Measurements of Thermal Properties of Vacuum Insulation Panels by using Transient Plane Source Sensor

P. Johansson[1], C.-E. Hagentoft[1], B. Adl-Zarrabi[1]
[1]*Chalmers University of Technology, Gothenburg, Sweden*

Abstract

At the construction site only visual, physical and dimension controlling of Vacuum Insulation Panels (VIP) are possible. However, there is a need of fast and accurate determination of the thermal properties of the product. The properties can be measured using a direct measurement method such as the Transient Plane Source (TPS) method. To investigate whether the method could be suitable to measure VIP, the recorded temperature increase and the supplied heat flow by the TPS sensor was used in a numerical analysis. An analytical solution was developed to study the heat propagation in the foil material. In order to simplify the TPS measurements, the VIP was replaced with polystyrene with and without aluminium foil. As expected, there was little consistency between the measurement results of VIP with the TPS method and values for VIP found in the literature. The numerical and analytical analysis, together with the TPS measurements, pinpoints the problems with use of conventional TPS. The presented analysis gives some promising results indicating the feasibility of modification of the method.

1 Introduction

Vacuum Insulation Panels (VIP) consists of two main parts, the porous core material and the encapsulating impermeable foil, maintaining the vacuum in the core. The panels are very prone to damages during manufacture and on the construction site. A perforated panel has a five times higher thermal conductivity than new evacuated ones. During the service life of the panel, the intrusion of gases and moisture into the panel raise the thermal conductivity so that it is around twice the original thermal conductivity after 25 years [1].

Users of building materials need assurance concerning quality and performance of the product in a building e.g. thermal performance. Thus, the thermal properties of a product need to be determined and evaluated. At the construction site only visual, physical and dimension controlling of VIP products are possible, which only can give an indication of the state of the panel. At the manufacturing facility, the pressure can be measured in a vacuum chamber with the “foil lift-off method”, with the suction cup measurement or with an integrated pressure sensor in the panel [2]. However, these methods rely on the empiric relation between pressure and thermal conductivity which give rise to some uncertainties in the results, why direct measurements of the thermal properties are preferred.

The thermal conductivity, λ (W/m/K), of low conductive materials is commonly measured in a guarded hot plate apparatus [3]. VIP have different thermal properties in the foil and core material, which increases the difficulties in measuring the thermal properties of the assembled material. Transient measurement methods e.g. the Transient Plane Source (TPS), also give the possibility of measuring the thermal diffusivity (m^2/s), of the material. The methods have been developed to speed up the measurement time and thereby lower the cost of the measurement process. This paper aims to explore the propagation of heat in layered thermal insulation materials using transient measurement. Numerical and analytical solutions are compared to results from TPS measurements. The general and specific procedures for measurements of thermal properties by the TPS method are described in ISO 22007-2 [4]. However, a short description of the method is necessary for understanding the measurement results presented in this paper.

2 TPS method

Silas Gustafsson, Chalmers University of Technology, Sweden, first demonstrated the TPS principle in 1979 [5]. The TPS method involves the use of a very thin double metal spiral, 10 μm thick, sandwiched between two layers of Kapton, 25 μm thick, in close contact with the material to be investigated. The double metal spiral serves both as the heat source and as a resistance thermometer. When making measurements in solid bodies, the sensor is clamped between two surfaces of the same material, as shown in Figure 1.

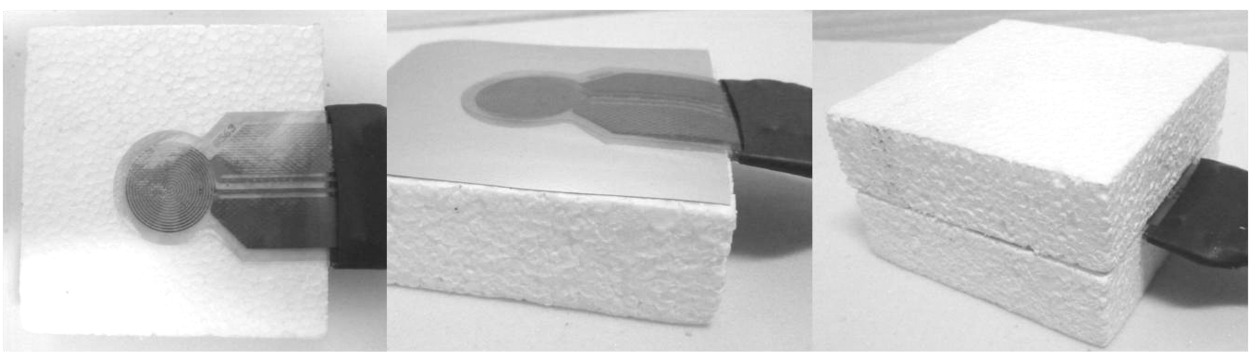

Figure 1. a) TPS sensor on polystyrene, b) TPS sensor on polystyrene covered with aluminium c) TPS sensor clamped between two samples of polystyrene.

