the relationship between the aging test condition and the real condition, accelerated factor (AF_{temp}) was presented:

$$AF_{temp} = e^{-\frac{E_a}{K}\left(\frac{1}{T_A} - \frac{1}{T_U}\right)} \qquad (3)$$

where AF_{temp} is the acceleration factor under stressed temperature, E_a is the activation energy of failure mechanism, K is the Boltzmann constant which equals 8.617×10^{-5} eV/K, T_A is the accelerated temperature, and T_U is the use condition temperature. The accelerated temperature of VIPs samples was 70˚C, and the constant use condition temperature was assumed at 15 ˚C. The thermal conductivity was measured, before and after the aging of each sample, in order to assess VIP thermal performance according to the ASTM C518 using heat flowmeter equipment HFM 436. The measurements were carried out in a temperature range of -10˚C to 30˚C with 5 ˚C temperature step. The temperature difference between the plates was kept at 10˚C.

3 Results
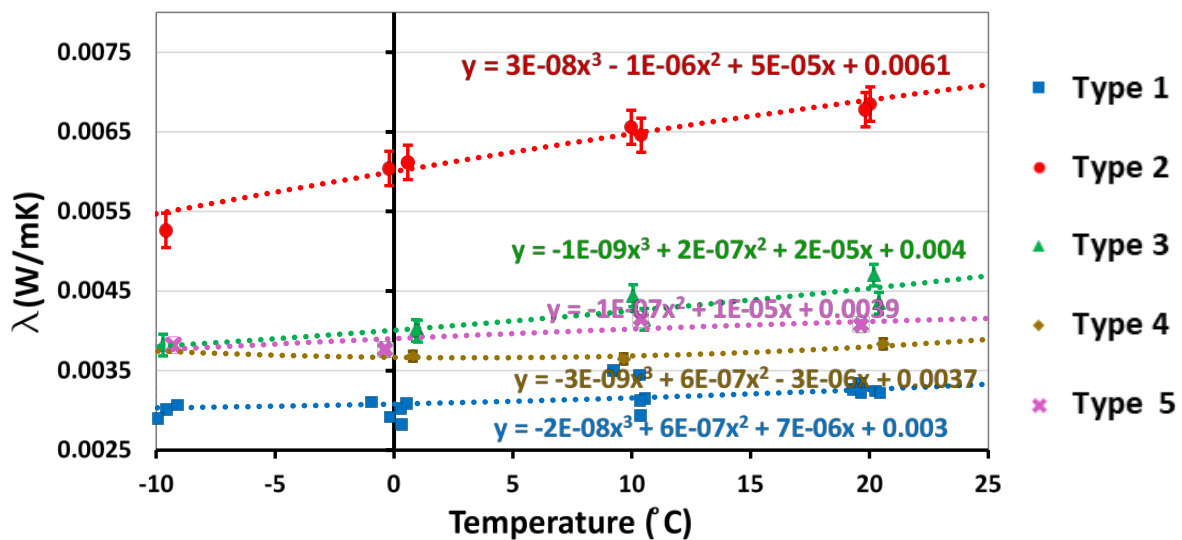
3.1 Pristine and Aged Thermal Conductivity

The thermal conductivity of various VIPs with different core panels including fiberglass, fumed silica, compressed microporous silica, and compressed microporous silica with celluloses fiber, were tested in this study. Different types of multilayer films which are common in the market were selected. The employed films include metal foils (AF), metalized films (MF) and polymer films (PF). The most common types can be described as follows:

• AF: In these ones, the thickness of the aluminum in the center is up to 5-10 μm and this layer is laminated by a polyethylene terephthalate (PET) as a protective layer in outer and polyethylene in the inner side of the layer (Wegger *et al*., 2011; Kalnæs *et al*., 2014).

• MFs: In these ones, there are three barrier layers of aluminum metalized PET and polyethylene (PE) sheets on the inner side with an aluminum coat of 20-100 nm thickness (Simmler *et al*., 2005; Ghazi Wakili *et al*., 2011; Alotaibi, 2014). This is a standard solution to make VIPs applicable in buildings because multiple aluminum layers provide a better impermeable layer in comparison to one-layer aluminum. However, MF type has a low thickness which is an issue as a low thickness results in higher gas and moisture permeance compared to the AF laminates. Table 2 reports the main characteristics of the selected VIPs.

3

Table 2. Experimentally characteristics of VIPs provided by manufacturers.

