Hanita Coatings

Thermal Conductivity of VIPs as a Function of Internal Pressure

The insulation properties of a VIP panel are determined by its effective thermal conductivity, as described in Eq.1. The lower the thermal conductivity of the panel, the better the insulation properties.

$$(1)\ \lambda_{EFF} = \lambda_{COP} + \lambda_{TB}, \left[\frac{mW}{m \cdot K}\right]$$

Where:

λ_{TB} - The contribution to λ_{EFF} due to the heat conducted by the envelope - known as **the thermal bridge** effect. λ_{TB} stays constant along the VIP operation time and is dependent on the structure of the encapsulating laminate (metallized film or Al foil based).

λ_{COP} - The contribution to λ_{EFF} due to heat transferred through the **center of the panel** (from the hot side to the cold side). The value of λ_{COP} changes over time because of permeation in of atmospheric gases. The rate of change depends on the barrier properties of the film (permeation rates of water vapor and air).

The increase of λ_{COP} depends on the specific properties of the core material and the surrounding air pressure. Many organic and inorganic insulation materials (such as the commonly used glass fiber and fumed silica) with a porous, open cell structure are available to use as a core for VIPs. In such porous materials, specific heat conductivity can be defined as a function of gas pressure.

In porous materials, heat is propagated by three processes [1]: thermal conductance through the solid core (λ_S), IR radiation (λ_R) and heat convection (λ_{CV}) through the pores by the gas molecules, as presented in Eq.2,

$$(2)\ \lambda_{COP} = \lambda_S + \lambda_R + \lambda_{CV}, \left[\frac{mW}{m \cdot K}\right]$$

Since λ_S and λ_R do not depend on pressure, Eq.2 can be written as follows,

$$(3)\ \lambda_{COP} = \lambda_0 + \lambda(P), \left[\frac{mW}{m \cdot K}\right]$$

Where:

$\lambda_0 = \lambda_S + \lambda_R$ is the initial (immediately after evacuating the panel) thermal conductivity of the core material.

$\lambda(P)$ changes over time as the pressure inside the VIP increases due to the short term outgassing mechanism and long term gases permeation.

The amount of heat transferred by convection is determined by the density of gas molecules, which in turn determines the inter-particle collision frequency and the internal pressure. The influence of air pressure on the thermal conductivity of porous materials can be expressed analytically by the following formula [2]:

$$(4)\ \lambda(P)=\frac{\lambda_g}{1+2\beta K_n}$$

Where:

$$Kn=\frac{l\,mean}{\delta}\ \text{and}\ l\,mean=\frac{k_B\cdot T}{\sqrt{2}\cdot\pi\cdot d_g^2\cdot P_g}$$

where Kn - the Knudsen number - is the ratio between the mean free path. $l\,mean$ is the average distance the molecule passes between two collisions with other air molecules . δ is the characteristic pore size, d_g is the diameter of the gas molecules and β is a constant between 1.5 and 2.0, characterizing the efficiency of energy transfer when gas molecules hit the solid structure of the porous material. k_B and T are Boltzmann constant and temperature respectively. The constant β depends on the gas type, the solid material and the temperature. If we rewrite the previous Eq. (4) as a formula which accentuates the three main parameters for gaseous heat conduction in porous media as appears in Eq. (3) we get:

$$(5)\ \lambda(P)=\frac{\lambda_g(T)}{1+C\left(T/\delta\cdot P_g\right)}=\frac{\lambda_g(T)}{1+\left(P_{1/2,g}/P_g\right)}$$

Where:

λ_g is the thermal conductivity of the gas in open space (λg=25.5 mW/mK in the case of air)

$P_{1/2,g}=\frac{CT}{\delta}$ is the pressure at which the gas thermal conductivity reaches the value of one half of λ_g,

and C is a factor defined as $\frac{2\cdot\beta\cdot k_B}{\sqrt{2}\cdot\pi\cdot d_g^2}$. $P_{1/2,g}$ is the internal pressure at which the thermal conductivity of the panel increases by 12.5mW/mK over the value of λ_0.The value $P_{1/2,g}$ is strongly dependent on δ (the average pore size of the core material. The smaller the average pore, the larger the $P_{1/2,g}$.

