Analytical model to calculate the temperature increase in a low conductive material covered by a highly conductive layer

Pär Johansson, Lic.Tech. [1]
Johan Claesson, Professor [1, 2]

[1] Chalmers University of Technology, Sweden
[2] Lund University, Sweden

KEYWORDS: *TPS method, quality assurance, vacuum insulation panel, thermal conductivity, analytical solution, numerical model*

SUMMARY:
There is a lack of measurement methods that can be used to determine the thermal conductivity of vacuum insulation panels (VIPs) on the construction site. With the transient plane heat source (TPS) method, the thermal properties of an isotropic material can be evaluated after a short measurement period. Heat is supplied in the TPS sensor which raises the temperature in the sensor. The thermal properties of the material are calculate based on the temperature increase. A novel analytical solution of the TPS method makes it possible to use the method on a low conductive material covered by a highly conductive layer. The aim of this study is to investigate the applicability of the analytical solution by comparing it to a numerical calculation model and TPS measurements. Five different setups were tested with good agreement between the analytical solution and the numerical calculation model. The TPS measurements deviated from the calculated temperature increase which could be explained by uncertainties regarding the influence of the contact surface between the sensor and material.

1. Introduction

The energy use in the European buildings should be decreased with 20% by 2020 and 50% by 2050 compared to the year 1990 (European Parliament 2010). To reach these goals, existing buildings need to be retrofitted to increase the thermal resistance of the building envelope (IVA 2012). One limitation when retrofitting existing buildings is the demand on a maintained rentable floor area which limits the possible additional thickness of the added thermal insulation layer. The façade of the building should also be protected for its architectural and historical features which limits the possible systems using conventional thermal insulation materials such as mineral wool and expanded polystyrene (EPS). A solution could be to use highly efficient thermal insulation components such as vacuum insulation panels (VIPs) in parts of the building envelope. The required thickness is reduced by a factor of 5-10 when using VIP instead of conventional insulation materials with the same thermal resistance.

Apart from the use of VIPs in buildings, they can also be used as thermal insulation in refrigerators and freezers, as pipe insulation, for insulating boilers, etc. The different purposes put high demand on the durability of the component which is composed of two parts; the open porous core material and the envelope separating the evacuated core from the ambient environment. The most common core material for VIPs in buildings is fumed silica and the envelope is composed of a metalized multi-layer polymer laminate. To reach the low thermal conductivity of the VIPs it is important to ensure a low internal gas pressure since the thermal conductivity increases with increasing gas pressure, decreasing the service life of the component.

At the production site different quality assurance measures can be taken to make sure that the internal pressure is low enough when shipping the panels to the construction site. The foil lift-off method can be used to determine the internal pressure by reducing the ambient pressure in a pressure chamber until the laminate separates from the core material. Other available methods to measure the internal pressure are the spinning rotor gauge and remote sensing with active or passive chips using the RFID technique. Another approach is to measure the internal pressure by an indirect method, i.e. by measuring the thermal properties of the VIP. One of these methods is a patented technique where a metallic disk is inserted in the core material and a warm sensor is placed on the surface which is cooled down and the temperature decline registered for a short time period making it possible to determine the internal gas pressure (Caps *et al.* 2008). The transient plane heat source (TPS) method can be used in a similar way to determine the thermal conductivity by measuring the temperature increase in a sensor with a constant heat supply during a short time period.

The aim of this paper is to investigate the applicability and validity of a novel analytical solution of the TPS method on a low conductive material covered by a highly conductive layer. The analytical solution developed for this purpose is presented and elaborated in (Claesson 2012). In this paper it is compared to numerical simulations and TPS measurements exemplified in five setups: EPS, EPS covered by aluminum foil and VIP laminate respectively, and for functioning VIPs (evacuated) and damaged VIPs (punctured). The setup with EPS have been reported earlier in (Johansson *et al.* 2011) and (Johansson *et al.* 2012) where also the setup with EPS covered by aluminum foil was reported. The TPS measurements of the five setups were summarized in (Johansson 2012). The ultimate goal of this work is to develop the TPS method to be used at the construction site for measurements of VIPs after they have been installed in the building to ensure that the thermal performance becomes as good as possible.