Passage of a constant electric power through the spiral develops heat, raising the temperature and thus the resistance of the spiral. The rate of this temperature rise 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 specific heat capacity of the material.

3 Thermal properties of VIP

The principle of the TPS method is not suitable for measurement of thermal conductivity of the VIP. However, as long as the applied heat flow and the temperature increase can be measured, it is possible to analyze the measurement data by the TPS sensor for determination of thermal conductivity of the VIP products.

3.1 Measurement of VIP with the TPS method

The thermal conductivity of a VIP was determined by the TPS method with the associated mathematical model. The power output, measuring time and sensors radius were 0.02 W, 1280 s and 6.4 mm, respectively. The result of the measurement is presented in Table 1. The presented results are related to different choice of time windows.

Table 1. The measured thermal conductivity of the VIP.

Measuring Time s	Thermal conductivity W/m/K	Thermal diffusivity mm^2/s
32-160	0.0268	0.1477
32-320	0.0269	0.1388
32-640*	0.0271	0.1244
32-960*	0.0272	0.1138
32-1280*	0.0274	0.1055

* The time window did not fulfil the requirements related to the mathematical model associated with the method.

The predicted thermal conductivity in the literature is about 4-8 mW/m/K [1]. The measured thermal conductivity by the TPS method was three to six times higher than the predicted value. This deviation was expected. The TPS sensor was in contact with the protection layer of the VIP which has a high thermal conductivity in comparison to the core of the VIP.

3.2 Using TPS sensor compared to numerical simulation

It is assumed that the deviation in the results from the TPS measurement of the VIP depends on the influence of the protection layer. Thus, new measurements with new setups were conducted. The basic idea was to use the measurement results: temperature increase and heat flow, for further numerical analysis to determine the influence of the protection layer of the VIP. In order to simplify the measurements, the VIP was replaced with polystyrene.

In the first measurement, thermal properties of the polystyrene specimens were determined by TPS method. Furthermore, the measurement setup was simulated by heat transfer software HEAT3, using the measured thermal properties of the polystyrene as input data. The numerical software uses finite differences to solve three-dimensional transient heat conduction [6]. Finally, the recorded temperature increase by TPS sensor was compared to the calculated temperature increase by HEAT3.

The power output and measuring time was 0.02 W and 40 s respectively, i.e. the totally emitted heat flow was 0.8 J. In the numerical model, the power needs to be lowered to take the heat capacity of the Kapton layer surrounding the sensor into account. The TPS measurement of polystyrene gave the thermal conductivity and volumetric heat capacity of 0.032 W/m/K and 0.051 $MJ/m^3/K$ respectively. This data corresponds well with measurements of the thermal conductivity of expanded polystyrene found in the literature and from reference measurements in guarded hot plate at SP Technical Research Institute of Sweden. This data was used in the three-dimensional fine grid numerical simulation and analytical solution. The comparison between the measured and calculated temperature increase is presented in Figure 3.

3.3 Influence of the protection layer

In order to investigate the influence of the protection layer a new setup was used. The setups involved specimens of polystyrene covered once by pure aluminium foil and once by the protection layer of the VIP, see Figure 2. The thermal properties of the protection layer were not known, thus by using pure aluminium foil with known properties, the influence of the protection layer could be studied.

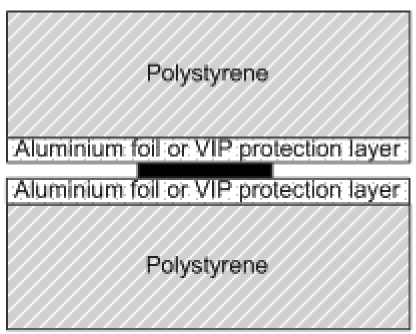

Figure 2. The setups for determination of the protection layer's influence.