For air molecules the relation between the average pores diameter ϕ and $P_{1/2}$ is given by:

$$(6)\ \phi(\text{in } \mu) = 230/P_{1/2}(\text{mbar})$$

Summary:

Summarizing all said above, the relationship between the thermal conductivity of VIPs and their internal pressure is given by:

$$(7)\ \lambda(P) = \lambda_0 + \frac{\lambda gas}{\left(1 + \frac{P_{1/2}}{P}\right)}$$

Where:

λ_0 is thermal conductivity at low pressure, such as $1\times10^{-2}\ mbar$ for glassfiber cores, and

λgas is the thermal conductivity of air in free space ($25.5\frac{mW}{m \cdot K}$). $P_{1/2}$ is the characteristic pressure that depends on the average pore size of the core material.

A proprietary method developed by Hanita for determining the characteristic values of λ_0 and $P_{1/2}$ of an inspected core material

This simple technique is based on simultaneous measurement of the internal pressure and the center of the panel thermal conductivity (see Figures (a) and (b) below).

(a) Sample for core material characterization

(b) Sample inside thermal conductivity measurement device (LaserComp FOX314)

At first, measurement of initial thermal conductivity λ_0 (hot plate at 35°C, cold plate at 10°C) is made after the whole system was evacuated by a turbo molecular vacuum pump. This ensures that the pressure inside the envelope is kept at a low level of 1×10-3 mbar.

Later on, controlled amounts of gas are injected into the envelope through the leak tight connector. The thermal conductivity is measured after each air injection together with corresponding pressure measurement.

The following Figure (c) shows the results of two tests on the same glass fiber core (not the same sample),

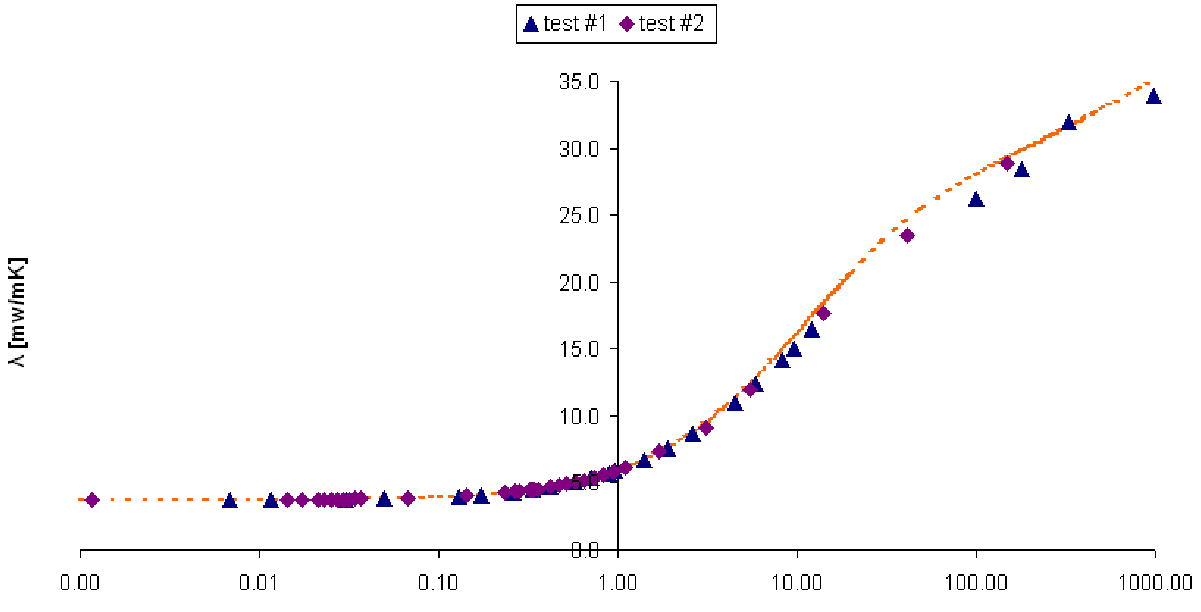

Figure (c): Thermal conductivity after gas injection

The blue and purple marks describe the test results, while the orange line is the best fitted plot of Eq.7. The characteristic parameters found for the tested FG core material are shown in Table 1.