2. Measurements with the transient plane heat source (TPS) method

The general and specific procedures of the transient plane heat source (TPS) method for measurements of thermal properties are described in ISO 22007-2. The method uses a sensor composed of a 10 μm thick double nickel spiral, sandwiched between two layers of 25 μm thick kapton (polyimide film). The spiral serves both as heat source and as electric resistance thermometer. A constant electric power is supplied through the spiral which develops heat by the electric resistance of the nickel, raising the temperature of the sample. The rate of the temperature increase depends on how quickly the heat developed in the spiral is conducted away through the surrounding materials. Heating is continued for a period of time, with the voltage across the spiral being registered. As the current is held constant, the voltage changes in proportion to changes in the resistance of the spiral. With knowledge of the temperature variation with time, i.e. variation of voltage, and the supplied heat flow, it is possible to calculate the thermal conductivity and volumetric heat capacity of the material. The sensor is clamped between two samples of the material as shown in FIG 1. It may be noted that the laminate surface becomes rugged due to the vacuum in the VIP that sucks the laminate inwards.

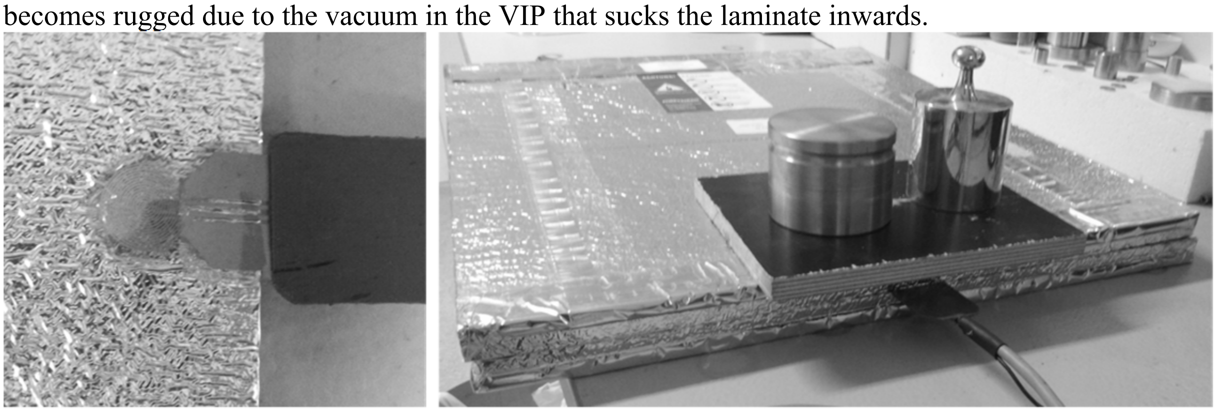

FIG 1. TPS sensor on a functioning VIP (left) and measurement setup with the sensor clamped between two VIPs (right). There is a pressure of 4.7 kPa applied on the upper sample to increase the contact with the sensor.

Measurements on the five setups with the TPS sensor was performed with a constant power of 20 mW applied during 160 s through the sensor with a radius of 6.4 mm. The average dimensions of the polystyrene were 70 mm x 70 mm x 20 mm (length x width x thickness) and the VIPs were 300 mm x 300 mm x 20 mm. The measured thickness of the aluminum foil and metalized multi-layer polymer laminate were 10 µm and 100 µm respectively. The samples were pressed together by applying a weight on top of the upper sample creating a pressure of 4.7 kPa. Each setup was tested at least 3 times with a break of 20 minutes between each measurement to make sure it was cooled down to the surrounding air temperature of 20.5°C.