The measured thickness of the aluminium foil and protection layer of the VIP were 0.01 mm and 0.1 mm respectively. The average dimensions of the polystyrene were about 70x70x20 mm (length, width and thickness) and the average weight of the specimens was 2.9 g which gives a density of 28.7 kg/m^3. The thermal conductivity and heat capacity of aluminium, used in the numerical model are 226 W/m/K and 2.48 $MJ/m^3/K$.

The temperature increase measured by the TPS sensor and the numerical simulations of the setups with only polystyrene and polystyrene covered with aluminium foil and are shown in Figure 3. For comparison, the result from TPS measurement of polystyrene covered with a VIP protection layer is also shown in Figure 3.

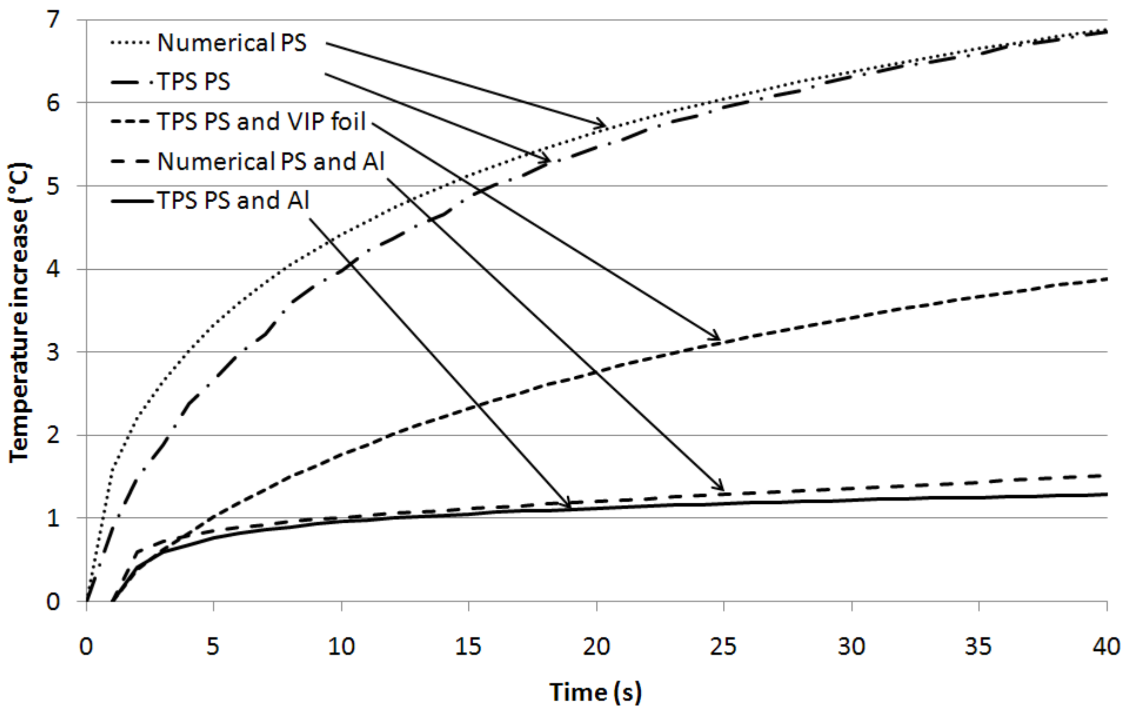

Figure 3. The recorded temperature increase by TPS sensor and the calculated temperature increase by HEAT3. Comparisons for only polystyrene (PS) and polystyrene covered with pure aluminum (PS and Al) or VIP protection layer (PS and VIP foil).

As expected, the temperature increase was much lower when the polystyrene was covered by aluminium. A comparison between measured and calculated values showed good agreement. The measurement results for the polystyrene covered with the VIP protection layer showed that the heat was transferred slower in this foil compared to the pure aluminium foil.

4 Analytical solution

The measurements on aluminium foil and polystyrene indicated that a large part of the heat is transported away from the sensor area through the highly conductive foil. In order to study the temperature process in the foil, an analytical solution for the case of an infinite long hollow cylinder with infinite outer radius, with heat injected at the inner radius, was analyzed. This corresponds to the case with a foil surrounded by highly insulating materials on both sides, i.e. approximately the case with negligible heat flowing from the foil to the surroundings.