$\lambda_0[mW/mK]$	$\lambda gas[mW/mK]$	$P_{1/2}[mbar]$
3.7	25.5	10.5

Table 1: FG parameters

There are wide varieties of core materials with different properties, and four of them are presented in Table 2 below:

Name	Type	$\lambda_0[mW/mK]$	$P_{1/2}[mbar]$
Type I	Glass fiber	1.75	3.2
Type II	Glass fiber	1.8	7
Type III	Glass fiber	2.65	14
Type IV	Fumed silica	3.8	670

Table 2: Core types

Figure (d) below shows the thermal conductivity of core materials as a function of pressure:

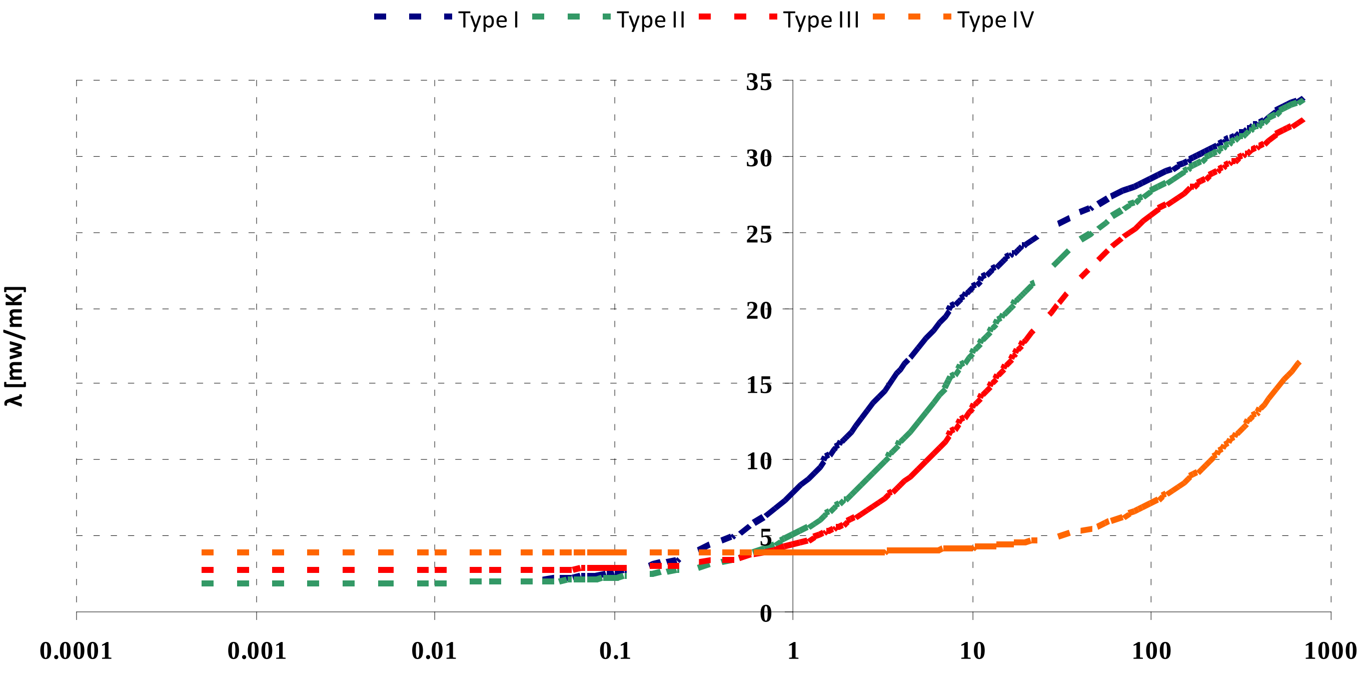

Figure (d): Thermal conductivity of the 4 types of core materials as a function of the internal pressure

The difference between the cores at low pressure is more obvious when the curves are plotted using linear pressure scale, as presented in Figure (e).