Sample type	Envelope type	Thermal conductivity (W/mK)	Company density (kg/m^3)	Core material	Pressure (mbar)	Size (cm x cm)
1	*NA*	0.0028	250	Fibreglass	≤ 5	30 x 30
2	MF3	0.0048	190	Fumed Silica	≤ 5	24 x 13.7
3	MF2	0.0037	208	Compressed microporous silica	≤ 5	30 x 30
4	MF2	0.0070	200	Compressed microporous silica + celluloses fibre	≤ 2	30 x 30
5	MF2	0.0070	250	Compressed microporous silica	≤ 5	30 x 30

The initial thermal conductivity of all samples is shown in Fig. 1. The experimental results validate that fiberglass provides the lowest thermal conductivity; in fact, the core of fiberglass, an open porous composite, allows easier air evacuation (Quenard and Salle, 2005; Kwon *et al.*, 2009). Pressed powder microporous silica would be the second option for high performing VIPs. The results in Fig. 1 shows a generally consistent behaviour of the VIPs and their lower thermal conductivity at lower temperatures (Berardi, 2019).

Figure 1. Value of pristine thermal conductivity for five types of VIP samples.

The induced changes in thermal conductivity of VIP samples with the exposure at high temperature, simulating their accelerated aging, are presented in Fig. 2. The results are shown for the average temperature between the two plates of the HFM of 18 °C. The thermal conductivity results were collected every five years of aging for each type of sample.

As can be seen in Fig. 2, Types 1 to 5 have a close initial thermal conductivity in the range from 0.003 W/mK to 0.0045 W/mK. While Type 1 with fiberglass core has the lowest initial thermal conductivity in comparison to the other samples, an increasing trend of thermal conductivity occurred compared to the other types in the same size. Types 3, 4 and 5 have an approximately constant thermal conductivity over 25 years. The type of the envelope and the thickness of the foil through the laminate affected the thermal conductivity. In fact, Type 5 which had an MF3 envelope showed minimal aging effects.
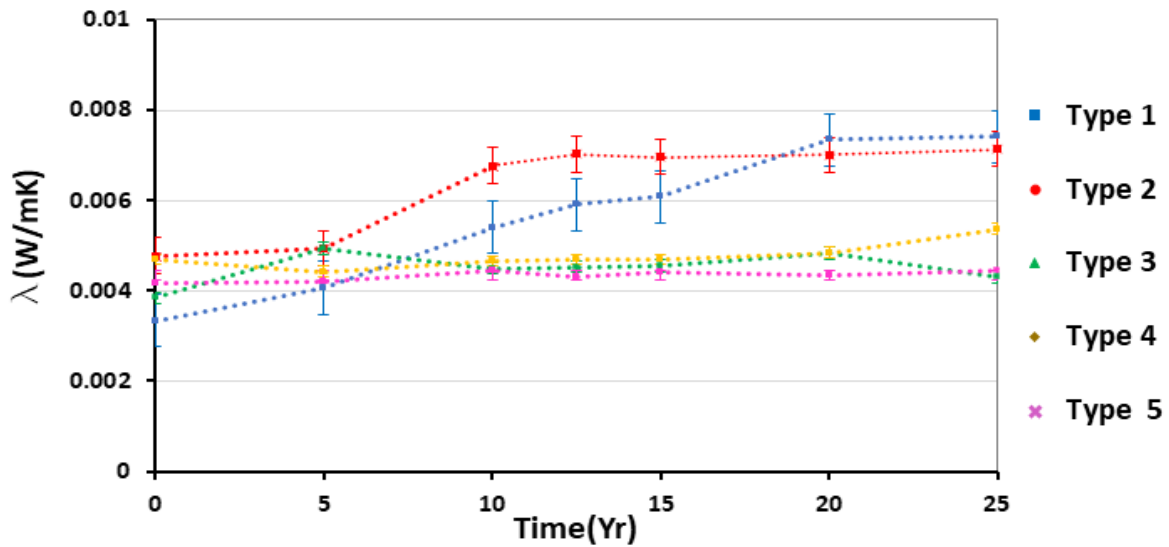
Figure 2. Dynamic variation with the accelerated aging of the thermal conductivity of the VIPs at 18 °C.