From [7] we can deduct the following analytical temperature solution:

$$T = \frac{Q}{d\lambda} f\left(\frac{\sqrt{at}}{r_0}, \frac{r}{r_0}\right) \qquad f(\alpha,\beta) = -\frac{1}{\pi^2}\int_0^\infty \left(1 - e^{-s^2\alpha^2}\right)\frac{J_0(s\beta)Y_1(s) - Y_0(s\beta)J_1(s)}{s^2\left(J_1^2(s) + Y_1^2(s)\right)}ds \qquad (1)$$

Here, Q (W) is the heat injected at the inner radius, r_0 (m). The thickness of the foil is denoted by d (m).The thermal diffusivity is denoted by a (m^2/s) and the thermal conductivity is λ (W/m/K)). The formula is expressed by an integral containing the Bessel function of the first and second kind.

The formula will give the maximum propagation of heat into the foil, neglecting the heat loss into the surrounding thermal insulation. Figure 4 shows the function f for different distance, r/r_0, from the interior of the cylinder where the heat is released and different times $\sqrt{at}/r_0$.

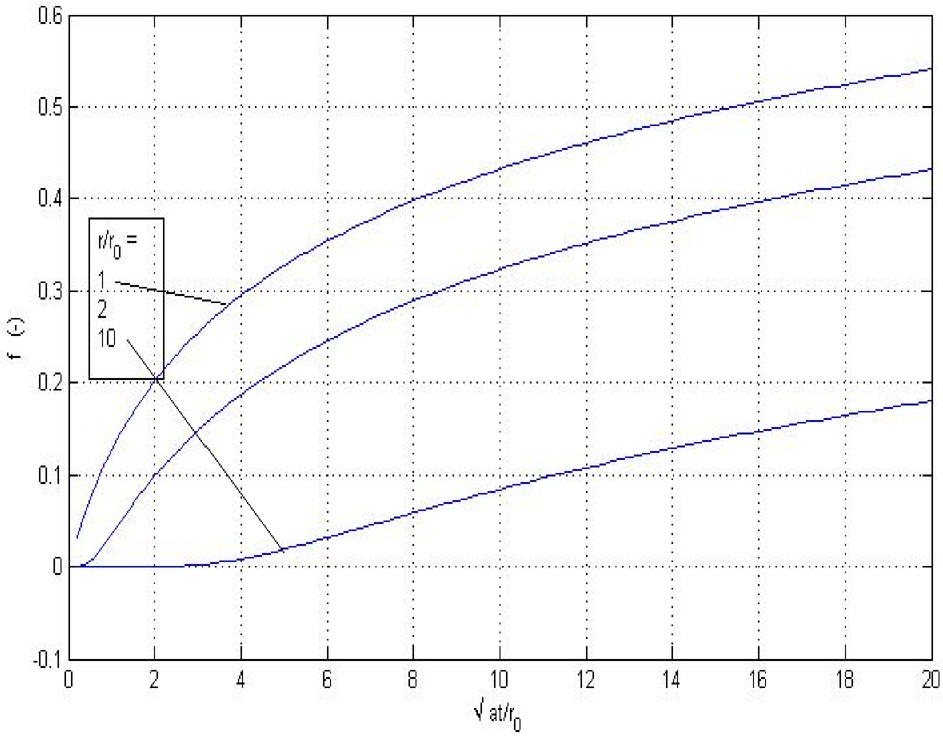

Figure 4. The function f for different distance, (r/r_0=1, 2, 10) from the interior of the cylinder where the heat is released and different times $\sqrt{at}/r_0$

Using the data for a single layer of aluminium foil with the thickness 0.01 mm, a released heat of 0.02 W at the radius 3 mm, we have at the periphery of the sensor area after 40 seconds:

$$\frac{Q}{d\lambda}=\frac{0.02}{2\cdot 10\cdot 10^{-6}\cdot 226}=4.43 \qquad \frac{\sqrt{at}}{r_0}=\frac{\sqrt{226/900/2700\cdot 40}}{3\cdot 10^{-3}}=20.3 \qquad (2)$$
$$r/r_0=0.0064/0.003=2.13$$

The value for f becomes 0.42 and T becomes 1.9. This is approximately a 48% to high temperature compared with the measurements results. Figure 5 shows the temperature distribution and how it progress at different dimensionless times.