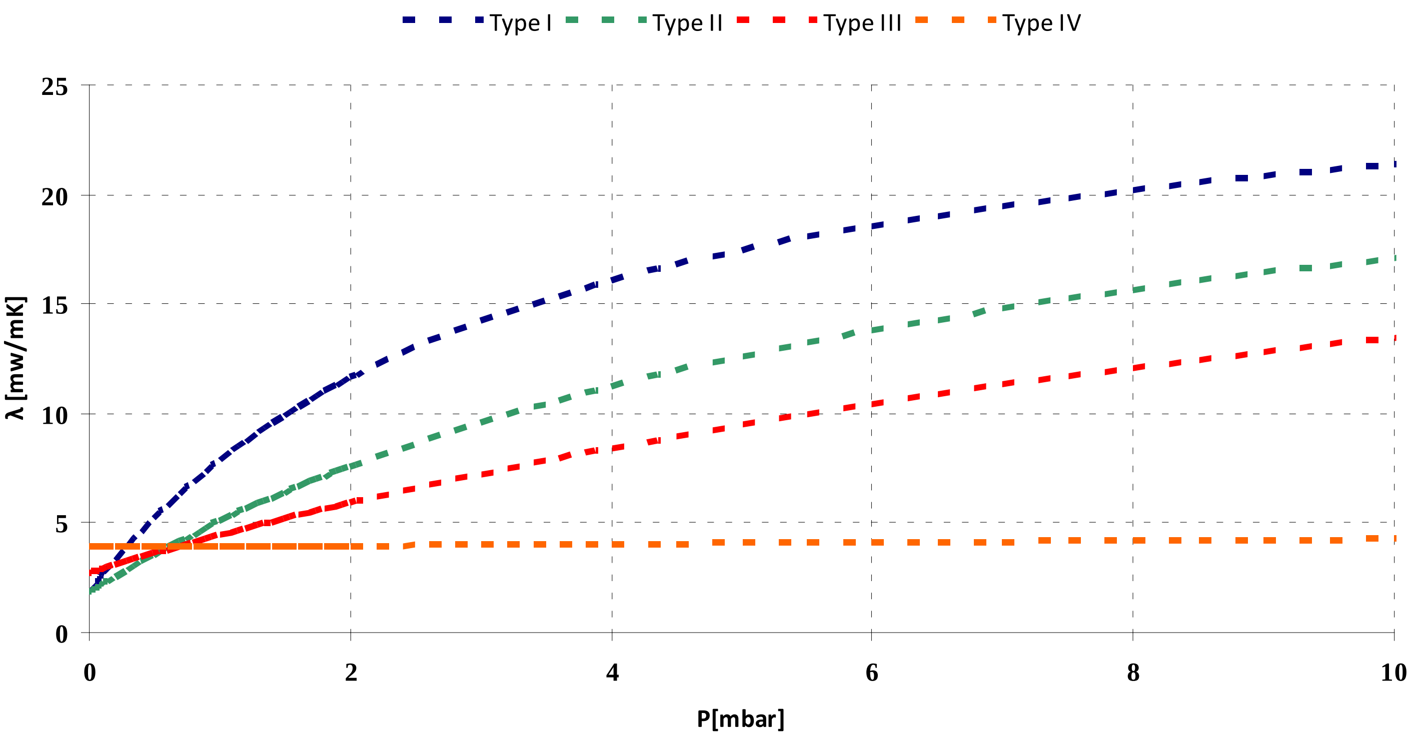

Figure (e): Thermal conductivity of core materials as a function of pressure - linear

The graph (f) below describes as an example how λCOP of the panels with the 4 different cores increase along 10 years of service life. For the calculation it was assumed that the same envelope was used for all 4 panels, and that the pressure increase rate at a steady state was 0.3 mbar per year for all.