2.1 Numerical model

The numerical model is based on the three-dimensional setup which is transformed into cylindrical coordinates. The heat source is clamped in the center of two identical material samples. During short calculation periods when only a small part of the heat has reached the boundary of the sample, the setup can be treated in the cylindrical coordinate system, see FIG 2. The thermal disturbance created by the heat source reaches the outer boundaries (two upper and four vertical ones) after a rather short time. These boundaries are treated as adiabatic, i.e. no heat passes through them. The solution presented here will not be correct when the thermal disturbance from the adiabatic boundaries reaches the heat source. The solution with these simplified boundary conditions is certainly correct during the first few minutes which are considered here.

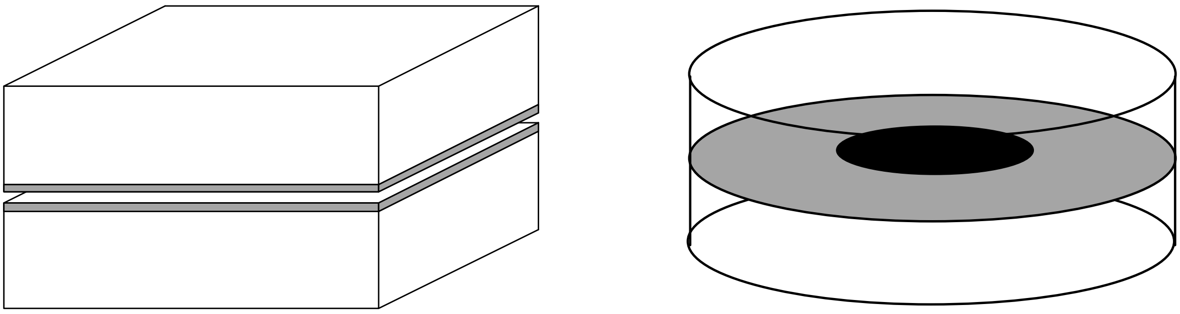

FIG 2. Test setup. Left: VIP with laminate in gray. Right: heat source in the center between two samples of the material. The three-dimensional setup is transformed into cylindrical coordinates.

The heat capacity and thickness of the sensor and the heat capacity of the laminate are disregarded in the model. The laminate is treated as an additional thermal conductance which is added to the thermal conductance of the first cell of the core material. The numerical calculations were performed in Matlab (R2009b) using a numerical finite difference calculation procedure (Hagentoft 2001). The numerical model was validated in (Johansson *et al.* 2012). The tabulated material properties that were used in the calculations are presented in TABLE 1. The weighted arithmetic mean of the thermal conductivities of the materials in the VIP laminate is 280-490 mW/(m·K). In this study a higher thermal conductivity was used which is based on the findings by Ghazi Wakili *et al.* (2011).

TABLE 1. Tabulated material properties for the materials used in the five setups. The properties of the EPS were measured with standardized measurement techniques.

Material	Thermal conductivity λ [mW/(m·K)]	Bulk density ρ [kg/m^3]	Specific heat capacity c [J/(kg·K)]	Thermal diffusivity $a = \lambda / (\rho \cdot c)$ [mm^2/s]
Aluminum	226 000	2 700	920	90.98
EPS	32	29	1 760	0.627
Silica (evacuated)	4	175	850	0.027
Silica (punctured)	20	175	850	0.134
VIP laminate	2 000	1 100	1 800	1.010

