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RESEARCH ARTICLE

Using transient plane source sensor for determination of thermal properties of vacuum insulation panels

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Abstract
The energy use in buildings has to be decreased to reach the targets and regulations in the European Union. One way of reducing the energy demand is to use vacuum insulation panels (VIP) in the building envelope. To make sure the declared thermal properties of the VIP are valid for the mounted panels, in situ measurements are needed. The transient plane source (TPS) method allows fast measurement of the thermal properties of a variety of materials. However, the large anisotropy of the VIP makes it hard to interpret the temperature increase in the TPS sensor. This paper presents a comparison between an analytical solution, numerical simulations and TPS measurements of polystyrene and polystyrene with aluminum film. Polystyrene and aluminum were used instead of VIP to increase the number of setups. The numerical simulation model was validated by comparing the simulated temperature increase with an analytical solution for the polystyrene sample. The simulated temperature increase in the polystyrene sample after 40 s was 7.8% higher than the TPS measurements. For the case with polystyrene with aluminum film, the deviation was 5.7%. Losses in the wires of the TPS sensor, uncertainties regarding the material parameters and surface resistances could explain the deviations.

1. Introduction

There is a large focus on reducing the energy demand for heating of buildings in Europe. The European Parliament has defined the targets as a cut on energy consumption with 20% in 2020 and 50% in 2050. To reach these targets, the existing building stock is in need of energy retrofitting measures. One possible way of reducing the energy demand for heating is to use vacuum insulation panels (VIP) in the building envelope.

VIP consists of a porous core material encapsulated by a metalized multi-layered polymer film. The film is prone to

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damages and creates thermal bridges around the panels. The pristine thermal conductivity of the panel is 4 mW/(m K) but with regard to aging effects, a thermal conductivity of 7–8 mW/(m K) should be used in design calculations (Simmler et al., 2005). In case a panel is punctured the thermal conductivity increases to 20 mW/(m K) for a VIP with fumed silica in the core. Therefore it is important to ensure that panels mounted in the building envelope are undamaged and have the declared thermal conductivity.

In situ measurements of the thermal conductivity on the construction site are complicated with the techniques available today. On the other hand, at the VIP production plant, the thermal conductivity of the finished VIP can be measured by an indirect measurement method which is described by Caps (2004). The measurement method is integrated in the quality assurance process of the VIP production line. An integrated heat sink in the core material together with a fiber material of known thermal conductivity at different pressures makes it possible to determine the thermal conductivity of the panel. A warm sensor is placed on the surface of the panel, close to the heat sink, during a specified time period. The temperature decrease of the sensor is registered and with the known relation between the temperature decrease and thermal conductivity of the fiber material, the interior pressure of the VIP can be determined (Caps, 2004).

It is interesting to study whether the method described by Caps (2004) can be refined and if it is possible to use without the heat sink material for in situ measurements of VIP. In an earlier study Johansson et al. (2011) compared the temperature increase from the transient plane source (TPS) sensor with numerical three-dimensional simulations. The results showed that the TPS method could be modified to be feasible for VIP measurements.

This study aims to explore the TPS method further and investigate the applicability of the TPS method for measurements of thermal properties on VIP. A numerical simulation model in circular coordinates was used together with an analytical solution to calculate the temperature increase in the TPS sensor in two different setups. In the first setup the TPS sensor was clamped between two samples of pure polystyrene and in the second setup a thin aluminum film covered the polystyrene.

The TPS sensor used in the setup had a radius of 6.4 mm and was placed between two samples ($70 \times 70 \times 20\ mm^3$) of the material. A constant electric power of 0.02 W was conducted through the spiral and the electric resistance was registered and transformed into a temperature increase. The measurements are based on 8 subsequent measurements with 30 min break between.

2. The transient plane source method

Before introducing the measurements and modeling of the TPS method it is good to have knowledge of the measurement technique. The TPS method 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 spiral serves both as the heat source and as a resistance thermometer. The sensor is clamped between two samples of the same material and a constant electric power is conducted through the spiral. Heat is developed which 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).

A number of studies of comparisons between TPS method and steady-state measurement techniques have been described in the literature. Almanza et al. (2004) tested the TPS method on low-density polyethylene foams with different density. The results were compared to steady-state measurements using heat-flow meters. It was found that the results from the TPS method follow the same trends as the steady-state measurements. However, the values obtained with the transient measurements were always 20% higher than the steady-state results. Round robin tests of the steady-state method showed that it has a precision of $\pm 2.5\%$, while the precision of the TPS method still has to be evaluated. Furthermore, Almanza et al. (2004) discussed the sources of the deviation between steady-state and transient measurements. One of the suggested sources was the initial temperature gap between the heat flow sensor and the surfaces of the sample. By removing the first measurement points from the results, the deviation decreased by 7%. Other possible contributions to the deviation were the stiffness of the sample, differences in the average temperature in the sample and the different size of samples used in the two methods. Almanza et al. (2004) concludes that the TPS method is a powerful tool for comparative studies of thermal properties, but that the interpretation of the absolute values given by the method should be done with care.

Analytical solutions or numerical simulations can be used in the evaluation of thermal properties based on the temperature increase in a sensor during transient conditions. Model (2005) proposed a method for determination of the thermal properties of layered materials from the temperature increase from transient measurements based on an analytical solution using Green's function. The thermal properties for a given temperature increase and experimental setup was found using the Levenberg-Marquardt method. Model and Hammerschmidt (2000) used numerical models to simulate the influence of different boundary conditions when measuring with transient methods. The models showed good agreement with measurements and an open problem was solved using numerical models.

Carbon-filled nylon 6,6 composites were tested with the TPS method and compared to numerical finite-element analysis (Miller et al., 2006). The TPS method was evaluated for 5 s with a supplied power of 1 W. The sensor was a 3.5 mm radius Kapton encapsulated nickel sensor clamped between two samples of 63.5 mm diameter composite disks. FEMLAB was used for the numerical evaluation where the