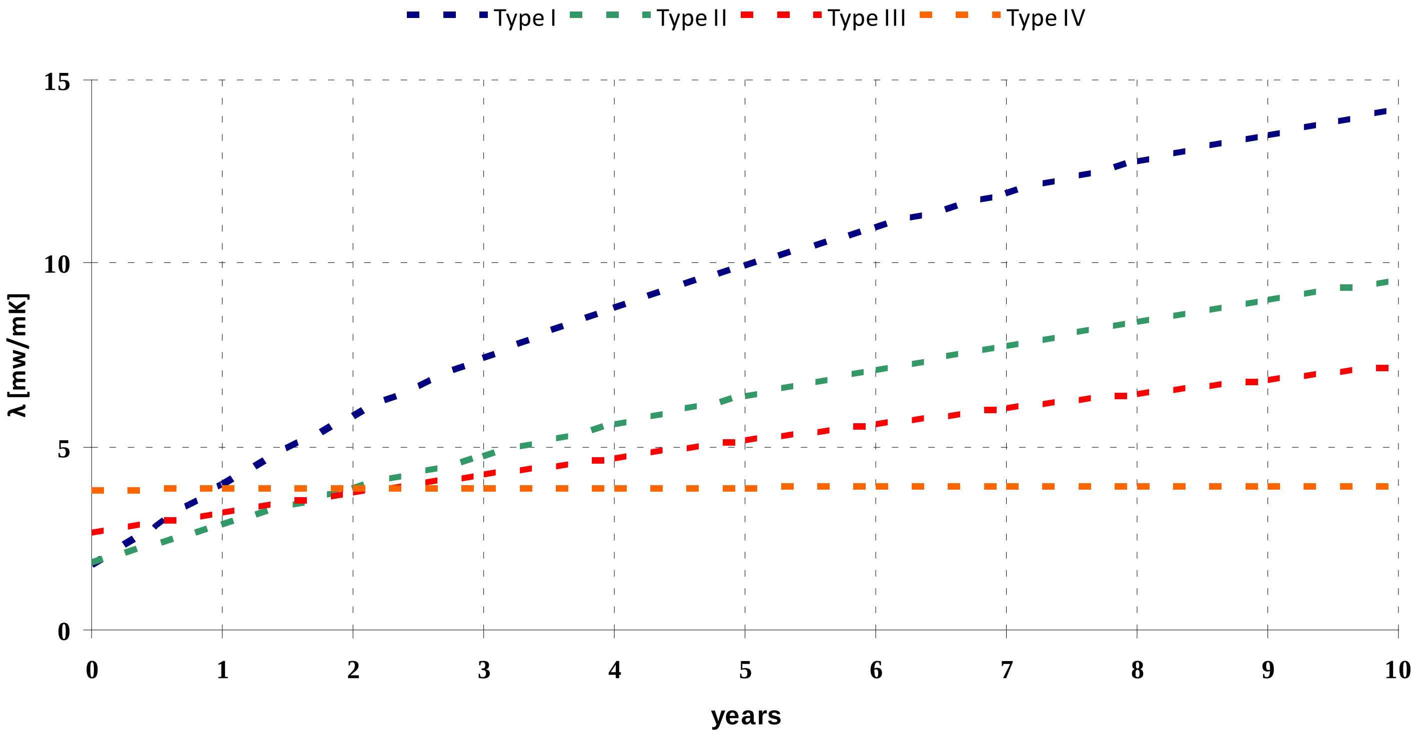

Figure (f): Thermal conductivity of different core material over panel lifetime

Remarks:

1. In real life, the thermal conductivity of a fumed silica panel (Type IV) will increase faster than described in the graph below due permeation of water vapor during the operation period. The permeated water molecules are absorbed by the FS powder particles causing λ_S to increase in time. Theoretically, the thermal conductivity of fumed silica increases by 0.5 mW/mK per 1%wt of absorbed H_2O molecules. In the case of FG cores, desiccants are always used and they ensure no effect of the water vapor permeation on λ as long as the desiccants have not been saturated.
2. The figure above describes only the thermal conductivity of the center of panel. In real life applications, the thermal bridge effect should be added to total thermal conductivity. A major part of the heat transferred may be due to thermal bridge, which is dependent on the envelope type and panel size.

References:

[1] H. Schwab, Vakuumisolationspaneele - Gas- und Feuchteeintrag sowie Feuchteun Wa¨rmetransport, PhD thesis, Bayerischen Julius-Maximilians-Universita¨ t Wu¨ rzburg, Wu¨ rzburg, 2004, 115 pp

[2] E.H. Kennard, Kinetic theory of Gases, with an Introduction to Statistical Mechanics, Mc-Graw-Hill, New York, 1938

[3] R. Caps, U. Heinemann, M. Ehrmanntraut, J. Fricke, Evacuated insulation panels with pyrogenic silica powders: properties and applications, High Temperatures- High Pressures 33 (2001) 151–156.

Eddie Shufer
Materials Science and Engineering, M.Sc.
R&D Ultra High Barrier Laminates
Hanita Coatings RCA Ltd