2.2 Analytical solution

The analytical solution for the heat supply over a part of a circular surface of an isotropic material can be derived from (Carslaw & Jaeger 1959). This solution is used for the setup with only EPS while for the four other setups there was no solution available in the literature. Claesson (2012) derived the analytical solution for the transient temperature in the point *r*, z (m) at time *t* (s) in an isotropic material covered by a thin highly conductive layer. The final solution is

$$T(r,z,t) = T_0 \cdot \int_0^\infty J_0(sr') \cdot J_1(s) \cdot f_c(s,z',t')ds \tag{1}$$

$$f_c(s,z',t') = \frac{2p}{s(a's+2p)} \cdot e^{-z's} - \frac{2}{\pi}\int_0^\infty e^{-s^2 \cdot t' - u^2 \cdot t'} \cdot I_f(u,s,z')du \tag{2}$$

$$I_f(u,s,z') = \frac{2pu}{s^2+u^2} \cdot \frac{2pu \cdot \cos(z'u) + \left[(a'-1)\cdot s^2 - u^2\right] \cdot \sin(z'u)}{\left[(a'-1)\cdot s^2 - u^2\right]^2 + 4p^2u^2} \tag{3}$$

$$T_0 = \frac{qR}{\lambda},\ r' = \frac{r}{R},\ z' = \frac{z}{R},\ t' = \frac{t}{t_1},\ t_1 = \frac{R^2}{a},\ p = \frac{R\rho c}{2D_0\rho_0 c_0},\ a' = \frac{a_0}{a},\ a_0 = \frac{\lambda_0}{\rho_0 c_0} \tag{4}$$

Here, T (°C) is the temperature increase due to the heat supply in the region $z = -D_0$ (m) with constant heat flux q (W/m^2) in the circular area with radius $r < R$ (m) and zero flux in $r > R$ (m). D_0 (m) is the thickness of the highly conductive layer with thermal conductivity λ_0 (W/(m·K)), density ρ_0 (kg/m^3) and specific heat capacity c_0 (J/(kg·K)). The properties of the isotropic material is given by λ, ρ and c, defined above. J_1 and J_0 are the Bessel functions of the first kind of the first and zeroth order.

The general solution for the *average* temperature increase in the sensor area is

$$T_{av}(t') = 2T_0 \cdot \int_0^\infty \frac{1}{s} J_1(s)^2 f(s,0,t')ds \tag{5}$$

with the parameters defined above.

3. Results

3.1 Measured temperature increase

Each setup was tested at least 3 times with a break of 20 minutes between each TPS measurement to make sure it was cooled down to the surrounding air temperature of 20.5°C. The results for the five setups are presented in FIG 3 where the average values for all the measurements of each setup have been calculated.