3.2 Ageing Model Verification

Here, the studies in (Simmler *et al.* 2005b; Kim 2017, Mukhopadhyaya *et al.*, 2011) are used as a reference model for evaluating the thermal conductivity trend. According to these papers, a simple version of the ageing thermal conductivity is:

$$\lambda_{tot} = \lambda_{init} + \lambda_p t + c\left(1 - exp\left(-\frac{t}{\tau_w}\right)\right) \qquad (4)$$

where, λ_{init}, λ_p, c, and τ_w are regression parameters depending on the envelope and the core material. The parameters used in (Kim, 2017) are given in Table 3 as the reference model. In this research, the mentioned parameters (λ_{init}, λ_p, c, and τ_w) are derived from experimental result using Python curve fitting libraries. These unknown parameters are estimated such that the difference between the measured data and the model output is minimum. Table 3 lists these parameters for each sample and parameters in (Kim, 2017) as the reference.

Table 3. Parameters measured for samples under test and reference data proposed by Kim (2017).

Parameters	λ_{init} (mW/m K)	λ_p (mW/m.K.year)	c (mW/m K)	τ_w (year)
Reference Model (Kim 2017)	3.9 to 4.8	0.07	3.2	35.6
Type 1	3.20	0.17	1.30	35.6
Type 2	4.20	0.07	2.20	20.0
Type 3	4.00	0.05	0.66	35.6
Type 4	4.00	0.05	0.66	35.6
Type 5	4.08	0.019	0.02	35.6

Figure 3 shows the thermal conductivity behaviour of these samples over 25 years. As it can be seen from this figure, overall, the thermal conductivity shows a linear trend over time for these samples. For Type 1, thermal conductivity measurements follow the reference model very well. The trend starts from 0.003 W/mK and uniformly increases to 0.008 W/mK, with a slope of 0.0002 W/mK per year. The thermal conductivity in this sample approximately increases by

160% over 25 years. In this type of sample, based on Table 3, the effect of λ_p is dominant. For Type 3, the thermal conductivity value increases by about 70% over 25 years, as thermal conductivity begins with 0.0041 W/mK and slowly reaches 0.0045 W/mK. Figure 3 shows a small increase for Type 4 thermal conductivity measurement over time, where thermal conductivity starts from 0.0041 W/mK and reaches to 0.0055 W/mK and it shows 34% of thermal conductivity increase. This thermal conductivity shows a linear trend with a slope of 0.00006 W/mK per year. Type 5 has a trend with a thermal conductivity raises up to 10%, and based on Table 3, it has a low gas thermal conductivity.
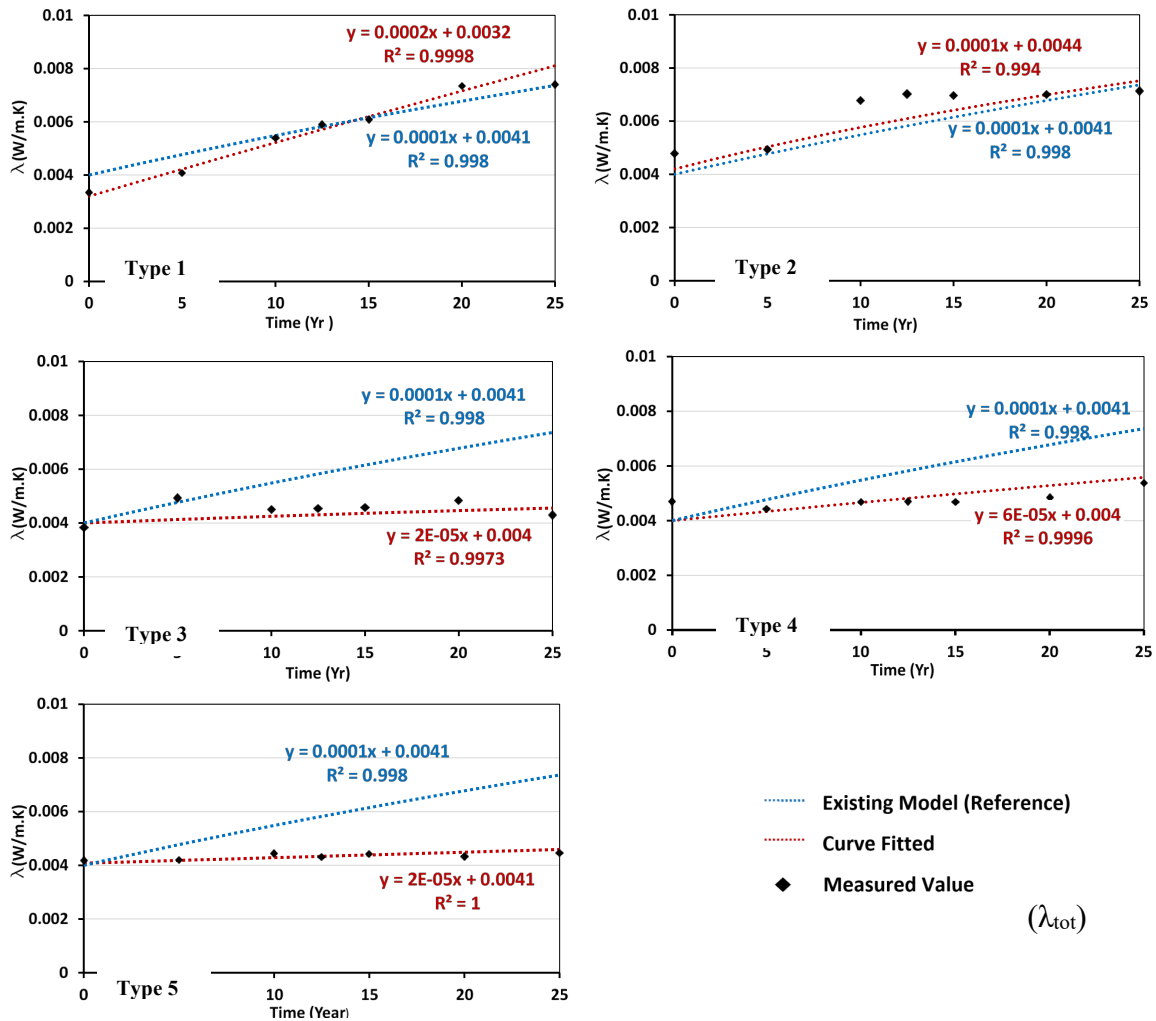

