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Determination of Anisotropic Thermal Conductivity of VIP Laminate using Transient Plane Source Method

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ABSTRACT
The use of super insulation materials, such as vacuum insulation panels (VIP), is expected to increase in buildings in the future. One key aspect for successful implementation is the quality control. At the factory, the thermal performance can easily be controlled by measuring the internal pressure of the VIP. Preferably, the performance should be controlled again at the construction site before installation. The thermal conductivity of a VIP is possible to measure by using the transient plane source method (TPS). This method uses a sensor which measure the temperature increase during a heat pulse. For the analysis of the measurement, information on the thermal conductivity of the metalized multi-layer polymer laminate, used around the VIP, is needed. This paper presents the results obtained from different measurement setups of the laminate. The aim of the study is to identify a practical approach to analyse the results, and to give recommendations on the best measurement setup. Two measurement submodules were used; 'anisotropic' and 'thin film'. The thermal conductivity of the laminate was measured in-plane and perpendicular to in-plane. The volumetric heat capacity was measured by differential scanning calorimeter (DSC). The measurement results were compared to calculations. The results from the 'anisotropic' module was in best agreement with the calculated results. It was also illustrated that the TPS may be used for relative measurements to find damaged VIP.

KEYWORDS
VIP, laminate, thermal conductivity, TPS, measurement

INTRODUCTION
There is a large focus on reducing the energy demand for heating of buildings in Europe. The European Union has targeted an overall energy efficiency improvement by at least 32.5% by 2030 to achieve a highly energy efficient and decarbonised building stock by 2050. To reach these targets, the existing building stock needs energy retrofitting measures. One possible way of reducing the energy demand for heating is to use super insulation panels in the building envelope. An insulation material can be defined as a super insulation material when the thermal conductivity of the material is lower than 20 mW/(m·K). Super insulation materials yield a step-change in performance over conventional insulation materials but at significantly higher cost.

A construction site is generally a rough environment for all type of materials. Due to the fragility of the laminate surrounding the VIP, punctures before installation into building components on a construction site may lead to loss of the excellent insulation property. Therefore, controlling the function of the VIP at the construction site can be part of the quality assurance process for achieving a good quality of the building component. The transient plane source method (TPS) is an established method to measure thermal properties which could be used for fast determination of the functionality of VIP on a construction site. Previous studies on EPS covered by aluminum foil showed that there is a challenge to evaluate materials with highly anisotropic properties (Johansson et al., 2011; Johansson et al., 2012). For this purpose, an analytical solution was developed by Claesson (2012) which was compared to numerical simulations and TPS measurements for five setups; EPS, EPS covered by aluminum foil and VIP laminate respectively, and VIP (evacuated and punctured) (Johansson and Claesson, 2014). It was found that the material properties of the VIP laminate had to be better determined to make the TPS method applicable. Therefore, this paper presents results obtained from different measurement setups of the laminate using TPS. The aim of this study is to identify a practical approach to analyse the results, and to give recommendations on the best measuring setup.

METHODS

The TPS method, ISO 22007-2, uses a circular double nickel spiral, 10 µm thick, sandwiched between two layers of Kapton (polyimide film), each 25 µm thick, in contact with the material sample. The sensor is clamped between two samples of the same material and a constant electric power is conducted through the spiral. The heat raises the temperature and thus the resistance of the spiral. The rate of this temperature increase depends on how quickly the heat developed in the spiral is conducted away through the surrounding material. Heating is continued for a period of time, with the voltage across the coil being registered. As the power is held constant, the voltage changes in proportion to changes in the resistance of the coil. With knowledge of the voltage variation with time i.e., variation of temperature with time and the heat flow, it is possible to calculate the thermal conductivity and volumetric heat capacity of the material. The mathematical solution used in the TPS method is described by Gustafsson (1991).

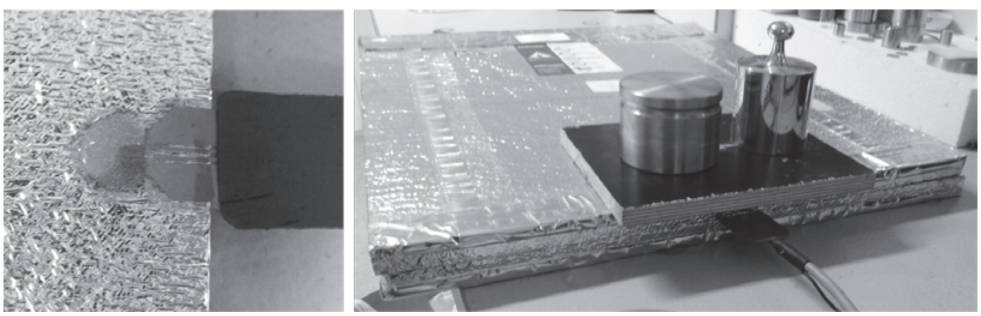

Figure 1. TPS sensor on a functioning VIP (left) and measurement setup with the sensor clamped between two VIP (right).