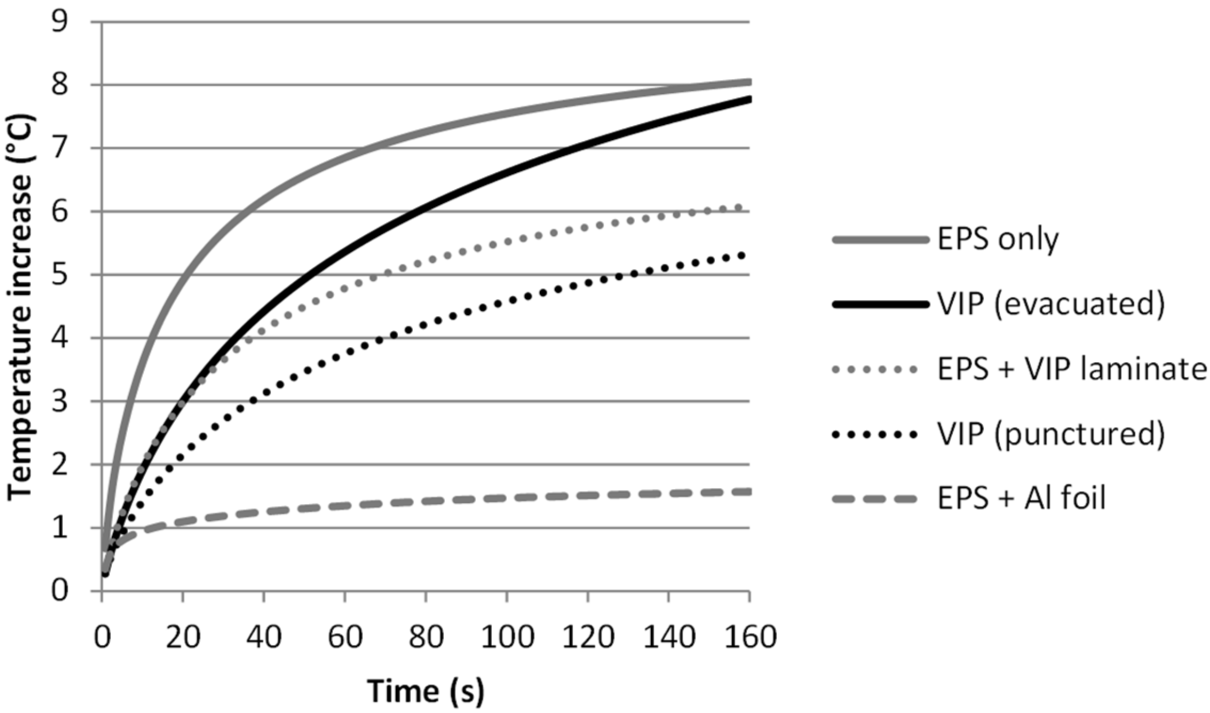

FIG 3. Average temperature increase in the five setups with a power of 20 mW supplied during 160 s in the 6.4 mm TPS sensor.

The temperature increased with 8.0°C in the EPS setup while it was lower for the two setups where the EPS was covered by the aluminum foil and VIP laminate. In these setups the heat was spread away from the sensor area through the highly conductive layer. The lowest temperature increase was found for the aluminum foil with 1.6°C while the VIP laminate gave a temperature increase of 6.1°C. Even though the VIP laminate is 10 times thicker than the aluminum foil, the heat was spread faster in the latter setup which shows the substantially higher thermal conductivity in the aluminum foil than in the VIP laminate.

To use the TPS method on the construction site to identify a damaged VIP, the difference in temperature increase has to be big enough between the evacuated and punctured VIP. For the evacuated VIP, the measured temperature increase was 7.8°C while it was 5.3°C for the punctured VIP. The thermal conductivity increases 5 times when the VIP is punctured while the temperature decreased with only 46%. Also, the temperature increase for the evacuated VIP and the EPS only differed by 0.2°C while the thermal conductivity of the evacuated VIP is one eighth of the EPS. This discrepancy shows the importance of the laminate and the possible influence by the contact heat transfer resistance between the sensor and laminate. The rugged laminate gets less rugged when the VIP is punctured compared to the evacuated VIP which increases the heat transfer through the laminate.

A reliable measurement procedure should have a low standard deviation for repeated measurements. One way to evaluate the reliability is by using the coefficient of variation (CV), i.e. the standard deviation divided by the average measurement result. The CV was 0.12% for the EPS setup while it was 0.79% and 0.21% for the EPS with VIP laminate and aluminum foil respectively. For the evacuated and punctured VIP setups, the CV was 0.56% and 0.18%. The low CV indicates a good reliability and repeatability of the TPS measurements on the five setups.

3.2 Comparison of the measured temperature increase to the calculations

The temperature increase from the numerical model, analytical solution and TPS measurements after 160 s are compared and presented in FIG 4. A constant power of 20 mW was applied during 160 s in the TPS sensor of 6.4 mm radius and the material data used in the calculations was presented in TABLE 1.