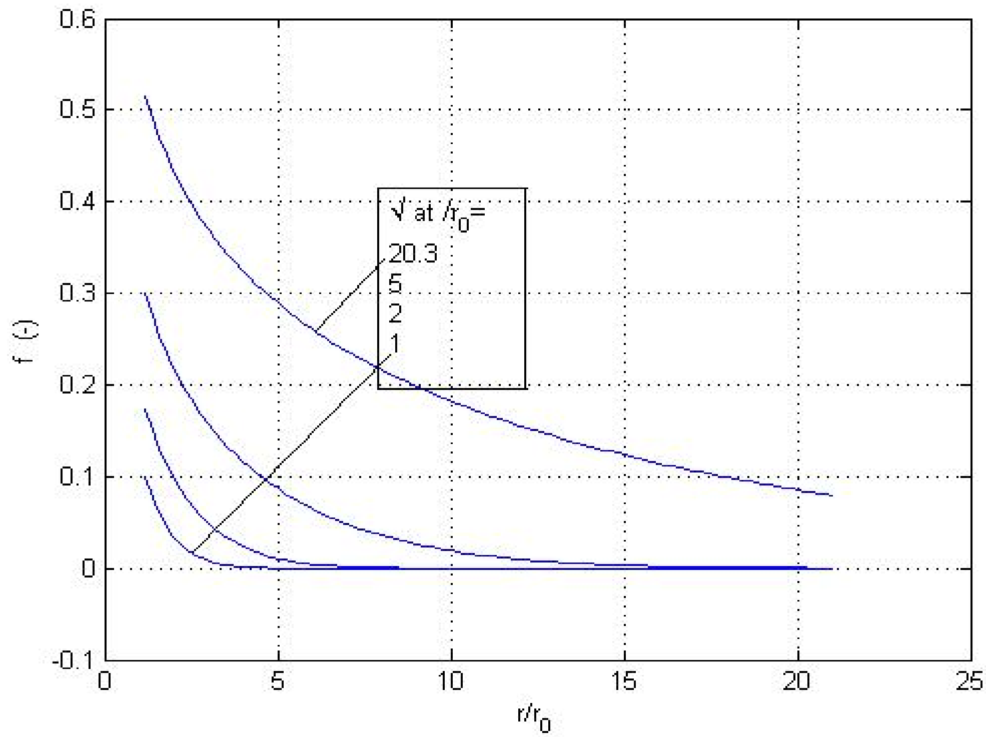

Figure 5. Temperature distribution at different dimensionless times ($\sqrt{at}/r_0$ =1, 2, 5, 20.3).

In order to estimate the heat uptake by the polystyrene insulation materials on both sides of the foil, due to a step change in the temperature of ΔT, a simple one dimensional step-change approximation can be used [7].

$$E = 2\frac{2A\lambda_{PS}}{\sqrt{a_{PS}\pi}}\Delta T\sqrt{t} = 2\frac{2\cdot 0.07\cdot 0.07\cdot 0.032}{\sqrt{0.032/900/28.7\cdot\pi}}\Delta T\sqrt{40} = 2.0\cdot\Delta T \qquad (3)$$

This corresponds to an average power during the 40 seconds of:

$$\overline{Q} = \frac{2.0\cdot\Delta T}{40} = 0.05\cdot\Delta T \approx 0.05\cdot 4.43\cdot\bar{f} \approx 0.05\cdot 4.43\cdot 0.2 = 0.044 \quad \text{W} \qquad (4)$$

Here, $\bar{f}$ is the average value between r/r_0 equal to 6.4/3 and 70/3, i.e. between the sensor perimeter and the perimeter of the insulation layer, for the time $\sqrt{at}/r_0 = 20.3$ (corresponding to 40 seconds). The heat flow is around 2 times higher than the total heat released into the foil. It means that in a more detailed analysis, also taking into account the interaction between the insulation layer and the foil, the spread of heat through the foil out from the sensor area and into the insulation is substantial. It leads to a lower temperature increase in the area below the sensor i.e. the analysis will give a lower temperature, more in line with the measurements. This effect will be less dominant when using VIP protection layer instead of aluminium foil. However, when measuring on a VIP the thermal conductivity below the foil will be much lower, which once again make the heat flow out into the foil more of an dominant effect.

5 Conclusion and Discussion

TPS measurements and numerical simulations of the temperature increase in polystyrene samples with and without aluminium foil were conducted. The measurements and numerical simulations were in good agreement. An analytical solution was conducted which showed less agreement with the measurements and needs further refinement.

The current mathematical model used by the TPS method did not give accurate values for VIP. Therefore, the algorithm used to interpret the temperature increase of the sensor needs to be modified. It should take into account the thermal properties and thickness of the protection layer. The thermal analysis presented in this paper gives promising results indicating the feasibility of this type of modification. Further investigations are ongoing to e.g. find the relations between the heat flow in the foil and the temperature increase by time in the core material.

References

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