The TPS method offers several submodules that make it possible to measure isotropic and anisotropic material. Furthermore, it is possible to measure the thermal conductivity of thin films. However, the commercially available software for analysing the measured data by TPS method is not suitable for determination of the thermal conductivity of VIP. Thus, two approaches were investigated. In the first approach, ‘relative measurement’ of evacuated and punctured samples was used. The second approach needs accurate determination of thermal properties of VIP i.e. protection layer and the core material of a VIP. Furthermore, the measured data by TPS method should be analysed by a heat transfer software.

RESULTS

Measurement results obtained by the relative measurements and two different setups are presented in the following sections.

Results from the relative measurement

The TPS method, submodule ‘isotropic’, was used for the determination of the thermal conductivity of two VIP samples, one evacuated and one punctured. The selected submodule is used as baseline for all other measurements. The measurement time was 160s. The measurement results are presented in Table 1 as mean values of eight repeated measurements.

Table 1. Measured thermal properties of evacuated and punctured VIP.

Samples VIP	Thermal conductivity (W/(m·K))	Thermal diffusivity (mm^2/s)	Volumetric heat capacity (MJ/m^3K)	Penetration depth (mm)
Evacuated	0.026	0.127	0.202	8.57
Punctured	0.040	0.153	0.259	9.39

The measurement results deviate significantly from the expected thermal conductivity. The deviation is caused by the unknown properties of the VIP laminate which is highly conductive and anisotropic, compared to the VIP core material. However, the results in Table 1 also show a significant difference between the evacuated and punctured sample. Therefore, the method could be used as a 'relative method' for identification of damaged VIP. The measurement time was 160 seconds which could be reduced to 80 seconds with the same measurement results.

Characteristics of the VIP laminate

In the second approach, the thermal conductivity of the laminate and core material should be determined. The protection layer in this type of VIP is a thin metalized multi-layer polymer laminate, see Figure 2, with a thickness of about 100 µm. Determining thermal properties of thin films is a challenge, especially when the film is anisotropic.

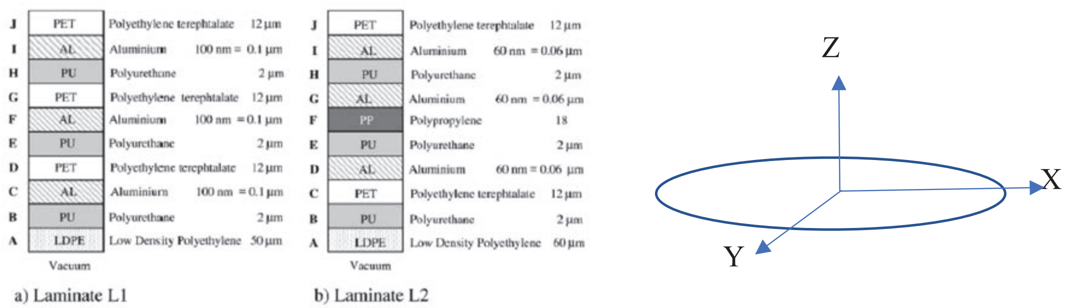

Figure 2. Examples of composition of VIP laminate (left). Illustration of the anisotropy (right).

Theoretically determined thermal properties of the VIP laminate

The thermal properties of laminate L1 and L2 were calculated to be used as a reference value for the measurement results. The calculations are based on literature values and series/parallel coupled thermal resistance (electrical circuit model), see results in Table 2. The ranges are caused by the variation of thermal properties of the different layers found in the literature.

Table 2. Calculated thermal properties for the laminates under observation

Thermal properties	Laminate L1	Laminate L2
λ_z (W/(m·K))	0.133-0.17	0.144-0.165
λ_{xy} (W/(m·K))	0.97-1.07	0.61-0.68
C_p (MJ/m^3K)	1.619	1.733

Measured thermal properties of the VIP laminate

The thermal properties of the VIP laminate were measured by using two different TPS method submodules; 'thin film' and 'anisotropic'. The 'thin film' module provides the thermal conductivity (λ_z) perpendicular to the surface of the thin film. The mean value of λ_z for four repeated measurement was 0.19 W/(m·K) which was about 10% higher than the maximum calculated values in Table 2.

The ‘anisotropic’ module needs information on the volumetric heat capacity of the laminate. Therefore, the heat capacity was measured using differential scanning calorimeter (DSC). The measured volumetric heat capacity was 1.745 MJ/(m^{3}K). This is in good agreement with the calculations for L1 and L2 in Table 2. The results of the anisotropic measurements are presented in Table 3.

Table 3. Calculated and measured thermal properties by the ‘anisotropic’ module.

Thermal properties	Calculated L1	Calculated L2	Measurement
λ_z (W/(m·K))	0.133-0.17	0.144-0.165	0.175
λ_{xy} (W/(m·K))	0.97-1.07	0.61-0.68	0.958
C_p (MJ/m^{3}K)	1.619	1.733	1.745

CONCLUSIONS

A quality assurance procedure is needed for controlling the performance of VIPs at the construction site. The results of the measurement presented in this paper indicate the TPS method can be used as an in-situ measurement method, using a relative measurement procedure. More research is needed to use the TPS method for absolute measurements of the thermal conductivity of a VIP.

Two TPS measurement modules were used to determine the thermal conductivity of the multi-layer aluminum laminate around a VIP. The setup ‘anisotropic’ was in very good agreement with the calculations.

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