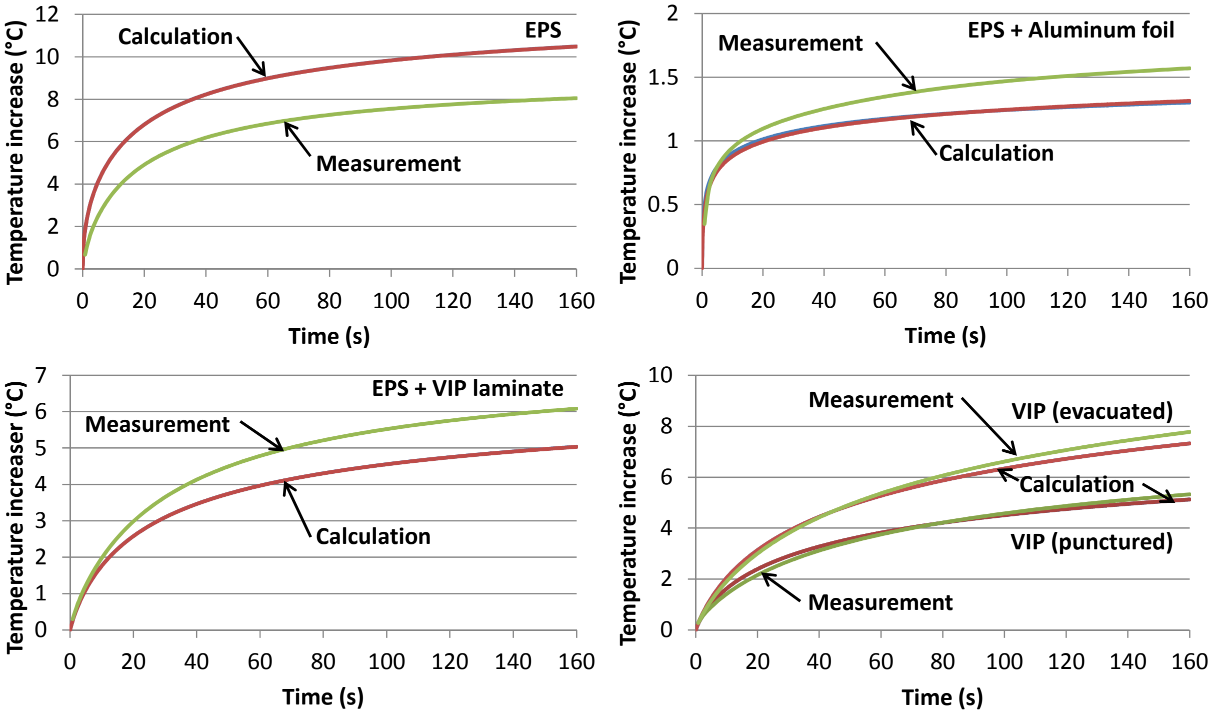

FIG 4. TPS measurements compared to the results from the numerical model and analytical solution for the five setups. EPS setup (top left), EPS covered by aluminum film (top right), EPS covered by VIP laminate (bottom left) and the punctured and evacuated VIP (bottom right).

The numerical simulations and analytical solution predicted a 30% higher temperature increase for the EPS setup than the TPS measurements showed. The difference between the numerical model and analytical solution after 160 s was 0.043%. The material properties used in the calculations of the EPS were measured with standardized measurement techniques which shows there is still more investigations needed for the effect of the contact heat transfer resistance between the material and the TPS sensor.

For the EPS covered by aluminum foil and VIP laminate, the measurement results were higher than the calculated temperature increase. The difference between the numerical calculation model and the analytical solution was 0.091% and 0.022% respectively after 160 s while the temperature increase was 17% lower than the measurements in both setups. The difference between the calculated and measured temperature increase could be caused by uncertainties regarding the thermal properties of the highly conductive layers and the properties of the contact surface.

The two VIP setups showed better agreement between the calculations and measurements. The difference between the numerical model and analytical solution was 0.037% and 0.029% for the evacuated and punctured VIP setups. After 160 s, the measured temperature increase was 5.8% and 3.8% lower than the calculated temperature increase for the two setups. Also here the different contact surfaces may be an important contributor to the difference between the calculated and measured temperature increase.

4. Conclusions

The analytical solution was compared to the numerical model with good agreement for all the five setups. The solution is therefore considered to be validated.

The CV was low for the five setups which indicate a good reliability and repeatability of the TPS method. The measurement conditions change when moving the equipment to the field which needs further investigations.