Figure 3. Thermal conductivity trend for different VIPs over time.

4 Discussion and Conclusions

Service life is one of the main characteristics of VIP assessment. The threshold value for the first definition of service life (ASTM C1484) is assumed to be 0.008 W/mK and 0.011 W/mK based on different references (Tenpierik *et al.*, 2010).

The threshold limitation and the service life of each specimen are reported in Table . Types 3 and 5 have the most extended service life among other types, formerly it followed by Types 4, 2, and 1 respectively.

6

Table 4. Service life of VIPs samples under test.

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Service life for 0.008 W/mK	25 years	30 years	> 100 years	70 years	> 100 years
Service life for 0.011 W/mK	40 years	65 years	> 100 years	> 100 years	> 100 years

The primary variables which define the quality of VIPs are the density of the core, the transmission rates of gas, and water vapor through the film barrier. Here, the test results collected from thermal conductivity measurements show that the thermal performance of the samples is mainly affected by temperature and, the amount of effect by moisture is minimal as they were also exposed to different levels of humidity without any appreciable results.

The analysis of the collected results represents that gas permeance is the factor that has the most considerable influence on VIP performance. The obtained results of Sample 1, 2 prove that the thermal resistance of the vacuum insulation panels reduces over time because of their higher gas and moisture transmittance. The thermal performances of Types 3, 4 and 5 are more stable. By comparing Types 1 and 3, it is obvious that the core materials with lower pore sizes have longer life spans due to less gas concentration. More results are reported in the paper Berardi *et al.*(2020).

Overall, the experimental analysis shows that:
- The thermal conductivity increases about 1%-2.5%, 2%, and 5%-11% a year, on average for compressed microporous silica-based, for compressed microporous silica with cellulose fiber, and for compressed microporous silica with cellulose fiber respectively.
- A small variation of thermal conductivity for compressed microporous silica and fiberglass-based cores was observed at temperatures below 0 ºC. However, since their core material porosity is dissimilar, they present different thermal conductivity behavior. The performance of the VIP microporous silica type is moderately better than that of the fiberglass over time.
- Although the initial thermal conductivity of VIP with fiberglass core is less than that of the compressed microporous silica one, fiberglass shows a significant increase in thermal conductivity after aging.
- The numerical reference model used by NRC is adapted for VIPs with fumed silica and fiberglass-based core material. However, a different mathematical model needs to be developed for compressed microporous silica and compressed microporous silica with cellulose. A significant mismatch is observed between the theoretical model plotted in Fig. 3, and the measurement results of these types.

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