The measured temperature increase deviated from the calculated temperature increase in all the five setups. There are a number of factors which could influence the temperature increase in the area of the sensor. The thermal properties of the highly conductive layer on top of the low conductive material determine the spread of heat outside of the sensor area while the properties of the low conductive material determine how fast the heat is spread in the perpendicular direction. Only the thermal properties of the EPS were fully known by the use of standardized measurement techniques, while the other material properties were taken from the literature.

When the VIP is punctured and the pressure on the laminate around the core is reduced, the contact surface between the TPS sensor and sample is increasing. The changed gas pressure on the laminate changes the ruggedness of the laminate surface, which means that more heat can be transported away from the sensor area through the laminate. Therefore it is essential to know the thermal properties of the laminate and the required amount of pressure applied on the sample to increase the contact area with the sensor. The reduced ruggedness of the laminate gives a flatter surface, with less entrapped air which leads to a lower surface heat transfer resistance.

Research remains to make the TPS method applicable for measuring the thermal properties of VIPs in field. The contact heat transfer resistance needs further investigations and the influence by the loss of vacuum on the rugged contact surface should also be investigated. Also the material properties of the VIP laminate should be better determined by standardized measurement techniques.

5. Acknowledgements

The work is supported by the Swedish Research Council Formas. Thanks to Jimmy Forsberg and Remi Sørensen who made some of the TPS measurements in their Bachelor's thesis project at Chalmers University of Technology.

References

Caps, R., Beyrichen, H., Kraus, D., & Weismann, S. 2008. Quality control of vacuum insulation panels: Methods of measuring gas pressure. Vacuum, 82(7), 691-699.

Carslaw, H. S., & Jaeger, J. C. 1959. Conduction of heat in solids. 2nd ed. London, UK: Oxford University Press. (Eq. 4, p. 264).

Claesson, J. 2012. Mathematical report: heated disk in contact with insulation material covered by thin highly conductive layer (Report 2012:11). Gothenburg, Sweden: Chalmers University of Technology, Department of Civil and Environmental Engineering.

European European Parliament. 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings (recast). Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32010L0031:EN:NOT.

Ghazi Wakili, K., Stahl, T., & Brunner, S. 2011. Effective thermal conductivity of a staggered double layer of vacuum insulation panels. Energy and Buildings, 43(6), 1241-1246.

Hagentoft, C.-E. 2001. Introduction to building physics. Lund, Sweden: Studentlitteratur.

IVA. 2012. Energieffektivisering av Sveriges flerbostadshus: Hinder och möjligheter att nå en halverad energianvändning till 2050 (Energy efficiency in the Swedish multi-family building stock: obstacles and possibilities to reach a halved energy use by 2050). [In Swedish]. Stockholm, Sweden: Kungl. Ingenjörsvetenskapsakademien (IVA).

Johansson, P. 2012. Retrofitting of old Exterior Wall with Vacuum Insulation Panels: Meaurements of Thermal Properties, Moisture Performance and Practical Considerations (Lic. Thesis 2012:2). Gothenburg, Sweden: Chalmers University of Technology, Department of Civil and Environmental Engineering.

Johansson, P., Adl-Zarrabi, B., & Hagentoft, C.-E. 2011. Measurements of Thermal Properties of Vacuum Insulation Panels by using Transient Plane Source Sensor. Proceedings of the 10th International Vacuum Insulation Symposium, Ottawa, Canada, September 15-16, 2011.

Johansson, P., Adl-Zarrabi, B., & Hagentoft, C.-E. 2012. Using Transient Plane Source Sensor for Determination of Thermal Properties of Vacuum Insulation Panels. Frontiers of Architectural Research, 1(4), 334-340.

SS-EN ISO 22007-2:2008. Plastics - Determination of thermal conductivity and thermal diffusivity - Part 2: Transient plane heat source (hot disc) method. Geneva, Switzerland: International Organization for Standardization (ISO).